Country CDR readiness assessment

Deployment potential

of carbon dioxide removal methods in France

2024

Study carried out by:

Carbon Gap

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Glossaire

BDD-BR: Database on the resource requirements of CDR methods, the result of collaboration between RMI and Carbon Gap

BECCS: Bioenergy with Carbon Capture and Storage.

CIMSE: Cultures Intermédiaires Multiservices Environnementaux (Multiservice environmental intermediate crops)

Citepa: Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique (Interprofessional technical centre for the study of atmospheric pollution)

CKD: Cement Kiln Dust

CCS: Carbon Capture and Storage (at emitting sites)

DACCS: Direct Air Capture with Carbon Storage

CDR: Carbon Dioxide Removal (CDR)

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC: International Panel on Climate Change

L-DAC: Liquid Direct Air Capture

Mha: Millions of hectares

MtMS: Million tonnes of dry matter

MtMB: Million tonnes of raw material

OAE: Ocean Alkalinity Enhancement

ONRB: Observatoire National des Ressources en Biomasse (National Biomass Resources Observatory)

OWP: Organic waste products

PPE: Programmation pluriannuelle de l'énergie (Pluriannual Energy Plan)

S-DAC: Solid Direct Air Capture

SDES: Statistical Data and Studies Department

SGPE: Secrétariat Général à la Planification Ecologique (General Secretariat for Ecological Planning)

SNBC: Stratégie Nationale Bas Carbone (National Low Carbon Strategy)

SNMB: Stratégie Nationale de Mobilisation de la Biomasse (National Biomass Mobilisation Strategy)

TRL: Technology Readiness Level

1. Executive summary

To achieve the objectives of the Paris Agreement and stabilise global warming well below two degrees Celsius, most countries must achieve climate neutrality by 2050 at the latest. In addition to reducing their emissions as quickly as possible, countries must rapidly develop their carbon dioxide removal (CDR) capacities to neutralise their residual emissions and prepare the net negative phase required to stay within the carbon budget.

However, it remains unclear how much CDR each country should deploy, what are their potential capacities for deploying CDR without tampering with their efforts to cut emissions, and finally how to achieve a rapid and fair deployment that is supported by civil society. This information is necessary to enable countries to plan for the deployment and use of CDR, and to avoid the risks of mitigation deterrence if some countries are tempted to rely more heavily on future deployment of CDR and reduce the pressure on short-term emissions reductions (1).

Providing answers

This report presents the results of the **"Country CDR readiness assessment"** project for France, carried out by Carbon Gap. The main objective of this project is to provide initial quantified answers to the questions mentioned above, to support countries in adopting ambitious yet responsible CDR objectives. The study proposes a bottom-up analysis of the resources available in France to estimate the theoretical and then achievable potential for deploying CDR methods. Because the deployment of new methods such as CDR is not just a technical issue, the study also looks at the 'social geography' to characterise the perceptions of stakeholders on this subject, including the general public. It is structured around the following steps:

1. Evaluation and **selection of the CDR methods** to be considered in the assessment;
2. Characterisation of **resource requirements** for the selected CDR methods;
3. Assessment of the maximum theoretical **availability** for each **of the resources** required for the CDR methods: renewable electricity, waste heat, biomass, capacity for geological storage of CO_2, etc...;
4. Estimation of the maximum **theoretical CDR potential**;
5. Evaluation of the French **regulatory, economic and political environment**;
6. Analysis of **societal perceptions** of the desirability of deploying CDR in France;
7. Estimation of the **practical CDR potential in France** up to 2050, with a cut-off point in 2030, based on three scenarios;

Significant potential

The various CDR methods, grouped into (i) biomass conversion, (ii) improved ecosystem management, (iii) electrochemical methods and (iv) geochemical methods, are all reviewed in the report, and their respective theoretical potentials are assessed based on the available resources. This "maximalist" assessment initially leads to a theoretical CDR potential of around 780 $MtCO_{2eq}$/year in France by 2050. This potential represents a theoretical maximum if all available resources were directed towards CDR, which would be unattainable in practice under current conditions.

Three possible scenarios

In drafting this report, the researchers applied additional constraints and more conservative assumptions on resource uses to identify the proportion of this theoretical potential that would be achievable under conditions close to the current situation. Three scenarios were then built and compared with the level of residual emissions anticipated by the SNBC2, i.e. 80 $MtCO_{2eq}$ of which ~30 $MtCO_{2eq}$ of fossil origin and ~50 $MtCO_{2eq}$ of biogenic origin. With the deployment of carbon capture and storage (CCS) at a level of 10 $MtCO_{2eq}$/year to intercept part of these residual emissions, natural sinks and CDR would have to neutralise around 70 $MtCO_{2eq}$/year for France to meet its carbon neutrality target by 2050. This assumption is used as a target value in the construction of scenarios.

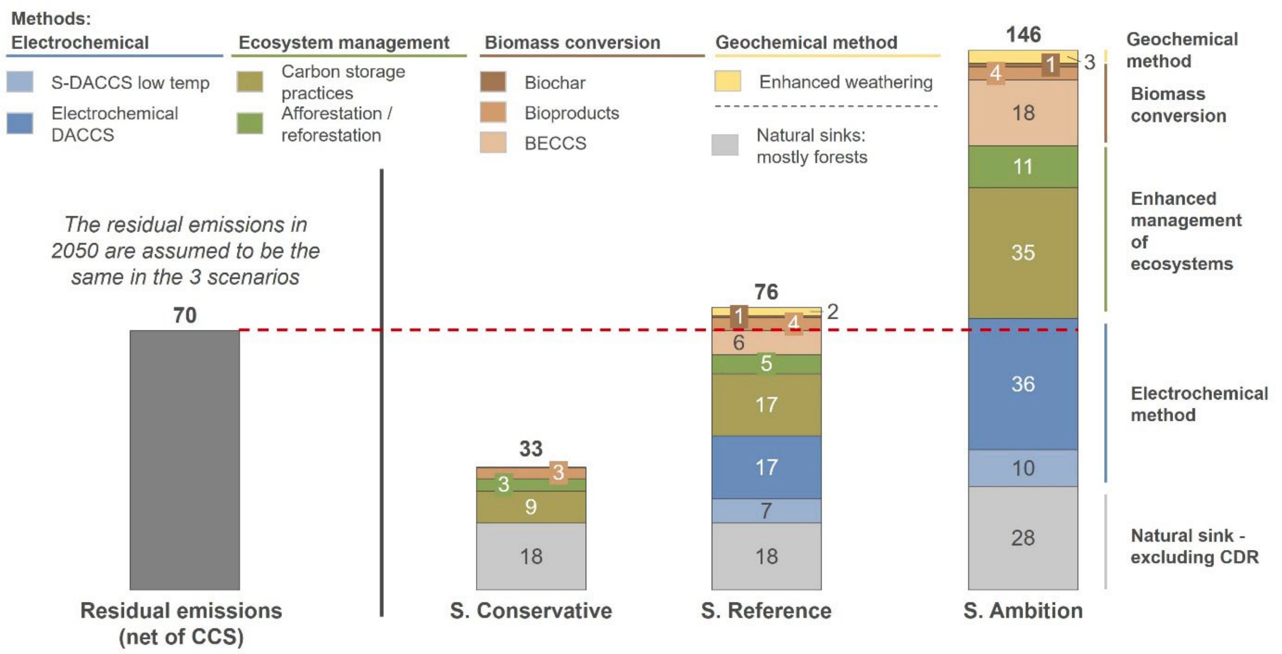

Figure R1 - Composition of the total carbon sink in the conservative, reference, and ambition scenarios in 2050, compared with the volume of residual emissions anticipated in the SNBC 2, in $MtCO_{2eq}$/year

In the '**reference**' scenario, France proactively diversifies its carbon sinks and achieves a CDR capacity of 76 $MtCO_2$ /year by 2050, slightly above the target, which provides a safety margin. This reference scenario uses the full range of CDR methods available. Direct air carbon capture and storage (DACCS) and carbon farming are the two CDR methods that enable the most CO_2 removal, in addition to natural sinks (remaining forests). Bioenergy with carbon capture and storage (BECCS) is also leveraged, but the biogenic CO_2 captured is largely directed towards the production of electro fuels instead of geological storage, thus limiting the CDR potential for this method. The reference scenario requires a CO_2 geological storage capacity of 40 $MtCO_2$ /year.

The '**ambition**' scenario describes a trajectory in which France commits faster and more strongly to CDR, allowing it to harness more of the achievable potential, and to reach CDR capacities of almost 146 $MtCO_2$ every year by 2050. This scenario would enable France to either exceed its decarbonisation targets and thus become net negative before 2050, or to compensate for a higher-than-expected level of residual emissions, linked to a delay in the decarbonisation trajectory adopted by France. To achieve these higher CDR volumes, more CO_2 geological storage capacity will need to be unlocked which, in this scenario, amounts to ~75 $MtCO_2$ /year. In addition, more resources are used by the various CDR methods, particularly for renewable electricity, where the needs raised from around 20 TWh to almost 30 TWh. BECCS is also much more heavily used in the ambition scenario, contributing to eliminating 18 Mt CO_2 each year, compared with just 6 Mt CO_2 in the reference scenario.

The third scenario, called '**conservative**', describes the status quo, a scenario in which France invests less and later in CDR, with weaker assumptions about public support and technical readiness of certain CDR technologies. Decarbonised electricity for CDR is not available, as France is too far behind in decarbonising its production and meeting the decarbonised electricity needs of other sectors. Geological storage capacity remains limited and can only meet the needs of CCS. In this scenario, all the carbon sinks available to France are of limited permanence and are not sufficient to achieve carbon neutrality. Nearly 45 Mt CO_{2eq} would still be emitted each year in 2050

Reaching durable net zero

By diversifying the CDR methods deployed, the reference and ambition scenarios make it possible to achieve net zero by 2050. France could even go beyond and become net negative before 2050 if, at the same time, the official decarbonisation targets were met. These scenarios also make it possible to achieve "durable net zero", a state in which residual emissions are offset by CDR according to the "like-for-like" principle, whereby the origin of residual emissions is matched by the level of permanence of the method used.

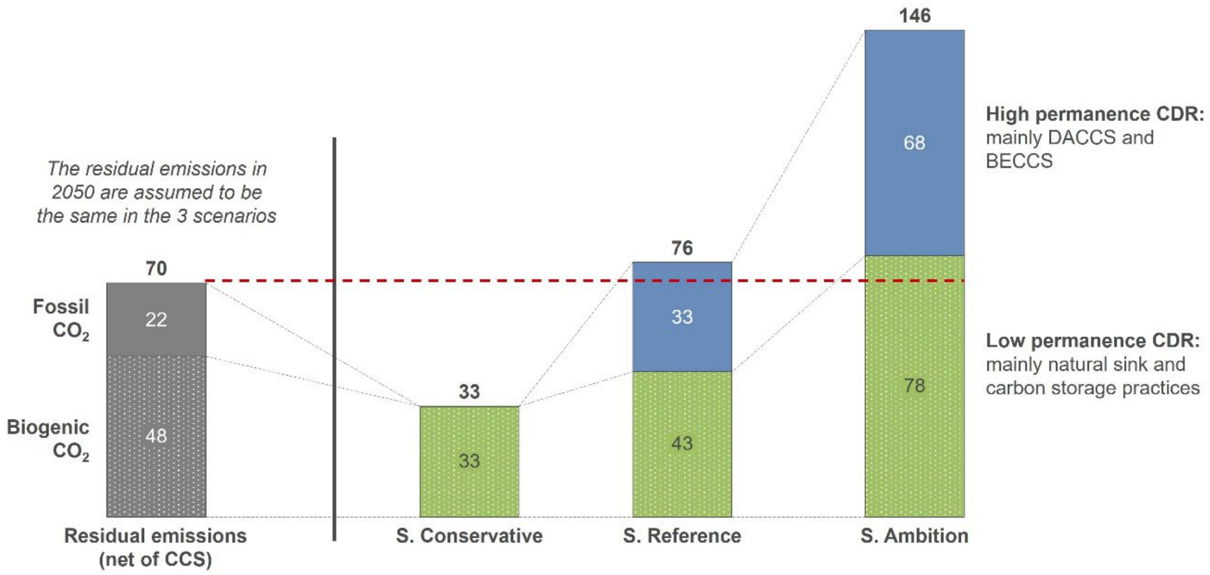

Figure R2 - Comparison of the origin of residual emissions with the permanence of carbon sinks mobilised in the three considered scenarios, in $MtCO_2$/year

A portfolio approach

The proposed deployment scenarios leverage a variety of CDR methods. Nevertheless, the study clearly shows that the availability of geologic storage capacity, the availability of additional decarbonised energy, and the level of remuneration for carbon farming practices are the main limiting factors for a deployment at scale.

Proactive, coordinated policies are needed to remove these obstacles and build a regulatory environment that provides the necessary guarantees for a responsible use of CDR. Given the diversity of methods and the multiple dependencies on related sectors (such as energy), it seems important to build a genuine French CDR strategy that would enable France to meet its climate commitments while harnessing the benefits of the chosen CDR activities and their organised development throughout the territory.

2. Introduction

As climate change accelerates, causing more and more damage, many governments and private players have committed to achieving net zero by the middle of the century. Therefore they must reduce their emissions as much as possible and as quickly as possible, but also **plan for sufficient carbon dioxide removal (CDR) capacity to neutralise their residual emissions**.

Carbon dioxide removal (CDR) refers to 'a set of human activities aimed at **removing CO_2 from the atmosphere and storing it permanently** in geological reservoirs, on land or in the oceans, or in products' (2). These activities generate 'negative emissions' and are considered as the third pillar of climate action: reduce, adapt, remove.

CDR differs from two other, better-known families of carbon management methods: carbon capture and storage (CCS) and carbon capture and utilisation (CCU). As opposed to CDR, these methods allow for reducing emissions from high-emission sites and recycling CO_2, but do not generate negative emissions.(3)

In its sixth assessment report, the IPCC forecasts the need to remove several hundred billion tonnes of carbon dioxide by the end of the century, in order to stabilise climate change at levels compatible with the Paris Agreement. Recent reports continue to confirm the need to deploy large-scale CDR before mid-century(4; 5).

Yet, no government currently has a robust plan for developing and deploying CDR at the scale suggested by the IPCC. There are many reasons for this policy gap, among them **the lack of clarity on the volumes of CO_2 countries should remove (targets), the CDR capacities that they can deploy (potential), and how to deploy them (strategy)**.

Indeed, most estimates of the targeted volumes of CDR are given at the global scale, and there is a lack of data to determine what is achievable at the level of each country. Current estimates of the amount of CDR that can be deployed are also most often based on modelling(6) focusing on only a few CDR methods at a time(7) and fail to account for the competition uses of resources and reconciliation issues(8). These estimates are also largely technical and pay little attention to the social aspects such as the levels of awareness and public support(9). Addressing these questions is not only crucial in determining the amount of CDR that could be deployed, but the picture also varies a lot from one country to another.

In order to draw up a realistic plan and accelerate the deployment of CDR techniques, it is necessary to undertake a bottom-up assessment of existing resources and their level of availability on a country-wide scale, and to consult the key players and the general public in each country.

To fill this information gap and help countries accelerate the deployment of CDR, **Carbon Gap is conducting the Country CDR readiness assessment project**. Inspired by the Renewables Readiness Assessments(10) published by the International Renewable Energy Agency, this project aims to estimate the potential for CDR deployment at national level, and to co-create country-specific roadmaps. These roadmaps seek to describe in detail what is needed to successfully deploy CDR on a significant scale and are drafted with the active participation of national stakeholders in each country, in order to help decision-makers identify the opportunities that exist and the actions that need to be taken to implement them.

This report presents a bottom-up assessment of the potential for CDR in France and proposes an optimal portfolio of CDR methods to be deployed.

The report begins with an **overview of the existing CDR methods**, explaining how they work and why some have been excluded from this study. For the selected methods, we then look at their resource requirements to operate and produce negative emissions (energy, water, land, storage, etc.). The data on these requirements has been compiled in a database, which methodology and results are presented.

The report then looks at the **availability of the various resources needed**, assessing existing fluxes while considering constrained volumes and priority uses. Beyond just a snapshot of a resource at *a given* time, we also analyse possible trends in the near future, in particular to assess whether additional volumes can be mobilised without compromising existing uses.

To complete this first part of the report, **the current regulatory environment is analysed** in order to identify the factors that favour and hinder the development of CDR.

By combining the maximum volumes of resources theoretically available with the requirements of the CDR methods set within the limits of the regulatory framework, we obtain **an estimate of France's theoretical maximum potential for deploying negative emissions**. This highly theoretical result concludes the first part of the report.

In the second part of the report, the objective is to refine the working hypotheses to produce an estimate of the practical (achievable) potential. Using published data, the report provides an overview of the structure of the French economy, its political landscape, and attitudes towards the issue of climate change, as well as documented characteristics of French society. The report also describes information gathered during a citizens' panel held in Rennes in November 2023, as well as during more than fifteen targeted interviews conducted with strategic stakeholders in CDR development to complete this **analysis of the 'social geography' of France on the issue of CDR**.

Finally, the assumptions about the availability of resources are revisited to take into account the elements documented in this second part and to quantify **the practical potential of scaling CDR** on the basis of the elements known today. This analysis makes it possible to propose **three scenarios reflecting different levels of ambition that are achievable** without major changes to current conditions.

This report has been used as the basis for developing **a roadmap of actions required to accelerate the deployment of CDR in France**, which was prepared by the project team, together with a sample of key stakeholders in France. The roadmap is published in a separate document.

This report was prepared by a team from **E-CUBE** in collaboration with the **Carbon Gap** team and with the support of **RMI**'s CDR initiative, as part of the "Country CDR readiness assessment" project coordinated by Carbon Gap and funded by the **Grantham Foundation**.

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3. Carbon dioxide removal methods and their resource requirements

3.1. The diversity of CDR methods

There is a wide variety of CDR methods, which can be classified into four categories; (1) biomass conversion methods and (2) enhanced ecosystem management methods rely on the natural process of photosynthesis to extract CO_2 from the atmosphere, whereas (3) electro-chemical methods rely on the use of synthetic materials in industrialised processes to treat large volumes of air and selectively extract CO_2. Finally, (4) geochemical methods are based on natural reactions between gases, water, and rocks at the earth's surface.

France has a wealth of ecosystem, geological, maritime, and low carbon energy resources. This diversity of resources provides potential access to all CDR methods.

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3.1.1. Biomass conversion methods

This family of methods is based on the natural ability of plants to capture atmospheric CO_2 through photosynthesis and store it in their biomass. The carbon stored in this way forms part of the short carbon cycle (11) and is normally rapidly remobilised along trophic chains before returning to the atmosphere when the biomass is degraded. The challenge is therefore either to extract the carbon contained in the biomass in order to store it, or to stabilise the biomass to prevent its degradation.

In this report, bioenergy with carbon capture and storage (BECCS) covers two approaches to extracting carbon from biomass: combustion and fermentation (or anaerobic digestion).

Biomass **combustion produces energy but also emits** exhaust gases that are relatively concentrated in CO_2 (typically 10 to 16%vol), which can be treated by a CCS process to recover and store the CO_2. Many power plants, boilers and furnaces already burn biomass for its heat, but without intercepting the emitted CO_2. By adding a capture module, these sites could be rapidly converted from sources to sinks, with a CDR potential of around 200 $MtCO_2$ /year in Europe(7).

Fermentation is another way of extracting carbon from biomass through microbial digestion. The biogas produced is a mixture of methane, CO_2 and water that can be purified to separate the three gases. Today, some agricultural anaerobic digestion plants and even wastewater treatment units already carry out this process so that the methane can be reinjected into the natural gas network. Pure CO_2 is released into the atmosphere but could be liquefied for transport and storage.

A first approach to **stabilising biomass** is to use it in long-lasting biobased products, mainly timber. Since trees have accumulated carbon from the atmosphere during their growth, using wood products conserves this carbon and prevents it from being re-emitted when the tree dies and decomposes. Wooden houses are an example of carbon sink associated with this CDR method.

It is also possible to bury the biomass to protect it from the biological and chemical agents responsible for its degradation on the surface. One method is to cultivate algae and then bury them at the bottom of the ocean, at depths sufficient to guarantee the stability of the biomass, or to dry them and then store them in natural or specially created cavities.

Finally, the process of pyrolysis (combustion without oxygen) converts biomass into **biochar and/or bio-oil**. Pyrolysis recombines the carbon atoms into more stable molecules, making the biochar inert and thus a durable carbon storage solution. Biochar can be stored, spread on soils to provide improved water and nutrient retention, or used in industry as a building material. Generally speaking, the use of biochar leads to numerous co-benefits, which are only partially covered in this report. For example, in the case of agricultural or forestry soils, it stimulates soil life, which can increase biomass production from plants on the surface. In this way, biochar can potentially form a positive feedback loop: increasing biomass growth and further enhancing carbon sequestration.

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3.1.2. Enhanced ecosystem management methods

Ecosystems naturally exchange and store carbon within a short carbon cycle. Depending on their state, they can either capture more carbon than they emit and act as carbon sinks, or they can act as a source of emissions. Some ecosystems are richer in carbon than others, particularly peatlands and mangroves.

For ecosystems to sequester carbon and generate negative emissions, humans can implement improved management to maintain these ecosystems in optimal conditions (known as carbon storage practices), or even increase the surface area of these ecosystems by changing land use.

Carbon storage practices

Depending on the ecosystem, different strategies can be adopted to preserve or increase their natural capacity to remove carbon dioxide.

Carbon storage practices in forests

Forest carbon storage practices refer to biomass harvesting and forest management. Specifically, the practices related to biomass harvesting are:

- Stop/avoid harvesting forest biomass, such as stumps and tops (branches and twigs).
- Limit thinning (cutting) at a rate of less than 35%(12).

The first practice aims to leave as much biomass as possible to decompose in the forest to stimulate carbon storage in forest soils. The second is to avoid cutting down all the trees in a forest at the same time. In fact, it is preferable to cut only a proportion of the trees (less than 35%) at once to avoid disturbing the soil too much and causing a loss of carbon storage.

Carbon storage practices linked to forest cover management consist of:

- Favouring natural regeneration of a forest over planting;
- Reducing the need for mechanical preparation (ploughing, trenching) when planting new trees and assisting the regeneration of a forest;
- Increasing the density of trees in the forest;
- Increasing the diversity of the population;
- Favouring tree species that store the most carbon;
- Favouring the renewal of trees with the “high forest” method instead of ‘thicket’;
- Favouring forests with several age groups;
- Increasing the time between regeneration of the forest and the final cut;
- Adding nitrogen fertilisers to forest soils.

Carbon farming practices

The agronomic management of various crops can be improved to foster carbon storage in soils. INRAE (the French national research institute for agronomy and environment sciences) has identified six **agricultural** practices that significantly improve the soil carbon content and that are sufficiently documented in the literature:

1. The development of **agroforestry** on cultivated plots involves combining trees with crops or pasture to increase carbon capture and storage capacity per hectare;
2. The introduction of **temporary grassland** into arable crop rotations or extending the duration of grassland in rotations that already include it;
3. The use of **intermediate crops** involves inserting more intermediate crops between the harvesting of a main crop and the sowing of the next one or extending the duration of intermediate crops when they are already used by farmers;
4. A switch to **direct seeding and abandoning ploughing** involves sowing directly into the residue of the previous crop, without prior tillage;
5. The spreading of new **organic resources** not previously spread on agricultural soils;
6. **The planting of hedges** to increase the number of trees and shrubs sequestering carbon.

For more details on these practices, see appendices 10.3 of the INRAE study(12).

Carbon farming in vineyards

The main carbon farming practice in vineyards is **cover cropping**. This practice consists of planting grassy areas between rows of grapes. This grass cover may be permanent or present only in winter. Grass cover has long been practised in all French vineyards. However, it is not a statutory requirement. Winegrowers have mastered this practice, which enables them to control weeds, improve the biological functioning of the soil, increase the amount of organic matter in the soil and reduce erosion.

Carbon farming practices in grassland

The first practice consists of **replacing mowing with grazing** to increase offtake and stimulate meadows. Increasing the number of grazing days improves the condition of the grassland canopy, allows organic matter to return to the soil via animal restitutions and improves soil structure and chemistry as well as the activity of enzymes and communities of soil micro-organisms, which are essential in the process of storing carbon in the soil.

The second practice involves a **moderate increase in mineral nitrogen fertilisation** of permanent grassland (+50 kgN/ha/year), especially for permanent grassland that does not currently use any. This practice helps to stimulate the regrowth of grassland after winter or after a past harvest to increase grass production. Doing so increases the return of organic carbon to the soil, which improves the negative CO_2 emissions generated by permanent grassland. It is important to note, however, that nitrogen fertilisers are currently manufactured by producing hydrogen through the steam reforming of (fossil) natural gas, which is used in the production of NH_3 ammonia, ultimately transformed into various nitrogen fertilisers. The decomposition of these nitrogen fertilisers in the fields releases N_2O, a powerful greenhouse gas (global warming power of 310) (13). Dosage must therefore be optimal to minimise losses.

Carbon storage practices in peat bogs

Peatland restoration practices involve restoring historically damaged peatlands and preserving those that are in good condition. Restoring peatlands generally involves putting water back into the damaged peatland by removing drains and building “peat dams”. Artificial drainage of peatlands for agriculture, forestry or to clean up these environments has seriously degraded peat bogs by aerating the soil and increasing the decomposition of organic matter, which has led to carbon emissions into the atmosphere.

Carbon storage practices in mangroves and seagrass

The **practices used to store carbon in mangroves and seagrass** are often referred to as “blue carbon”. They mainly involve protecting these natural ecosystems to slow down their degradation or even allow them to regenerate.

Change in land use

In addition to improved management of existing environments, it is possible to convert areas to increase the surface area of carbon-rich ecosystems.

On land, increasing the area of forest increases the natural carbon sink, because forests store carbon in the soil and *via* the biomass contained in living trees (trunks, branches and foliage) and dead wood. They enable the production of wood products in which carbon is also *ultimately* stored. Afforestation is the process of planting trees where there were none before, and reforestation is the process of restoring forests in areas where trees have been cut down or degraded. It is important not to confuse CO_2 sequestration (annual carbon flow in kgC/ha/yr) in forest ecosystems with the total carbon stock of a forest (tC/ha).

Peatlands are special wetlands which, according to the government’s Statistical Data and Studies Service (SDES), *‘store more than twice as much carbon as all the world’s forests […] even though they currently cover only 3% of the Earth’s surface’* (14). In continuously waterlogged soils, organic matter from plants only partially decomposes and carbon accumulates over the long term. An increased surface area of peatlands could enable more carbon to be stored. However, suitable peatland areas are rare, so the potential is limited.

Within marine environments, **mangroves** are unique coastal ecosystems that store CO_2 from the air through photosynthesis. Mangroves absorb CO_2 from the air and transform it into organic carbon, which they use for their growth and development. The reconstruction of mangroves that have been damaged or destroyed in the past could lead to an increase in the elimination of CO_2.

Seagrass beds are underwater meadows of aquatic grasses that develop in shallow waters along coastlines. These marine ecosystems act as carbon sinks by capturing carbon dioxide from the atmosphere through photosynthesis and storing it in the form of organic matter in the plant tissues and roots of the seagrass beds. Unfortunately, like mangroves, seagrass beds are facing increasing threats from pollution, coastal development and climate change itself. Measures to increase the area of seagrass beds would help to increase natural carbon sinks.

Fertilising the oceans with iron is another solution that was studied in the 2000s. The idea is to spread fine iron powder in specific areas of the oceans where this element is the limiting growth factor of phytoplankton, in order to increase photosynthetic activity and therefore the absorption of atmospheric CO_2. However, the large-scale experiments that have been carried out have produced mixed results, with the phytoplankton bloom causing major destabilisation of local ecosystems and much of the carbon captured being rapidly re-released as the biomass produced degrades.

3.1.3. Geochemical methods

In the natural carbon cycle, spontaneous geochemical reactions between the atmosphere, rocks and water enable long-term storage of carbon in the earth's crust and in the oceans. This family of CDR methods aims at accelerating these relatively slow natural processes. They include enhanced weathering (EW), ocean carbon removal methods such as ocean alkalinisation, and artificial surface/deepwater pumps.

Enhanced rock weathering is a CDR approach that aims to accelerate the natural dissolution of alkaline rocks rich in calcium, magnesium and iron with the carbonic acid generated by the dissolution of atmospheric CO_2 in rainwater. The dissolution of these rocks releases cations and converts the carbonic acid into bicarbonate ions. Ultimately, these chemical substances in solution migrate to the oceans via rivers and stimulate the natural mineralisation process whereby the CO_2 initially dissolved in rainwater is sequestered in carbonate minerals. Some examples of weathering reactions are shown below for the most reactive minerals (Figure 1):

olivine	$Mg_2SiO_4+2CO_2 \rightarrow 2MgCO_3$
pyroxenes	$CaMgSi_2O_6+2CO_2 \rightarrow CaMg(CO_3)_2+2SiO_2$
serpentine polytypes	$Mg_3Si_2O_5(OH)_3+3CO_2 \rightarrow 3MgCO_3+2SiO_2+2H_2O$
brucite	$Mg(OH)_2+CO_2 \rightarrow MgCO_3+H_2O$

Figure 1 - Mineralization reactions caused by the dissolution of certain silicate minerals (National Academies of Sciences 2019)

To accelerate the kinetics of these reactions, the specific surface area of these rocks needs to be increased. To that aim, the rocks can be crushed to a particle size of between 1 µm and 100 µm (15) but this requires energy.

Carbonate rocks are a special case; activated lime and magnesium oxide, which are used as agricultural soil improvers, react spontaneously with ambient CO_2 to form calcite or magnesite, and therefore have the capacity to eliminate atmospheric CO_2. However, they are produced by calcination of calcite or magnesite, a reaction that releases fossil CO_2, according to the following reactions:

$$CaCO_3 \rightarrow CaO+CO_2$$
$$MgCO_3 \rightarrow MgO+CO_2$$

For the process to be net negative, we would therefore need to capture the fossil CO_2 released during calcination using CCS modules and store this CO_2 in geological reservoirs, then allow the activated lime and magnesium oxide to mineralise ambient CO_2.

Different versions of this method exist, depending on whether the crushed rock is spread on land (e.g. on agricultural land), or along the coast to take advantage of the natural crushing provided by the tide.

Alkalinisation of the oceans is a second approach that aims at increasing the capacity of the oceans to store CO_2 in dissolved form. Alkalinity can be understood as the ability of a solution (in this case ocean water) to neutralise an acid. CO_2 dissolved in water produces carbonic acid, which is responsible for the acidification of the oceans. By artificially increasing the alkalinity of the oceans, we can counteract this phenomenon and increase the quantity of CO_2 the ocean absorbs.

Mineral ocean alkalinisation involves spreading fine alkaline rock powder in the ocean. As it dissolves, it neutralises carbonic acid into bicarbonate ions and increases the alkalinity of seawater. As a result, an exchange of CO_2 from the atmosphere to the ocean takes place to rebalance the partial pressures of CO_2 at the ocean/atmosphere interface. The CO_2 in the atmosphere is then ultimately trapped in the form of the bicarbonate ion HCO_3- in the ocean in a stable form. The main dissolution equations involved in ocean alkalinisation are as follows:

$$CaCO_3+CO_2+H_2O++2HCO_3-$$
$$Mg_2SiO_4+4CO_2+4H_2O \rightarrow 2Mg_2++4HCO_3-+H_4SiO_4$$

However, this approach suffers from slow kinetics due to the slightly basic pH of the ocean.

Electrochemical ocean alkalinisation involves electrochemically separating the acidic and basic phases of seawater, removing part of the acidic phase which must then be neutralised, and then recomposing the seawater with a composition identical to that of the water removed, but with increased alkalinity. Increasing the alkalinity allows CO_2 to be absorbed according to the following reaction:

$$CO_2 + HO^- \rightarrow HCO_3^-$$

The artificial surface/deepwater pump is called *"artificial upwelling & downwelling"*. It refers to two solutions: *upwelling and downwelling*.

"Upwelling" involves using pipes or other methods to pump water from the nutrient-rich depths of the ocean to the surface, where it has a fertilising effect and stimulates the growth of phytoplankton, which consume CO_2 as they grow. *"Downwelling"* involves carrying out the reverse flow, i.e. transferring carbon-rich surface water to the deep ocean to encourage the physical transfer of carbon from the atmosphere to the ocean (2).

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3.1.4. Electrochemical methods

This last family of methods is based on synthetic processes that make it possible to selectively extract CO_2 directly from air or water.

The direct capture of CO_2 from the air, known as Direct Air Capture (DAC) or Direct Air Capture with Carbon Capture and Storage (DACCS), refers to industrial processes that absorb CO_2 from the atmosphere. The CO_2 can then be stored underground in geological reservoirs. The main current technologies for capturing CO_2 use synthetic solid sorbents (S-DAC, requiring low-grade heat at 80°C - 100°C to regenerate the sorbent), or liquid solvents (L-DAC, requiring high-grade heat of 300 - 900°C to regenerate the solvent). Other technologies are emerging (TRL 6), such as electrochemical DACCS, which do not require heat to operate. (16).

The direct capture of CO_2 from the ocean refers to the extraction of CO_2 from seawater (with storage). This process can be achieved by creating a vacuum over the seawater. Removing CO_2 from the ocean surface causes the water to become undersaturated, forcing CO_2 present in the atmosphere to dissolve in the ocean to restore equilibrium. It can also be achieved by temporarily acidifying seawater with a mineral acid, or by electrodialysis and electrolysis to convert bicarbonate ions (HCO_3-) into CO_2 (2) thus forcing its degasification.

3.2. Selected CDR methods

There are many CDR methods, and not all are at the same stage of development. While many are still at an early stage of maturity, and therefore still need to be proven, others, such as ocean iron fertilisation, have faced counter-performances, and have been sidelined. In this study, the methodological choice was to consider all the methods likely to be developed in the near future. TRLs are obviously a valuable indication. However, some methods, such as electrochemical DACCS, are progressing faster than reported in the literature, with demonstrators already operational. Such methods have therefore been included.

The CDR methods mentioned below were included in the study, while seaweed burial, ocean fertilisation and upwelling/downwelling where excluded as the benefits of these methods have not been sufficiently demonstrated in the literature.

The IPCC presents an overview of the various CDR methods with their possible implementations, the means of storage (mineral, geological, soil, marine sediment) and the duration of carbon storage (centuries, millennia, etc.). The selected methods, the means of storage and the duration of storage are shown in Figure 2.

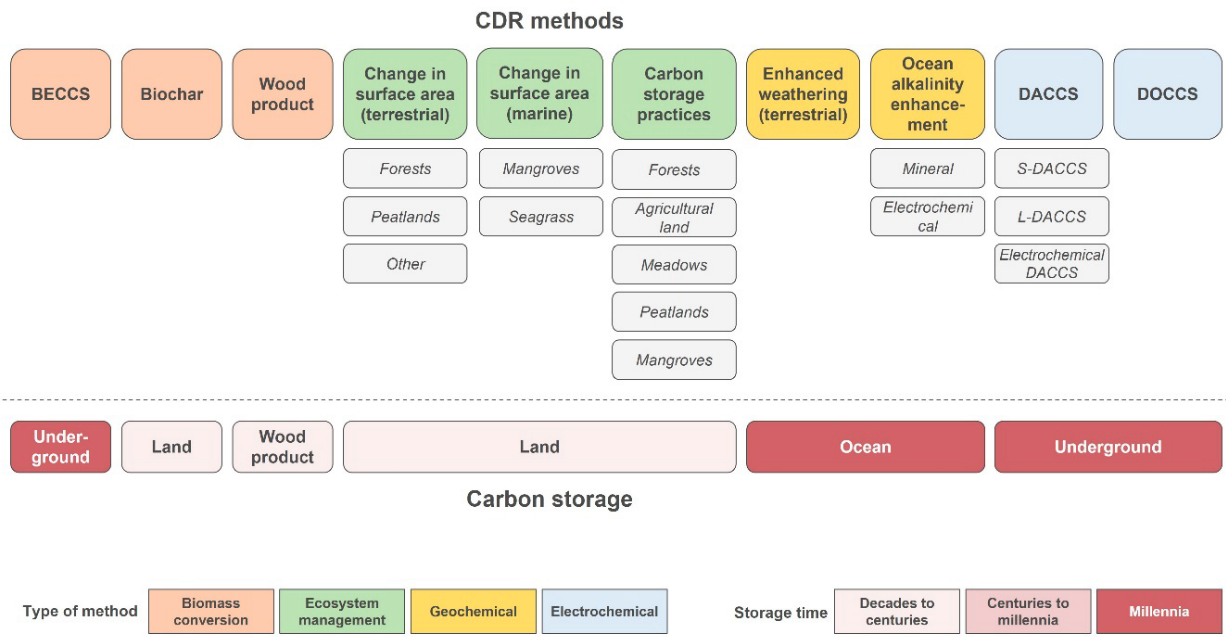

Figure 2 - Overview of selected CDR solutions. Adapted from (2)

An essential characteristic of CDR methods is the duration of carbon storage they allow. A distinction is thus made between CDR methods with temporary storage (or low permanence) and methods with long-term storage (or high permanence). While all methods are necessary, the climate benefits created by these two categories are different. This criterion is used in Part 8 to compare the level of permanence of the proposed CDR portfolio with the nature of the residual emissions that France anticipates for 2050.

3.3. Resource requirements for selected CDR methods

To estimate the deployment potential of each of the methods considered, we need to know their resource requirements, for example how much water, how many hectares of land or megawatt hours of electricity are needed to remove one net tonne of CO_2. There are two challenges to accurately quantifying these requirements:

- There is a wide diversity of methods, with several variants in each "family" that can be significantly different.
- Data is still scarce as most methods are still in very preliminary stages of development and there is a lack of field data.

In addition, it is necessary to compare methods on a common basis. All carbon removal methods generate some greenhouse gas emissions in their operation. It is therefore necessary to quantify resource requirements on the basis of a net tonne , i.e. once the emissions generated by the process have been deducted from the gross volumes. Therefore, we are mostly interested in quantified data based on a life cycle analysis (LCA) of the process.

Such data can be found in the scientific literature with the advantage of being published with details of the method used to produce them, and of having undergone a peer review process. On the other hand, the majority of studies are based on laboratory-scale experiments or modelling, which is itself based on a limited amount of data. The relevance of these data in real-life conditions is therefore uncertain. Furthermore, very few scientific studies include an LCA.

Data from "doers", i.e. companies launching demonstrators or even those already in business, is rare but does exist. It can be found, for example, in the application files for the Frontier fund, which are publicly accessible (17). This data comes from actual projects and therefore better represent today's performance of the CDR methods. On the other hand, there is less information on how they are obtained, and they could be considered as "declarative" since they were not peer reviewed.

To build a database to estimate these resource requirements, Carbon Gap teamed up with RMI. Given the difficulties mentioned above, the team chose to build its database on three pillars: scientific literature, data from Frontier applications (three cohorts) and a survey conducted directly with CDR operators.

The database will continue to evolve after the publication of this report, but at the time of publication includes:

- 333 data points obtained from 87 scientific articles;
- 90 data points obtained from 67 Frontier files;
- 46 data points obtained from 11 survey responses.

Figure 3 gives an overview of the data collected on mineral requirements for enhanced weathering and on energy consumption for DACCS and DOCCS. It also illustrates the challenges mentioned above, with significant variability depending on the source, and a regular bias in the scientific literature towards optimistic values.

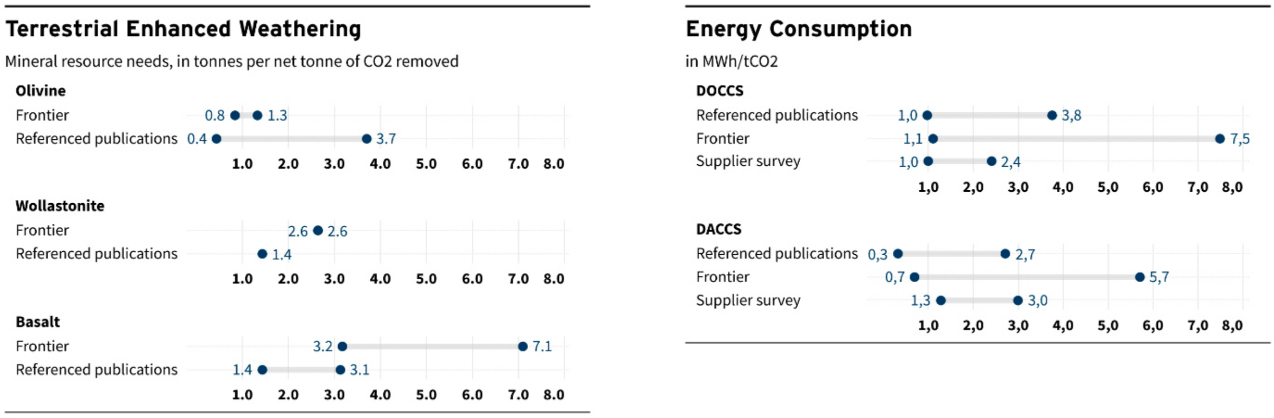

Figure 3 Overview of data collected on resource requirements for enhanced weathering (left), DACCS and DOCCS (right).

The data was compiled to produce consolidated values for each of the resources required for CDR methods. These values are used in the rest of the report to estimate the potential of CDR methods based on the available resource feedstocks.

4. Availability of the resources required to implement CDR methods

In this section, the availability of the physical resources required to implement the selected CDR methods is assessed, to determine their current level of availability, and the prospects for the foreseeable future (growth, stagnation, or decline). Where possible, the geographical distribution of each resource is also characterised.

Each of the following sections focuses on a resource and begins with a summary of the results, before presenting the methodology used in more detail

4.1. Decarbonised electricity

In a nutshell

The estimate of the theoretical availability of decarbonised electricity is largely based on the work published by Réseau de Transport d'Electricité (RTE) in the report *'Futurs énergétiques 2050'* (18). In the long term (2050), up to 382 TWh of decarbonised energy could be made available. Photovoltaic energy, offshore wind, and onshore wind would be the main sources for such potential. To reach such volumes, the development of these renewable energies was pushed to the maximum. This estimate is based on a scenario of maximum consumption: 'deep reindustrialisation' type, to preserve existing uses and anticipate electrification of many processes. If this potential (382 TWh) were to materialise in 2050, it could, in theory, be allocated to CDR, which would then become the main consumer of electricity in France, ahead of industry and the residential sector, as shown in figure 4 .

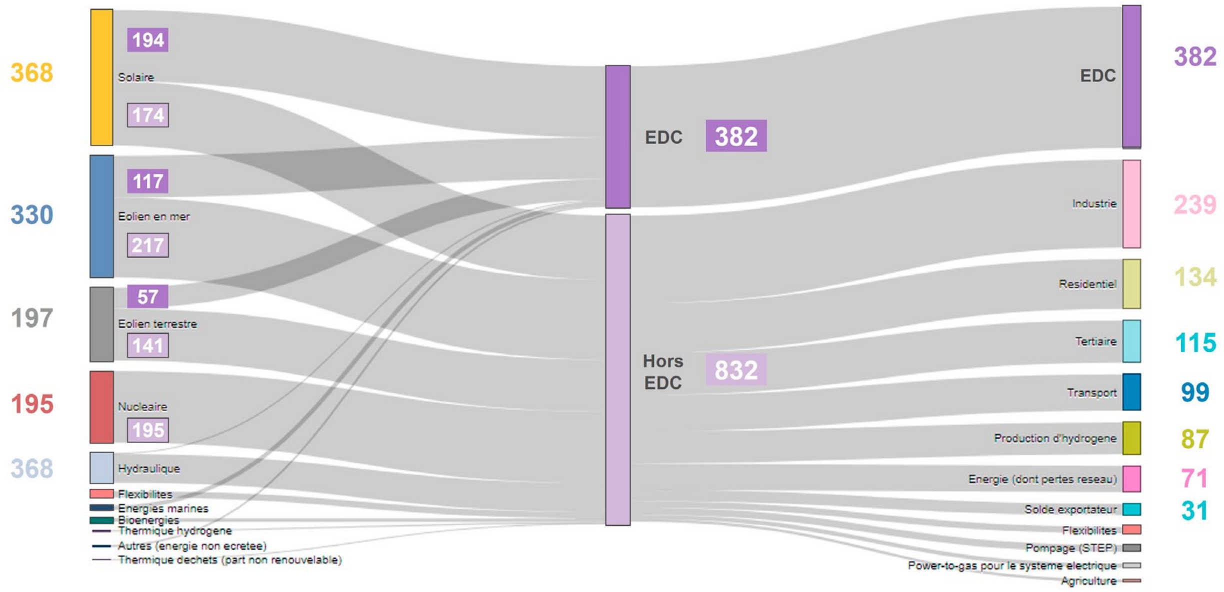

Figure 4 - Long-term (2050) electricity production (left) and consumption (right) (in TWh) and the available electricity for CDR technologies

A breakdown of the electricity consumed by the various CDR methods will be provided in part 5 of the report.

Detailed methodology

The methodology used to estimate the potential is based on the RTE report "*Futurs énergétiques 2050*", based on six electricity generation scenarios for 2022-2050: M0, M1, M23, N1, N2 and N03. The first three show a strong development of renewable energy, while the other scenarios show a balanced development between renewable energy and nuclear power. Scenario N03 is the most ambitious in terms of nuclear power development. Three consumption trajectories are explored, a reference trajectory (or trend), a reduced demand scenario and a "deep reindustrialisation" scenario in which electricity consumption increases to a maximum due to the needs of relocated industry.

The methodology for estimating the volume of electricity available for CDR can be summarised as follows:

1) Collect production data by energy source from the six RTE scenarios in 2060;
2) Choose the average of scenarios N1 and N2 as the reference scenario;
3) Identify and collect the maximum production values for each of the renewable energies in all the scenarios;
4) Sum the maximum production of all renewable energies to obtain a maximising scenario;
5) Subtract the volume of decarbonised electricity generated in the reference scenario from the maximising scenario to quantify the extra capacity that it would theoretically be possible to generate by deploying all renewable energies to the maximum.

Box 1 - Methodology for estimating electricity generation

To estimate the maximum decarbonised electricity production, the authors used the **maximum production potential** for each source among the six RTE production scenarios (M0, M1, M23, N1, N2 and N03) in 2060. They obtained the reference value by averaging the N1 and N2 scenarios, as these scenarios appear to be the most realistic in light of recent statements by the French government regarding the construction of new nuclear reactors in France, in particular the speech given by French President Emmanuel Macron in Belfort on 10 February 2022 (speech transcript). In the rest of this report, the authors use the average scenario between N1 and N2 as the "**baseline**" scenario.

The maximum production scenario described above was then compared with the "baseline" scenario. The difference between the volume of decarbonised electricity produced in the two scenarios gives an estimate of the additional production potential. In addition, it is assumed in the analysis that the addition of a large number of CDR units in France would make it possible to absorb surplus renewable electricity production. All curtailed energy is therefore channelled to CDR in our analysis.

With this approach, the decarbonised electricity production (reduced from curtailed electricity) would be 615 TWh in the 'baseline' scenario (to 2060) and 997 TWh in the maximum production scenario. The difference between the two scenarios gives a value of 382 TWh for the electricity available for CDR (up to 2060).

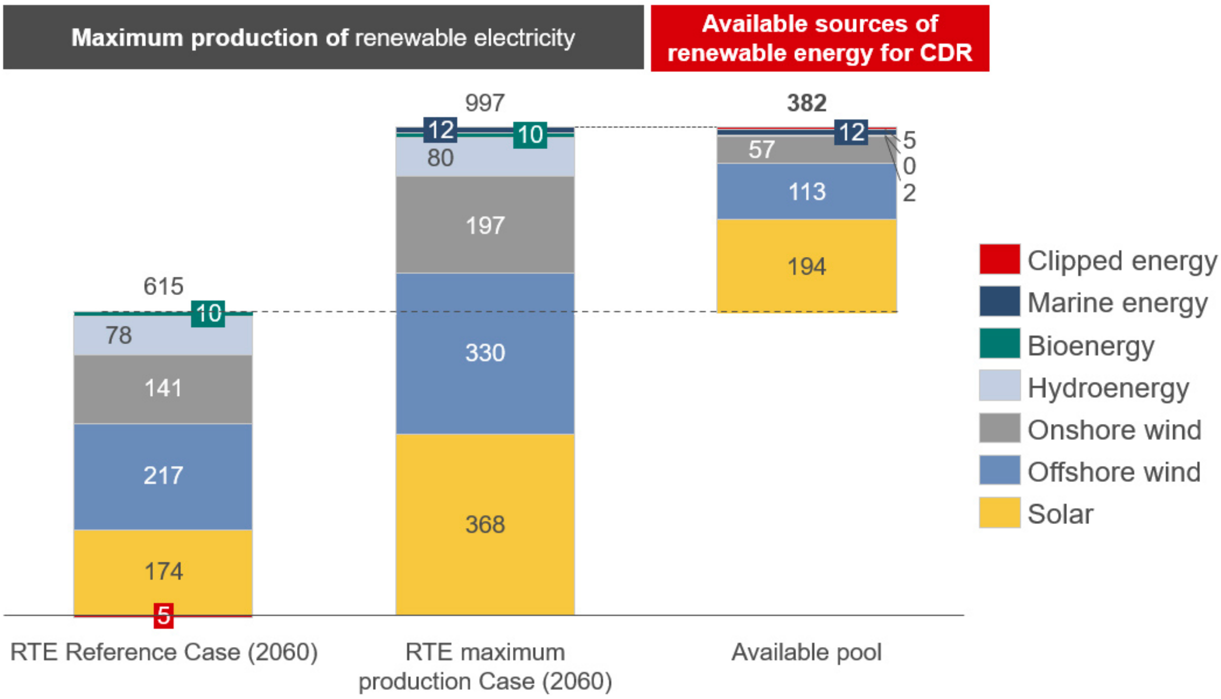

Figure 5 - Estimated maximum production and renewable electricity resources available for CDR (in TWh)

The authors only considered the additional renewable electricity in the estimate of available volumes for CDR. Fossil electricity sources are not relevant for CDR, and the development of the nuclear fleet is highly dependent on government decisions and is generally subject to long lead times. In the rest of the report, the value of 382 TWh is used as theoretical maximum renewable electricity available for CDR.

With the development of small modular nuclear reactors (SMRs), an additional source of low-carbon electricity could emerge and represent a significant amount of energy. As this sector is still too immature, the authors have not considered it when estimating the electricity available for CDR methods.

4.2. Waste heat

In a nutshell

Many CDR methods require heat to operate, but at different temperatures. Producing decarbonised heat to then run CDR processes would not be energy-efficient compared to electrochemical CDR methods. This report therefore only considers waste heat; available waste heat above 100°C amounts to **52.9** TWh.

Methodology

The methodology can be summed up in a few words:

1) Identify the total source of waste heat in France;
2) Remove waste heat with a temperature below 100°C from this amount, as S-DACCS requires heat above 100°C.

Box 2 - Methodology for estimating the heat source

France generates an estimated ~117 TWh (19) of waste heat. Most of this heat comes from industry (109 TWh). The remaining 8 TWh are spread across other sectors, such as data centres, wastewater treatment plants (WWTP) and household waste incineration plants (HWIP).

The table below shows the industrial sources and temperature breakdown for each sector:

Sectors of activity	Breakdown of the 109.5 TWh industrial sources	Range of temperatures for main flux	Range of temperatures for secondary flux
Food industry	31%	< 40 °C	100 - 250 °C
Plastic chemistry	22%	< 40 °C	100 – 250 °C
Paper and cardboard	13%	< 80 °C	100 – 250 °C
Metals including steel	12%	200 – 250 °C	> 500 °C
Non-metallic materials (cement, glass)	11%	100 – 250 °C	400 – 500 °C
Refining	3%	200 – 250 °C	150 - 200 °C
Other	8%	n/a	n/a

Table 1 - Breakdown of waste heat in industry (19)

This report does not consider waste heat from various French thermal power stations (mainly nuclear), representing several hundreds of TWh, because, by design, these heat sources are not exploited or are not easily exploitable, particularly in the case of nuclear power stations where safety and certification constraints make retrofits difficult in practice.

None of the identified sources provide high grade heat between 300°C and 900°C (required for L-DACCS technology with liquid solvent). Therefore, the waste heat potential for this technology is considered to be zero.

For S-DACCS, the temperatures must be above 80°C. The French Environment and Energy Management Agency (ADEME) only gives an overview of waste heat for industry above 100°C, which amounts to **52.9 TWh**. This value has been taken as the source of waste heat for S-DACCS. Yet, this value is conservative because the temperature considered is above the temperature required by the technology and because it does not consider the heat potentially available from French nuclear plants, gas and coal-fired power stations at temperatures above 100°C. On the other hand, it is likely that the waste heat availability will decrease between now and 2050, through the implementation of energy efficiency measures, and as the resource is harnessed for an increasing number of applications (competition for the resource).

With the development of small modular nuclear reactors (SMRs), another low-carbon heat source could emerge and represent a significant amount of energy. As this sector is still too immature, it has not been considered when estimating the heat available for CDR methods.

4.3. Biomass

In a nutshell

Biomass is used as an input by various CDR methods: biochar, BECCS and biobased products. The assessment presented in this section suggests a theoretical maximum of **61 million tonnes of non-forest biomass** and **37 million m³ of wood** that could be available for CDR. The first category is an aggregated view of four different biomass sources: biomass from non-food agriculture, urban waste, co-products from the agri-food industry and forest biomass. Each category itself contains several different types of biomasses.

Category	Type of biomass	Unit	Feedstock for CDR
Biomass from non-food agriculture	Dedicated crops	MtDM/year	0,1
	Intermediate crops	MtDM/year	4,4
	Agricultural waste	MtDM/year	17,8
	Livestock manure	MtDM/year	24,7
	Fibre plants	MtDM/year	0,3
	Perfume plants	MtDM/year	0,03
Municipal waste	Green urban waste	MtRM/year	5,14
	Used edible oils	MtRM/year	0,08
	Paper and cardboard waste	MtRM/year	0,14
	Wood waste	MtRM/year	2,3
	Sewage sludge	MtDM/year	0,2
	Household and similar waste	MtDM/year	4,9
Co-products of the agri-food industry	Oilseed crushing	MtRM/year	0,64
	Sugar beet	MtRM/year	0,15
	Processed fruit and vegetables	MtRM/year	0
	Vinification	MtRM/year	0,06
	Meat industries	MtRM/year	0,36
	Egg products	MtRM/year	0
	Fishing and aquaculture	MtRM/year	0,04
	Wine distillation	MtRM/year	0,18
	Cider mills	MtRM/year	0,01
	Potato	MtRM/year	0
Forest biomass	Hedgerows and agroforestry	Mm³/year	3,4
	Forest harvesting	Mm³/year	33

Table 2 shows the different categories, types of biomasses and the biomass available for CDR.

Methodology

The methodology used to estimate the biomass feedstocks can be summarised as follows for each type of biomass:

1) Identify the total volume of biomass produced annually;
2) Remove constrained volumes (technical constraints and volumes not relevant to CDR);
3) Remove volumes allocated to priority uses (food, soil improvement, etc.);
4) Distribute the remaining volumes between the different uses (combustion and anaerobic digestion for BECCS, materials and recycling for bio sourced products, biochar) (cf. section 6);
5) Sum the volumes according to the uses relevant to CDR (see scetion 6).

Box 3 - Methodology for estimating biomass reserves.

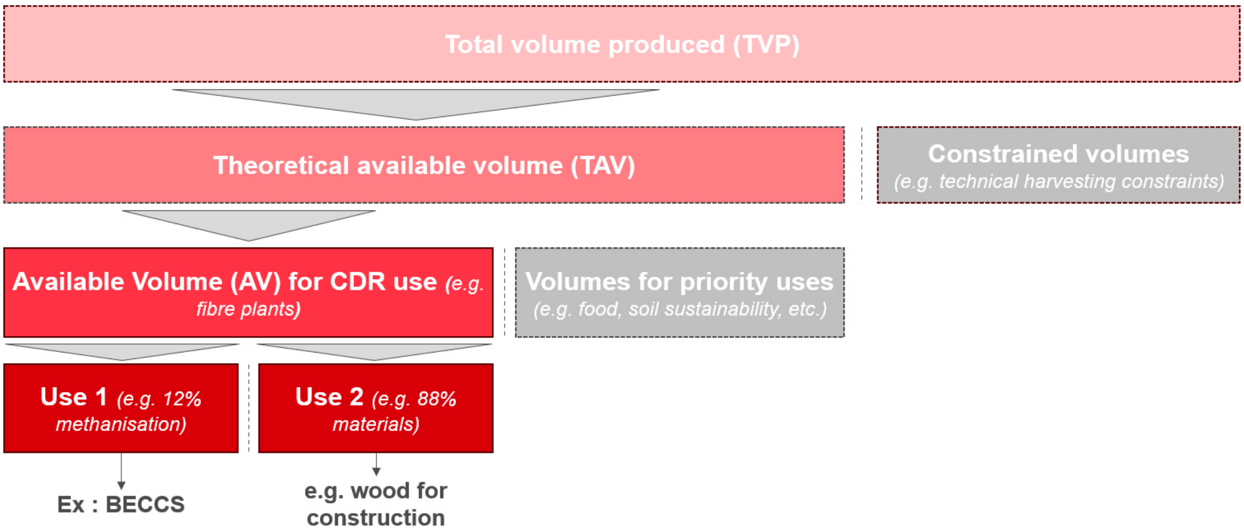

Figure 6 - Methodology for estimating the available volumes of biomass for CDR methods

This methodology is broken down according to the type of biomass, depending on available data. Details are given in the table below. The main sources are:

- ONRB: National Observatory of Biomass Resources,
- Modecom database (2017),
- SINOE database, managed by ADEME (2021),
- Institut national de l'information Géographique et forestière (IGN) forest inventory (2012 - 2020),
- ADEME, '*Un mix de gaz 100% renouvelable en 2050?*' (2018).
- Agreste database (2021).

On an aggregated basis, the application of the methodology for non-forest biomass gives an estimated 61 Mt/year available for CDR from a total volume of biomass of 273 Mt/year (Figure 7). The total availability is estimated based on historical values for 2018-2021 for each category of biomass, on which observed changes are relatively limited. No change is anticipated to estimate the total feedstock in 2050.

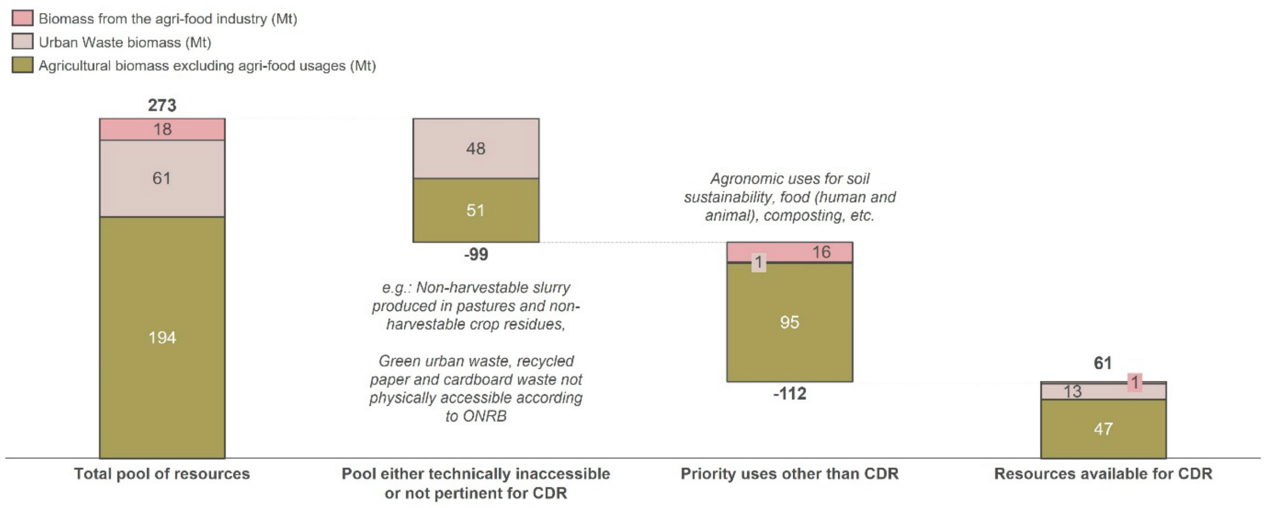

Figure 7 - Estimated available non-forest biomass for CDR, in Mt/year (DM or RM)

For forest biomass, the application of the methodology results in 37 Mm³/year of wood available for CDR, from a total of 91 Mm³/year of wood produced annually in French forests (Figure 8). It should be noted, however, that the quality of this resource tends to decline over time. Indeed, tree mortality has been on the rise in recent years, and growth has been slowed by the effects of global warming, particularly the lack of water.

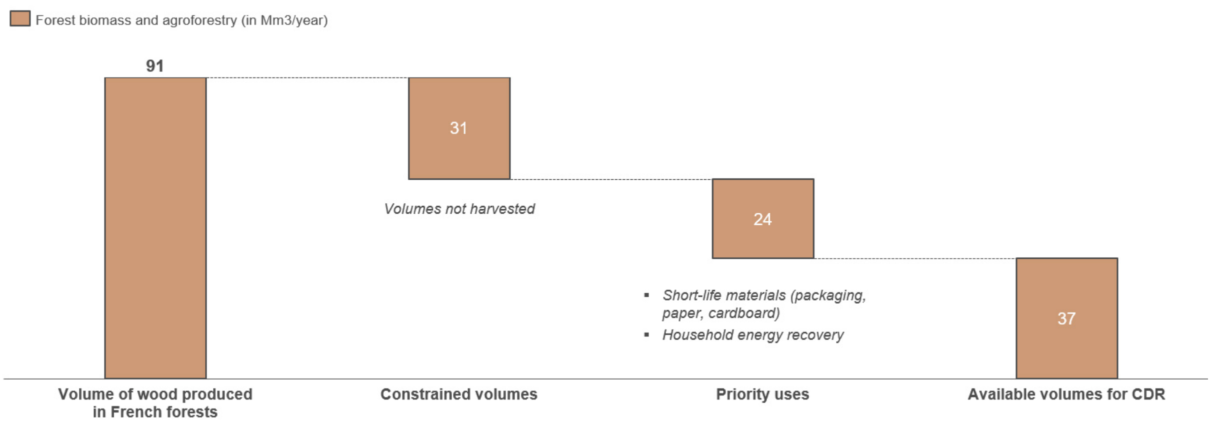

Figure 8 - Estimated wood available for CDR, in Mm/year³

As a result, the biomass resources available amount to around 60 Mt for non-forest biomass and 37 Mm³ for forest biomass.

4.4. Land areas

In a nutshell

The estimation of land surface availability focuses on afforestation and reforestation methods, changes in peatland areas and carbon farming practices. The land required for BECCS, DACCS or biochar units is considered negligible.

According to ADEME's S1 scenario, the most favourable CDR development in terms of land area would be an increase of 2.9 Mha in forest area between now and 2050. On the other hand, this scenario anticipates a reduction in cropland and grassland.

Methodology

The methodology used to estimate the availability of land is based on the following references:

- The ADEME report 'Transition 2050' (2020),
- INRAE report 'Stocker du carbone dans les sols français' (2021)
- The report 'Les milieux humides et aquatiques continentaux' by the French General Commission for Sustainable Development (2018)
- The report 'Pourquoi restaurer les tourbières?' by the Conservatoire d'Espaces Naturels (France)
- The 'Corine Land Cover' and 'TERUTI LUCAS' databases

The overall methodology is described in the box below.

To increase the area of forests and peatlands:

- **Afforestation and reforestation:**
  - Identify the ADEME scenario with the highest natural sink and define it as the maximalist scenario;
  - Identify the changes in land areas in this maximalist scenario, in particular regarding forest areas;
- **Increase in the area of peatlands:**
  - Use the "Corine Land Cover" and "TERUTI LUCAS" databases to estimate the current surface area of peatlands;
  - Use the report 'Continental wetlands and aquatic environments' by the Commissariat Général au Développement Durable (2018) to estimate the loss of peatlands between 1945 and 2022 and thus the potential increase in peatland areas if former peatlands were restored.

For carbon farming practices:

- **For crops, meadows, and vineyards:**
  - Identify the maximum areas in 2021 on which carbon farming practices could be implemented on the basis of the INRAE report;
  - Identify the maximum areas where carbon storage practices could be implemented in 2050, based on area changes as seen by ADEME.
- **For forests:**
  - Identify the total forest area;
  - Assume (simplify) that forest stocking practices can be applied to the entire surface area of the forest.
- **For peatlands:**
  - Use the 'Corine Land Cover' and 'TERUTI LUCAS' databases to estimate the current surface area of peatlands;
  - Use the report 'Why restore peatlands?' by the Conservatoire d'espaces naturels to estimate the proportion of current peatlands in a degraded ecological state and which could therefore be restored.

Box 4 - Methodology for estimating the area available for afforestation and reforestation, increasing the area of peatlands and carbon farming practices in 2050.

Estimating the potential for increasing forests and peatlands areas:

For forests:

The ADEME report '*Transitions 2050*' presents four scenarios for the transition to carbon neutrality in 2050. The scenarios are called 'Frugal Generation' (S1), 'Territorial Cooperation' (S2), 'Green Technologies' (S3) and 'Restorative Bet' (S4).

Each of the scenarios anticipates a change in the natural carbon sink of greater or lesser significance between 2030 and 2050. Scenario S1 presents the highest natural carbon sink capacity in 2050 and therefore the most favourable change in related land area. Scenario S1 has therefore been selected to estimate the potential changes in land areas.

The ADEME scenarios describe changes in areas under 'forests and plantations', 'fruits and vegetables', 'heathland, fallow land, fallow fields', 'orchards', 'artificial surfaces', 'vineyards', 'permanent grasslands', 'temporary grasslands' and 'crops (cereals, oilseeds, protein crops, industrial crops)'. However, ADEME makes no mention of changes in the surface areas of wetlands (including peatlands) and other natural soils. This report classifies areas not described by ADEME as 'other land' in order to complete the picture of France's total finite surface area. The change in surface area per type of land between now and 2050 according to ADEME's S1 scenario is shown in Figure 9.

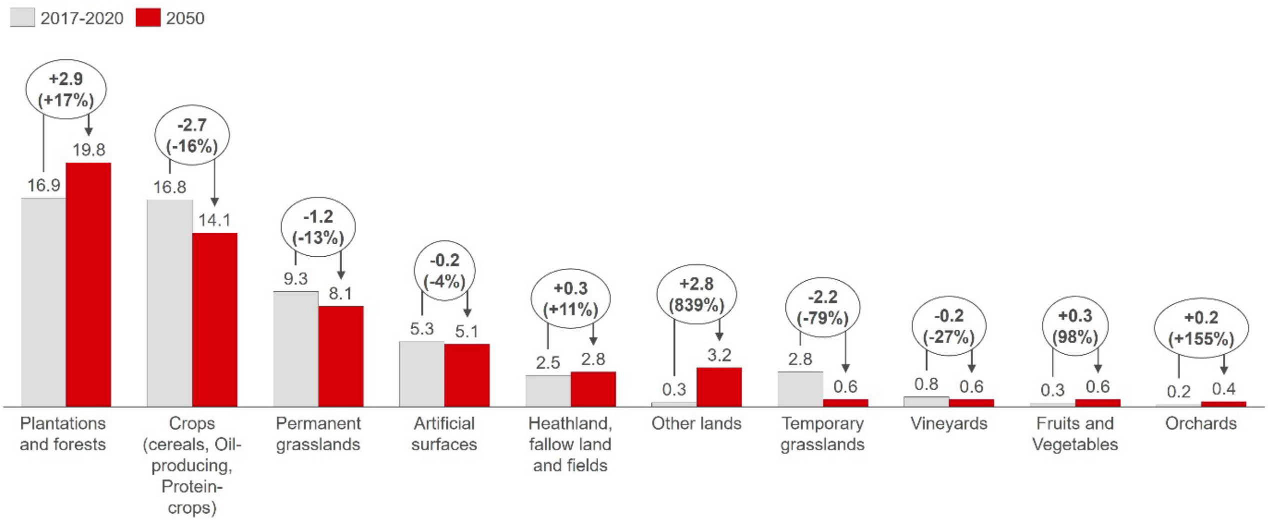

Figure 9 - Change in land distribution (Mha) between 2017-2020 and 2050 according to ADEME's S1 scenario (20)

According to this scenario, forests are expected to increase by 2.9 million hectares between 2050 and 2017-2020, and fruit and vegetables crops, heathland, fallow land, and orchards are also expected to grow. On the other hand, the areas under permanent grassland, temporary grassland, and arable crops (cereals, oilseeds, protein crops and industrial crops) are expected to decrease. These changes in surface areas can be explained by the characteristics of ADEME's S1 scenario. In particular, this scenario assumes:

- No more land artificialisation, followed by a reduction in artificialised areas,
- A deep transformation in agricultural practices (agroecology, plant cover, direct seeding, etc.),
- A considerable increase in the number of wilderness reserves,
- A deep change in diet habits (meat consumption down by 70%),
- Limiting wood cutting.

For peatlands:
The report uses data from the 'Corine Land Cover' (CLC) and 'TERUTI-LUCAS' databases to estimate the current surface area of peatlands. These statistical sources are explained below:

Corine Land Cover (CLC) is a biophysical inventory of land cover and land use change, comprised of 44 items for mainland France and 50 items for the French overseas departments (DOM). This database is run by the European Environment Agency and is based on satellite observation. The information is coded at three levels, from 5 to 44 items. After its first edition in 1990, CLC provides a complete picture of land use and its evolution every six years since 2000.

Teruti-Lucas is a database run by the Ministry of Agriculture and based on a statistical survey of the physical occupation of land (grass, wheat, etc.) and its use (agricultural, natural and habitat, leisure, industry, etc.) in order to monitor and quantify changes in the occupation and use of land and the structure of landscapes over time. (88). This survey has been carried out every year since 1981 by the Department of Statistics and Forecasting of the Ministry of Agriculture and Food.

The researchers collected and aggregated CLC data on surface areas per municipality to obtain national surface areas. The CLC data was then adjusted so that the sum of the 'wetlands' and 'water surfaces' areas derived from CLC (2018) was consistent with the area of the 'underwater' category in TERUTI-LUCAS (2019-2020-2021). The results suggest a peatland surface area of 7111 ha in 2006 and 7,690 ha in 2018.

According to the report '*Les milieux humides et aquatiques continentaux*' by the French General Commission for Sustainable Development (2018), 'on estime notamment que la moitié des tourbières ont disparu entre 1945 et les années 2000'(21). There were twice as many peatlands in 1945 as there are in 2000 (e.g. 2006), i.e. around 14,000 ha of peat bogs in 1945.

From a theoretical point of view, there is therefore a **theoretical potential for peatlands** recreation of **~6,500 ha**. The most favourable changes in land area are listed in Table 3 (rounded numbers):

Surfaces	Unit	Maximum area evolution capacity (2050 horizon)	Maximum surface area available by 2050	Surfaces today (2017-2020)
Forests and plantations	**Mha**	**+2.9**	**19.8**	**16.9**
Crops	Mha	-2,7	14,1	16,8
Vineyards	Mha	-0,21	0,58	0,79
Permanent grassland	Mha	-1,2	9,3	8,1
Temporary grassland	Mha	-2,2	2,8	0,6
Peatlands	Mha	0,0065	0,0142	0,0077
Artificial soils	Mha	-0,2	5	5,2

Table 3 - Scenario for the most favourable trend in land area

Surface area available for carbon storage practices:

Only part of the surface area of forests and plantations, vineyards, meadows, and peatlands could be used to implement carbon storage practices, due to technical constraints linked to the specific nature of the soil, the climate of the region, the type of plantation cultivated depending on the geographical location, etc. In this section, the physical potential in terms of surface area for implementing these practices is estimated in three stages: firstly crops, meadows and vineyards, then forests, then peatlands.

For crops, meadows, and vines:

The INRAE report '*Stocker du carbone dans les sols français*' (2020) presents the surface areas for implementing carbon-storing practices in forests, crops, meadows and vineyards in France. For each carbon storage practice, INRAE has applied criteria to estimate the surface area on which it is possible to implement these practices. These criteria are detailed in the appendix. 10.3. The areas available for the implementation of carbon storage practices are shown in Figure 10.

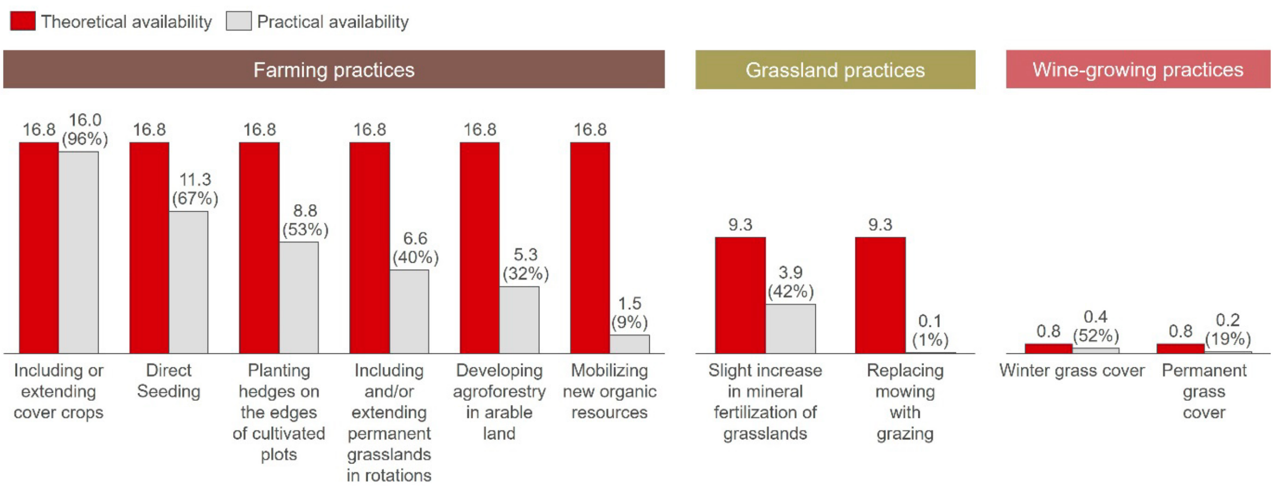

Figure 10 - Areas on which practices could be theoretically (without constraints) and realistically deployed in 2020, in Mha (12)

By combining the work of ADEME on the distribution of available land in 2050, and that of INRAE (ratio of land eligible for carbon storage practices), it is possible to estimate the amount of land that could support the implementation of carbon storage practices. Figure 11 shows the potential in 2020 and 2050 according to the type of crop: farmland, meadows and vineyards. In absolute terms, the areas that could support the implementation of carbon storage practices vary from 1.5 to 16 million hectares for agricultural practices, from 0.1 to 3.9 million hectares for grassland practices and from 150,000 to 410,000 hectares for vineyards.

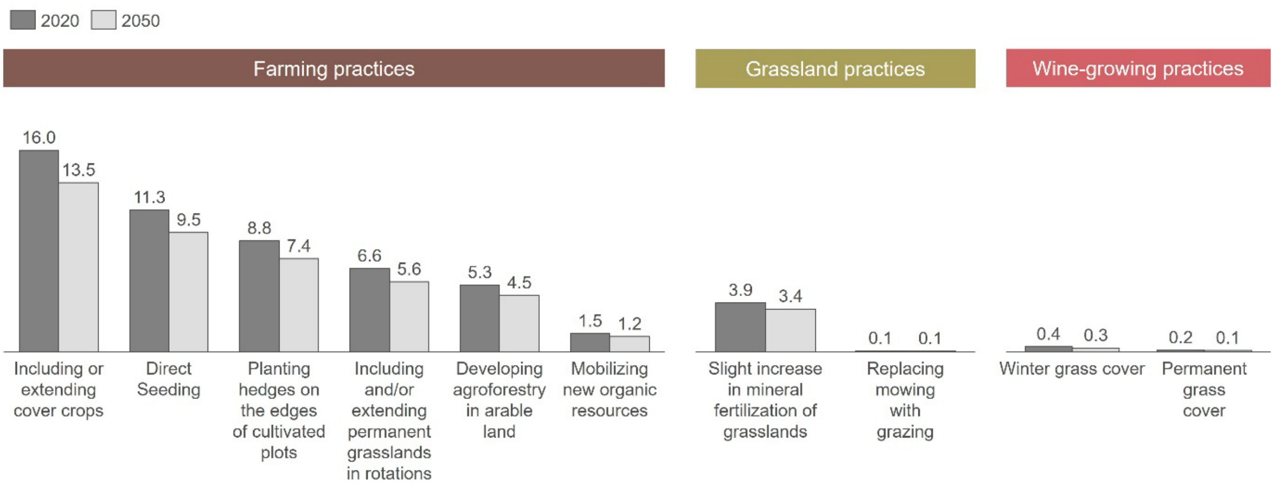

Figure 11 - Areas where carbon storage practices could plausibly be deployed in 2020 and 2050, in Mha (ADEME and INRAE)

For forests:
For forestry practices, the initial assumption is that 100% of French forests could be better managed so as to absorb more carbon. In a second phase, the assumption could be refined by considering the different types of ownership of French forests (public, private, etc.). The area available for implementing these practices would therefore be 16.9 Mha (forests and poplar plantations) in 2020 and 19.8 Mha in 2050.

For peatlands:
The estimation of share of peatlands that could be restored is based on the estimation of the Conservatoires d'espaces naturels, by which '*89% of the surface area of peat habitats in France is in an unfavourable (degraded) state of conservation*'(22). The current surface area of peatlands is estimated at 7,690 ha according to *Corine Land Cover* (2018), adjusted with TERUTI-LUCAS data (average for 2019-2020-2021). The potential peatland area to be restored is therefore around 6800 ha (89% of 7690 ha).

The proportion of land that can be used to implement carbon storage practices is summarised below.

Carbon storage practice	Targeted area	Useful part	Surface area (2020) (Mha)	Surface area (2050) (Mha)
Agricultural carbon farming practices				
Insertion and prolongation of intermediate crops	Arable crops (cereals, oilseed and protein crops, forage crops)	96%	16,0	13,5
Direct seeding		67%	11,3	9,5
Planting hedges on the edge of cultivated plots		53%	8,8	7,4
Extending and including temporary grassland in crop rotations		40%	6,6	5,6
Developing agroforestry on cultivated plots		32%	5,3	4,5
Mobilising new organic resources		9%	1,5	1,2
Grassland carbon farming practices				
Moderately increase nitrogen fertilisation of permanent grassland	Permanent meadows	42%	3,9	3,4
Substitute grazing for mowing		1%	0,1	0,1
Wine-growing carbon farming practices				
Winter grassing	Vineyards	52%	0,4	0,3
Permanent grassing		19%	0,2	0,1
Forest carbon storage practices				
Stop/avoid harvesting forest biomass (stumps, crowns)	French forests	100%	16,9	19,8
Carry out thinning at a rate of less than 35%.		100%	16,9	19,8
Favour natural regeneration of a stand over planting		100%	16,9	19,8
Reduce the need for mechanised preparation (ploughing, trenching) when planting new trees or regenerating a forest stand.		100%	16,9	19,8
Increase the density of trees in the forest		100%	16,9	19,8
Increasing the diversity of the population		100%	16,9	19,8
Favour tree species that store more carbon		100%	16,9	19,8
Favour the renewal of trees by the "high forest" method instead of "thicket"		100%	16,9	19,8
Favour forests with several age classes		100%	16,9	19,8
Increase the time between regeneration of the forest and the final cut		100%	16,9	19,8
Adding nitrogen fertilisers to forest soils		100%	16,9	19,8
Carbon storage practices in peat bogs	Peat bogs	89%	6844 ha	12660 ha

Table 4 - Proportion of available land on which carbon storage practices could be implemented

4.5. Coastal marine areas

4.5.1. French coastline length

Some CDR methods require access to the coastline, and some in particular, use beaches to naturally accelerate the weathering of rocks or minerals. The total length of the French coastline is 20,000 km, as shown in Figure 12. The overseas territories account for almost 75% of the total length. Metropolitan France accounts for the remaining quarter, with almost 5,500 km of coastline(23). However, there is a not enough data to estimate the proportion of this coastline that could be suitable for geochemical methods (particularly unused beaches).

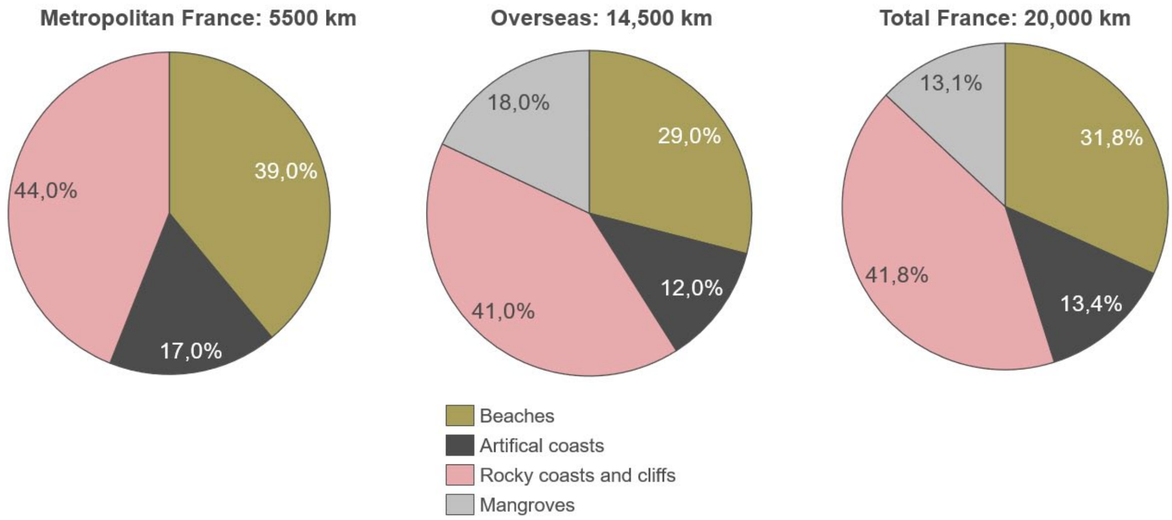

Figure 12 - Distribution of the different types of French coast (23)

4.5.2. Mangrove potential for CDR

France currently has 104,000 ha of mangroves, of which 70,000 ha are in French Guiana, 26,000 ha in the Pacific Ocean (New Caledonia, Wallis, French Polynesia), 6,000 ha in the West Indies (Guadeloupe, St Martin, St Barthélémy, Martinique) and 1,000 ha in the Indian Ocean (Mayotte and Europa)(24). These figures date from 2018 and may have fallen slightly today given the current downward trend.

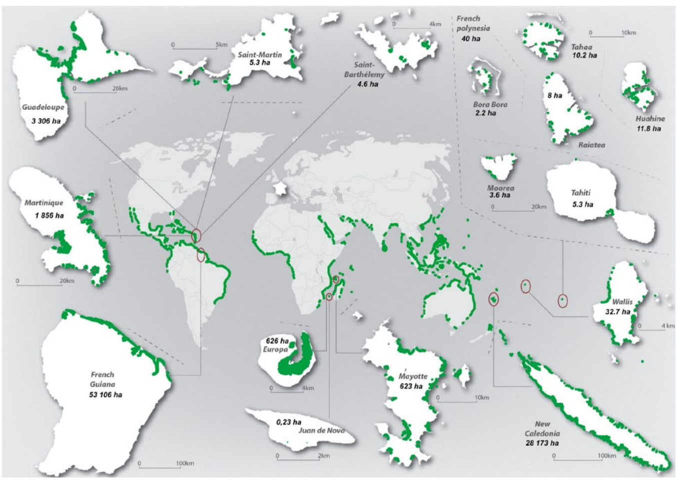

Figure 13 - Location of mangroves around the world: focus on French mangroves (25)

The references used are:
- The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES),
- The Mangrove Observation Network (ROM),
- French assessment of ecosystems and ecosystem services (EFESE), '*Les écosystèmes marins et côtiers*' (2018).

The IPBES estimates that, on a global scale, 38% of mangroves surface area has been lost between the end of the 19th century and the present day. However, as mentioned above, French mangroves (of which French Guyana accounts for 70% of the total surface area) have not suffered significant losses, as opposed to the global trend. In Guadeloupe, for example, the surface area of mangroves increased by 524 ha between 1950 and 2020(26). We can therefore try to increase the area of mangroves where possible, but the challenge today is mostly to preserve existing mangroves and current areas. To be conservative, the potential for increasing the surface area of mangroves in the French exclusive economic zone (EEZ) is considered to be zero.

In addition, **carbon storage practices** aimed at storing more carbon in mangroves could be deployed on the 104,000 hectares of mangroves in France. However, as described above, French mangroves are in relatively good condition and therefore have negligible potential for restoration, so the challenge is mostly to preserve existing mangroves rather than deploy carbon-storing practices on them.

4.6. Underwater surfaces

In a nutshell

The French underwater areas can be used for CDR, more specifically to increase the surface area of seagrass beds and use them as storage. Currently, seagrass beds occupy an underwater surface area of 220,000 hectares in France, divided between the Overseas Territories (55%), the Mediterranean Sea (40%) and the English Channel, the North Sea, and the Atlantic coast (5%)(24).

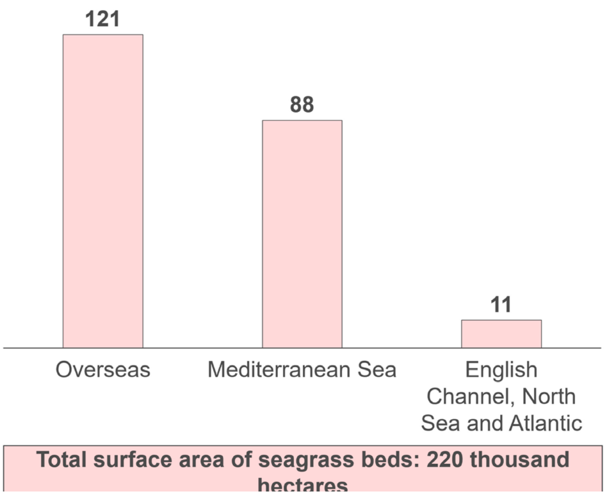

Figure 14 - Surface area of seagrass beds in France by geographical zone, in thousands of hectares (24)

The maximum theoretical capacity for increasing the surface area of seagrass beds in France would be around 8,000 ha. This value corresponds to the estimated loss of seagrass beds in the Mediterranean (Posidonia meadows) between 1980 and 2012, which it might be possible to recreate.

In addition, carbon storage practices in seagrass beds could be implemented on the total surface area of seagrass beds, i.e. 220,000 hectares, even though there are no precise studies on the spatial distribution and state of health of seagrass beds.

Methodology

The bibliographic resources used are:

- Évaluation française des écosystèmes et des services écosystémiques (EFESE) *'Les écosystèmes marins et côtiers'* (2018)
- IPBES *'The global assessment report on biodiversity and ecosystem services'* (2019)
- The French Initiative for Coral Reefs (IFRECOR) *'Etat de santé des récifs coralliens, herbiers marins et mangroves des outre-mer français'* (2021)
- IFRECOR and Hily, *'Les herbiers de phanérogames marines de l'outre-mer français'* (2010)
- Telesca, *'Seagrass Meadows distribution and trajectories of change'* (2015)

Maximum theoretical potential for increasing seagrass beds:

- Identify the decline in seagrass beds between 1980 and today using Telesca (2015) and EFESE (2018);
- Assume that the areas of meadows destroyed between 1980 and today could be recreated in the future.

Carbon storage practices in seagrass beds:

- Identify the current total surface area of seagrass beds in France,
- Assume that stocking practices can be implemented on all these areas.

Box 5 - Methodology to estimate the maximum theoretical potential for increasing the surface area of meadows and for implementing practices in meadows

The general methodology is:

CDR potential associated with seagrass beds:

Seagrass species vary according to geographical region. In the French overseas departments and territories, seagrass meadows are much more diverse than in mainland France, with between 16 and 18 different recorded species. In the Mediterranean, seagrass beds are very common all along the coast, from the surface to a depth of 30 to 40 m and are mainly composed of the *Posidonia Oceanica* species. In the Channel, North Sea and Atlantic coast, the meadows are mainly made up of species known as eelgrass and dwarf eelgrass (*Zostera marina* and *Zostera noltei*).(24).

Carbon storage practices could be implemented on the total surface area of the meadows, i.e. 220,000 hectares, even though there are no precise studies on the spatial distribution and state of health of the meadows.

Regarding the growth potential of **seagrass beds**, since the end of the 19th century, 30% of their area has been lost worldwide, with a loss of 10% per decade of seagrass beds in recent decades (27), (28).

The decline in the surface area of seagrass beds is unevenly and uncertainly reflected in the French EEZ. Due to a lack of data, it is impossible to quantify changes in the surface area of seagrass beds in New Caledonia (40% of the total surface area of French seagrass beds)(29). The seagrass beds in the Channel, North Sea and Atlantic are thought to be declining at some sites (species: *Zostera noltei*) but increasing in the Channel (*Zostera marina*). Lastly, Posidonia meadows in the Mediterranean have lost almost 2,800 ha, falling from around 97,000 ha in 1980 to 94,000 ha in 2011 (9% loss) (30). Other estimates provided by EFESE give a 2012 figure of almost 88,000 ha of seagrass beds in the Mediterranean. The theoretical gain in seagrass areas as a CDR approach could be ~9,000 hectares (97 - 88,000 ha).

However, climate change could, depending on the warming scenarios, play a significant role in the development of seagrass beds. Posidonia meadows in the Mediterranean are doomed to disappear in the IPCC's RCP6 and RCP8.5 scenarios, thus greatly limiting the potential for marine reforestation, particularly in the Mediterranean Sea with the Posidonia meadow (31).

4.7. Silicate and carbonate rocks and minerals

In a nutshell

Methods of enhanced weathering or mineral ocean alkalinisation require alkaline and reactive rocks. The feedstocks identified in France are summarised in the table below. The commentary details the assumptions underlying these estimates.

Rocks	Maximum theoretical feedstock (Mt/year)	Comment
Basalt	**3**	Estimate carried out by Climerock using by-products (fines) from existing basalt mines currently operating in France.
Limestone	**5,2**	3.0 Mt/year of agricultural soil improvers and 2.2 Mt/year due to a 10% increase (for CDR) in annual limestone production (current total production is 22 Mt/year)
Olivine	**3**	Opening mines in the Etang de Lherez, Tuc Desse, Bois du Fajou, Bois de la Pinouse and Pic de Geral, to exploit the entire olivine feedstock (approx. 150 Mt), including the difficile difficult-to-access feedstock, over a period of 50 years
Dolomite	**0,18**	10% increase in current total annual dolomite production (approx. 1.8 Mt/year) for CDR
CKD	**0,25**	10% increase in current total annual production of CKD (approx. 2.5 Mt/year) for CDR purposes
Magnesite	0	French magnesite feedstock unknown
Wollastonite	0	Small feedstocks in the Pyrenees, Massif Central and Alps but not economically viable

Table 5 - Maximum theoretical rock feedstocks for CDR

Methodology

The references used to estimate the feedstock come mainly from BRGM (French geological survey):

- *Mémento - Carbonates calciques et magnésiens*, BRGM (2017)
- *Mémento - Roches et minéraux industriels - Carbonates calciques et magnésiens et produits dérivés à usage industriel et agricole*, BRGM (2000)
- *Mémento - Roches et minéraux industriels dolomie, magnésite et produits dérivés à usage industriel et agricole*, BRGM (1989)
- *Panorama du marché français des matériaux de carrière et produits dérivés*, BRGM (1999)
- *Mémento - Roches et minéraux industriels Wollastonite*, BRGM (1991)
- *Silicate production and availability for mineral carbonation*, P. Renforth (2011)
- *Le ciment en chiffres*, France Ciment (2022)
- *Caractérisation et utilisation de poussières de four de ciment CKD dans la stabilisation/solidification des déchets de l'unité BCR*, Faiza Khouan
- *Valorisation des déchets de four à ciment (CKD) de la cimenterie de Ain-Al-Kebira (Algérie) dans le Mortier*, Amar Guettouche (2019)

Box 6 outlines the methodology used to estimate maximum theoretical rock feedstocks for CDR.

Basalt:
- Identify the volume of basalt currently extracted for aggregates and other uses;
- Quantify the share of this production that is currently lost in fine particles when crushing the extracted rocks;
- Assume all of the fines are used for CDR purposes.

Limestone:
- Identify the volume of limestone currently used to make lime as an agricultural soil improver;
- Assume that plants producing lime from limestone by calcination are equipped with CCS, so that agricultural spreading of lime can be considered negative in terms of GHG emissions;
- Identify the volume of limestone currently produced annually in France;
- Assume a 10% increase in current annual limestone production for CDR;
- Sum the volumes of limestone already used for land application and the volumes resulting from the increase in national annual production to obtain a theoretical maximum annual deposit of limestone available for CDR.

Olivine :
- Identify olivine deposits in France (geography and volumes);
- Assuming the opening of mines to exploit these deposits.

Dolomite and CKD:
- Identify French annual production of dolomite and CKD;
- Assume a 10% increase in this production for CDR.

Magnesite:
- Magnesite deposits are unknown in France, so no CDR deposits have been considered.

Wollastonite :
- Identifying wollastonite deposits in France;
- Considering that deposits are too small and economically unattractive to exploit for CDR purposes.

Box 6 - Methodology for estimating maximum theoretical rock deposits for CDR in France

Basalt

In France, nearly 80 basalt quarries are in operation. Average quarry production is estimated at around 150,000 tonnes/year, with the largest quarries producing around 500,000 tonnes/year. Conservatively, therefore, between 10 and 15 million tonnes of basalt are produced each year. It should also be noted that in 2020, France ranked 1st in Europe (ahead of Germany, Italy, and Austria) in terms of aggregates production (25% of total EU production), according to Eurostat 2022 data.

Of these volumes, it is estimated that between 15- 20% ends up as fine particles, a co-product of rock crushing. These co-products are ideal for CDR, as they are already crushed and have no value in the current quarry business model and could therefore be diverted to enhanced weathering. The theoretical feedstock is therefore estimated at around **3 Mt** of basalt.

Limestone

For limestone, the average production value over the last 25 years is estimated at **22 Mt/year** based on available data (32)(33). Assuming a 10% increase in total annual production, an additional 2.2 Mt/year of limestone would be available for CDR. In addition, large volumes of limestone (3 Mt/year) are currently used in France to produce activated lime (CaO) by calcination, according to the equation:

$$CaCO_3 \rightarrow CaO + CO_2$$

This lime is then spread as conditioner on agricultural land, specifically for regulating soil acidity. The CO_2 released during calcination is currently not captured which represents significant CO_2 fossil emissions. But if the CO_2 was captured during calcination, the spreading of lime and magnesium oxide could generate negative emissions. Assuming that all lime production plants were equipped with CCS, lime conditioning in the fields would enable CDR. Since the volume of limestone used today to make activated lime as an agricultural conditioner is 3 Mt/year, a theoretical feedstock of 3 Mt/year of limestone would be available for CDR.

In total, the maximum theoretical feedstock of limestone usable for CDR would be **5.2 Mt/year**, i.e. the sum of the 2.2 Mt/year of limestone due to a 10% increase in annual limestone production and the 3 Mt/year due to the addition of CCS to activated lime production plants as agricultural soil conditioner.

Olivine

France does not currently produce olivine on its territory (34) despite several olivine deposits, notably in the lherzolite of the Pyrenees (35). This deposit is estimated at 153 Mt, of which BRGM (French geological Survey) considers 88 Mt to be easily accessible, spread between the Pic de Géral, the Bois de la Pinouse and the Etang de Lherz. The Bois du Fajou and Tuc Desse deposits are considered more difficult. However, there is no study showing the economic viability of this olivine deposit. Other olivine deposits exist in France, in the Aure valley, or overseas such as the olivine basalts of La Réunion, or even in Guadeloupe, but there are no quantified deposits available (BRGM).

The French government has granted a mining concession for olivine for a period of 50 years (Mining Code). This value is used as a reference for estimating the life of the olivine deposit. Assuming the opening of mines in the Etang de Lherez, Tuc Desse, Bois du Fajou, Bois de la Pinouse and Pic de Geral, exploiting the total olivine deposit of around 150 Mt over 50 years would give a theoretical maximum feedstock of around **3 Mt/year** of olivine for CDR purposes.

Dolomite

For dolomite, the average value of dolomite production between 1989 and 2015 based on available data is **1.8 Mt/year**(36) (33). Assuming a 10% increase in annual dolomite production for CDR, a theoretical maximum feedstock of **0.18 Mt/year** of dolomite would be available for CDR.

CKD

Cement Kiln Dust (**CKD**), like silicate and carbonate rock, can be used for enhanced weathering on land or ocean mineral alkalinisation. These dusts are a mixture of several alkaline and silicate materials such as lime (calcium oxide CaO) and silicon dioxide (SiO_2). It is produced when limestone is heated to high temperatures in a kiln, for example to produce cement. Today, CKD is re-injected into cement kilns or used as an additive in road surfacing as a stabiliser. In the future, this by-product of cement production could be used to absorb CO_2 via CDR methods.

Each tonne of cement produced generates between 150 and 200 kg of CKD (37). France produces an average of 16.5 Mt of cement every year (38). Using a conservative ratio of 150 kg of CKD per tonne of cement, **2.5 Mt of CKD** would be produced in France each year and could theoretically be used for enhanced weathering or mineral alkalinisation of the oceans. Assuming a 10% increase in annual CKD production (2.5 Mt/year) for CDR, an extra potential of **0.25 Mt/year** would be available for CDR.

However, CKDs have a number of limitations, as they can harm human health and, by extension, biodiversity, if dispersed in the environment (39) (40). These limitations have not been considered in estimating the maximum theoretical feedstock of CKD available for CDR.

Magnesite

France does not currently produce **magnesite**, despite annual consumption of 192 kt in 1998 (36) (41). Nor is the total French deposit available or known. For lack of information, no theoretical maximum magnesite feedstock has been considered in this report.

Wollastonite

Regarding wollastonite, France has a few traces of wollastonite in the Pyrenees, the Massif Central and the Alps, but their exploitation would be of little economic interest (42). The feedstock is therefore considered to be zero.

4.8. Geological storage of CO_2

In a nutshell

Theoretical CO_2 storage capacity in France is estimated at 27 $GtCO_2$. However, some specific studies have characterised a few reservoirs, which means most capacities have yet to be proven. By aggregating the proven capacities, we obtain a usable reservoir of 1,100 $MtCO_2$ distributed between the Paris basin, Aquitaine and the Rhône valley.

4.8.1. How CO_2 geological storage works

Geological storage of CO_2 involves injecting the captured CO_2 into underground rock layers that have the necessary characteristics to trap it over long periods. This process is an essential component of some CDR value chains, as it enables CO_2 extracted from the atmosphere to be stored permanently, thereby generating permanent CDR. There are several approaches to implement geological storage of CO_2.

Storage in deep aquifers: Aquifers are porous rock formations filled with brine. They are generally located at depths of more than 800 m. Saline aquifers are preferred for storing CO_2 because they offer large volumes and have no other use (water not suitable for consumption). The CO_2 is injected under pressure into these formations, where it is stored in gaseous form (supercritical state) and dissolved in salt water. A cap rock is essential to guarantee long-term storage.

Storage in depleted oil/gas reservoirs: CO_2 is injected into depleted oil or gas reservoirs. This technique is already in use and has been developed in existing reservoirs with enhanced oil recovery (EOR- CO_2).

Storage in unmined coal seams: CO_2 is injected into unmined coal seams where it binds to the surface of the coal. Storage by mineralisation: CO_2 is dissolved into water and injected into porous alkaline rocks (typically basalts or peridotites). The dissolved CO_2 reacts naturally with the host rock and mineralises in the form of thermodynamically stable carbonate minerals.

The figures below illustrate the different technologies for geological storage of CO_2.

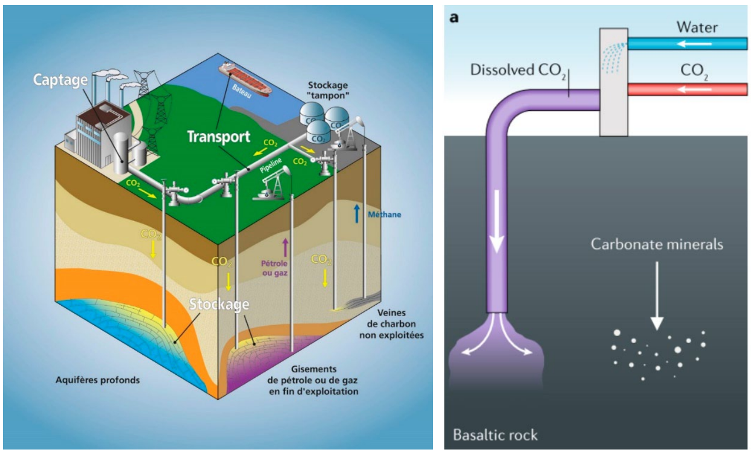

Figure 15 - Schematic representations of the different forms of geologic storage of CO_2: left panel reproduced from (43) right panel reproduced from (44).

Numerous publications detail how this storage method works, its risks, how to manage them and its costs, and give estimates of storage potential (45; 46).

4.8.2. Needs for geologic storage of CO_2

In 2050, between 20 and 100 MtCO_2 /year will have to be captured and stored depending on the scenarios envisaged by the SNBC 2 (47). CO_2 storage capacities must therefore be studied to enable France to develop sovereign capacities to meet its needs. Indeed, even if it is possible to export some of the CO_2 captured to the countries bordering the North Sea (which have already taken the lead in developing their reservoirs) studies show that doing so will not be enough to meet the needs of all European countries. It is essential for all countries to develop their own reservoirs so that there is sufficient storage space and to reduce the need for transport infrastructures (48).

4.8.3. Theoretical potential

In 2010, the CO_2 storage potential in France is estimated at 27 GtCO_2 with the Metstor project (49). This number is a theoretical maximum that needs to be confirmed by in-depth, local studies of each reservoir, which are spread over several geographical areas as illustrated in the figures below. Among them, offshore storage in sedimentary layers in the Celtic Sea and Bay of Gascogne would represent around 10 GtCO_2 in the French EEZ (~10 additional GtCO_2 outside the EEZ) (50) (see Figure 16).

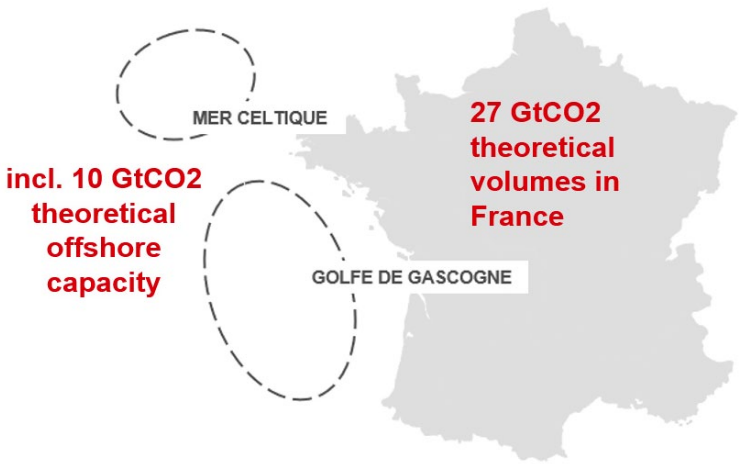

Figure 16 - Theoretical storage capacity in mainland France

4.8.4. Proven capacities

France does not yet have a 'proven' carbon storage capacity. Currently only 'probable' capacity is available, which needs to be demonstrated by further studies. Capacity becomes proven when a specific geological study confirms the previously estimated volume.

Depleted gas/oil reservoirs are well known since we know their extracted volume, from which we can deduce the minimum volume likely to be available for CO_2 injection. One such case is the Paris Basin, whose minimum capacity is estimated at 65MtCO_2.

Figure 17 below shows the map of the CO_2 storage reservoirs according to the latest studies and according to (conservative) oil production data (51).

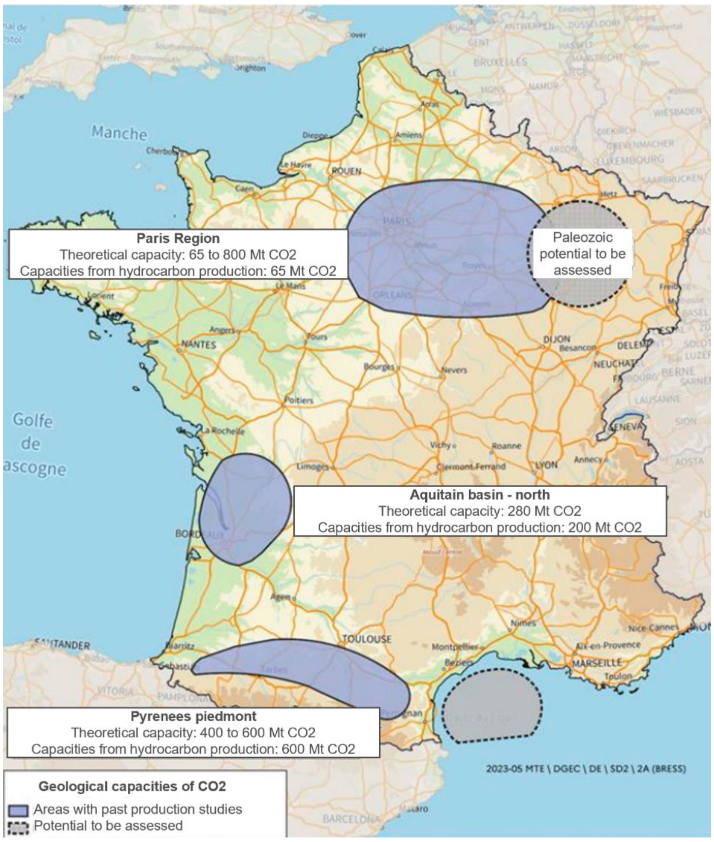

Figure 17 - Estimated geological CO_2 capacities in mainland France (Source: Ministry of Ecological Transition)

More specific studies have been carried out in the Paris Basin and in the Pyrenean foothills, enabling theoretical estimates to be refined.

4.8.5. Pyrenean piedmont: Lacq

The aim of the PYCASSO project, launched in 2021, is to assess the CO_2 storage potential in the Aquitaine basin, based on the reuse of depleted reservoirs. The reservoir is intended to meet the needs of CCS projects in the CO_2 emitting industries of Lacq, south-western France and northern Spain. Scientists estimate that the Lacq reservoir alone would represent a storage capacity of 500 $MtCO_2$(52). Phase 1 of the project plans to inject 1 to 3 $MtCO_2$/year by 2030, and 5 $MtCO_2$/year for phase 2 from 2035. These numbers are consistent with previous government estimates of a potential 600 $MtCO_2$ in the Pyrenean foothills (51).

4.8.6. Paris Basin

A recent study carried out in conjunction with BRGM (the French geological survey) details the storage potential of three different reservoirs in the Paris Basin (53) (see Figure 18)

- 140 $MtCO_2$ for the South Keuper,
- 81 $MtCO_2$ for the North Keuper,
- 165 $MtCO_2$ for the Dogger,

As such, the Paris Basin could store ~400 $MtCO_2$ pending further studies to determine the potential of other units.

4.8.7. Rhône Valley

The VASCO study 'Valorisation et Stockage du CO_2 ' carried out in 2012 by BRGM estimates a storage capacity for the Saintes-Maries-de-la-Mer aquifer of between 80 $MtCO_2$ and 180 $MtCO_2$. We considered a capacity of around 100 $MtCO_2$ (54).

4.8.8. Total storage capacity

Despite the high uncertainties concerning the capacity of the various CO_2 storage reservoirs, Figure 18 gives an aggregated view of the various French storage capacities calculated on the basis of specific studies. Summing up the capacity of identified reservoirs gives a **total storage capacity of ~1100$MtCO_2$**.

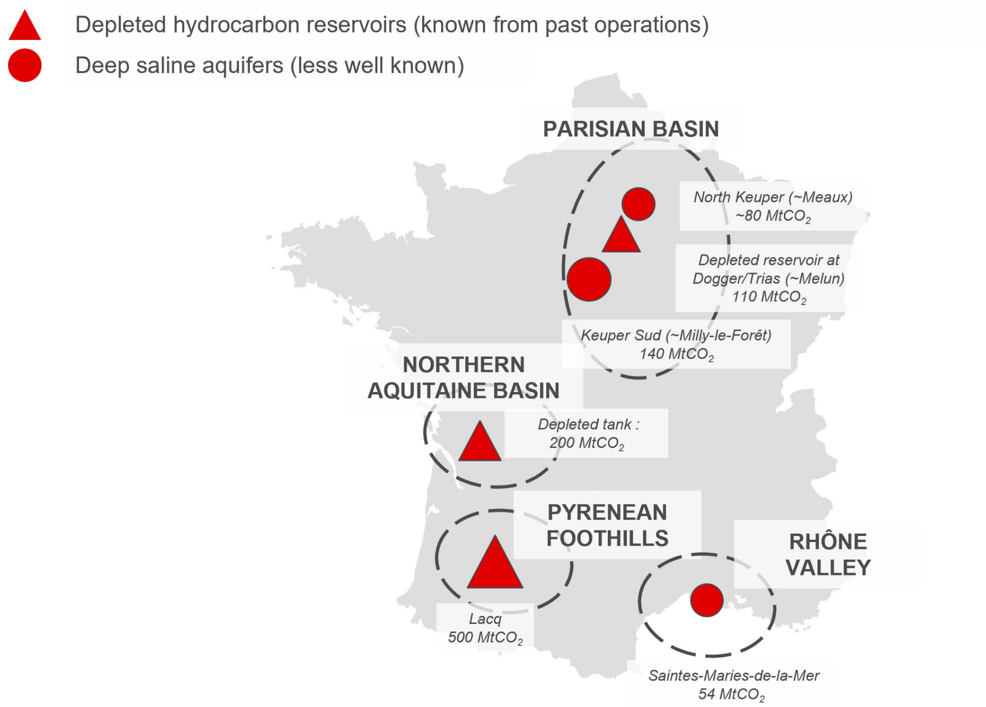

Figure 18 - Onshore CO_2 storage capacities identified in France in 2022 (in $MtCO_2$)

Other studies in the future will help to prove certain capacities that are currently estimated, particularly offshore in the Celtic zone and the Bay of Gascogne where theoretically 10 $GtCO_2$ could be stored in sedimentary formations.

4.9. CO_2 Transport

4.9.1. How it works

There are several ways of transporting CO_2 within the country: by pipeline or by road, rail, river, or sea. During transport, CO_2 is either compressed or liquefied (as is the case for H_2 or CH_4). It can then be exported by sea to storage areas, as in the North Sea, with liquefaction terminals acting as an interface between the gaseous CO_2 from pipelines and the liquefied CO_2 on ships. For example, tankers carrying liquified petroleum gas today could be used to transport CO_2 by sea (55). There are, however, technical constraints in the presence of humidity, for example, CO_2 becomes corrosive.

4.9.2. CO_2 transport needs

The French CCUS strategy anticipates a development of CO_2 transport in parallel with the introduction of CCUS, which will be implemented over the next few years to reduce French GHG emissions. It predicts that the volumes of CO_2 captured by CCUS could reach 4 to 8.5 $MtCO_2$/year by 2030, and between 15 and 20 $MtCO_2$ by 2050 in the industrial sector. However, it does not include the CO_2 transport needs from CDR methods that require CO_2 storage such as BECCS, DACCS or DOCCS (51). It indicates that in the short term, CO_2 transport infrastructures will have to be developed in industrial clusters and CO_2. export hubs. Therefore, to benefit from CO_2 transport infrastructures, CDR methods such as BECCS and DACCS will have to be developed nearby these industrial zones.

4.9.3. French strategy and projects

In the short term, the French strategy is to focus on:
- The development of pipelines in the industrial basins of Dunkirk, the Seine axis and the Rhône axis;
- The development of liquefaction terminals (CO_2 hubs) at major ports to export captured CO_2, and mature geological storage sites that are already available (particularly in the North Sea);
- For isolated sites, the development of river and rail transport.

In the medium term, up to around 2035, there are several CO_2 transport projects in France, all linked to a CCS project. These projects are divided into three deployment phases (51).

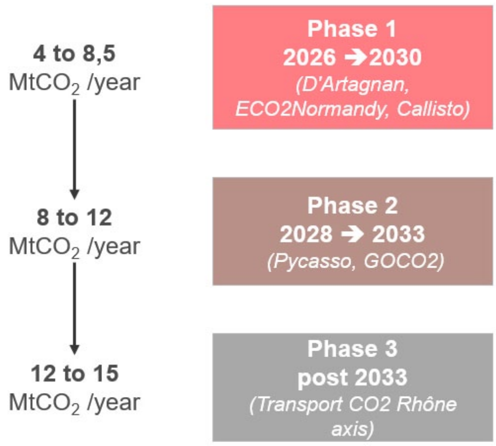

Figure 19 - Different deployment phases of French CCUS projects, and their associated CO_2 transport requirements

Phase 1 (2026-2030):
- **D'Artagnan project:** The Dunkirk industrial zone is joining forces with the d'Artagnan project, which aims to capture and then liquefy and export to the North Sea 3 to 4 $MtCO_2$/year by 2030.
- **ECO2Normandy project:** In Le Havre and the Seine valley, this project aims to enable CO_2 transport on the Seine and to open CCS or CDR (BECCS or DACCS) possibilities for certain isolated sites on the Seine. The CO_2 will then be liquefied in the CO_2 hub of Le Havre, from where it will be exported to the North Sea.
- **CALISTO (Carbon Liquefaction transportation and STOrage) project:** This project will develop a CO_2 hub in Marseille, which will collect CO_2 from the Rhône valley by river, or by pipeline if an existing pipeline can be reused. The CO_2 will then be liquefied and sent by ship to the Ravenna hub in Italy, which will collect CO_2 and send it to the offshore geologic storage site in the Adriatic Sea (56).

Phase 2 (2028-2033):

- **PYCASSO Project (PYrenean CO_2 Abatement through Sustainable Sequestration Operations):** In an initial phase between 2030 and 2034, this project aims to transport and store industrial CO_2 emissions from Lacq, south-west France and northern Spain via dedicated pipelines, supplemented by maritime and rail transport segments. The CO_2 will be stored in the aforementioned Lacq storage reservoir. The project plans to transport up to 2.5 $MtCO_2$/year between 2030 and 2034.
- **GOCO2 project:** From 2030, four major industrial companies, including cement manufacturers and refiners in the Loire estuary, will use CCS to capture ~1.5 $MtCO_2$/year by 2033. The CO_2 will be transported to the hub at the port of Nantes-Saint-Nazaire by pipeline, then exported by sea to storage sites that have yet to be defined.

Phase 3 (from 2033):

- **PYCASSO project (PYrenean CO_2 Abatement through Sustainable Sequestration Operations)** From 2035, the Pycasso project will extend to CO_2 emitters located to the north and south (in Spain between San Sebastian and Bilbao) of the storage platform. To transport this CO_2, a northern pipeline and a southern cross-border pipeline will be used. In this second phase, the project anticipates the transport of up to an additional 3.4 $MtCO_2$/year, i.e. up to ~6$MtCO_2$/year.
- **CCS in the Grand Est:** From 2033, the deployment of carbon capture and storage (CCS) is envisaged in the Grand Est region. Storage will take place either on land in national capacities, or by connecting to a CO_2 transport network extending the Rhône axis on a European scale (51).

All these projects are linked to industrial CO_2 emissions. It is therefore possible to consider building BECCS or DACCS in these same industrial basins to benefit from CO_2 transport and export infrastructures.

4.9.4. Conclusion on CDR

Transporting CO_2 is an essential link in the CCUS chain, and some CDR methods, such as BECCS, DACCS and DOCCS, also require geologic storage of the captured CO_2. These technologies will therefore have to be installed close to existing CO_2 transport infrastructures, in particular pipelines, as well as liquefaction terminals for the maritime export of CO_2. DACCS and DOCCS infrastructures that do not exist today can be built in the most appropriate location, directly next to an electricity supply and a CO_2 transport infrastructure. On the other hand, BECCS units can only be built on large facilities (biomass plants, for example), most of which already exist today and are potentially located in geographical areas far from a CO_2 transport network. BECCS should therefore be favoured in geographical areas close to industrial basins, where CO_2 transport infrastructures will exist in the next few years to manage the CO_2 captured by CCUS solutions.

4.10. Outlook of resource requirements

Developing each CDR method requires one or more physical resources. It is therefore necessary to determine which of these physical resources is limiting its implementation and estimate the maximum potential. The process for doing so is described in Figure 20 with the resources that will be limiting for the method concerned in red.

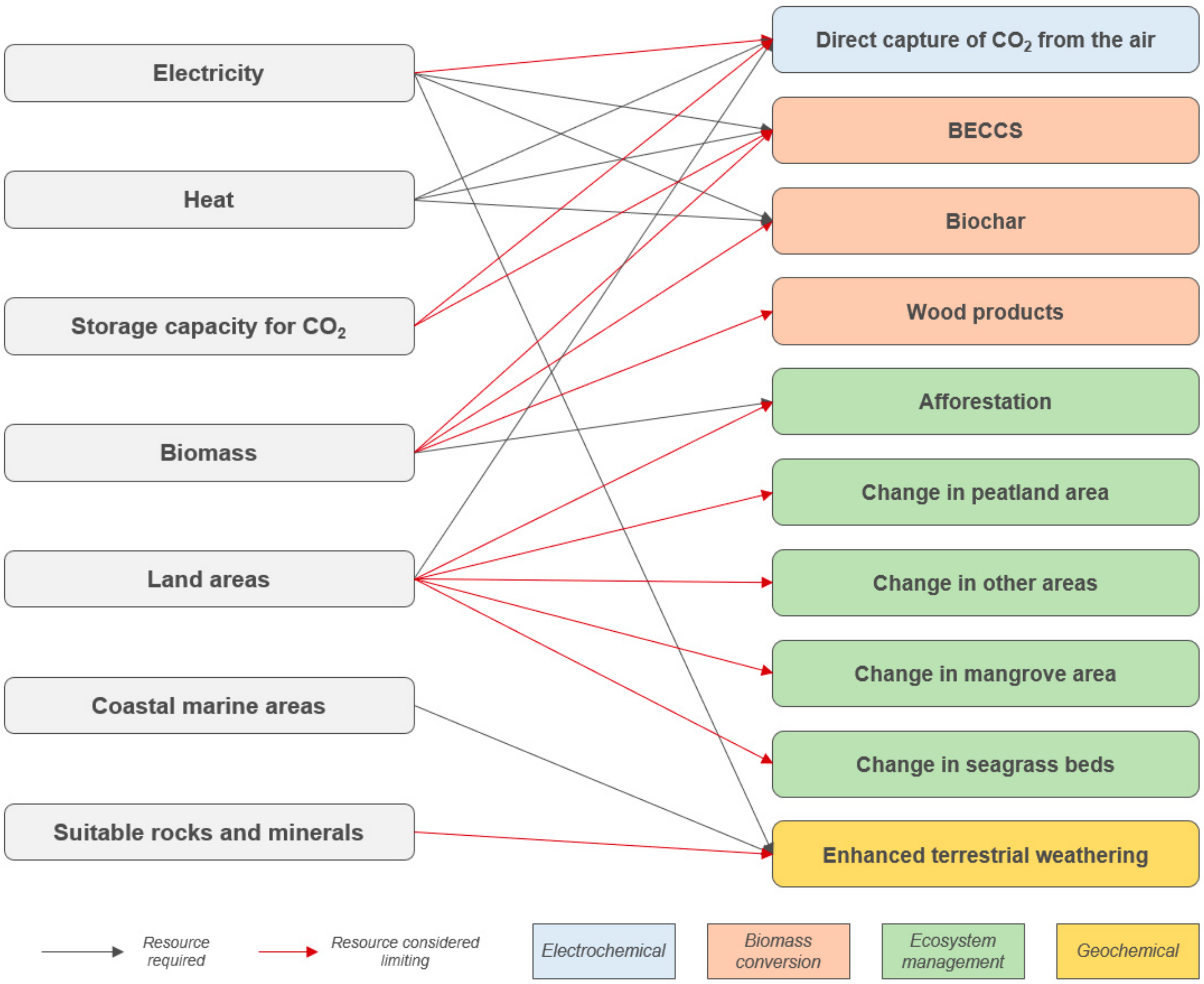

Figure 20 - Illustration of the dependencies between resource requirements and CDR methods (non-exhaustive)

5. Regulatory and legal framework relevant to CDR

5.1. Introduction

France has begun to explore the role of CDR as part of its long-term strategy to achieve climate neutrality by 2050, primarily looking at land- and biomass-based CDR methods. With its Low Carbon Label, France has also established a certification framework applicable to a range of carbon removal methods.

At the time of writing, in spring of 2024, France is in the process of revising its energy and climate strategy, including the new *energy and climate programming law*, which will define the GHG emission reduction targets for three successive five-year periods (probably 2023-2038) and the national energy targets for two successive five-year periods (probably 2023-2033). Planned in the 2019 Energy-Climate Act, this law should set the main objectives of the new PPE 3 (2024-2033) and the new SNBC 3. This law should have been adopted in July 2023 but has not yet been presented at the time of writing this report.

The current PPE covers the period 2019-2028 and was adopted on 21 April 2020. The PPE must be compatible with the greenhouse gas emission reduction targets set by the carbon budgets, particularly for the energy sector, and with the National Low-Carbon Strategy (SNBC).

5.2. Relevant legal frameworks

Legal framework for national climate policies

The Decree no. 2020-457 of 21 April 2020 on national carbon budgets and the national low-carbon strategy sets the annual target GHG emissions budgets for France. These budgets were readjusted in July 2022 following a change in emissions inventory methodology by CITEPA (57). These budgets are:

$MtCO_{2eq}$/year	2e adjusted carbon budget (2019-2023)	3e adjusted carbon budget (2024-2028)	4e adjusted carbon budget (2029-2033)
Transport	129	113	94
Buildings	77	59	72
Agriculture/Silviculture	80	75	70
Industry	75	65	53
Power generation	48	35	30
Waste	12	10	9
Total excluding LULUCF	**421**	**358**	**299**
UTCATF	-38	-38	-41
Total with LULUCF	**383**	**320**	**258**

Table 6 - France's adjusted carbon budgets in July 2022 (57)

Additionally, the SNBC 2, adopted in 2020, sets targets for reducing greenhouse gas emissions and proposes a pathway to carbon neutrality by 2050.

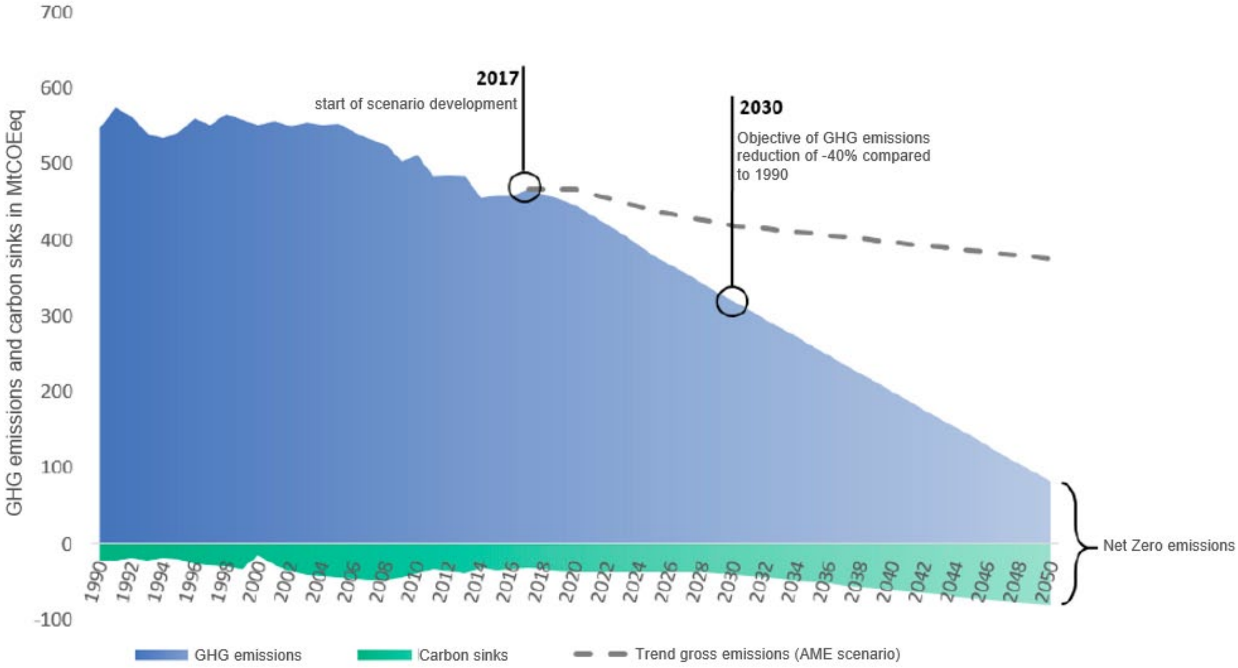

Figure 21 - Evolution of GHG emissions and sinks in France between 2005 and 2050 according to the SNBC 2

In September 2023, the SGPE (French General Secretariat for Ecological Planning) announced a target aiming to reduce annual GHG emissions by 55% between 2030 and 1990, i.e. a reduction of 4 to 5% per year (58). The SGPE also points out that the first carbon budget (2015-2018) was not respected, while the second budget (2019-2023) so far has been.

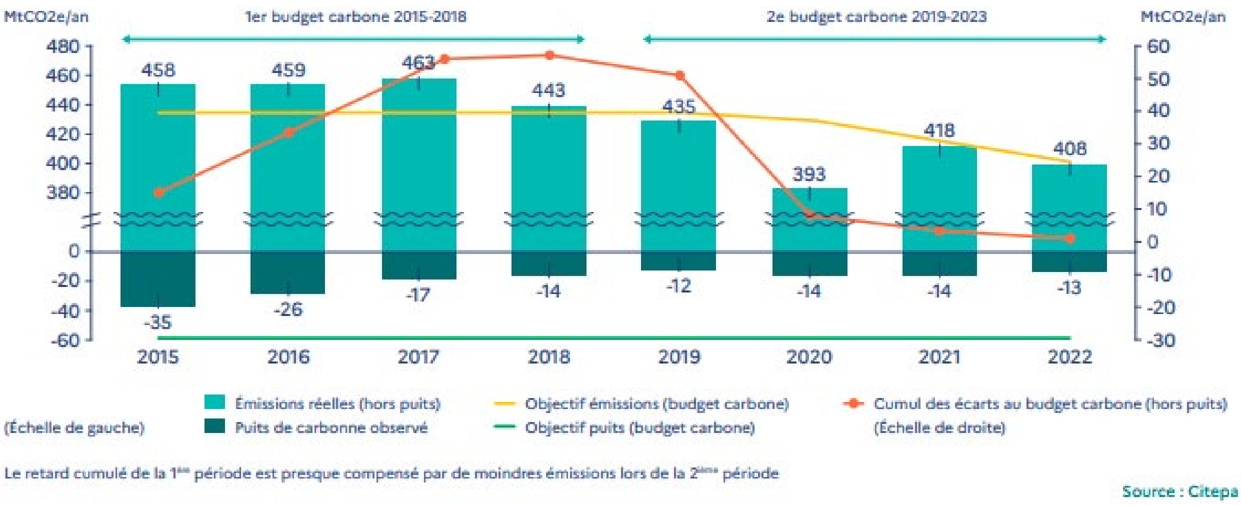

Figure 22 - France's carbon budgets for 2015-2018 and 2019-2023 (58)

France's climate commitment is in line with that of the European Union to achieve carbon neutrality by 2050 and to reduce its emissions by at least 55% between 2030 and 1990 following the "Fit for 55" package. The carbon neutrality objective is enshrined in Regulation (EU) 2021/1119.

Relevant legal framework for CDR methods:
In France, a **low-carbon label** was introduced in 2018. This is France's official certification scheme for greenhouse gas reduction or sequestration projects carried out on its territory. It brings clear rules and transparency to the national voluntary carbon market by introducing a framework for monitoring, reporting and auditing greenhouse gas emission reductions, or negative carbon emissions, to encourage such projects. The label is based on emission reduction or carbon removal methods approved by the French Ministry for Ecological Transition. As of October 2023, a total of 726 projects have received the label and 151 projects have been 100% financed via the label.

At the European level, the 2009 CCS Directive provides a framework for CO_2 transport and storage activities. The EU is also preparing to develop its Carbon Removal Certification framework. This framework specifies that there are several ways of removing and storing carbon, all of which can be certified within the EU framework:

- Nature-based solutions, such as forest and soil restoration and innovative farming practices qualified as carbon farming;
- Sustainable products and materials, such as wood-based construction;
- Permanent CDR, such as bioenergy with carbon capture and storage or direct capture from the air.

At the time of writing, the European Commission's proposal will soon be discussed with the European Parliament and the Council.

Furthermore, CO_2 captured and stored (CCS) is not currently considered as "emitted" in the ETS system. Since the Emissions Trading Directive was amended in 2015, CO_2 capture, transport and storage infrastructures have been explicitly included in the ETS (59). The ETS therefore favours CCS but does not currently value the storage of biogenic CO_2 in the form of "negative" allowances.

On the other hand, GHG emission reduction targets for aviation (-61% of GHG emissions between 2030 and 2005) and maritime (-80% of GHG emissions per unit of energy consumed per ship in Refuel EU Maritime) will create a demand for synthetic sustainable fuels produced from biogenic CO_2 and green/blue hydrogen. This could encourage industrial players to capture and then sell biogenic CO_2 to make electro-fuels instead of burying it in geological cavities for BECCS. Competition for biogenic CO_2 could thus arise between BECCS and the production of electro-fuels.

5.3. The role of CDR in national policy

The **national low-carbon strategy (SNBC 2)** sets the objective of achieving net zero emissions by 2050 and proposes projections for greenhouse gas (GHG) emissions and removals for 2050, based on the assumption that France will still emit around 80 million tonnes (Mt) of CO_{2eq} per year and that GHG sinks will absorb just over 80 Mt of CO_{2eq} per year (including CCS as a sink). The strategy forecasts that by 2050, around 30 Mt of negative CO_{2eq} emissions will be generated annually by forests, 21 $MtCO_{2eq}$/year by wood products, 15 $MtCO_{2eq}$/year for CCS (including BECCS) and 12 $MtCO_{2eq}$/year in the other areas. These targets may change with the preparation and adoption of the SNBC 3.

The SNBC 2 makes several recommendations concerning carbon sequestration in soils, including (page 190):

- Preserving permanent grasslands;
- Widely developing agroforestry;
- Increasing restitution to the soil of crop residues and quality organic matter;
- Develop agroecological farming practices that favour carbon sequestration, in particular combining reduced tillage, permanent soil cover and longer crop rotations, as well as the development of grassed banks;
- Preserving wetlands.

About forests, the SNBC 2 recommends to (page 191):

- Develop afforestation, while considering the ecological challenges of woodland renewal (preserving biodiversity, landscape aspects, etc.);
- Preserve forest areas by reducing forest clearance;
- Reduce the risk of damage linked to natural hazards (storms, fires, drought, pest attacks, etc.) through improved silvicultural management aimed at adapting forests to climate change.

Concerning CCS and CCU, the SNBC 2 adopted in 2020 recommends *"supporting the development of pilot and possibly commercial units for carbon capture and storage (CCS) and carbon capture and utilisation (CCU) with the use of* CO_2 *as a raw material in the manufacture of fuels or chemicals"*. It also recommends strong support for the use of CCS with bioenergy units to *"generate negative emissions"* (page 191). However, no incentive mechanism has since been put in place for BECCS.

The recommendations of the SNBC 2 are set out in more detail in the CCUS strategy presented by the French government in June 2023, which states that *'CCUS technologies are part of the solution. They must make it possible to capture the incompressible residual emissions from industry; they provide solutions where decarbonisation options do not exist; they make it possible to accelerate by capturing carbon emissions until industry can implement more sustainable solutions.'* Carbon capture's potential is estimated at **4 to 8 MtCO_2e/year by 2030** and between **15 and 20 MtCO_2e/year by 2050**. This figure of 15 to 20 MtCO_2e/year in 2050 is consistent with the SNBC 2 objectives of capturing 15 MtCO_2e/year by CCS in 2050.

In the near future:

The *Energy and Climate Programming Act (LPEC)*, provided for in the 2019 Energy and Climate Act, is being discussed at the time of writing. It should have been voted on in July 2023, but has been postponed due to a busy parliamentary agenda. This new law should set the major objectives of the new PPE 3 (2024-2033) and the new SNBC 3.

Following the adoption of the LPEC, a new iteration of the National Low-Carbon Strategy (SNBC3) should follow, as well as the next Multiannual Energy Framework (PPE 3, 3rd iteration for 2024-2033) which will define the tools for managing energy policy and the revised National Climate Change Adaptation Policy (PNACC 3, 3rd iteration). These legislative initiatives will provide technical roadmaps for the implementation of the SFEC and LPEC.

Another potentially relevant development for CDR is the '*industrie verte*' (green industry) law supported by the Minister of Finance and adopted in July 2023. This law aims to support green technologies through the 'green industry investment' tax credit, to support the decarbonisation of existing industries and to mobilise private savings to finance green industry. In this respect, the Green Industry law reiterates that the France 2030 strategy plans to invest €5.6 billion in subsidies dedicated to decarbonising industry. However, the document makes no mention of CDR solutions.

5.4. Support for R&D and innovation

French vision

The **Low Carbon Label** can encourage ecosystem-based greenhouse gas emission reductions (by enhancing natural sinks). CDR methods such as biochar and enhanced rock weathering could potentially benefit from these incentives, but certification methods still need to be developed (the structure of the Low Carbon Label allows for the integration of new certification methods on an ongoing basis).

Additional funding is planned in the **France 2030** strategy. Three billion euros will be made available to decarbonise industry with CCS and for deeptech/frontier startups as part of this plan. CDR may correspond to the description of the technological innovation targeted by the strategy, but it is not explicitly targeted.

European vision

At the European level, there is additional support for R&D and innovation for CDR.

According to **The State of Carbon Dioxide Removal** (2023), '*As part of its sustainable carbon cycle initiative, the Commission plans to increase **incentives** for all LULUCF-based CDR methods (under the term carbon farming), develop **support for innovation** in CCS-based CDR methods, such as BECCS and Direct Air Carbon Capture and Storage (DACCS), and establish a **certification framework** for a wide range of CDR methods.*'

The European Innovation Fund (fed by revenues from the EU Emissions Trading Scheme) has so far been the main tool for supporting the development of new CDR technologies, complemented by funding under the **EU's research and innovation programme (Horizon Europe)**.

In this regard, the European Commission announced in April 2022 that it is co-financing a CDR demonstration project (BECCS Stockholm) for a total of €180 million from the **European Innovation Fund**, in addition to projects that fall into the broader category of 'carbon management' (i.e. carbon capture and storage), which will shape the future expansion of CDR. This project will capture and store emissions from a biomass power plant in Stockholm at 0.8 $MtCO_{2eq}$/year.

The second funding mechanism for CDR at the EU level is **Horizon Europe**, the EU's research, development, and innovation programme. This programme supports a variety of CDR methods. For example, the '3D' project in Dunkirk, as part of the **Horizon Europe** research programme, aims to demonstrate the effectiveness of an innovative process for capturing CO_2 from industrial activities. This project is also part of France's new decarbonisation strategy, which aims to halve the emissions of 50 of the 120 largest carbon-emitting industrial sites in France over the next ten years.

In Germany, the government is also supporting projects. According to **The State of Carbon Dioxide Removal** (2023) report, '*Since 2021, the German Federal Ministry of Education and Research has funded two major research missions: one on ocean-based CDR methods and marine CO_2 storage methods (CDRmare) and the other on terrestrial CDR methods (CDRterra). **CDRmare** began funding six projects in 2021 for a total of €26 million. **CDRterra** has begun funding projects on DACCS, biochar, rock weathering enhancement, BECCS and afforestation/reforestation, with a total value of €21 million*'.

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5.5. CDR players

In France, although support is lacking and the government is struggling to define a clear CDR strategy, an ecosystem of researchers, entrepreneurs, investors and think tanks is gradually developing.

Figure 23 gives an overview of this ecosystem at the time of writing.

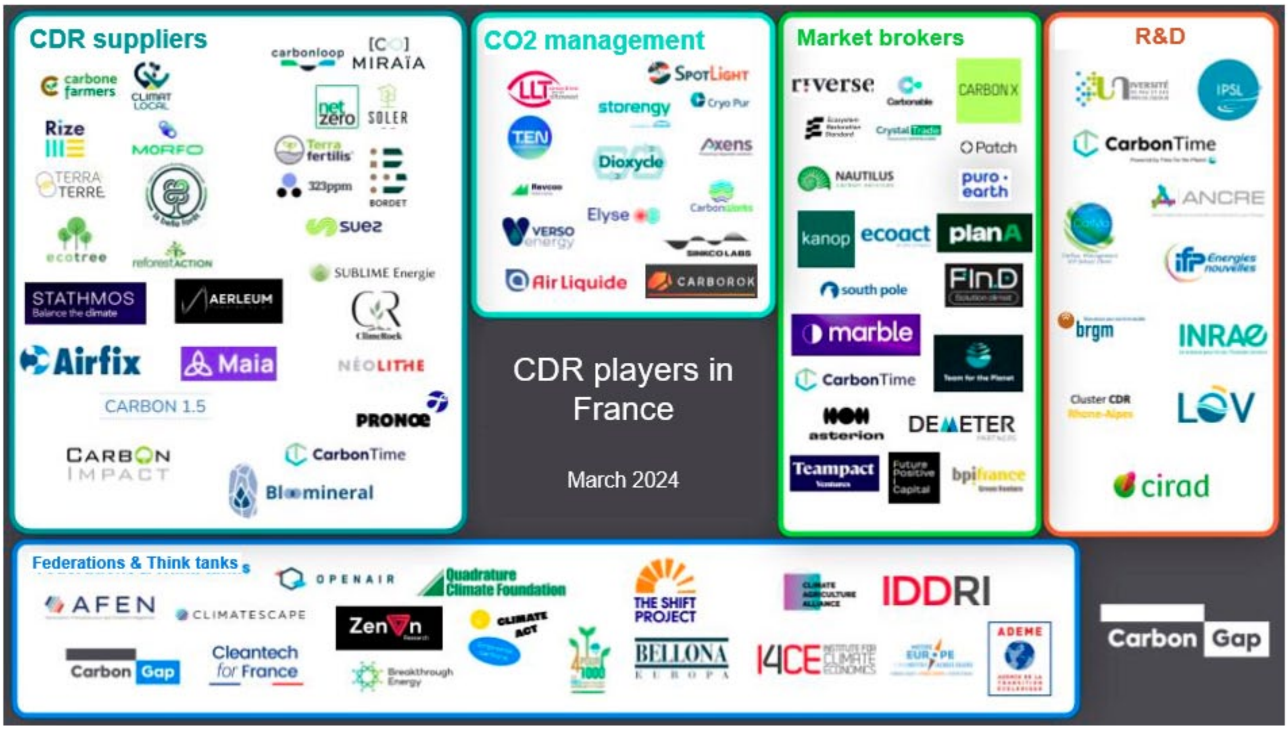


Figure 23 - Map of CDR players in France

Most CDR suppliers are still very young, although some major groups such as Suez are joining. The ecosystem already covers the majority of methods, with those based on ecosystem management are the most represented.

Major French companies are among the CO_2 managers, particularly in capture, liquefaction, transport, and storage. Newer companies, such as Dioxycle and Sinko Labs, are involved in the conversion and recovery of CO_2.

Market intermediaries include key international players such as Puro and Patch, as well as others operating from France such as CarbonX and Riverse. French investors are still few and far behind when it comes to CDR.

Finally, as regards the last two categories, research and federation/think tank, the organisations listed approach the subject of CDR from very different angles, some in a very tangential way, while others are specialised in the subject. More and more organisations are getting interested in CDR, and these two categories have grown rapidly in recent years.

6. Maximum theoretical CDR potential

6.1. Resource allocation methodology for CDR methods

Part 4 of this report assessed the maximum availability of resources in France for the various CDR methods. In this part 6, the **maximum theoretical** CDR potential is calculated assuming that all available resources (while preserving priority uses) are used for CDR. This approach is entirely **theoretical** and does neither represent reality nor where there could be competition from other sectors for these additional resources. Nevertheless, the theoretical potential is a useful reference point for the more conservative assumptions made later to define the achievable potential. It gives an idea of the maximum deployment of CDR in a different context, for example if society would engage in a "wartime effort" to halt climate change.

Calculation of theoretical CDR potential

To assess theoretical CDR potential, it is necessary to estimate the resource available to each CDR method. Each CDR method often requires several sources of energy, such as electricity, water, heat, etc. The different CDR methods using the same resources are first prioritised. This is particularly the case for the different types of DACCS, DOCCS and geochemical methods (grinding), which all require electricity. Once this prioritisation has been made, it is possible to define the **limiting resource** that will **determine** the potential of each CDR method.

The criteria for allocating electricity and heat are firstly, the cost of the technology, and secondly its energy efficiency. The cheapest technologies are the most likely to be developed and are therefore given priority. Next, energy efficiency determines the allocation priority, giving preference to the methods that consume the least electricity per tonne of CO_2 removed.

Technical constraints also need to be considered, as in the case of L-DACCS, which requires temperatures between 300 and 900°C, which are incompatible with the waste heat sources (<300°C for most of the sources). This technology is therefore excluded from the resource allocation exercise and will not be retained for CDR's maximum theoretical potential. The available waste heat is used by enhanced lime weathering and S-DACCS, known as low-temperature DACCS.

Figure 24 illustrates the allocation of electricity and waste heat, with priority given to enhanced olivine weathering, which consumes little electricity and is cheaper (~$125/$CO_2$) than electrochemical DACCS (~$200/t$CO_2$), followed by enhanced lime weathering, which is also cheaper than DACCS, then S-DACCS, which consumes the remaining heat, and finally electrochemical DACCS.

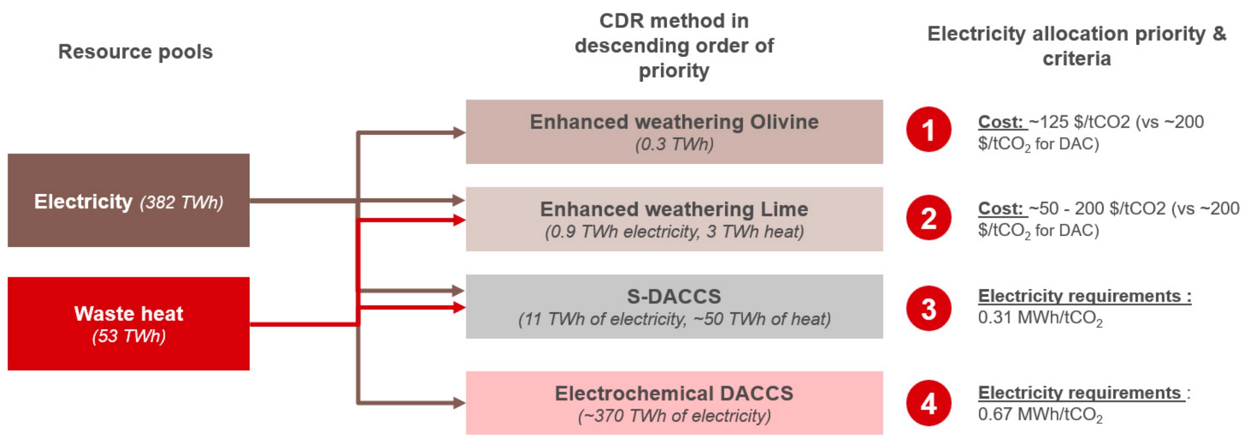


Figure 24 - Allocation of electricity and heat among the various electro-intensive technologies

The limiting resource for enhanced weathering methods will be the availability of rock. For electrochemical DACCS, it will be electricity.

Biomass is a distinct case as it is widely used for a variety of purposes, especially because it contributes to the decarbonisation of sectors that can use it as a substitute for fossil fuels. It therefore seems difficult to shift away from these uses. Moreover, the outlook for this resource is highly uncertain, with little chance of growing significantly.

The proposed biomass allocation is then largely based on similar published exercises (SNMB) (60) which are in line with the current uses of the existing sectors (Table 7). With this approach, few biomass resources are available for innovative sectors such as biochar production. However, depending on the carbon accounting rules for biomass, this situation could change. Thus, the CDR potential for biochar can be seen as conservative and depends greatly on the allocation of resources proposed in Table 7. For the sake of simplicity, when it is possible to use the same biomass simultaneously for several purposes (e.g. biochar production coupled with biofuel production), only the priority use is retained. On the other hand, for a given category of biomass, several prioritised usages may be considered, for example: ~75% of crops dedicated to non-food uses (Miscanthus, short rotation coppice, etc.) are directed towards combustion i.e. BECCS and ~25% for use in the form of materials.

For energy uses (combustion and anaerobic digestion), the resources in the various categories of biomass have been converted into energy. The values of the conversion factors are detailed in Table 16 (appendix 10.4) and give the total theoretical quantity of energy that could be produced from the various biomass sources. In fact, it is the quantity of energy that makes it possible to estimate the theoretical potential of CDR from other conversion factors compiled in the database on resource requirements and makes it possible to convert energy into the quantity of CO_{2eq} that can be removed from the atmosphere.

Category	Type of biomass	Source	Constraints	Priority uses	Unit	Total volume	Feedstock	Breakdown	Uses	CDR
Biomass from non-food agriculture	Crops dedicated to non-food uses	ONRB	**Harvesting constraints:** non-accessible volumes such as slurry produced in the field, harvest losses, etc.	Food and feed, fertilisation, mulching	MtDM/year	0.1	**0.1**	73% 27%	Combustion Materials	BECCS **Products**
	Intermediate crops	FS			MtDM/year	23.8	**4.4**	100%	Anaerobic digestion	BECCS
	Agricultural waste	ONRB / FS			MtDM/year	139	**17.8**	41% 59%	Combustion Anaerobic digestion	BECCS
	Livestock manure	ONRB			MtDM/year	30.5	**24.7**	100%	Anaerobic digestion	BECCS
	Fibre plants	ONRB			MtDM/year	0.8	**0.7**	12% 88%	Combustion Materials	BECCS **Products**
	Perfume plants	ONRB			MtDM/year	0.08	**0.025**	56% 44%	Combustion Anaerobic digestion	BECCS
Municipal waste	Green urban waste	ONRB / Modecom	Recycled waste not used for CDR	No	MtRM/year	61	**5.14**	0,4% 99,6%	Combustion Anaerobic digestion	BECCS
	Used edible oils	France AgriMer	No	Production of biofuels	MtRM/year	0.08	**0**		Biofuel[3]	
	Paper and cardboard waste	Modecom	Recycled waste not used for CDR	No	MtRM/year	6.8	**0.14**	100%	Combustion	BECCS
	Wood waste	Modecom	No	No	MtRM/year	2.3	**2.3**	21% 11% 68%	Combustion Biochar Recycling	BECCS Biochar **Products**
	Sewage sludge	SDES	No	Spreading, composting	MtDM/year	0.8	**0.2**	100%	Anaerobic digestion	BECCS
	Household waste	Modecom	No	No	MtDM/year	4.9	**4.9**	100%	Anaerobic digestion	BECCS
Co-products of the agri-food industry	Oilseed crushing	ONRB	Losses during processing but data unavailable	Composting, distillery, human food, animal feed, etc.	MtRM/year	3.70	**0**		Biofuel[3]	
	Sugar beet				MtRM/year	4.91	**0.15**	100%	Anaerobic digestion	BECCS
	Fruit-vegetables transf.				MtRM/year	0.08	**0**			
	Vinification				MtRM/year	2.30	**0.06**	100%	Anaerobic digestion	BECCS
	Meat industries				MtRM/year	1.17	**0.36**	52% 48%	Biofuels[2] Incineration	BECCS
	Egg products				MtRM/year	0.05	**0**			
	Fishing and aquaculture				MtRM/year	0.20	**0**		Biofuel	
	Wine distillation				MtRM/year	0.47	**0.18**	89% 11%	Combustion Anaerobic digestion	BECCS
	Cidrerie				MtRM/year	0.007	**0.006**	50% 50%	Anaerobic digestion Combustion	BECCS
	Potato				MtRM/year	0.24	**0**			
Forest biomass	Hedgerows and agroforestry	FS	Operating profitability	No	Mm^3 /year	3.6	**3.4**	90% 10%	Combustion Biochar	BECCS Biochar
	Forest harvesting	Agreste/IGN	Unused paper/ cardboard for CDR	Self-consumed wood not available to CDR	Mm^3 /year	88	**33**	63% 5% 32%	Combustion Biochar Products	BECCS Biochar **Products**

Table 7 Allocation of biomass sub-category feedstocks
Red - Type of biomass not exploitable for CDR, Green - Type of biomass exploitable for CDR

The following conversion factors between the energy produced and the quantity of CO_2 emitted have been used to calculate the maximum CDR potential for each energy use of biomass (anaerobic digestion and combustion):

- Combustion: 2.7 MWh/tCO_2
- Anaerobic digestion: 3.8 MWh/tCO_2

Finally, once the available resources are defined, they must be multiplied by a conversion factor to calculate the volume of CO_2 that can be removed from the atmosphere. These conversion factors, for example in tCO_2/tonne of biomass, or in tCO_2/MWh of heat or electricity, are those determined in part 3 of the report. For each CDR method studied, the table below describes the limiting resource, the associated source, the conversion factor from feedstock to CDR potential, and the result of the CDR potential in $MtCO_2$.

Macro-categories	Categories	Limiting feedstock that determines CDR potential	Maximum theoretical feedstock	Conversion factor	CDR ($MtCO_2e$/year)	Source conversion factor
Converting biomass	BECCS	Biomass for biofuels	10 TWh	3.6 MWh/tCO_2	3	Customs department
		Biomass for combustion	93 TWh	2.7 MWH/TCO_2	35	ADEME
		Biomass for anaerobic digestion	122 TWh	3.8 MWh/tCO_2	32	*Base Empreinte*
	Biochar	Biomass attributed to pyro gasification	1.7 Mt	1.6 t/tCO_2	0.52	BDD-BR
	Biobased products	Forest biomass allocated to biobased products	8 Mt	0.7 t/tCO_2	19	ADEME
Ecosystem management	Afforestation/reforestation	Change in surface area	2.9 Mha	0.27 ha/ tCO_2/year	16	BDD-BR
	Peatlands	Change in surface area	6.5 kha	0.5 ha/ tCO_2/year	0.003	EFESE
	Mangroves	Change in surface area	0 kha	0.56 tCO_2/HA/year	0	EFESE
	Seagrass beds	Change in surface area	8 kha	0.27 tCO_2/ha/year	0.03	EFESE
	Carbon storage practices	Surface areas (2050)			**61**	INRAE
	of which agricultural carbon storage practices					
	Inserting and extending intermediate crops	Surface areas (2050)	13.5 Mha	0.736 tCO_2/ha/year	9.9	INRAE
	Developing direct seeding	Surface areas (2050)	9.5 Mha	0.736 tCO_2/ha/year	1.9	INRAE
	Plant hedges around the edges of cultivated plots	Surface areas (2050)	7.4 Mha	0.736 tCO_2/ha/year	9.2	INRAE
	Include/extend grassland in crop rotations	Surface areas (2050)	5.6 Mha	0.736 tCO_2/ha/year	5.1	INRAE
	Developing agroforestry	Surface areas (2050)	4.5 Mha	0.736 tCO_2/ha/year	23.7	INRAE
	Mobilising new organic resources	Surface areas (2050)	1.2 Mha	0.736 tCO_2/ha/year	0.4	INRAE
	of which grassland stocking practices					
	Moderately increase nitrogen fertilisation of grassland	Surface areas (2050)	3.9 Mha	0.736 tCO_2/ha/year	0	INRAE
	Replace mowing with grazing	Surface areas (2050)	0.10 Mha	0.736 tCO_2/ha/year	0.10	INRAE
	of which wine-growing stocking practices					
	Winter grassing	Surface areas (2050)	0.4 Mha	0.736 tCO_2/ha/year	0.4	INRAE
	Permanent grassing	Surface areas (2050)	0.2 Mha	0.736 tCO_2/ha/year	0.2	INRAE
	of which forestry stocking practices	Surface areas (2050)	19.8 Mha	0.736 tCO_2/ha/year	9.88	INRAE
Geochemical	Enhanced weathering: limestone	Rocks/minerals	5.2 Mt/year	1.65 t/tCO_2	3.1	BDD-BR
	Enhanced weathering: olivine	Rocks/minerals	3 Mt/year	1.03 t/tCO_2	3.0	BDD-BR
	Enhanced weathering: basalt	Rocks/minerals	3 Mt/year	3.3 t/tCO_2	0.9	BDD-BR
	Enhanced weathering: dolomite	Rocks/minerals	0.2 Mt/year	3.3 t/tCO_2	0.1	Identical to basalt
	Enhanced weathering: CKD	Rocks/minerals	0.3 Mt/year	3.3 t/tCO_2	0.1	Identical to basalt
Electrochemical	Electrochemical DAC	Electricity	372 TWh	0.68 MWh/tCO_2	549	BDD-BR
	S-DAC	Low-temperature waste heat	48 TWh	1.66 MWh/tCO_2	29	BDD-BR
	L-DAC	High-temperature waste heat	0 TWh	1.9 MWh/tCO_2	0	BDD-BR
	DOCCS	Electricity	0 TWh	n/a	n/a	

Table 8 Maximum theoretical resources and removal potential for CDR methods

6.2. Maximum theoretical CDR potential

Summing up the potential offered by each method gives a **theoretical maximum CDR potential** for France of ~780 $MtCO_2$ eliminated per year by 2050 (cf. Figure 25). It is dominated by electro-chemical technologies such as DACCS, which account for ~550 $MtCO_2$/year of CDR. Carbon farming practices come in second place with nearly 90 $MtCO_2$/year. BECCS comes third, with ~70 $MtCO_2$/year of CDR.

It is important to remember that this annual potential is **purely theoretical**. It is achieved if all the French biomass available after allocation to priority uses is allocated to CDR methods such as BECCS, for example, and if France develops its renewable energy production capacity to the maximum (according to RTE studies) to allocate all the surplus electricity (382 TWh) to CDR methods such as DACCS. Figure 25 illustrates the annual CDR potentials by method and indicates the limiting factors in each case.

Some methods are too costly, with a too low energy yield, and have not been included in the calculation of maximum theoretical CDR potential. This is the case for DOCCS, electrochemical OAE, mangrove carbon storage practices and the burial of algae. It is therefore important to note that this theoretical potential includes a negative margin of error, with potential technical shortcomings that are difficult to quantify, but also a positive margin of error, with methods excluded from the estimate that could mature and materialise in the coming years.

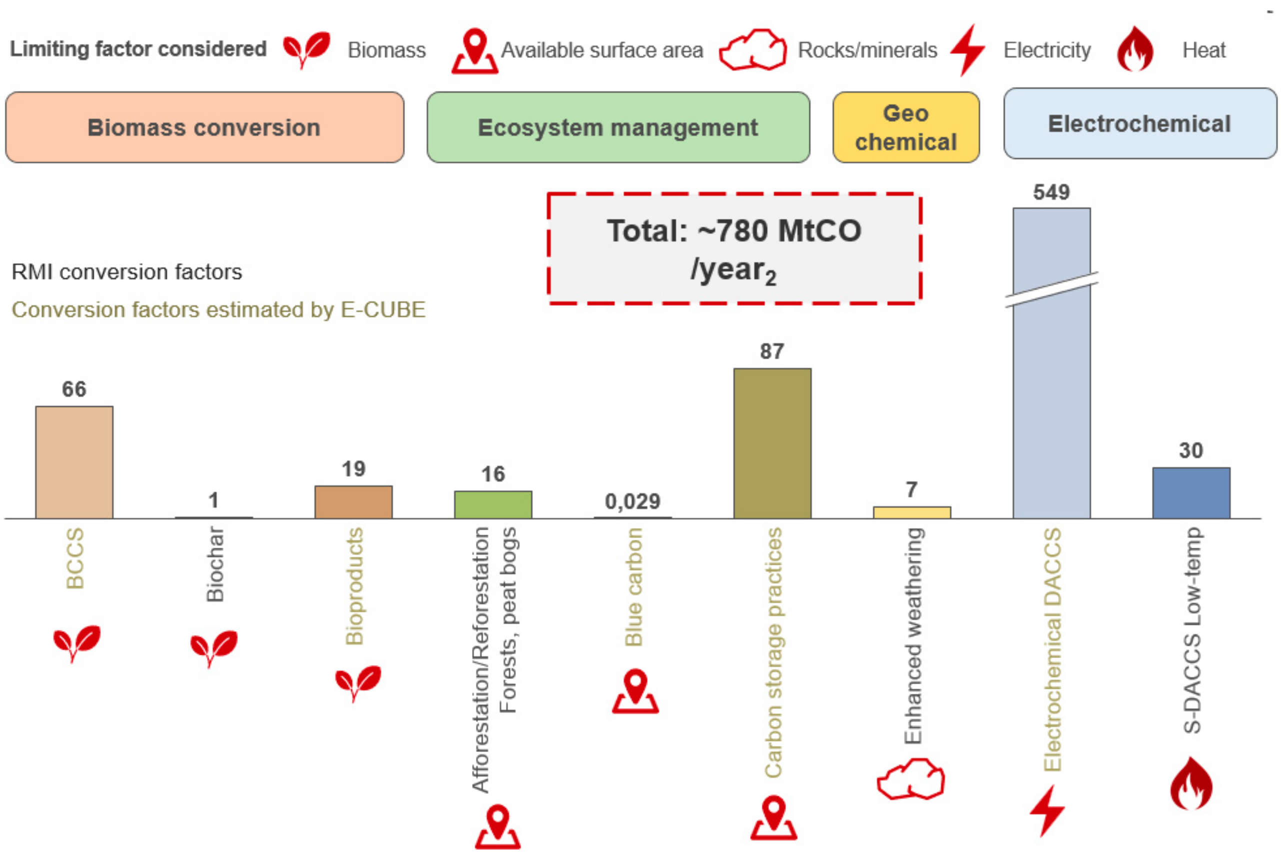


Figure 25 - CDR potential of different methods and technologies, with allocation of required resources [$MtCO_2$/year]

In section 8 of this report, the practical CDR potential will be estimated based on this maximum theoretical potential. It will consider additional constraints, such as the regulatory and economic environment, and public support, which will reduce the volumes presented below.

7. Socio-economic overview of France

In addition to the "physical" potential of CDR solutions, economic and social constraints also need to be considered in order to estimate a realistic potential for the deployment of these solutions.

To study these constraints, this section analyses France's economic performance and its capacity to finance the deployment of CDR solutions. The perceptions and positions of key actors (State, citizens, companies, associations) on CDR methods are also evaluated. Finally, the background values defining citizens' views of CDR methods are highlighted, using ADEME's work to explore public support for undertakings such as CDR.

7.1. French economy

France is the 7th richest country in the world in terms of GDP and the 28th richest country in terms of GDP per capita. Its GDP was EUR 2,501 billion in 2021 (INSEE). The French population was 67,8 million in 2022 (INSEE). The unemployment rate is 7.2% of the working population (excluding Mayotte) (INSEE). The French workforce is well-trained and has the skills needed to deploy CDR solutions. The GDP growth rate is around 1 to 2% per year, with a sharp decline during the Covid period. This rate has been declining since 1950 (INSEE).

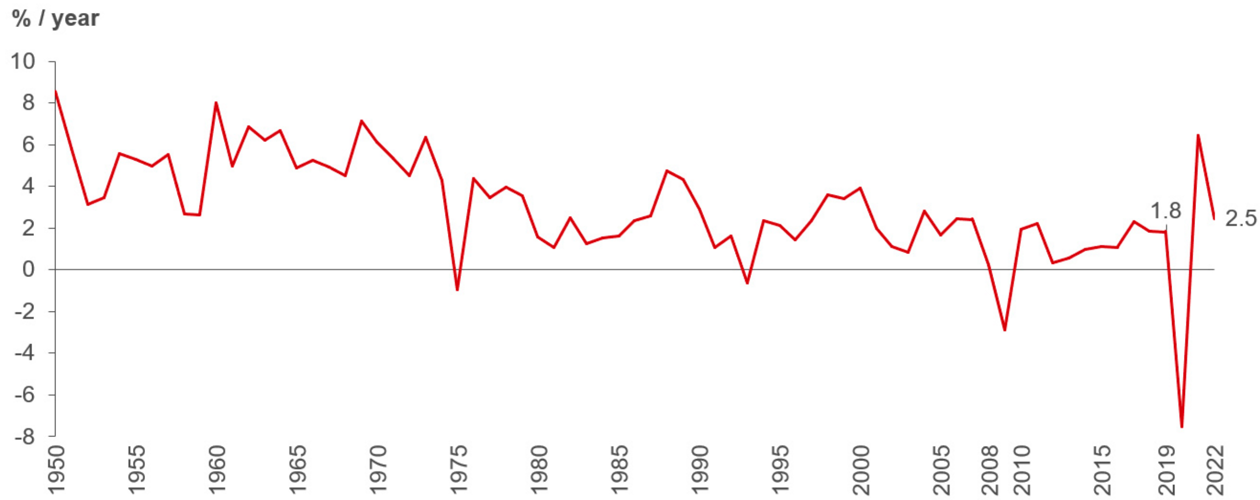


Figure 26 - Annual growth in GDP in France from 1950 to 2022, in % per year (INSEE)

The majority of value added in France comes from services (79%), followed by industry (13%), construction (6%) and agriculture (2%) (INSEE).

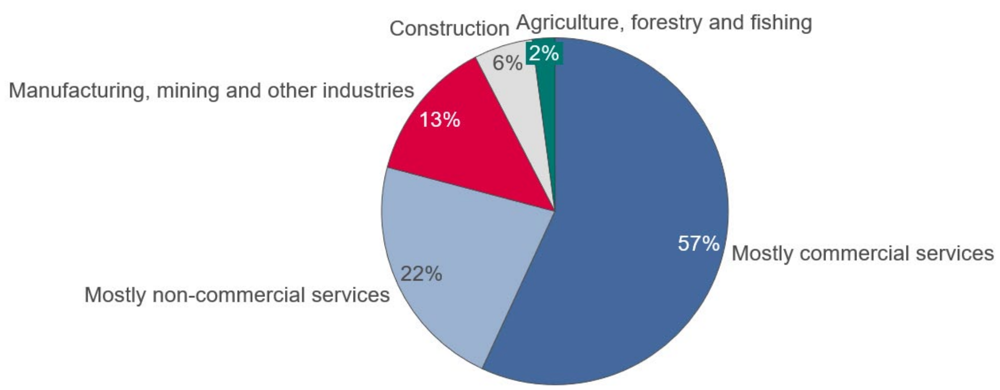


Figure 27 - Breakdown of added value in France by industry in 2022 (INSEE)

7.1.1. Exploration of the cost of deploying CDR methods according to different ADEME scenarios

The deployment of CDR technologies will require substantial investment. In the IPCC report "*Climate Change 2022, Mitigation of climate change*"(2) the IPCC estimates the abatement costs of the main CDR methods at maturity to be between USD 0 and USD 400/tCO_2, with costs of between USD 100 and USD 300/tCO_2 for electrochemical DACCS, and between USD 15 and USD 400/tCO_2 for BECCS.

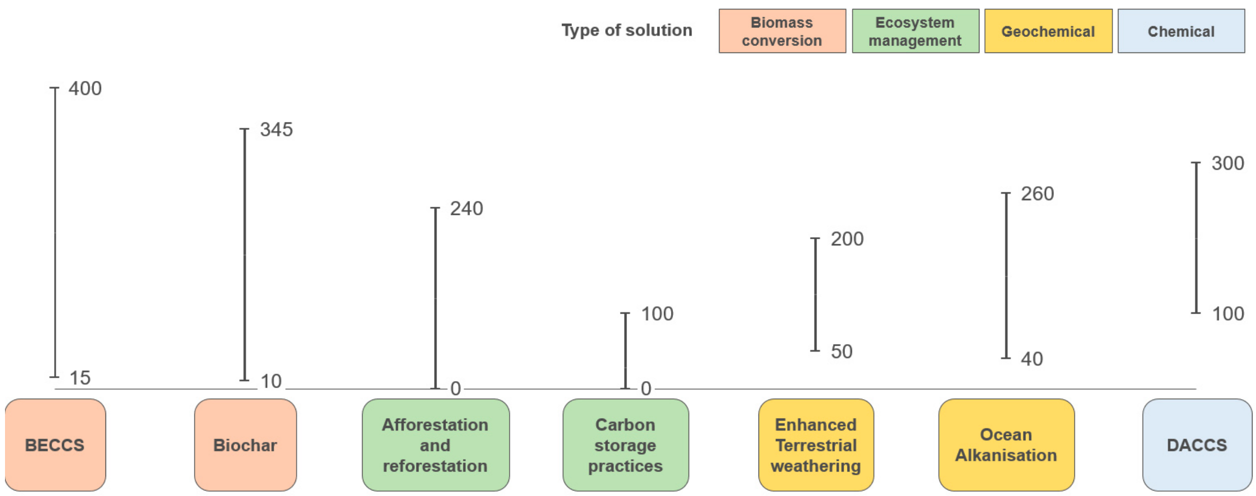


Figure 28 - Abatement cost of the main CDR solutions according to the IPCC, in USD/tCO_2

The ADEME report *Transitions 2050* (20) presents several estimates of natural and technological carbon sinks in 2030 and 2050. These sinks would remove the equivalent of 40 to 80 MtCO_{2eq}/year in 2030 and 93 to 133 MtCO_{2eq}/year in 2050, considering natural and technological sinks (BECCS, DACCS).

To estimate the cost of deploying these sinks, only the additional capacity for natural and technological sinks is considered. CCS is excluded because it does not generate negative emissions. Moreover, natural sinks already represented 44 MtCO_2,eq/year in 2017 according to ADEME. In the following analysis, these emissions are subtracted from the total carbon sink in 2030 and 2050 to consider only the increase in carbon sinks between now and 2030, and now and 2050.

The **additional** carbon sinks would therefore be between 6 and 35 MtCO_{2eq}/year in 2030 and between 34 and 72 MtCO_{2eq}/year in 2050 according to the ADEME scenarios.

To estimate the cost of deploying these additional carbon sinks, values of €100/tCO_2 for natural sinks and €200/tCO_2 for technological sinks are used, corresponding to the average abatement costs of reforestation/afforestation and technological sinks (BECCS, DACCS) as seen by the IPCC. The cost of deploying CDR is thus estimated at between €1.2 and €3.5 billion per year in 2030, and €3.9 to €11.2 billion per year in 2050 for the ADEME scenarios (trend, S1 to S4).

France's GDP was €2,501 billion in 2021. The cost of deploying CDR would therefore represent between 0.05% and 0.14% of GDP in 2030 and between 0.16% and 0.45% of GDP in 2050 under the ADEME scenarios.

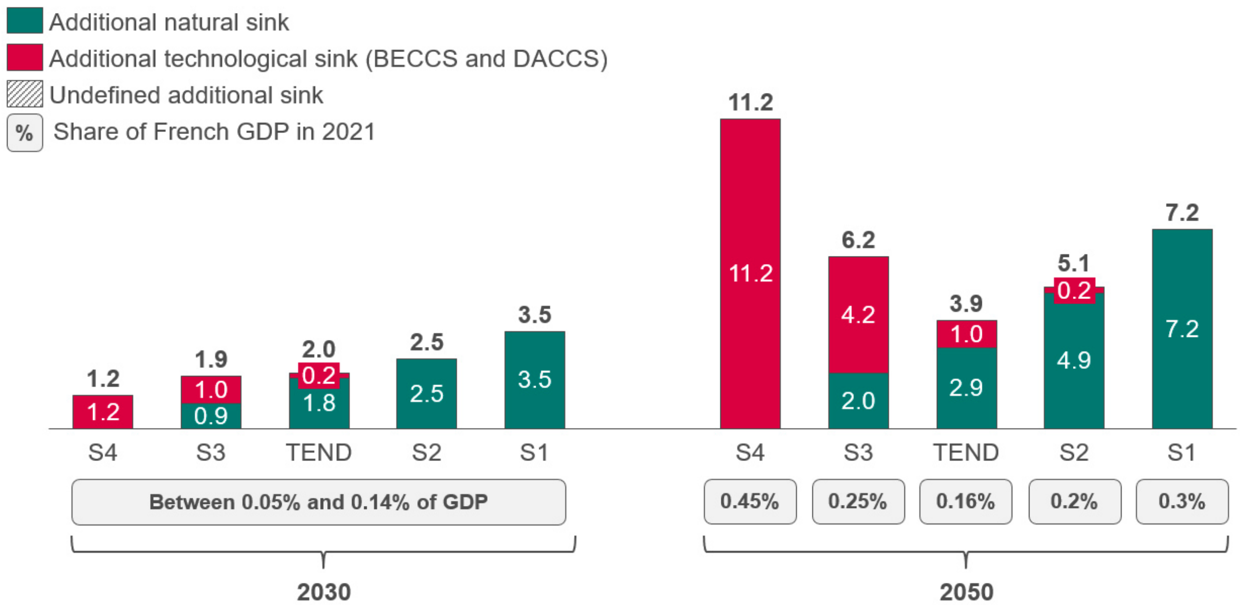


Figure 29 - Estimated cost of deploying additional natural and technological sinks between 2017 and 2030, and between 2017 and 2050, according to ADEME scenarios, in €bn/year (% share of French GDP in 2021)

These amounts are substantial and should be compared with France's financing capacity in the context of the ecological transition of its entire economy.

7.1.2. Estimate of France's financing capacity

Vision 2030

According to ADEME scenarios, at its peak in 2030, the deployment of CDR methods would represent a cost of around €3.5 billion, or 0.14% of France's GDP (in 2021). As a comparison, the ecological transition as a whole (excluding CDR) would require a **net additional** investment (compared with a scenario without transition) of €69 billion per year in 2030, or 2.8% of GDP, according to the report "*Les incidences économiques de l'action pour le climat*" by France Stratégie, Jean Pisani-Ferry and Selma Mahfouz (61). Between now and 2030, this sum of €69 billion corresponds to additional "green" investment of €101 billion a year, a €35 billion reduction in annual "brown" investment, and €3 billion for adaptation to climate change.

According to the government's "*Rapport sur l'impact environnemental du budget de l'Etat*" (The environmental impact of state's budget) (October 2022) and the Cour des Comptes' report "*Apprécier la contribution de la dépense publique à la transition écologique*" (Assessing the contribution of public spending to the ecological transition), the PLF 2023 (Finance Bill 2023) contains around €34 billion of budget spending that is favourable to the environment, €20 billion of budget spending that is unfavourable to the environment, €2 billion of mixed spending (impacts that are both favourable and unfavourable) and 90% of "neutral" spending (i.e. €510 billion) (62), (63).

The **additional** investment required for CDR technologies would therefore represent an additional 1.7% to 5.1% compared to the 69 billion annual investments required according to Pisani-Ferry. If this annual 69 billion were to be carried forward in 2050, investment in CDR would represent an additional budget of 6% to 16%.

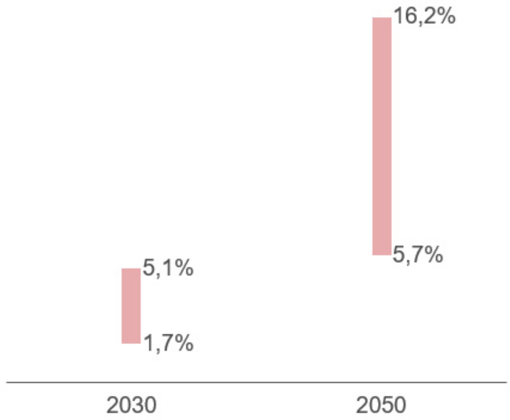


Figure 30 - Additional investment for CDR deployment in 2030 and 2050 compared with the €69 billion in annual investment for the ecological transition estimated by the Pisani Ferry report

These €69 billion of annual investments mainly concern the building sector (thermal renovation of housing), the energy sector (renewable energies, nuclear power), industry (electrification of processes, lower-emission processes, energy efficiency), adaptation to climate change, transport (development of electric mobility, rail, cycling, etc.) and agriculture.

These investments would be financed almost equally by the public sector (the State and local authorities) and the private sector (businesses and households).

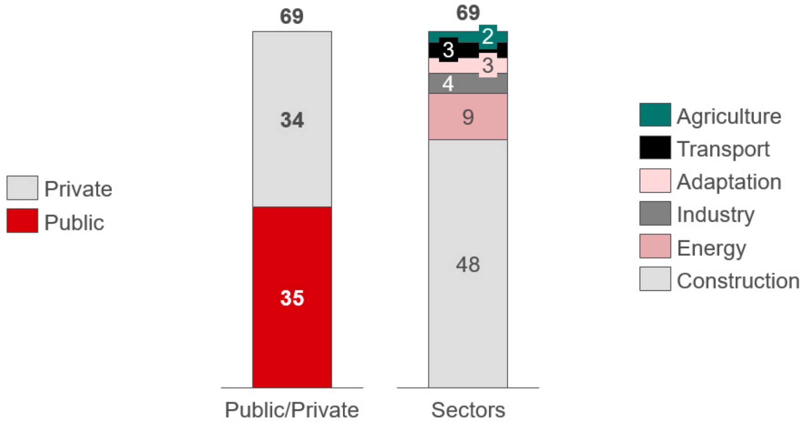


Figure 31 - Breakdown of additional investment needed in 2030 to achieve carbon neutrality by 2050 according to France Stratégie, in billions of euros per year (61)

Public investment is substantial and will have major economic repercussions. According to Pisani-Ferry, the risk of an increase in public debt (deviation from the reference scenario) would be of the order of 10% of GDP in 2030, 15% in 2035 and 25% in 2040. The additional annual investment required to deploy CDR (1.7 to 5.1% in 2030) will increase this public effort and its economic consequences.

Sources of funding:
Four sources of public funding could be used, according to the Pisani-Ferry report and the Institut Rousseau.

The first source of funding is the **redeployment of budget and tax expenditure**. According to Pisani-Ferry, "*the total gross expenditure and tax expenditure of general government is around €25 billion a year. The potential for redeployment is therefore more than significant*".

The second source is **debt**. Pisani-Ferry points out that, in principle, debt is desirable if the interest rate is lower than the nominal growth rate.

The third source is an **increase in taxes on capital**. Pisani-Ferry points out that "*economic analysis shows that the optimal response to prolonged exogenous shocks to public spending is to finance them through exceptional and explicitly temporary levies on capital*".

Finally, the fourth source of funding is a **change in monetary policy**. This source is mentioned by the Institut Rousseau in its report "*2% pour 2 degrés, les investissements publics et privés nécessaires pour atteindre la neutralité carbone de la France en 2050*" (2% for 2 degrees, the public and private investment required to reach net zero by 2050 in France) (64). Its' propositions include:

1. Introduction by the ECB of free money (debt-free) in limited volumes, decided under democratic control, in a reasoned manner and earmarked for the ecological transition.
2. Cancelling public debts held by the European System of Central Banks (ESCB), i.e. almost €750 billion for France, in exchange for the French government's commitment to invest in the ecological transition

In the first case, the ECB could, for example, buy bonds issued by the French public investment bank (BPI) and the French government, at zero interest, and keep them on its balance sheet indefinitely. The amounts of free money introduced would be determined by the French Parliament. These amounts would be used to invest in the ecological transition.

In the second case, the cancellation of the public debt held by the European central banks would make it possible to offer additional liquidity to the French State (because the debt burden would decrease). According to the report, "*the loss for the national central banks (NCBs) associated with the write-off of the public debt they hold could be offset by the ECB's power of money creation: this is specified in Article 32.4 of Protocol No. 4 on the functioning of the ESCB. Consequently, there would be no risk of negative core funds for the NCBs*".

CDR-specific sources of financing:
For CDR project developers, the main sources of finance would be carbon credits, public funding and investment by companies wishing to decarbonise internally (manufacturers deploying BECCS, for example). In addition, the State and local authorities, businesses, and households would have several ways of investing in CDR Figure 32.

Actor	Ways of investing in CDR
State and local authorities	• CDR public procurement • Support for innovation in CDR via BPI or ADEME funds • Tax expenditure (e.g. via tax credits) to encourage companies to carry out CDR projects • Creation of regulatory mechanisms to encourage CDR commissioning in value chains
Companies	• Purchase of carbon credits from CDR players • CDR projects funded directly by industry (BECCS, biochar) • Contributing to the public financing of CDR through taxation • Procure goods and inputs from sectors using CDR • Investing money in green savings plans
Households	• Contributing to CDR public financing through taxation • Investing money in green savings plans • Voluntary purchase of carbon credits, e.g. forest shares • Crowdfunding of CDR projects

Figure 32 – Investment means in CDR solutions (non-exhaustive) by the State and local authorities, businesses, and households

These investments could be stimulated by a number of instruments, including market-based instruments such as tradable carbon allowance markets and a carbon tax, and non-market-based instruments such as regulation (emission targets, standards) and public intervention (public investment, public tenders).

In particular, the carbon tax and the regulatory requirement for companies to decarbonise should stimulate the purchase of carbon credits issued by CDR project developers to reduce their accounting emissions. This trend would provide additional funding for CDR.

Long-term vision (2050):

Although in the short term (2030) investment in the ecological transition is likely to increase public debt, in the long term the implementation of the ecological transition should result in positive economic effects that could benefit the implementation of CDR solutions.

According to the "*Macroeconomic effects*" section of the ADEME report Transitions 2050 (65) by 2050, the ecological transition should involve:

- An annual GDP growth rate higher than the trend in all four scenarios, with the exception of scenario S1, which forecasts a drastic fall in industrial production and construction
- An increase in investment compared with the global trend
- An increase in the number of jobs compared with the global trend
- A contraction in foreign trade (except for S4) with an improvement in trade balance.

7.2. Political landscape and public opinion

Four types of stakeholders can be distinguished in the French political landscape: 1) citizens and public opinion, 2) the State, 3) private companies and 4) representatives of civil society (associations, trade unions, NGOs). Each stakeholder has a different vision of CDR.

The general positions of these types of players are summarised in Table 9.

Type of player	General position
State	Government departments are generally interested in BECCS and DACCS solutions, afforestation/reforestation, the protection of coastal and marine ecosystems, and the restoration of wetlands. They are less comfortable, however, with geochemical solutions and biochar, which are not mentioned in official texts. Overall, government departments are still relying mainly on nature-based solutions, which are better accepted by the general public.
Public opinion	The French citizens' level of environmental awareness stagnated between 2005 and 2022, but the importance of climate change as an environmental concern rose sharply between 2010 and 2022. Even though the French want the government to take action to protect the climate, there are many appeals against renewable energy projects and lithium mining projects. Additionally, there is a lot of rhetoric denouncing climate inaction. Appeals could prevent the deployment of renewable energies to supply electricity for DACCS or hinder the opening of olivine or limestone mines for geochemical methods.
Private companies	An ecosystem around CDR methods is developing and manufacturers seem to want to develop CCS solutions to decarbonise. However, companies that develop or buy CDR are still a minority, mainly because of the lack of visibility of these activities.
Associations	The Climate Action Network is cautious, even sceptical about CCS, as is Greenpeace, which describes carbon storage and geo-engineering solutions as "false solutions". The Confédération paysanne is calling for a moratorium on anaerobic digestion. Nevertheless, a number of associations are backing CDR, including Carbon Gap partners.

Table 9 - Summary of the general views of the four main categories of stakeholders in French society on CDR solutions

Public opinion:

The French population's level of sensitivity to environmental issues appears to have stagnated between 2005 and the present day. According to the SDES, "*On a scale of 1 to 7, the average environmental sensitivity score was 5.22 in 2005. This score reached 5.49 in 2011 before falling back in the following years. After rebounding slightly in 2019, this indicator will reach an all-time low in 2021 (4.94), which is cause for concern in a context marked by the Covid-19 pandemic*". (66).

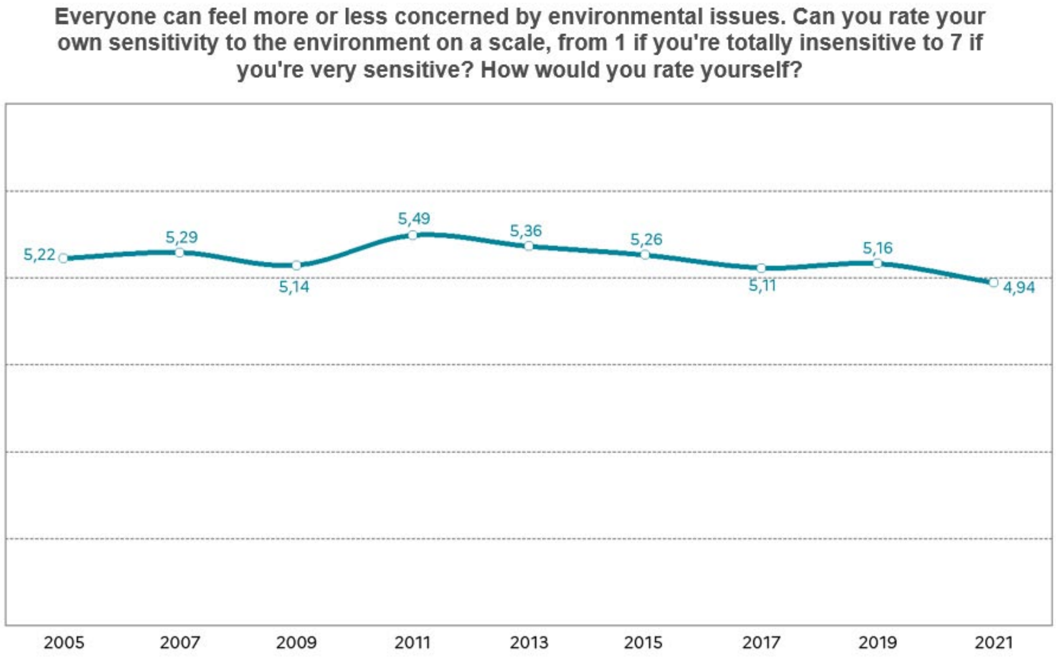


Figure 33 - Sensitivity of the French population to environmental problems (66)

The level of sensitivity also appears to be higher in older people than in younger people, with an average of 5.25 for those aged 60-69 compared with 4.73 for those under 25.

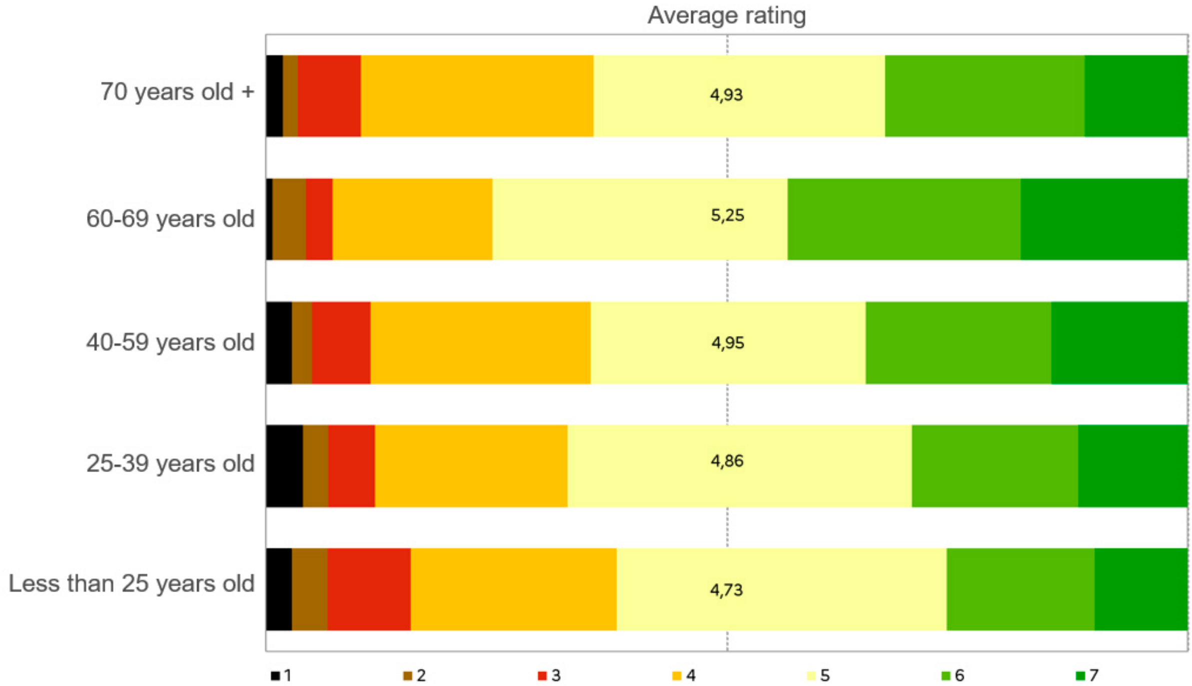


Figure 34 - Level of environmental sensitivity of the French population by age group (66)

Nevertheless, among environmental concerns, the French seem increasingly worried about climate change. Global warming is considered to be the most worrying problem by 44% of respondents in 2022, compared to around 16% in 2010 (Figure 35).

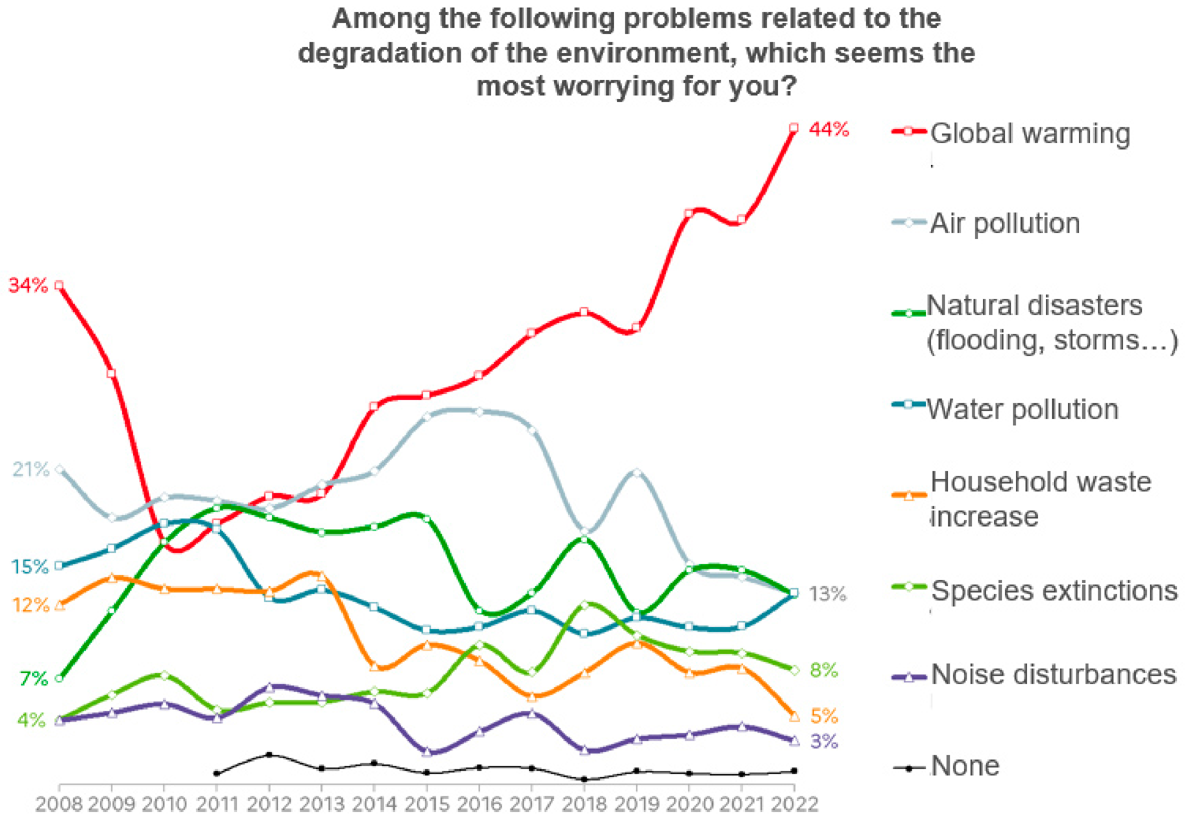


Figure 35 - How concerned are the French about environmental issues? (66)

53% of French people believe that the public authorities should take priority action to protect the environment (SDES).

Additionally, although the French are increasingly placing climate change at the top of their environmental concerns and want the government to make commitments in this direction, they are not all prepared to accept constraints such as speed limits on motorways or the deployment of renewable wind and photovoltaic energy. For example, there are often appeals against the installation of wind or photovoltaic projects. Yet the deployment of these renewable energies is necessary for the widespread deployment of CDR methods such as DACCS.

As another example, it is likely that citizens will also place appeals against the opening of olivine or limestone mines that would be useful for enhanced weathering on land. Citizens are already mobilising against the forthcoming opening of lithium mines in the Allier, Brittany, and Alsace.

Citizens' panel

As part of the project, Carbon Gap has teamed up with **Missions publiques** to carry out a citizens' panel on the general public's perception of CDR. The panel was held on 17 November 2023 in Rennes and brought together 24 participants covering a wide range of ages, genders, educational backgrounds, professions, and geographical origins. The main findings are summarised below:

- The participants pointed out how difficult it was for them to understand in such a short space of time and in detail each of the methods discussed, as well as their implications and the issues at stake;
- Participants stressed the importance of a fair distribution of efforts, complementarity with energy sobriety and efficiency, rigorous and transparent communication, and consideration of the impact on ecosystems and biodiversity;
- Participants were open to certain technologies, while expressing concerns about uncertain impacts, the need for clarity and transparency, and the importance of a fair distribution of costs between countries;
- Opinions ranged from support for a bold technological vision to confusion and the need for greater clarity on the subject, as well as the need for a fair distribution of costs between countries.

Lastly, even though climate has become the number one environmental concern for the French people, ongoing conflicting rhetoric may delay the implementation of climate-friendly solutions, including some CDR solutions. These discourses have been listed in a study by the University of Cambridge (67) and are presented in the illustration below.

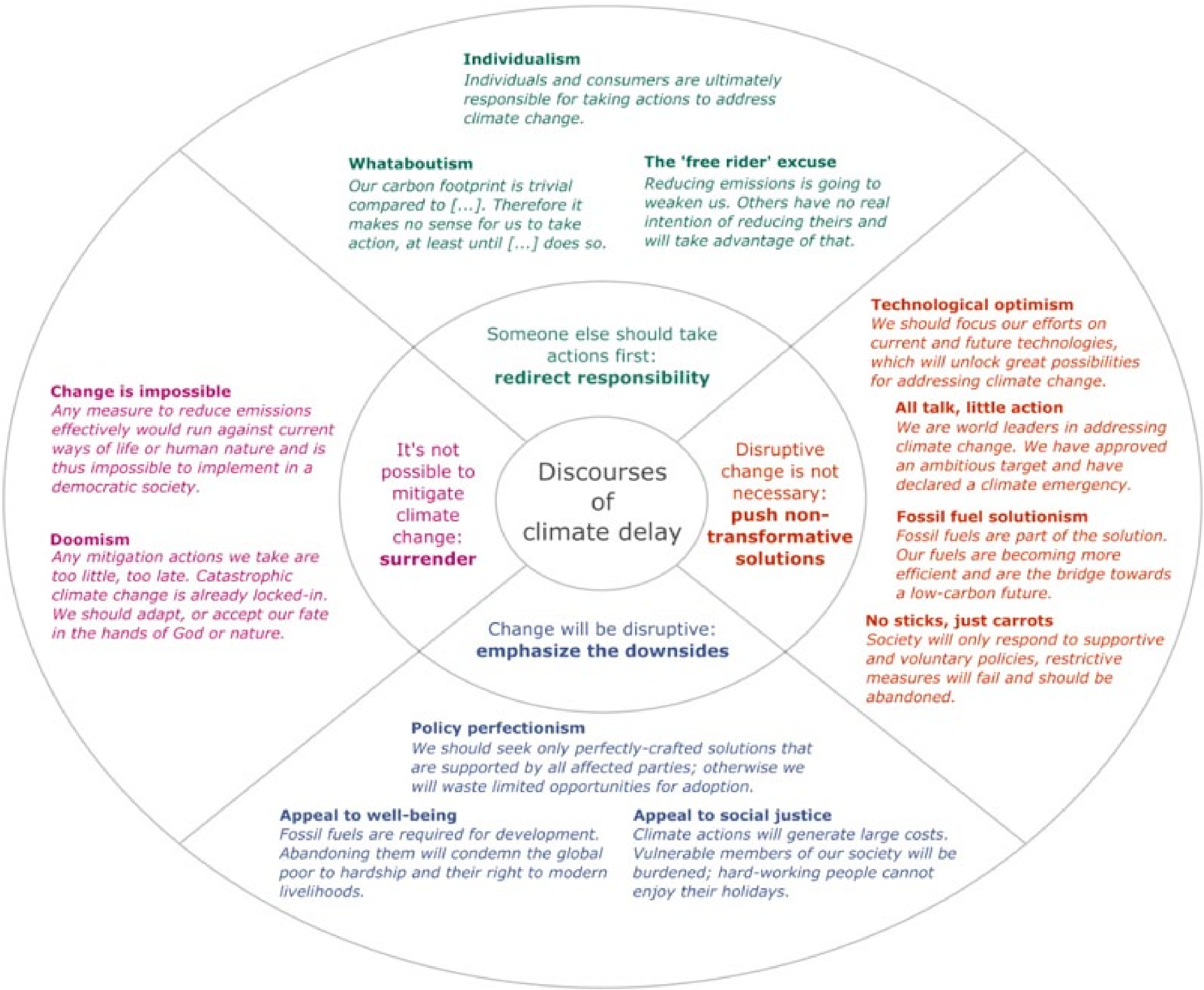


Figure 36 - Discourses that may delay climate action (67)

Among these discourses, the "*technological optimism*" discourse translating into "*we must concentrate our efforts on technologies that should provide solutions to global warming*" could nevertheless be favourable to the deployment of CDR methods representing technological carbon sinks such as BECCS, DACCS, biochar and geochemical solutions, although potentially for bad reasons.

Targeted interviews with stakeholders

Fifteen one-and-a-half-hour interviews were conducted with stakeholders in the sector to gather their perceptions of France's climate objectives, the resources deployed, their awareness of CDR and the role of these methods in achieving these objectives.

The State

The government has not given its opinion on all CDR solutions. However, BECCS, DACCS, land-use change, and carbon storage practices solutions have already been mentioned.

In this respect, the Secrétariat Général à la Planification Ecologique (SGPE) (the General Office to Ecological Forcasting) refers to BECCS, DACCS, afforestation/reforestation and the protection of ecosystems such as coral reefs and coastal ecosystems in its 2030 ecological planning plan.

Namely, the SGPE states in its CCUS strategy that the government wishes to "*deepen the BECCS and DACCS strategy" and "define funding mechanisms for industrial sites*" concerning CO_2 capture (68).

Concerning ecosystems, the SGPE aims to increase the surface area of forests in mainland France by 0.9 Mha over 11 years, and considers that "*the protection of emblematic ecosystems, including coral reefs, as well as coastal ecosystems, is a major challenge*". To this end, it wants to "*restore 50,000 hectares of wetlands by 2026*" (58).

The SGPE aims to "achieve zero net artificialisation by 2050, i.e. to reduce the rate of artificialisation of our land by 50% over the next decade" and to "create a coherent and ambitious network of protected areas, in particular by achieving 10% of strong protection in sensitive and threatened environments" (58).

In addition, the SGPE specifies that "*soil protection [...] represents an essential lever for storing part of the greenhouse gas emissions"* and wishes to encourage "*less soil tillage*" in grasslands and maintain existing hedges in cultivated land, as well as planting more than 5,000 linear kilometres of new hedges per year. It also wants to "*double the area of cover crops*". The SGPE is thus in favour of carbon storage practices in cultivated soils and grasslands (58). However, the State makes no mention of geochemical CDR methods (enhanced weathering on land) or biochar in its communication.

In this respect, it is worth mentioning that the 2004 Charter of the Environment enshrined the **precautionary principle** in the Constitution. According to Article 5 of the Charter, this principle stipulates that "*when the occurrence of damage, although uncertain in light of current scientific knowledge, could seriously and irreversibly affect the environment, the public authorities shall ensure, by applying the precautionary principle and within their areas of competence, the implementation of risk assessment procedures and the adoption of provisional and proportionate measures in order to prevent the occurrence of damage*". (69). This principle may prevent the implementation of geochemical CDR methods (weathering) and large-scale cultivation of algae for burial until their harmlessness has been demonstrated (2).

Private companies

As far as private companies are concerned, an ecosystem around CDR solutions seems to be emerging and manufacturers are showing interest in developing CCS technologies to decarbonise. These CCS technologies could then be deployed via BECCS if the captured CO_2 is biogenic.

While climate ambitions and the "Fit for 55" strategy are considered ambitious, they nonetheless face a major challenge. A consensus is emerging on the inadequacy of the regulatory framework and financial incentives to achieve them. In addition, the lack of awareness of climate commitments beyond the national level highlights the need for a more global vision and greater international cooperation. Regional initiatives such as SRADDETs and PCAETs, as well as European coalitions such as Real Zero Europe, are evidence of the concerted efforts being made to meet these challenges.

Against this backdrop, France is at a crossroads when it comes to implementing CDR. Although some progress has been made, obstacles remain and must be overcome quickly. While BECCS and DACCS are seen as the main CDR methods, a lack of knowledge of the sector has been noted on numerous occasions.

To overcome these challenges, appropriate financing strategies are needed, with a focus on investments and financial incentives aligned with climate objectives. Close collaboration between different players, whether governmental, institutional or from civil society, is essential, according to the interviewed panel, if these challenges are to be met and the climate ambitions set are to be achieved.

Associations

With regard to CCS and thus BECCS, the **Climate Action Network** considers that this is a solution of last resort to be used only for incompressible emissions: "*the removal of carbon from the atmosphere, through natural sinks or technological options, must be considered as a complement to efforts to reduce emissions, only for incompressible emissions, and not as an alternative". It adds that "all solutions for reducing greenhouse gas emissions must be pushed to the limit before deploying this technology*". (70).

In addition, the Climate Action Network points out that the potential for storing CO_2 in geological cavities is limited in France due to technical, geological, economic, regulatory and social constraints.

About **geochemical solutions**, **GreenPeace** points out that the Paris Agreement "*does not rule out false solutions, such as nuclear power, carbon storage mechanisms and geo-engineering*" (71).

In addition, the **Confédération Paysanne** is calling for a "*moratorium on anaerobic digestion*", arguing that "*a number of problems have been highlighted in the field: rising land prices, major investments in farms that risk creating locks in, competition between food and energy crops, digestate management and accidental health and environmental risks, particularly during the operation and maintenance phases*". This position would be detrimental to the development of CDR methods such as BECCS (72).

Nevertheless, although the Climate Action Network and Greenpeace are sceptical about CDR methods such as BECCS, DACCS and geochemical solutions, other associations support CDR solutions.

Figure 37 summarises the perceptions documented during the interviews, and once again confirms a preference for ecosystem-based methods.

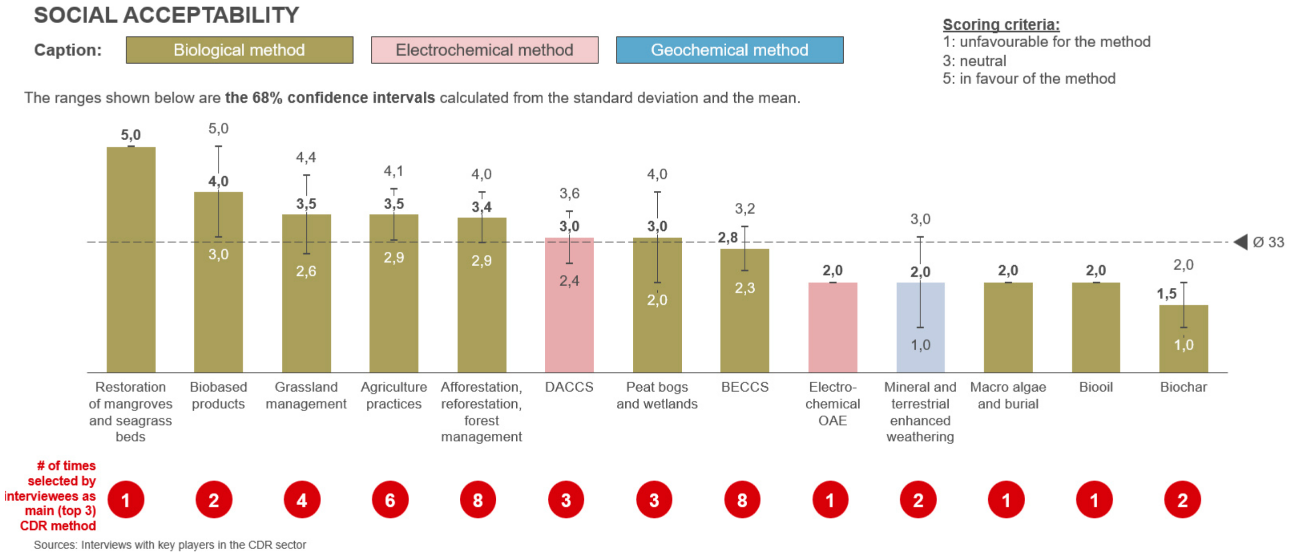


Figure 37 -Interviewees' assessment of the acceptability of different CDR methods

7.3. Attitudes and vision of the world

In its "*Transitions 2050*" report, ADEME defined four scenarios (S1, S2, S3 and S4) with different levels of deployment of natural and technological sinks. In this work, ADEME explored different possible imaginaries linked to the ecological transition. These worldviews influence how citizens and decision-makers perceive environmental issues and therefore, the strategies that will be favoured in climate action, particularly those linked to natural carbon sinks and technological carbon sinks.

According to ADEME, "*Scenarios carry with them different visions of the world, which may be fuelled by different ideologies, in the sense of a more or less coherent set of ideas, beliefs and doctrines specific to an era, a society or individuals, and which guide action. Symbolism is always more or less present in the perception of scenarios and their comparison. It can guide the preference for a strategy, a perception of what is feasible and desirable according to a societal vision of the ecological transition*" (20).

The report distinguishes four levels of analysis: metaphor, worldview, system, and litany. Metaphors and myths refer to founding narratives and unconscious cultural references that influence people's worldviews. These worldviews influence people's perception of the system in which they live. This perception of how the system works influences the discourse on the state of the world and the solutions to be implemented (litanies). Thus, depending on how the myths and worldviews of the French population evolve, certain CDR methods will be favoured over others.

According to ADEME, these worldviews are reflected in different changes in people's lifestyles and economic models.

	S1	S2	S3	S4
Business model	• Less attention paid to GDP growth than to how growth is achieved	• More qualitative than quantitative growth • Re-industrialisation of key sectors • Redistribution	• Greener growth • Continuation of the tertiarization of the economy • Techno-push • Supply policies	• Business still relatively carbon-intensive • Reducing poverty through strong growth
Lifestyles	• Frugality • Preference for local • Transparency of governance, of supply chains, etc. • Searching for meaning	• Redistribution • More sustainable lifestyles • Seeking access to uses rather than ownership of objects	• Green consumerism • Connected society	• Spread and amplification of the individual mass consumption model

Table 10 - Influence of worldviews on economic models and lifestyles (ADEME, Transitions 2050 2021)

According to ADEME, these worldviews and our new lifestyles and economic models should influence the development of CDR methods.

	S1	S2	S3	S4
Biomass conversion				
BECCS	• **No BECCS** • Reducing the use of biomass for energy • No geological storage of CO_2	• **BECCS considered** only on industrial units having implemented CCS and using network gas with a high proportion of renewable energy in 2050.	• **BECCS implemented in** particular on biomass boilers and industrial plants with CCS • Greater development of biomass demand for medium-sized boilers	• **Strong development of CCS and BECCS** throughout the country thanks to the development of the necessary infrastructure (CO_2 pipelines, geological storage). • Extensive use of biomass for energy production
Biochar	• Not mentioned	• Not mentioned	• Not mentioned	• Not mentioned
Wood products	• Mentioned	• Mentioned	• Mentioned	• Mentioned
Buried algae	• Not mentioned	• Not mentioned	• Not mentioned	• Not mentioned
Meilleure gestion des écosystèmes				
Change in land area	• **Drastic reduction in land artificialisation** • **Heavy afforestation**	• Significant reduction in soil artificialisation		• Weakest natural well • **Maintained state of development compared with current levels** • **Tendency to convert grassland** to cereals continues
Change in sea area	• Mangroves and sea grass beds not mentioned	• Mangroves and sea grass beds not mentioned	• Mangroves and sea grass beds not mentioned	• Mangroves and sea grass beds not mentioned
Carbon storage practices	• **Maximising the carbon storage role of ecosystems,** particularly forests	• **Changes in farming practices** to encourage carbon storage in the soil (planting hedgerows, agroforestry within plots, development of plant cover) • Moderate levels of wood cutting in forests	• **Reduction in forest sinks** compared with S1 and S2 • Carbon sequestration in soils, mainly driven by the development of plant cover, particularly for use in anaerobic digestion • Hedgerows and agroforestry less developed than in S1 and S2	• **Cultivated soils slightly increase carbon stocks** through the development of plant cover, in connection with anaerobic digestion
Geochemical	• Not mentioned	• Not mentioned	• Non mentionné	• Non mentionné
Electro-chemical	• **No DACCS** • No mention of DOCCS	• No DACCS • No mention of DOCCS	• Low use of DACCS (6 TWh/year in 2050) • No mention of DOCCS	• **DACCS strongly implemented** (50 TWh/year in 2050)

Table 11 - Influence of worldviews on the development of CDR solutions in the ADEME scenarios (ADEME, Transitions 2050, 2021)

Thus, according to these comparisons, a vision of infinite economic growth and techno-solutionism ('technology is the solution to all problems') would lead to technological CDR methods such as DACCS and BECCS. Visions based on a logic of orchestrated planning, indicators of well-being, nature protection and a return to the land approach, would instead lead to CDR methods such as changes in land use (afforestation, reducing the artificialisation of land) and carbon storage practices (forestry, grassland, and agriculture).

ADEME does not provide any information on geochemical solutions and their uncertain impact on biodiversity, but it seems likely that a vision based on human technological genius and infinite growth is more favourable to these solutions than a vision based on sobriety and the protection of nature.

8. Practical potential for CDR deployment in France

In this section, the theoretical potential estimated in section 6 of the report is used as a starting point, and the assumptions are adjusted to account for the socio-economic realities described in section 7 to arrive at a practical potential, i.e. one that can be achieved without radical changes to current conditions. To make this estimate as realistic as possible, conservative assumptions and estimates have been made, to create safety margins. Within this framework, however, several scenarios are still possible, depending mainly on the level of ambition shown by France. This is what the study seeks to show in this final section.

8.1. Proposed scenarios

8.1.1. Overview of the scenarios

Three scenarios are envisioned for the development of CDR in France: a **reference** scenario enabling carbon neutrality to be achieved by 2050, with an elimination capacity of around ~76 $MtCO_{2eq}$/year, an **ambition** scenario reaching a capacity of around 146 $MtCO_{2eq}$/year, which is equivalent to a negative net balance for France before 2050, and finally, a **conservative** scenario exploring the result of the status quo and based solely on natural sinks, with the assumption that no significant measures have been put in place to diversify CDR methods.

Reference scenario

The '**reference**' scenario makes it possible to achieve carbon neutrality by 2050 by complying with the principle of like-for-like neutralisation, with a total carbon sink of ~76 $MtCO_{2eq}$/year, including natural sinks and a diversity of CDR methods. Unlike the existing scenarios (ADEME and SNBC 2), this one envisages **a greater diversification of the carbon sinks** to achieve carbon neutrality, and makes more room for permanent CDR to durable net zero based on the principle of correspondence between residual emissions and CDR. This diversification allows to distribute the risk associated with the uncertainties on CDR deployment.

This scenario includes a small **safety margin** for achieving the decarbonisation objectives anticipated by ADEME, since a total of 76 $MtCO_{2eq}$/year of negative emissions is reached in 2050 for 70 $MtCO_{2eq}$/year of residual emissions (see below).

In this scenario, French CDR policies, investments and public support are sufficient to achieve net zero emissions. The low-carbon label, and the carbon offset market in general, make it possible to finance changes in agricultural carbon storage practices. The geological studies needed to enable geological storage of CO_2 are undertaken on time, making it possible to implement BECCS and DACCS. Lastly, the rate of installation of photovoltaic panels has been accelerated so that renewable electricity will be available for DACCS by 2050.

Ambition scenario

The second scenario, called '**ambition**', corresponds to a scenario in which France invests more voluntarily in CDR than in the reference scenario. CDR is developed beyond the requirements of net zero, still in line with the *like-for-like* concept, with a total carbon sink of around 146 $MtCO_{2eq}$/year, more than double the 70 $MtCO_{2eq}$ required for net zero.

In this scenario, France will either exceed its decarbonisation targets, and therefore be able to sell negative emissions to other countries or compensate for higher-than-expected levels of residual emissions, due to delays and/or increased difficulties in reducing emissions from certain sectors.

The tonne of CO_2 on the carbon offset market is traded at higher prices than in the reference scenario and makes it possible to better finance the various CDR methods, in particular agricultural carbon storage practices, biochar, BECCS and DACCS. Geological storage of CO_2 is more developed than in the reference scenario, with more investment in research and geological feasibility studies, thus favouring BECCS and DACCS. Renewable electricity production capacity is further developed to allow greater deployment of CDR methods based primarily on electricity consumption.

Conservative scenario

The third scenario, called '**conservative**', corresponds to a scenario in which France invests little and later in CDR, with lower assumptions about public support and technical maturity of certain CDR technologies. This scenario assumes that the natural carbon sink potential without CDR is similar to the reference scenario.

In this scenario, France has not invested sufficiently to develop its electricity generation capacity and the balance between supply and demand remains difficult in 2050, leaving no volume of electricity available for CDR, in particular DACCS. Furthermore, even if geological storage is deployed in Europe, the capacity used is reserved exclusively for the storage of fossil CO_2 captured by CCS, leaving no room for the development of BECCS and DACCS.

On the other hand, farmers are paid less for implementing carbon storage practices than in the reference scenario. As a result, fewer farmers are changing their practices.

8.1.2. Balance of CO_2 emissions by 2050 according to ADEME and the SNBC 2

In the National Low-Carbon Strategy (SNBC 2), the volume of residual emissions to be offset to achieve net zero by 2050 amounts to around 80 $MtCO_{2eq}$/year. To offset these emissions, the SNBC 2 proposed using enhanced ecosystems (forests and farmland), bio-economy products and materials based on plant matter (wood and straw), and industrial processes (carbon capture and storage, CCS) as carbon sinks.

In SNBC 2, but also in the ADEME scenarios (with the exception of ADEME S4), natural sinks and temporary CDR make it possible to offset most of the residual emissions. Figure 38.

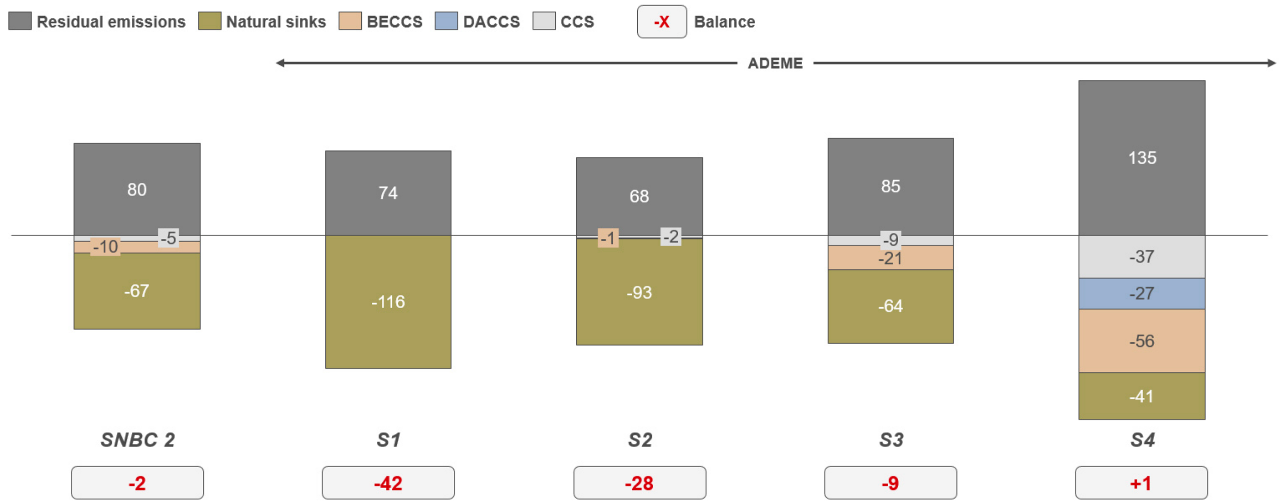


Figure 38 - Balance of CO_2 equivalent emissions ($MtCO_{2eq}$/year) in 2050 according to the ADEME Transitions 2050 and SNBC 2 scenarios

Furthermore, according to ADEME, scenarios S1, S2 and S3 anticipate a total sink with a capacity greater than the net residual emissions from CCS in 2050. France would thus go beyond net zero in 2050 in these scenarios, while S4 would barely reach carbon neutrality.

In the rest of the report, no matter the scenario considered, residual emissions are estimated at 80 $MtCO_{2eq}$/year in line with the SNBC 2, and an estimated volume of CCS of ~10 $MtCO_{2eq}$/year is subtracted in line with ADEME S3 in particular. **Consequently, achieving net zero requires carbon sinks with a total capacity of 70 $MtCO_{2eq}$/year**.

The SNBC 2 uses the results and methodology developed in the Citepa report on emissions in France (2023 edition) for the historical analysis of emissions. The future emissions reduction trajectory anticipated by the SNBC 2 keeps the same categorisation. As a result, it is possible to distinguish between residual emission sources, in particular between biogenic and fossil sources. Biogenic CO_2 emissions are all accounted for in the LULUCF sector or reduced to 0, with the exception of emissions from the agricultural sector. By 2050, again according to the SNBC 2, all emissions from the agricultural sector will be linked to livestock and crops. These emissions can therefore be characterised as biogenic emissions, representing 48 $MtCO_{2eq}$ in 2050. Conversely, emissions from all other sectors (Industry, Buildings, Waste, Energy and Transport) are considered to be fossil, and amount to 32 $MtCO_{2eq}$.

Achieving 10 $MtCO_{2eq}$ of CCS for the industry sector makes it possible to offset fossil emissions. Therefore, of the 70$MtCO_{2eq}$ to be offset in 2050, 22 $MtCO_{2eq}$ of residual emissions of fossil origin remain, that need to be offset by permanent CDR, and 48 $MtCO_{2eq}$ of biogenic origin remain that can make do with a low level of permanence.

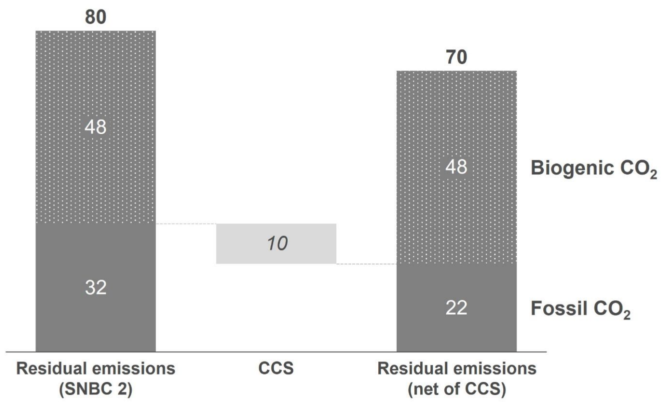


Figure 39 - Categorisation of residual emissions according to SNBC 2 for estimating permanent and non-permanent CDR requirements

8.2. Results

In the reference scenario, the total carbon sink (excluding CCS) is 76 $MtCO_{2eq}$/year in 2050, made up of 18 $MtCO_{2eq}$/year of natural forest sink and 57 $MtCO_2$/year of CDR. The most widely deployed CDR solutions are carbon storage practices, DACCS and BECCS.

The following illustration summarises the removal capacities deployed for each method, the proportion they represent in relation to theoretical capacities, the limiting resources for each, and the TRL for each CDR method. These CDR potentials consider a constraint on geological storage of CO_2 of a maximum of 30 $MtCO_{2eq}$/year available for BECCS and DACCS in 2050. Appendix 10.5 contains details of the limiting factors for establishing the reference scenario.

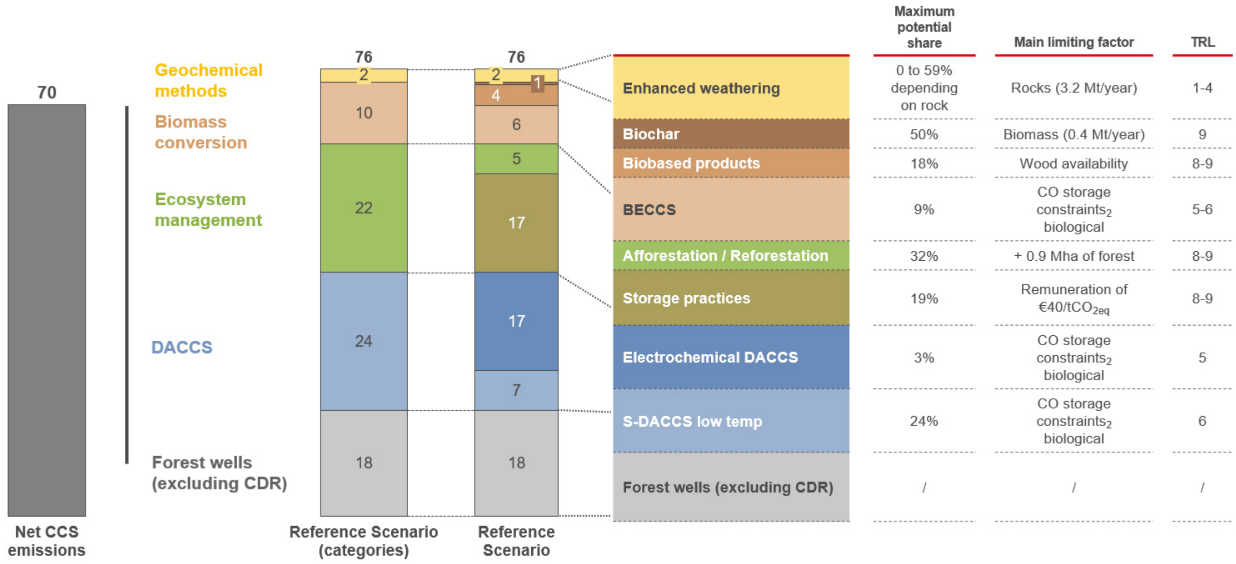


Figure 40 - CO_2 removal potential of CDR solutions and the forest carbon sink (excluding CDR) in the reference scenario in 2050, in $MtCO_{2eq}$/year

As per the level of permanence of the CDR methods, the notion of *like for like* (concept detailed in appendix 10.6) is respected in the reference scenario, and even exceeded, as shown in Figure 41.

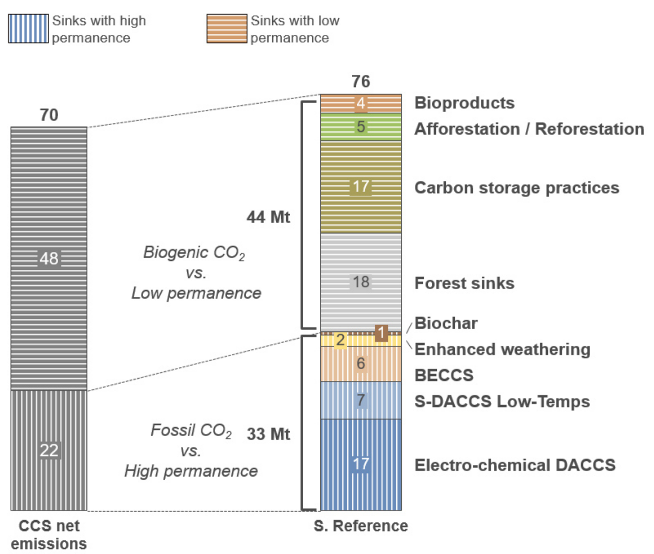


Figure 41 - Comparison of the permanence of residual emissions with planned sink capacities

In the **conservative** scenario, no electricity volumes are available for CDR methods because the supply-demand balance (low-carbon or decarbonised electricity) in 2050 has not yet been achieved. Consequently, CDR methods such as DACCS are not deployed. Furthermore, no geological CO_2 storage capacity for CDR is available in this scenario, which also prevents the implementation of BECCS. In addition, farmers are paid less for implementing carbon storage practices (€30/tCO_{2eq}) than in the reference scenario (€40/tCO_{2eq}) and fewer farmers implement them (30% compared with 50% in the reference scenario). The assumptions made in the conservative scenario (status quo) do not allow for the deployment of BECCS, DACCS or geochemical methods and limit the extent of carbon storage practices. As a result, only 33 $MtCO_2$/year of removal capacity is available in 2050, and France fails to achieve net zero in time.

Conversely, in the **ambition** scenario, more renewable electricity is available for CDR (30 TWh) than in the reference scenario (18 TWh), because the acceptability of wind power (onshore and offshore) is assumed to be higher, allowing for additional renewable electricity production. In addition, the geological storage capacity of CO_2 available for BECCS and DACCS is assumed to be higher (63 $MtCO_2$/year compared with 30 $MtCO_2$/year in the reference scenario) thanks to greater public support, particularly for onshore storage projects in France. This makes it possible to deploy more DACCS and BECCS. In addition, the price paid to farmers for implementing carbon storage practices (€120/tCO_{2eq}) is assumed to be much more attractive than in the reference scenario (€40/tCO_{2eq}). As a result, more farmers (70%) are willing to change their practices than in the reference scenario (50%). Finally, the forest sink is assumed to remain the same as in 2021 (28 $MtCO_{2eq}$/year), again thanks to major forest protection measures.

To achieve the 146 $MtCO_2$/year of the ambition scenario, all the methods present in the reference scenario are mobilised at more ambitious levels. So, no single method or two will make the difference. We can only achieve these capacities by using a portfolio approach.

It should be noted that the targets achieved in the ambition scenario could be exceeded if the geological storage capacity for CO_2 were greater. This is because some CDR methods, such as DACCS and BECCS, are constrained not by the availability of the resource (renewable electricity and biogenic CO_2 respectively) but by the ability to store the captured CO_2 sustainably. In addition, certain methods have not been considered because they are not considered to be sufficiently mature at present or have not been sufficiently documented to be properly estimated, such as the burial of algae, upwelling/downwelling or ocean alkalinisation. Between now and 2050, these technologies could progress and provide additional capacities for removing atmospheric CO_2. These technologies could, for example, be described in greater detail in a future version of the report if there has been sufficient development in terms of maturity and literature. Furthermore, as a precautionary measure concerning the estimation of certain sources, certain technologies have not been included. This is the case, for example, with the production of low-carbon heat and/or electricity from small modular nuclear reactors. If these technologies rapidly reach a sufficient level of maturity, they could increase the available volumes that can be exploited by the various CDR methods and therefore enable France to further increase the potential of CDR.

Figure 42 shows and compares the three scenarios proposed, particularly in relation to the volume of residual emissions considered for 2050.

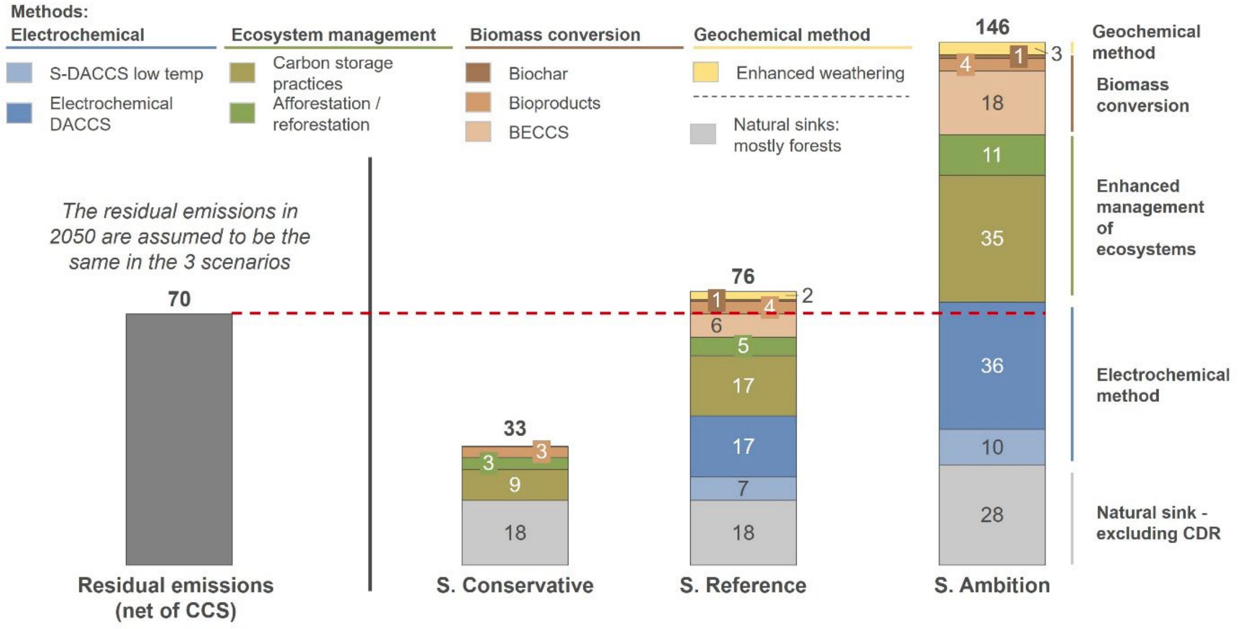


Figure 42 - Composition of the total carbon sink in the conservative, reference, and ambition scenarios in 2050, compared with the volume of residual emissions anticipated by the SNBC 2, in MtCO$_2$/year

Akin to the Reference scenario, the correspondence between the origin of residual emissions and the level of permanence of CDR mobilised to offset them (the like-for-like principle) is respected and even exceeded in the ambition scenario, i.e. carbon sinks with a high level of permanence make it possible to offset all residual fossil emissions, and to have an additional volume available to offset historical emissions.

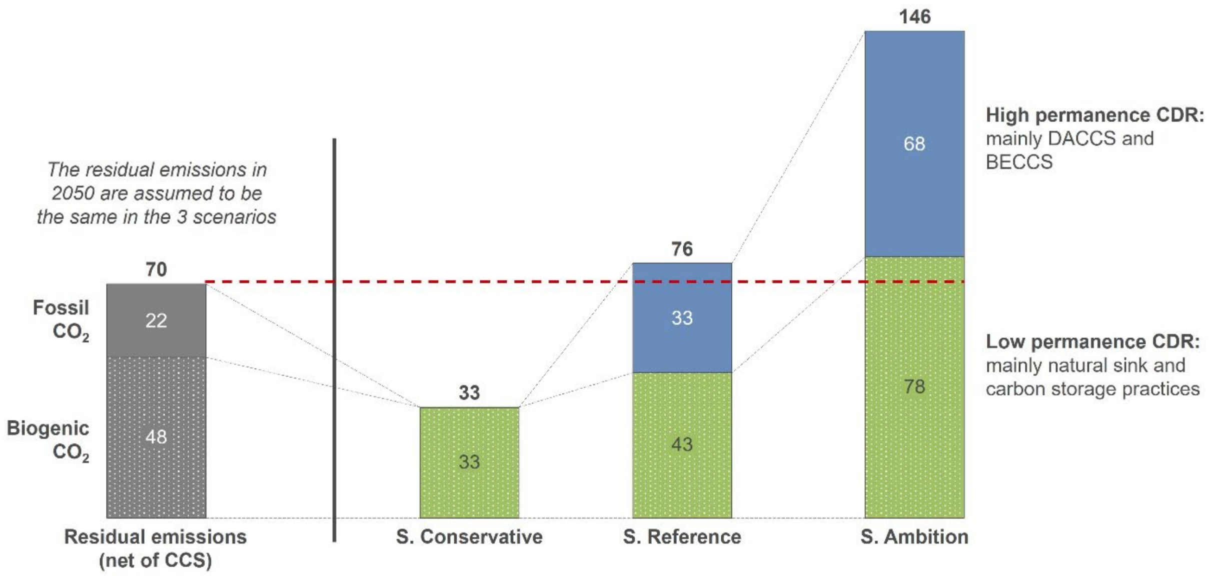


Figure 43 -Comparison of the origin of residual emissions with the permanence of the mobilised carbon sinks in the three scenarios considered

The main differences between the scenarios come from the available electricity, the capacity for geological storage of CO_2, the remuneration of carbon storage practices, the increase in forest area and the evolution of the current forest sink (excluding CDR) by 2050.

The reference and ambition scenarios rely fairly evenly on natural sinks (around 60% of total sinks in the reference scenario) and technological sinks, as in the ADEME S4 scenario. In contrast, the SNBC 2 and ADEME S1, S2 and S3 scenarios rely essentially on natural sinks to offset anthropogenic emissions.

About CCS, the volumes anticipated in this study are higher than the SNBC 2 and ADEME scenarios S1 and S2 but are consistent with scenario S3 (9 Mt CO_{2eq}). The CCS volumes in the ADEME S4 scenario are more than three times higher (Figure 44).

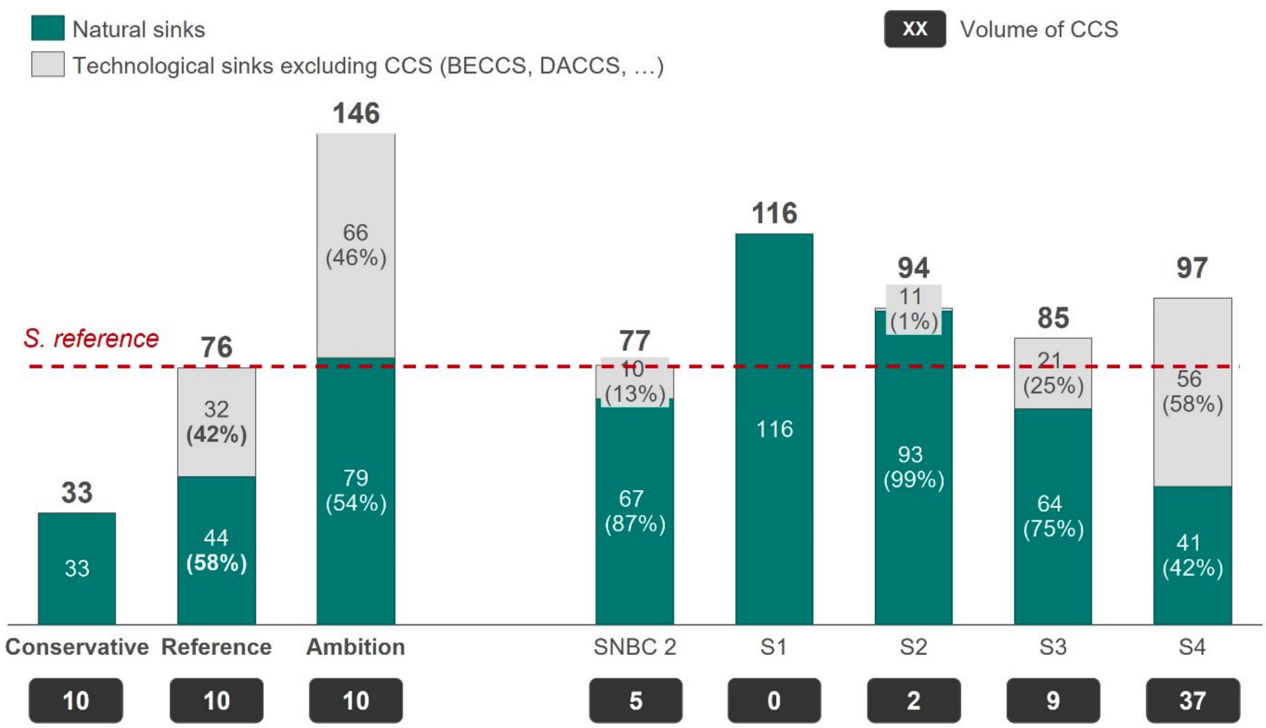


Figure 44 - Sinks (excluding CCS) in 2050 according to the conservative, reference, and ambition scenarios, as well as ADEME (S1, S2, S3, S4) and SNBC 2 scenarios, in $MtCO_2$/year

In terms of natural sinks, the reference scenario assumes volumes like the ADEME S4 scenario, but much lower than those anticipated in the other scenarios or the SNBC 2. These differences can be explained in part by the evolution of the current forest sink (excluding CDR), which appears to be deteriorating more rapidly than anticipated in the first three ADEME scenarios (35 to 74 $MtCO_2$eq/year). Details for natural sinks are shown in Figure 45.

The scenarios in this study and the ADEME scenarios assume similar sequestration volumes by wood products (3 to 4 $MtCO_2$/year), a far cry from the 21 $MtCO_2$/year of the SNBC 2.

Figure 45 - Natural sinks in 2050 according to the conservative, reference, and ambition scenarios, as well as ADEME (S1, S2, S3, S4) and SNBC 2 scenarios, in $MtCO_2$/year

In terms of technological wells, the reference scenario is generally more ambitious than the vision of the SNBC 2 and ADEME (excluding S3 and S4) (Figure 46). These differences are largely explained by the absence of DACCS in the SNBC 2 and the first three ADEME scenarios. Neither the SNBC 2 nor the ADEME scenarios anticipate enhanced weathering.

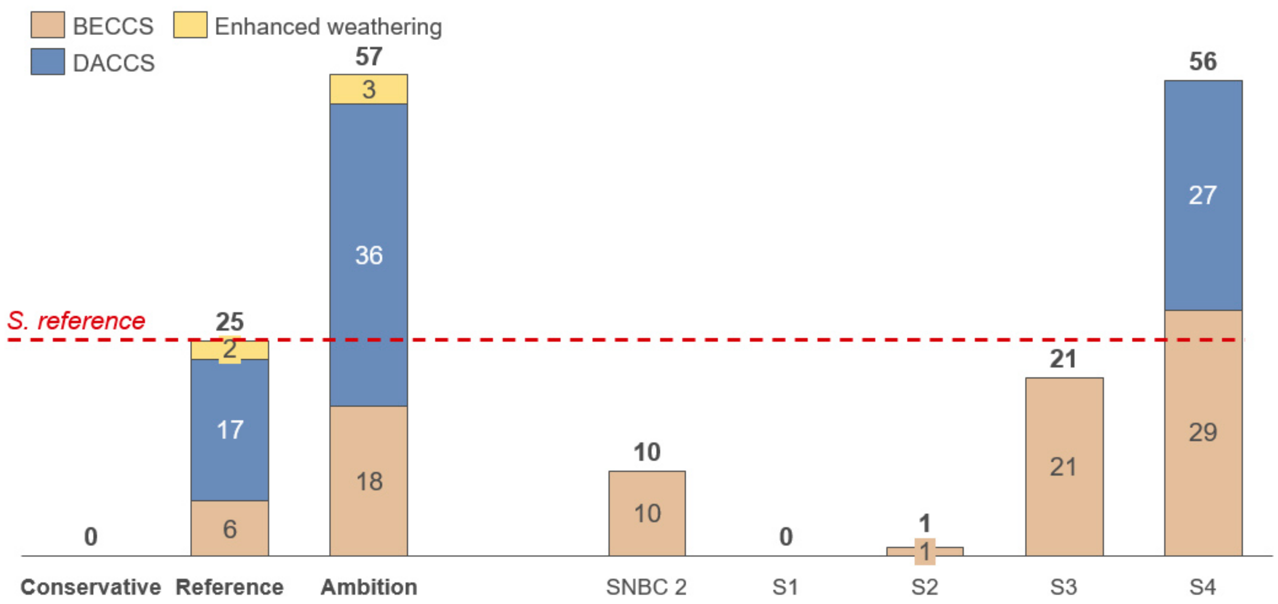


Figure 46 - Technological sinks (excluding CCS) in 2050 according to the conservative, reference and ambition scenarios, as well as ADEME (S1, S2, S3, S4) and SNBC 2 scenarios, in $MtCO_2$/year

8.3. Methodology

For each scenario and each CDR method, the practical CDR potential is calculated by multiplying the conversion factors by the actual resource availability as per the results of part 7 and the more conservative assumptions. The CDR potential in 2030 is calculated in the same way.

8.3.1. DACCS and enhanced weathering

8.3.1.1. Exploitable heat source

In the reference scenario, the amount of heat available for CDR (S-DACCS low temp) is 17 TWh_{th}/year in 2050. In the ambition scenario, heat is estimated at 20 TWh, but no heat is available for CDR in the conservative scenario. This amount of heat comes from the 53 TWh estimated in part 4, and refined according to the combination of technical constraints and public support.

The use of waste heat in district heating has been considered a priority over CDR. According to the French Ministry for Ecological Transition, waste heat in the vicinity of district heating networks with a temperature above 60°C is estimated at around 17 TWhth /year. Since this heat may compete in part with the heat requirements (of temperature > 80°C) of the S-DACCS, this heat has been subtracted from the estimation to be conservative. The remaining potential heat for CDR is therefore 36 TWh/year.

Not all industrial sites with waste heat are suitable for the installation of S-DACCS technology. The main problem with S-DACCS is the geological storage of the captured CO_2. An infrastructure is needed to transport CO_2 to nearby burial wells to limit technology costs. The ADEME report (49) analyses industrial sites with CCS potential. According to this study, 16% of the volume of CO_2 emitted by industry in France would be located too far from CO_2 geological storage sites. Assuming that the sources of waste heat are located in the same places as the CO_2 emitting sites covered by this ADEME document, and are evenly distributed, 16% of the remaining heat would therefore be assumed to be produced by industrial sites located too far from CO_2 geological storage sites. Consequently, they are subtracted from the remaining potential heat, giving a remaining value of 30 TWh_{th}/year.

Then, the ADEME report estimates that 44% of the remaining CO_2 emissions (after the previous geographical criterion) from industrial plants that could potentially be equipped with CCS are located close to a CO_2 storage site that is not socially accepted. Assuming that the heat sources correspond to the industrial sites mentioned in the ADEME report, 44% of the remaining waste heat (13 TWh_{th}) is considered unusable as the nearest geological storage site is not socially accepted. This quantity is also subtracted from the remaining potential heat, giving a quantity finally available for S-DACCS of 17 TWh_{th}/year in 2050 (Figure 47).

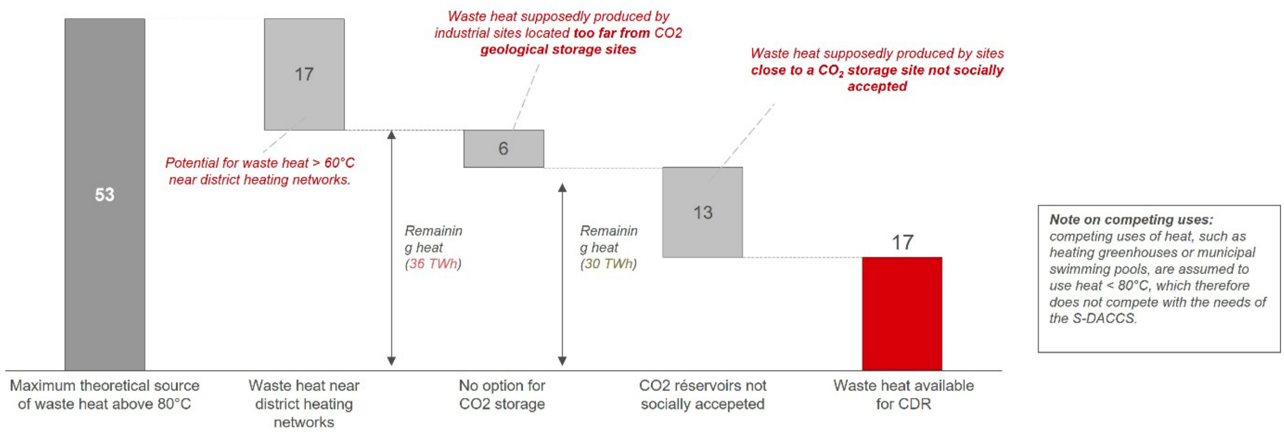


Figure 47 - Estimate of waste heat sources available for CDR in 2050 in the reference scenario, [TWh/year]

In the ambition scenario, public support is assumed to be higher. Therefore, the amount of waste heat that can be exploited for S-DACCS is estimated at 20 TWh_{th}.

8.3.1.2. Rocks

In the reference scenario, the volumes of rock available for CDR are 3 Mt/year of limestone and 0.18 Mt/year of dolomite. No volume of olivine would be available because no mine would be opened in the next few years. CKD would not be used in this scenario because of the risks for the environment. These volumes of rock would make it possible to absorb 1.9 $MtCO_2$/year in 2050.

In the ambition scenario, the volumes of rock available for CDR would make it possible to absorb approx. 2.6 $MtCO_2$/year.

In the conservative scenario, despite the availability of certain rocks, the absence of electricity prevents the rocks from being crushed and therefore, the CDR potential from being exploited.

The method used to estimate these volumes for each scenario depends on the rock.

For **limestone**, the reference scenario assumes that all agricultural lime production plants would be equipped with CCS in 2050 and that there will be no increase in limestone production for CDR in 2050. Today, 3.0 Mt/year of limestone is produced each year for calcination to produce lime which is spread on fields as an agricultural soil improver. Without additional production of lime for soil conditioning, this volume would remain at 3.0 Mt/year in 2050. With the addition of CCS on all lime production units, the carbon emitted during calcination is captured and the spreading of lime as an agricultural soil conditioner would generate negative CO_2 emissions and therefore CDR. This addition of CCS is included in the 10 $MtCO_2$/year of CCS envisaged in the reference scenario.

For **basalt**, the reference scenario assumes a national production of 10Mt (low value of the production estimated by ClimeRock) and that 10% of this production is suitable (fine particles, by-products of the grinding) and directed towards enhanced weathering, enabling 0.3Mt CO_2 to be removed from the atmosphere.

For **dolomite**, the volume available for CDR in the reference scenario would be 0.09 Mt/year, corresponding to a 5% increase in current annual production (1.8 Mt/year).

For **olivine**, no volume would be available for CDR in 2050 in the reference scenario because it does not include the opening of olivine mines for CDR. According to several public sources, the only olivine deposit identified appears to be the lherzolite deposit in the Pyrenees, located in a protected area. The opening of a mine would therefore appear to be socially unacceptable, given the environmental impact of such a mine.

In the reference scenario, the volume of **CKD** (cement kiln dust) available for CDR is considered to be zero. This is justified by the fact that the external effects of CKD on ecosystems are currently unknown and may in some cases be dangerous for health and the environment (40). As a precautionary measure and pending scientific studies demonstrating the absence of negative externalities from the application of CKD to crops, the theoretical CKD feedstock is not exploited for CDR in 2050.

In the **conservative scenario**, in the absence of available electricity (see next sub-section), whatever the anticipated available quantity of rock, it cannot be extracted or crushed. Consequently, the enhanced weathering process cannot take place.

In the **ambition scenario**, the total volume of rock available is 4.5 Mt/year (all rock combined). In particular, all lime production units are assumed to be equipped with CCS and the total annual production volume of limestone in France is assumed to increase by 10% for CDR, giving a total limestone volume of 4.2 Mt/year. The plausible feedstock of CKD (cement kiln dust) is this time evaluated at 50% of the theoretical maximum feedstock (i.e. 0.13 Mt/year), but it is considered to be zero for the same reasons as in the reference scenario. The volume of dolomite national production is increased by 10% (i.e. 100% of the theoretical maximum feedstock and 0.18 Mt/year). The volume of olivine is still assumed to be zero, as in the reference scenario.

Types of rock	Maximum theoretical feedstock *[Mt/year]*	Conservative scenario		Reference scenario		Ambition scenario	
		Resource feedstocks *[Mt/year]*	CDR potential *[$MtCO_2$/year]*	Feedstock resources *[Mt/year]*	CDR potential *[$MtCO_2$/year]*	Feedstock resources *[Mt/year]*	CDR potential *[$MtCO_2$/year]*
Limestone	5,2	1,5	0	3,1	1,9	4,2	2,5
Basalt	3	0	0	1	0,3	3	0,9
Olivine	3,1	0	0	0	0	0	0
Dolomite	0,18	0	0	0,09	0,03	0,18	0,05
CKD	0,25	0	0	0	0	0	0
Total	**11,7**	**1,5**	**0**	**3,2**	**2,2**	**7,5**	**3,5**

Table 12 – Rock feedstocks available for enhanced weathering in 2050 in the three scenarios [Mt/year].

8.3.1.3. Exploitable decarbonized electricity

Around 18 TWh would be available for CDR in the reference scenario, 0 TWh in the conservative scenario and 30 TWh in the ambition scenario. The vast majority of these resources are made up of photovoltaic electricity.

In the reference scenario, the volumes of renewable electricity available for CDR come from a comparison of the average of the RTE 2050 N1 and N2 scenarios based on a “deep reindustrialisation” level of demand and the N1 scenario, which is slightly more ambitious on renewables. The additional volumes of renewable electricity made available for CDR are therefore based solely on a comparison of the two most likely scenarios from RTE’s work. In addition, only the additional volumes of solar electricity have been kept, on the conservative assumption that the additional volumes of wind power are not deployed because of societal opposition.

The difficulties in making wind power acceptable are already apparent, since it takes twice as long to build an onshore wind farm in France as the European average (seven years in France compared with three to five years in the rest of Europe), mainly because of the numerous legal appeals (73). Additionally, the development targets for onshore wind power were revised downwards during Emmanuel Macron’s Belfort speech in February 2022: 37 GW of onshore wind power were planned for 2030 in the current PPE and have now been pushed back to 2050. Furthermore, the offshore wind deployment targets recently announced by the SGPE (June 2023) fall short of the targets in the RTE scenarios combining renewable and nuclear (N1 and N2).

A comparison between RTE average N1 and N2 “deep reindustrialisation” scenario and RTE N1 scenario suggests a volume of renewable electricity available for CDR of around 40 TWh, including 22 TWh from wind and the remainder from photovoltaic and hydro (~18 TWh). Given the difficulties in gaining public support for wind power, only 18 TWh are assumed to be available for CDR in the reference scenario (Figure 49).

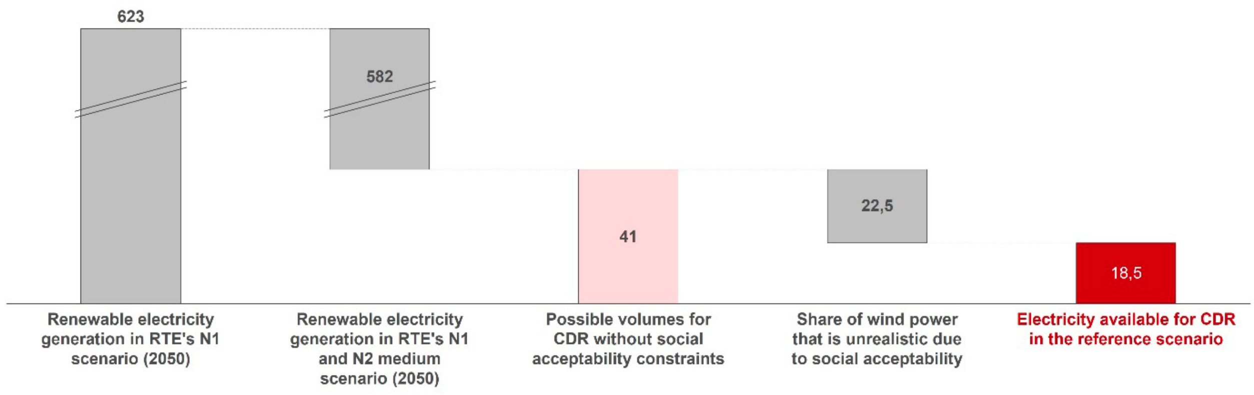


Figure 48 - Methodology for estimating the volume of renewable electricity available for CDR in the reference scenario, TWh/year in 2050

In the conservative scenario, no electricity is available for CDR in 2050. It is assumed that, for economic and public support reasons, renewable electricity generation will only be able to achieve electricity supply-demand balance in 2050.

In the ambition scenario, the main assumptions are the same as in the reference scenario, except social endorsement of wind projects is assumed to be higher. There are fewer legal cases against them, and it is assumed that half of the wind-generated electricity resulting from the comparison between the average scenario N1 and N2, and N1, is available for CDR.

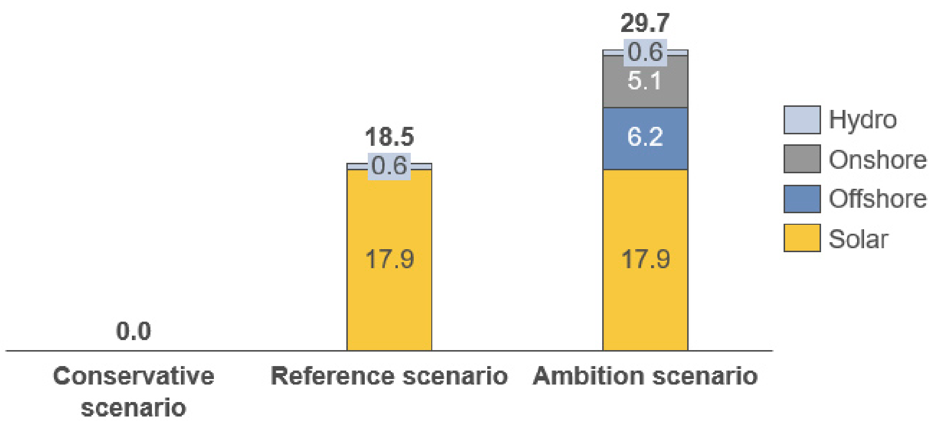


Figure 49 - Volume of electricity available for CDR according to scenarios and sources, TWh/year in 2050

The renewable electricity sources identified in this section are therefore an order of magnitude smaller than the maximum theoretical potential identified in section 7 and consider the social reality and the specific characteristics of France concerning renewables.

8.3.1.4. Allocation of available electricity without storage constraints

To allocate the available electricity of 18 TWh in the reference scenario, and 30 TWh in the ambition scenario, we use a merit order based on the cost of CDR methods (costs taken from the IPCC, the main allocation criterion) and their energy efficiency. Once the costs and efficiency of each method has been considered, the limiting resource for each method was assessed. These were rock for enhanced weathering, heat for S-DACCS, and electricity for electrochemical DACCS. Once these limiting factors have been identified, the electricity allocated corresponds to the 'stoichiometric' conditions for deploying the technology. For example, S-DACCS consumes both heat and electricity, and the latter is limited by the amount of waste heat available: 17 TWh_{th}.

In the reference scenario, the 18.5 TWh of available electricity are divided into 0.5 TWh for enhanced weathering from limestone and 0.4 TWh for enhanced weathering from basalt. The implementation of S-DACC uses 2.7 TWh, leaving a potential of 14.9 TWh for electrochemical DACCS. These estimates are based on the limiting factors discussed in the sub-sections above (8.3.1.1 to 8.3.1.3). The estimated electricity requirements for the three methods above are calculated using the same conversion factors as in part 7. For instance, for electro-chemical DACCS, electricity consumption is estimated at 0.67 MWh/tCO_2. The costs shown in the graph below are taken from the "*Mitigation of climate change*" report in the IPCC's 6th report (2022) (2).

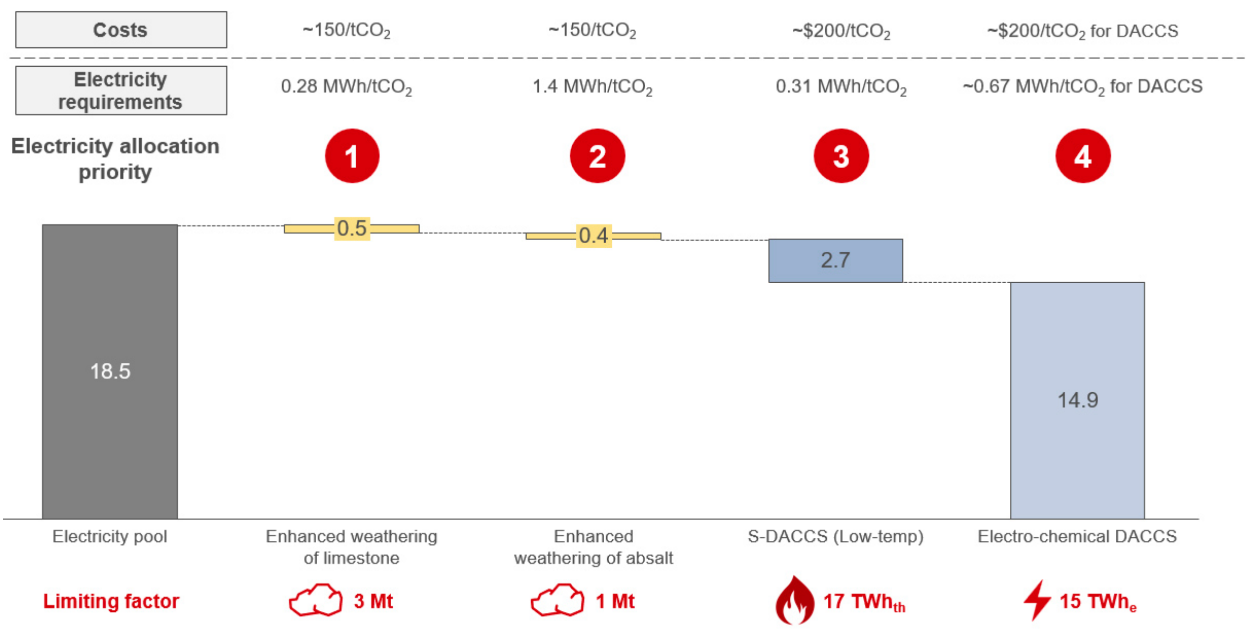


Figure 50 - Breakdown of the uses of the available electricity among the various CDR methods in the reference scenario [TWh/year].

In the ambition scenario, the 30 TWh of available electricity is divided into 2 TWh for enhanced weathering (Limestone + Basalt), 3 TWh for S-DACCS, leaving 25 TWh for electrochemical DACCS. More details in appendix 10.8.

In the conservative scenario, there is no decarbonised electricity available for CDR.

8.3.1.5. CDR potential with and without geological storage constraints

In the reference scenario, the CDR potential of electricity-consuming methods, shown in Figure 51 peaks at **33 MtCO$_2$/year**. In the **ambition** scenario, the CDR potential of electricity-consuming methods presented in appendix 10.8 peaks at **52 MtCO$_2$/year**.

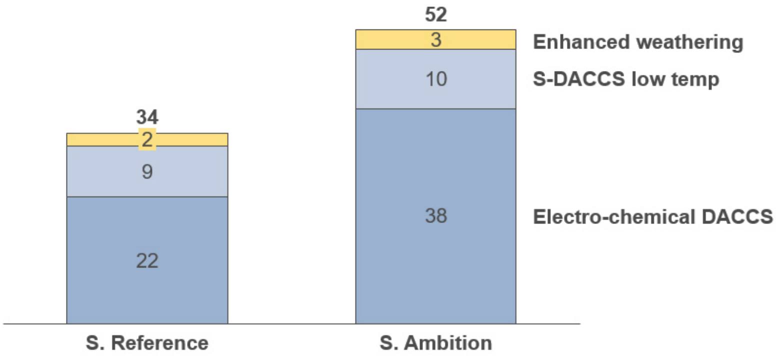


Figure 51 - CDR potential of electricity-consuming methods in 2050 in the reference scenario and ambition [MtCO$_2$/year]

In the conservative scenario, the plausible CDR potential of DACCS and enhanced weathering is **zero**, given that there is no available zero-electricity in this scenario.

The CDR potentials presented in the graphs above take into consideration the amount of electricity available for each method **but do not consider the constraint of geological storage of CO$_2$**, which reduces the potential of methods such as DACCS.

Considering the constraints on geological storage of CO$_2$, the reference scenario falls from 31 MtCO$_2$/year to 24 MtCO$_2$/year for DACCS methods. More details are available in the section dedicated to geological storage limits (8.3.10).

8.3.2. BECCS

BECCS would make it possible to remove around 6 MtCO$_2$/year in 2050 in the reference scenario and 18 MtCO$_2$/year in the ambition scenario. There is no BECCS in the conservative scenario because France has no geological storage capacity for CO$_2$.

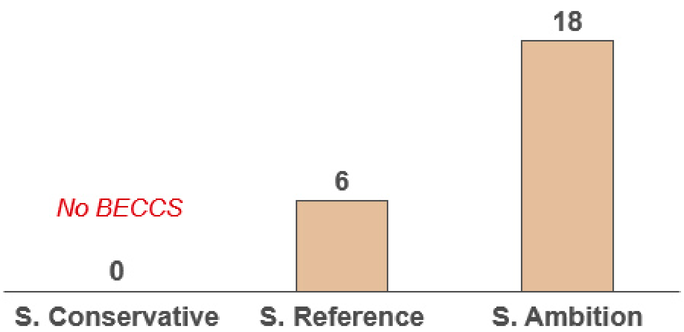


Figure 52 - BECCS potential in the different scenarios, in MtCO$_2$/year in 2050

In the reference scenario, the main assumptions are:

- **Development of biomass and BECCS for medium-sized boilers** in industry and district heating networks
- **Development of the use of biogas with CCS** in industry
- **Consideration of competition for biogenic CO_2 with air and sea transport for the production of sustainable fuels** (electro fuels), up to 7.4 $MtCO_2$/year for air transport (of which 0.7 $MtCO_2$/year have already been considered by ADEME) and 5.7 $MtCO_2$/year for sea transport (not considered by ADEME).

In more detail, the BECCS potential in 2050 for the reference scenario is taken from the ADEME S3 scenario in its "*Transitions 2050*" report. The BECCS potential of this ADEME scenario is 21 $MtCO_2$/year but does not consider additional constraints on CO_2 transport and storage infrastructures, public support, biomass availability and competition with air and sea transport in the use of biogenic CO_2.

Scenario S3 assumes significant development of biomass and BECCS for medium-sized boiler units in industry and heating networks (units with CO_2 emission volumes of between 10 and 50 $ktCO_2$/year), biorefineries and the use of biogas for industry. The units equipped with BECCSs selected are concentrated and close to geological storage sites, with the possibility of transporting CO_2 over 300 km.

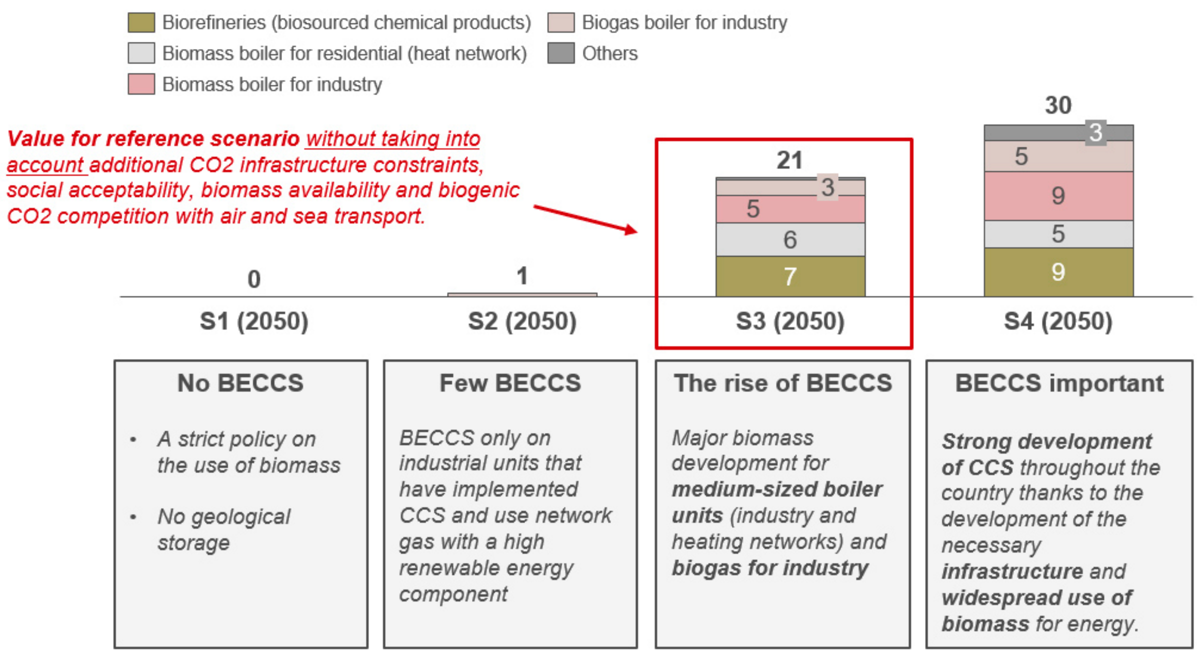


Figure 53 - CO_2 removal by BECCS in 2050 according to ADEME scenarios

The BECCS potential included by ADEME in the S3 scenario in 2050 has been reduced in the reference scenario by considering the biogenic CO_2 requirements of the aviation and maritime sectors for sustainable fuel production. This is because the aviation and maritime sectors have very strict medium/long-term targets for the incorporation of sustainable fuels (heavy penalties) under the European regulations Refuel EU Aviation and Fuel EU Maritime. The need for electro fuels has been revised upwards considerably since the ADEME scenarios were published, and these are synthesised from biogenic CO_2. As a result, the latter would be prioritised for fuel use rather than for geological storage (BECCS).

For aviation, the government's CCUS consultation (June 2023) anticipates a biogenic CO2 volume of 7.4 $MtCO_2$/year by 2050, of which 0.7 $MtCO_2$/year is already included by ADEME in the S3 scenario of the "*Transitions 2050*" report.

For the maritime sector, the need for biogenic CO2 for the production of sustainable fuels has been estimated at 5.7 $MtCO_2$/year and is not considered in the ADEME S3 scenario. The need for biogenic CO_2 is estimated based on the maritime sector decarbonisation roadmap (2022), which anticipates a need for ~25 TWh of electro fuels (e-methane and e-methanol in S3).

In total, the 7.4 $MtCO_2$/year of biogenic CO_2 required for aviation according to the CCUS consultation (including 0.7 already seen by ADEME) and the 5.7 $MtCO_2$/year of biogenic CO_2 required for maritime transport are deducted from the BECCS potential of ADEME S3 scenario (21 $MtCO_2$/year). This leaves a BECCS potential of 8.7 $MtCO_2$/year in the reference scenario, with no storage constraints. This potential is then further reduced because of the limited geological storage capacity (methodology detailed in section 8.3.10) of biogenic CO2 to reach the plausible capacity of 6.5 Mt CO_2.

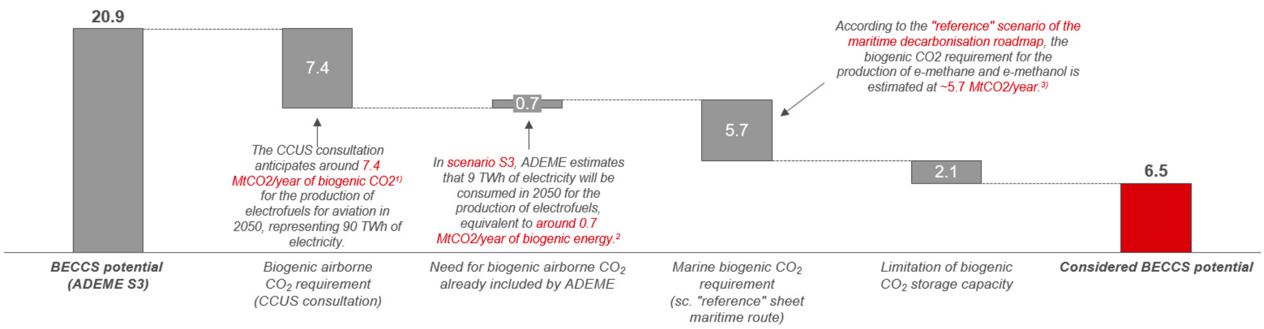


Figure 54 - Reduction of ADEME's BECCS potential (S3) considering competition from biogenic CO_2 with air and sea transport

In the **conservative scenario**, there is no BECCS in 2050, as France only has geological CO_2 storage capacity to store fossil CO_2 and not biogenic CO_2.

In the **ambition scenario**, estimated based on the ADEME S4 scenario, the BECCS potential is **18 $MtCO_2$/year** after deducting the need for electro fuels and considering the constraint on biogenic CO_2 storage capacities. This scenario therefore assumes strong development of infrastructures for transporting and storing CO_2 (even if they are not yet sufficient) throughout the country, as well as widespread use of biomass for energy. The need for biogenic CO_2 is still estimated at 7.4 $MtCO_2$/year for air transport and 5.7 $MtCO_2$/year for maritime transport for the production of electro fuels. However, unlike ADEME's S3 scenario, ADEME's S4 scenario anticipates a volume of electricity of 18 TWh for the production of sustainable fuels for aviation in 2050, which corresponds to approximately 1.5 $MtCO_2$/year biogenic in 2050 **as already included** by ADEME. More details in appendix 10.10.

8.3.3. Stocking practices (excluding forests)

Carbon storage practices (crops, grassland, vines, excluding forests) would absorb 17 $MtCO_{2eq}$/year in the reference scenario, compared with 9 $MtCO_{2eq}$/year in the conservative scenario and 35 $MtCO_{2eq}$/year in the ambition scenario. The carbon storage practices with the greatest potential would be agroforestry, cover crops, and hedge planting. The other practices have marginal potential for CO_2 removal.

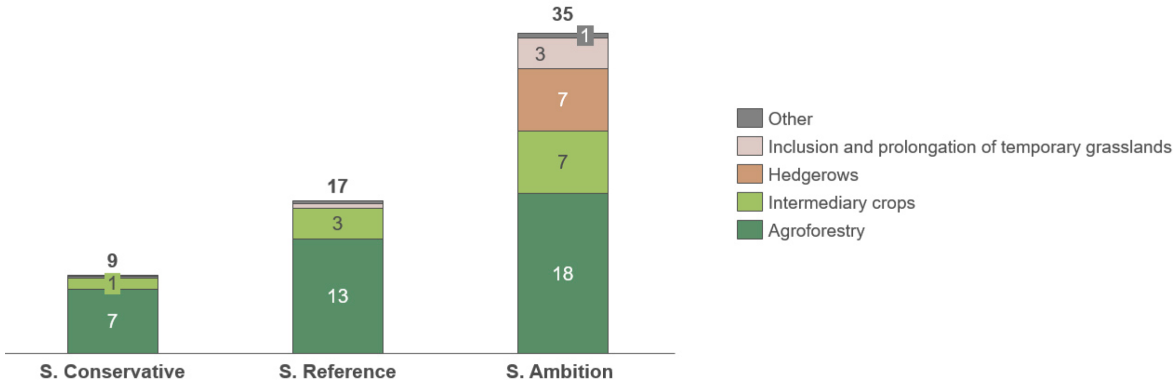


Figure 55 - CO_2 removal potential of carbon storage practices according to scenarios, in 2050 and in $MtCO_2$/year

In the reference scenario, the main assumptions are:

- **The implementation of a carbon credit market, with a remuneration per eliminated tonne of CO_2 of €40/tCO_{2eq} in 2050.**
- **By 2050, 50% of French farmers will have implemented carbon storage practices**

Estimates of the CO_2 removal potential of each carbon storage practice are taken from the INRAE report "*Stocker du carbone dans les sols français*" (2020). According to this report, there are three main limiting factors: economic, regulatory, and public support.

For the economic factor, the factors are:

- Cost of implementing the storage practices (new tools, more expensive seeds, lower yields, etc.),
- Remuneration per tonne of CO2 absorbed too low and uncertainty over future returns.

For the regulatory side, the limiting factors would be the absence of a carbon offset market and the lack of carbon credit certification systems. As far as public support is concerned, the limiting factors are essentially linked to the difficulty of changing farmers' habits.

In the reference scenario, the potential for eliminating carbon storage practices is estimated on the basis of the INRAE merit order of carbon storage practices, assuming a price per tonne of CO_2 of €40/tCO_{2eq} for farmers. This price is consistent with current prices and therefore reasonable for 2050:

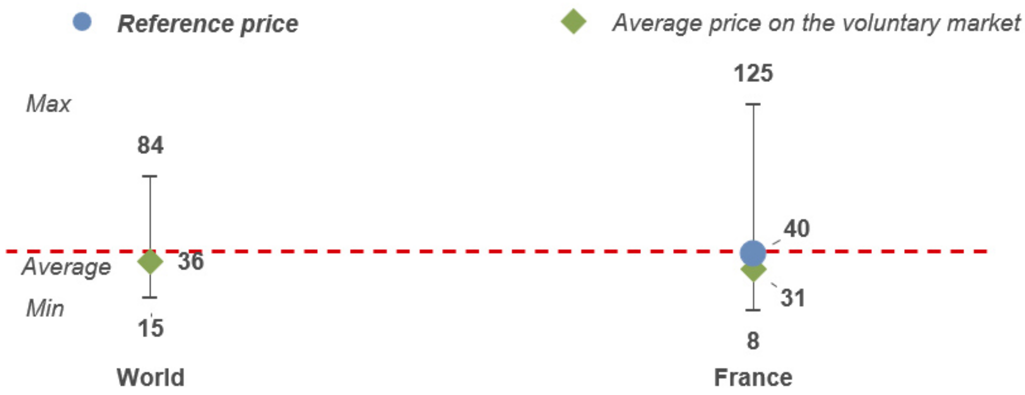


Figure 56 - Price per tonne of CO_2 (€/tCO_{2eq}) on the voluntary carbon offsetting market in France and worldwide

According to the INRAE merit order, the carbon removal potential of carbon storage practices would vary from 12 to 51 $MtCO_{2eq}$/year for a price ranging from €20/tCO_{2eq} to €140/tCO_{2eq}. This price has been adjusted to consider changes in cultivated fields, grasslands and vines as seen in ADEME's S3 scenario between 2050 and 2020.

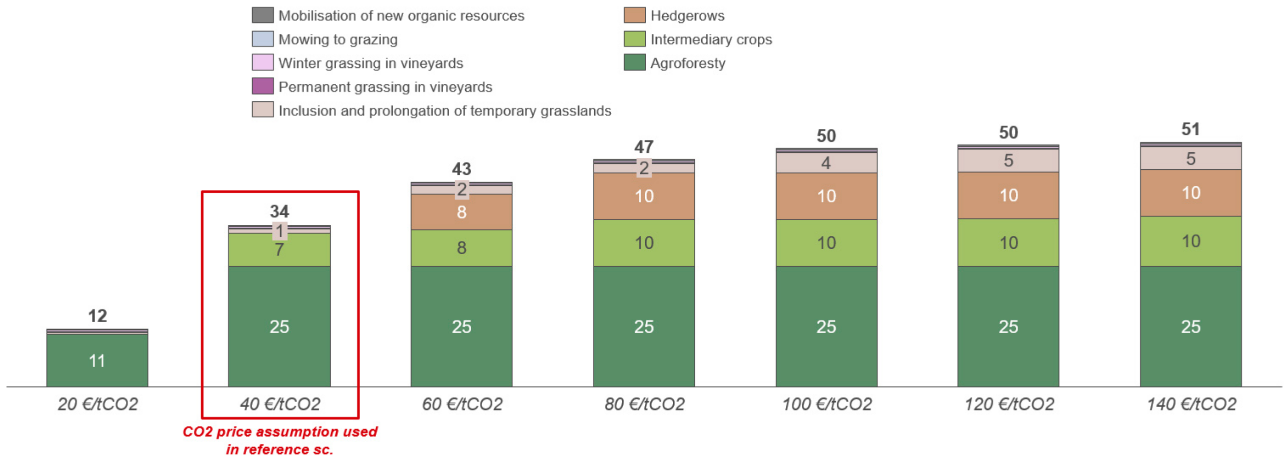


Figure 57 - CDR potenital of carbon storage practices depending on the remuneration per tonnes of CO_2, in $MtCO_{2eq}$/year, according to the INRAE merit order and adjusted with changes in the cropping area, grassland and vines as included in ADEME S3 scenario

The potential for removing CO_2 without public support and regulation constraints would be 34 $MtCO_{2eq}$/year (price of €40/tCO_{2eq}). The limitations are that INRAE's assessment of the costs of implementing practices has been calculated on the basis of average yields, costs, and prices over the 2009-2013 reference period, but could change in the future. Conversely, there are many non-financial co-benefits to adopting these practices (water management, biodiversity, etc.) that are not considered in the INRAE merit order.

In the **reference** scenario, a French or European carbon credit market is assumed to exist with sufficient certification capacity. By applying a conservative adoption rate of 50% of farmers, the potential for eliminating CO_2 reaches 17 $MtCO_{2eq}$/year in the reference scenario.

In the **conservative** scenario, the carbon offsetting market struggles to take off, with a remuneration of only €30/tCO_{2eq}, and only 30% of farmers implementing carbon storage practices, giving a potential of 9 $MtCO_{2eq}$/year.

In the **ambition** scenario, an efficient carbon compensation market is assumed to emerge by 2050, with a remuneration of €120/tCO_{2eq}, and 70% of farmers implementing carbon storage practices, giving a potential of 35 $MtCO_{2eq}$/year.

8.3.4. Afforestation/reforestation

Afforestation and reforestation would make it possible to absorb 4.5 $MtCO_2$/year in the reference scenario, 3 $MtCO_2$/year in the conservative scenario and 10.1 MtCO2 /year in the ambition scenario.

Forest area would increase by 0.9 Mha between now and 2050 in the reference scenario, by 0.6 Mha in the conservative scenario and by 2.0 Mha in the ambition scenario.

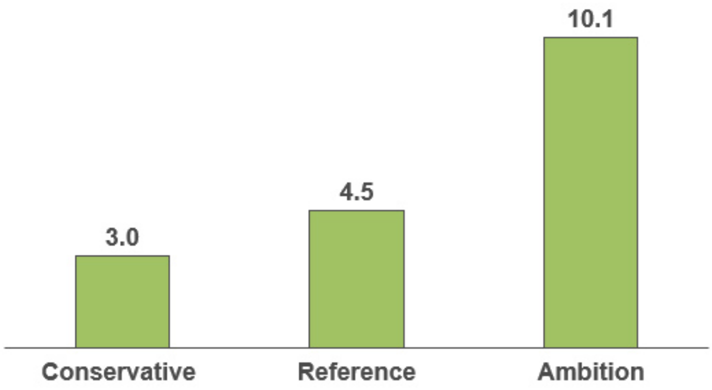


Figure 58 - CDR potential of afforestation according to the scenarios, in 2050 in $MtCO_2$/year

In the reference scenario, the main assumptions are:

- **Forest area increases by 0.9 Mha between 2023 and 2050**. This figure corresponds to both the 2035 SGPE target which would be delayed until 2050, and the additional area between 2023 and 2050 at the current trend rate (+0.3 Mha between 2010 and 2020), again according to the SGPE.
- **The increase in forest area is supposed to come from afforestation only**, not reforestation.

The increase in forest area between 2023 and 2050 of 0.9 Mha was selected in the reference scenario from several values available in the literature, in particular in the ADEME report "Transitions 2050" (scenarios S1, S2, S3 and S4), the SGPE and trend estimates.

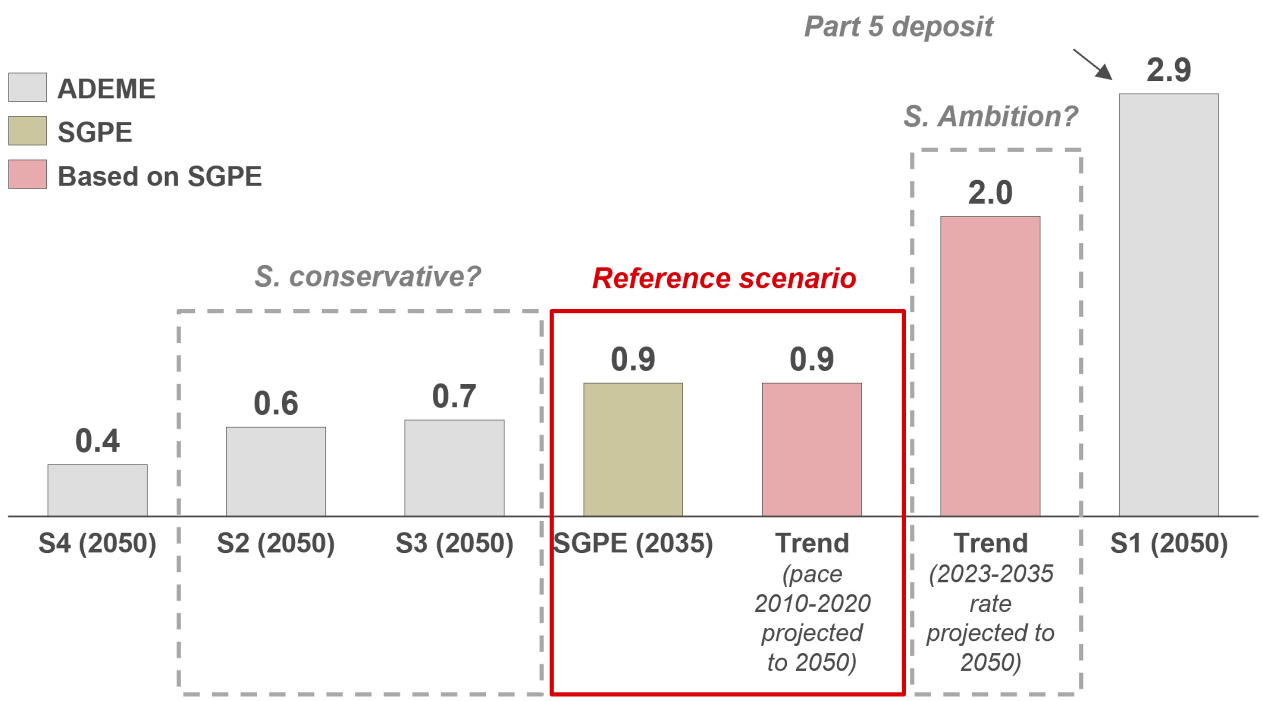


Figure 59 - Change in forest area between now and 2050 according to ADEME, SGPE and trend projections, in Mha relative to 2023

The increase value in forest area of +0.9 Mha has been kept in the **reference** scenario because it represents the achievement of the SGPE target 15 years later and also reflects the projection of the current rate of increase in forest area.

In the **conservative** scenario, the increase in forest area between now and 2050 is 0.6 Mha. This corresponds to the value seen in ADEME S2 and S3 scenarios.

In the **ambition** scenario, the selected increase in forest area between 2050 and today is 2.0 Mha. This corresponds to the projection to 2050 of the 2023-2035 rate that would be achieved if the SGPE target of +0.9 Mha is met between 2023 and 2035.

8.3.5. Forest sink (excluding CDR) and forest carbon storage practices

In the reference and conservative scenarios, forestry carbon storage practices would not allow to increase the potential for negative CO_2 emissions from forests compared with today. On the other hand, they would prevent part of the deterioration in the current forest carbon sink, which is assumed to be 18 $MtCO_{2eq}$/year in 2050 according to the SNBC 2, compared with 28 $MtCO_{2eq}$/year in 2021. This existing sink refers to the growth of current forests (excluding afforestation or reforestation) sequestering more and more carbon annually in the soil and above-ground biomass. Without human action, this is not CDR.

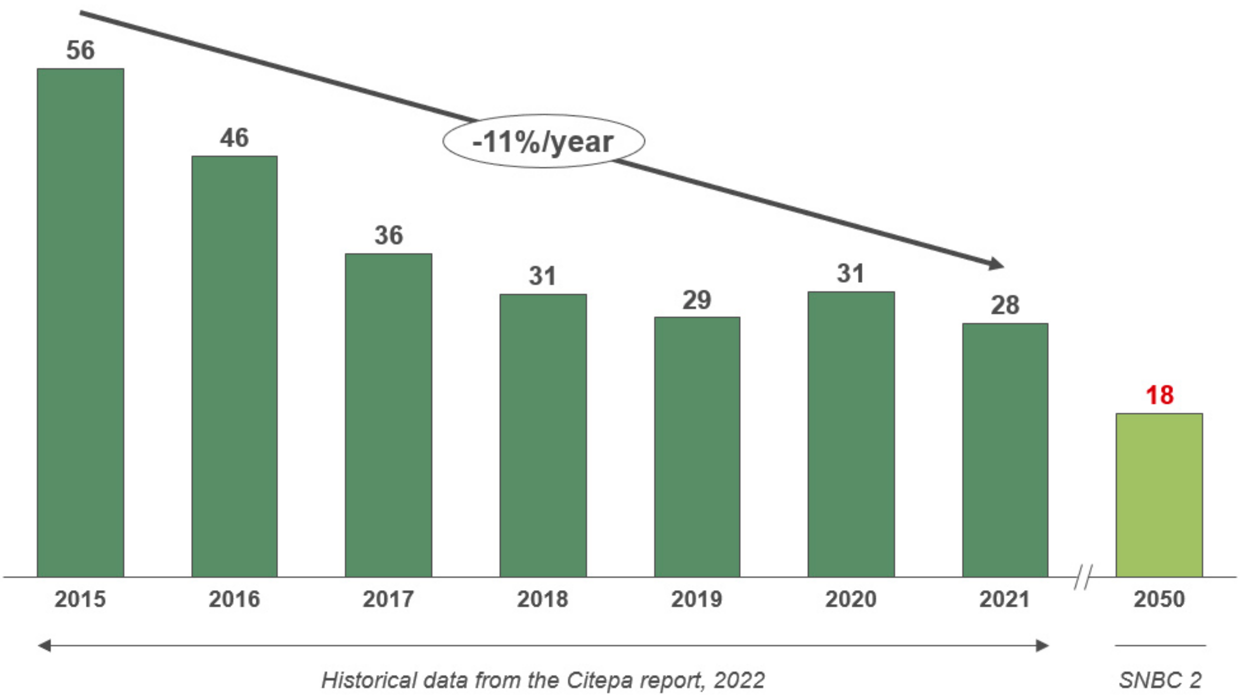


Figure 60 - Evolution of the natural forest carbon sink, in $MtCO_2$/year between 2015 and 2050

While forestry carbon storage practices would certainly prevent the forest carbon sink from deteriorating too much, it is unlikely that these practices would enable the forest to absorb more than it does today, given climate change and the current downward trend in the forest carbon sink.

According to the SGPE in the document "*La planification écologique pour la forêt*" (July 2023), the forest sink has already halved between 2010 and 2020 (62 $MtCO_{2eq}$/year to 31 $MtCO_{2eq}$/year) as a result of a drop in biological growth, particularly in areas of forest growth (bushes at the edge of forests gradually becoming forests), and a doubling of tree mortality (bark beetle crisis since 2018) and the intensification of droughts (74). This decline could continue as a result of climate change.

However, carbon storage practices have limited potential, since according to the INRAE report "**Stocker du carbone dans les sols français**" (2020), "*very few silvicultural management levers can be mobilised to increase the stock of [soil organic carbon] in forest soils*". So, "*the main challenge is to preserve this stock [of carbon] and its positive trend through sustainable silvicultural management practices*".

In the **ambition** scenario, the forest carbon sink (excluding CDR) is 50% higher than in the **reference** scenario, i.e. 28 $MtCO_{2eq}$/year in 2050.

8.3.6. Biochar

In the reference scenario, the volume of biomass available for biochar is 0.8 Mt/year, which would make it possible to absorb around 0.5 $MtCO_2$/year in 2050. This volume of biomass corresponds to half of the maximum theoretical availability estimated in part 4 of the report at 1.6 Mt/year.

A number of factors have been identified as limiting the use of biomass for biochar:

- **Technical:** There are different types of biochar of varying quality, and the effects on crops are not completely characterised, even though they have been the subject of advanced research to assess their impact. This lack of knowledge could be a limitation for some farmers and limit their development. Labels such as the EBC exist to guarantee the quality of biochar.
- **Public support:** About the technical constraint, if farmers do not have the assurance of an increase in agricultural yields and at least the certainty that the spreading of biochar does not generate any negative externalities, they will be reluctant to use biochar in their fields. However, according to biochar producers, feedback from farmers who have adopted such practices is positive.
- **Economic:** The cost of using biochar as an agricultural soil improver has not been considered in the assessment of the plausible volumes. According to the biochar players interviewed, biochar needs to be purified before being dispersed in fields, bringing the cost per tonne of CO_2 removed at $200, to be profitable.

Based on these limiting factors, an assumption of 50% of the theoretical maximum biochar volumes has been made in the **reference** scenario, which represents 0.8 Mt/year.

In the **ambition** and **conservative** scenarios, 100% and 10% of the theoretical maximum biochar volumes were considered to be available respectively, representing 1.6 Mt/year and 0.2 Mt/year respectively.

8.3.7. Biobased products

In the reference scenario, the potential for biobased products is estimated at 3.5 $MtCO_{2eq}$/year, based on the ADEME S3 scenario.

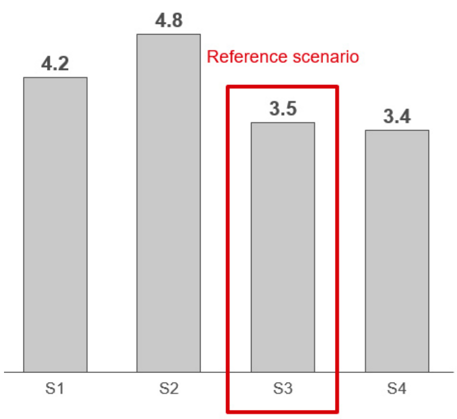


Figure 61 - CDR potential of wood products in the ADEME scenarios in 2050 [$MtCO_2$/year]

ADEME's *Transitions 2050* report was used to estimate the removal potential of biobased products in the **reference** scenario. For the sake of consistency with the BECCS section, where the values for scenario S3 were used, the CO_2 removal potential from wood products from the same scenario (S3) was used to estimate the potential for bio-based products in the reference scenario, i.e. ~3.5 $MtCO_2$/year in 2050.

For the **ambition** scenario, the potential for eliminating biobased products is approximately 4 $MtCO_2$/year. This corresponds to an intermediate value between scenarios S2 and S3.

For the **conservative** scenario, the CDR potential of biobased products is approximately 3 $MtCO_2$/year. This is a more conservative value than ADEME S3 and S4 scenarios, which could be explained by poor development of the wood industry, greater consumption of wood for the production of biofuels, or strong exports of wood abroad.

8.3.8. Peatlands

In the **reference**, **ambition** and **conservative** scenarios, the CDR potential of peatlands in 2050 is considered to be zero.

Indeed, given the high human pressure on French peatlands and their degradation, it is more reasonable to try to maintain such an ecosystem and preserve what exists than consider any reconstruction.

8.3.9. Blue carbon

In the **reference**, **ambition** and **conservative** scenarios, the surface area of seagrass beds and mangroves to be reforested is considered to be zero in 2050. The blue carbon CDR potential is therefore zero in 2050.

In the case of both seagrass beds and mangroves, despite the existence of a theoretical potential that could make it possible to store more CO_2 on a sustainable basis, the current state and degradation of these ecosystems do not suggest any additional storage capacity. According to scientific studies, global warming could even cause the extinction of all Posidonia meadows in the Mediterranean, under the RCP 6 and RCP 8.5 scenarios (31).

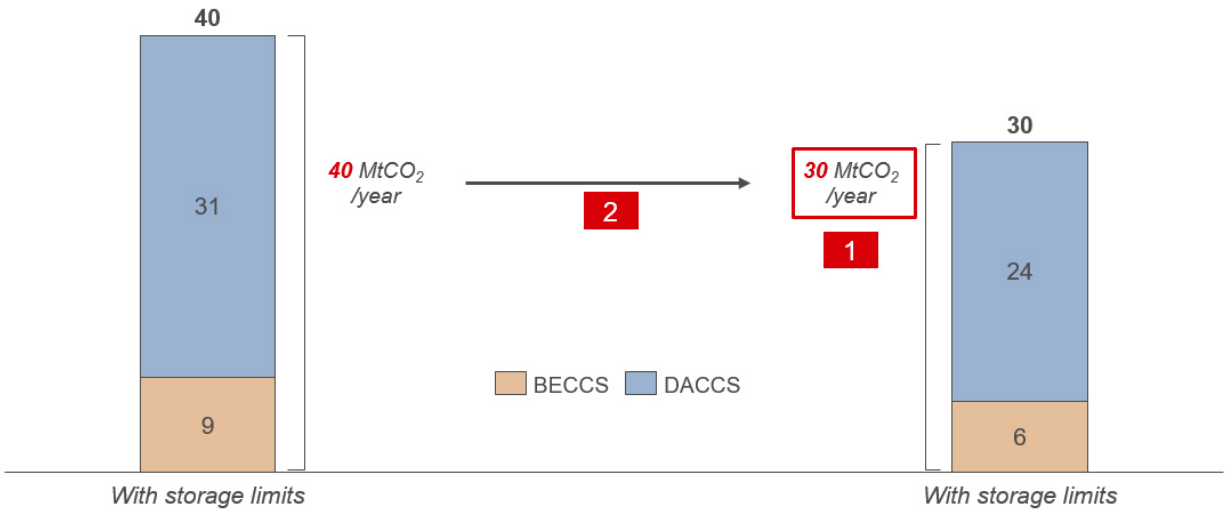
It therefore seems more reasonable to anticipate the preservation of the current surface areas of these marine ecosystems, which must be protected above all to prevent them from releasing the CO_2 that is currently stored, and also to protect the very rich biodiversity they host.

8.3.10. Accounting for the limited geological storage capacity

Geological storage of CO_2 and the associated transport infrastructure could be a limiting factor for BECCS and DACCS solutions. Geological storage capacity for DACCS and BECCS is 30 $MtCO_2$/year in the reference scenario and 63 $MtCO_2$/year in the **ambition** scenario. No BECCS and DACCS are included in the **conservative** scenario, as all storage capacity is used for CCS.

In the **reference** scenario, total storage capacity is assumed to be 40 $MtCO_2$/year, including 25 $MtCO_2$/year of storage in France (Onshore and Offshore), which is consistent with the CCUS consultation, which anticipates between 15 and 30 $MtCO_2$/year of storage in France. The remaining storage capacity (15 $MtCO_2$/year) is located abroad. This total capacity is shared between 10 $MtCO_2$/year of CCS for industry and 30 $MtCO_2$/year of DACCS and BECCS. Taking this constraint into account reduces the potential for eliminating BECCS and DACCS from 40 to 30 $MtCO_2$/year.

To clarify, the 10 $MtCO_2$/year of CCS in the reference scenario includes CCS equipment in half of the lime production plants used to spread lime on fields for CDR and soil conditioning.



1	In the reference scenario, **approximately 30 $MtCO_2$ /year of CO2 geological storage** could be available for BECCS and DACCS.
2	**The absorption potentials of BECCS and DACCS are reduced in proportion to their respective potentials, from a total of 40 $MtCO_2$ /year to a total of 30 $MtCO_2$** /year. BECCS and DACCS are thus reduced by 3 and 7 MtCO2/year respectively. This reduction in DACCS implies a reduction in electricity consumption of ~5 TWh

Figure 62 - Impact of the CO_2 geological storage constraint on the CDR potential of BECCS and DACCS in the reference scenario, in $MtCO_2$/year in 2050

These assumptions come from the CCUS consultation (June 2023), which forecasts CO_2 storage capacity in France (onshore and offshore) at 15 to 30 $MtCO_2$/year in 2050, i.e. 25 $MtCO_2$/year in the **reference** scenario. In addition, several projects are currently under discussion to export CO_2 to reservoirs in Norway (Northern Lights), the Netherlands (Aramis) and Italy (Callisto). Other projects could also be launched between now and 2050. CO_2 export volumes are assumed to be 15 $MtCO_2$/year for France, representing a total storage capacity of 40 $MtCO_2$/year attributable to France.

In addition, the quantity of CCS is estimated at ~10Mt (intermediate between the CCUS 15-20 Mt vision and that of the SNBC-2 which targets 5 Mt) and consistent with the ADEME S3 scenario. In the reference scenario, the remaining volume of geological storage of CO_2 for BECCS and DACCS is therefore 30 $MtCO_2$/year.

This constraint of 30 $MtCO_2$/year of geological storage for BECCS and DACCS reduces its potential from 40 $MtCO_2$/year (without constraint) to 30 $MtCO_2$/year.

In the **ambition** scenario, CO_2 storage capacity in France (onshore and offshore) is estimated at 43 $MtCO_2$/year in 2050, assuming greater public support for CO_2 storage than in the reference scenario. This value is taken from the ADEME document "*Avis de l'ADEME - Captage et stockage géologique de CO_2 (CSC) en France*" (2020). Assuming a doubling of export capacity compared with the reference scenario (30 $MtCO_2$/year), total CO_2 storage capacity would be 73 $MtCO_2$/year in 2050. With the same capacity of CCS as in the **reference** scenario (10 $MtCO_2$/year in 2050), the storage volume available for BECCS and DACCS would be 63 $MtCO_2$/year in 2050.

In the **conservative** scenario, all the geological storage capacity is used by CCS for fossil emissions. Consequently, there can be no DACCS or BECCS in the conservative scenario.

8.4. Estimated cost of implementing the scenarios

It is possible to estimate the costs associated with implementing the various scenarios based on the estimates given in the IPCC report "Climate Change 2022, Mitigation of Climate Change" (IPCC 2022). The mature abatement costs of the main CDR methods would range from USD 0 to 400/tCO_2 (average value considered) and are detailed in Figure 28.

As illustrated in Figure 63, the annual cost of implementing CDR methods is between 1.3 and 19.4 billion euros if all the methods have reached maturity. To achieve net zero, the objective of the reference scenario, an annual cost of 8.3 billion euros must be considered to deploy the selected method. The repartition of these costs between public authorities and private players will depend on the rules implemented. The costs of capturing and storing CO_2 according to the different methods considered are shown in the appendix 10.11.

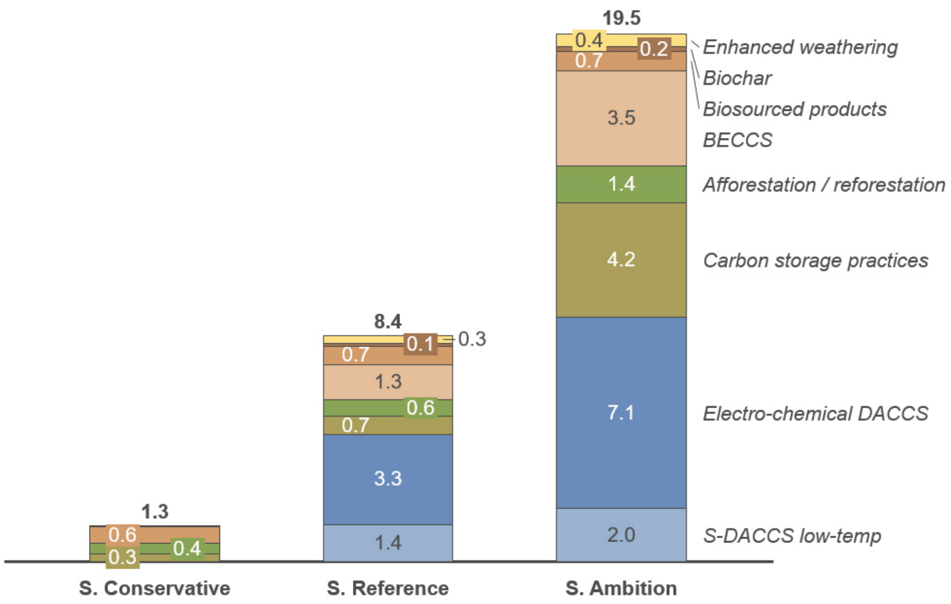


Figure 63 - Annual costs of implementing selected CDR methods, depending on the scenario considered (in billions of euros)

It is important to note that this figure only covers the cost of purchasing the removed tonnes necessary to achieve the target. It does not cover the upfront cost of supporting the development of these methods through research, innovation, and deployment.

8.5. CDR potential in 2030

In the **reference** scenario, natural carbon sinks and CDR methods add up to **32 MtCO_{2eq}/year** of carbon sinks in 2030.

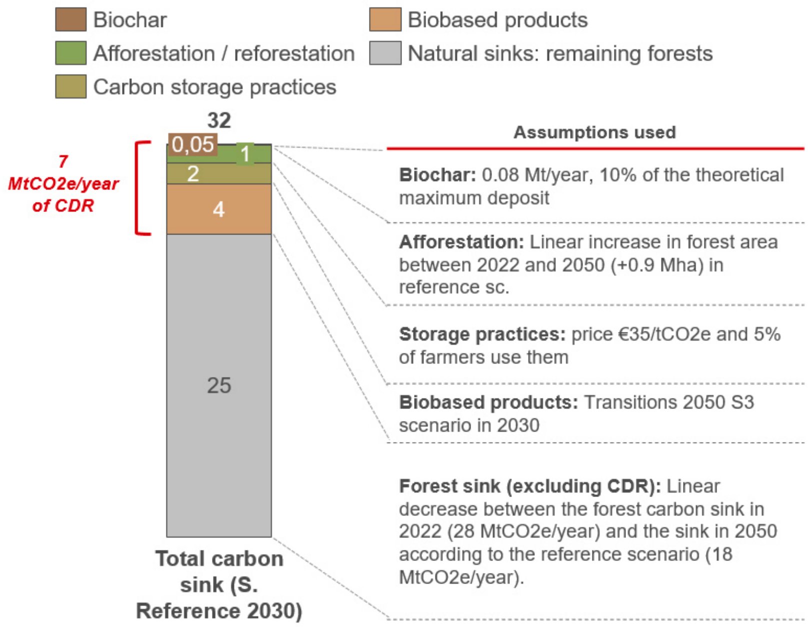


Figure 64 – Combined CO_2 removal potential from the natural forest sink and CDR in the reference scenario in 2030 (Mt/year)

In the **reference** scenario, no volume of electricity is assumed to be available for CDR, as the supply-demand balance in 2030 is already deemed difficult by RTE, mainly because of the rapid and substantial electrification of uses: mainly industry and electric mobility. Consequently, there is no DACCS in 2030 in France.

In addition, no geological storage capacity for CO2 is assumed to be available in 2030 for CDR because the first storage capacities would be used primarily to decarbonise heavy industry (e.g. the steel industry in Dunkirk) and cement through CCS. Consequently, there is no BECCS in 2030 in France.

Nevertheless, biochar is beginning to be deployed, and France is starting to plant trees to increase its forest area to achieve its target of +0.9 Mha of forest by 2050. A linear increase in forest area is assumed between now and 2050.

In 2030, carbon storage practices will also begin to be implemented thanks to the Low Carbon Label. A remuneration of €35/tCO_{2eq} is assumed, which is slightly higher than the current average for the Low Carbon Label (€32/tCO_{2eq}). Although the remuneration is beginning to look attractive, only 5% of farmers are beginning to change their habits to implement carbon storage practices.

Bio-sourced products are increasingly used by 2030, which will store more carbon.

Finally, the forest sink is gradually deteriorating as a result of the growing impact of climate change. This sink is assumed to decrease linearly between today (28 $MtCO_{2eq}$/year) and its value in 2050 according to the reference scenario (18 $MtCO_{2eq}$/year).

Table 13 summarises the different assumptions made for each resources required for the different CDR methods. The methods with a non-zero potential in 2030 are shown in red, including afforestation, bio-based products, biochar, agricultural carbon storage practices and the natural forest sink. The availability of renewable or low-carbon electricity available for CDR is considered to be zero in 2030, as is geological storage capacity, thus excluding BECCS and DACCS.

Resource	CDR method	Use of resources (2030)	Absorption potential ($MtCO_{2eq}$ /year)	Justification / hypothesis
Electricity	Electrochemical OAE	0 TWh_e	0	No additional renewable electricity
	Electrochemical DACCS	0 TWh_e 0 TWh_e	0	No additional renewable electricity
	S-DACCS (low-temp)	0 TWh_e	0	No additional renewable electricity
	Mineral alkalisation of the oceans	0 TWh_e	0	No additional renewable electricity
Heat	S-DACCS (low-temp)	0 TWh_{th}	0	No geological storage of non-fossil CO2
	Mineral alkalisation of the oceans	0 TWh_{th}	0	No rocks available
Areas of new land (forests, peat bogs, seagrass beds, mangroves)	Reforestation / Afforestation	***+0.3Mha***	***1,3***	***Linear trend 2022 - 2050***
	Increase in peatland area	+ 0 Mha	0	Difficulties in preserving them today → Maintaining current surface areas
	Increase in seagrass and mangrove areas	+ 0 Mha	0	Difficulties in preserving them today → Maintaining current surface areas
Practical storage areas	Storage practices	Depending on practices	***1,8***	***Price 35 €/tCO2e and 5% of farmers are implementing it because the process is underway***
Biomass	BECCS	0 TWh_{th}	0	No geological storage of non-fossil CO2
	Biobased products	***1.7 Mt***	***4,1***	***ADEME S3 in 2030***
	Biochar	***0.08 Mt***	***0,05***	***Easy to make, 10% of the maximum deposit***
Rocks and minerals	Enhanced weathering Mineral alkalisation of the oceans	0 Mt	0	No increase in limestone production, CKD production without CCS
Forest area	Natural forest carbon sink	***~18 Mha***	***~25***	***Linear trend 2022 - 2050***

Table 13 - Summary of CO_2 removal potential of each CDR method up to 2030

9. Conclusion

Developing and diversifying carbon dioxide removal capacities is now essential if we are to achieve our climate objectives. In France, this imperative is all the more immediate as the natural forest sink, on which the country has relied heavily to offset residual emissions, is showing signs of weakness, partly due to climate change (75).

But the information needed to plan the organised deployment of a diversified portfolio of CDR methods is amiss. Most countries are unaware of their capacity to deploy CDR and are therefore struggling to define a strategy.

This report explores this potential in France, assessing the various methods of Carbon Dioxide Removal (CDR) that could enable France to achieve or even exceed net zero. The deployment of CDR is not just a technical issue. It is part of a societal dynamic and depends on the participation of stakeholders and communities. To take account of this reality and maximise the value of the results of the study for decision-making, the methodology employed has focused in particular on (1) taking account of all the CDR methods available and how they relate to each other, (2) a bottom-up analysis of potential based on available resources and their actual availability, and finally (3) taking account of the French 'social geography' of CDR.

A variety of methods

Among all the existing or proposed CDR methods, the choice was made to keep all those that could be developed on a large scale between now and 2050. Some, such as electrochemical DACCS or enhanced rock weathering, are still classified as low TRL in the literature, but are already being deployed and/or are even the subject of major contracts. Others, however, such as ocean iron fertilisation, have been invalidated and discarded. Methods for which there is no demonstrator yet, and/or for which the question of the impact on open systems has not yet been clarified, have also been discarded. The final portfolio of methods used in the deployment scenarios nevertheless covers the four main families of CDR methods: (i) biomass conversion, (ii) improved ecosystem management, (iii) electrochemical methods and (iv) geochemical methods.

In the proposed deployment scenarios, it is interesting to note that no method stands out significantly in terms of volumes. The four families of methods are used in similar proportions. This is also made evident by comparing the reference scenario with the ambition scenario. The increase in capacity is indeed made possible by the contribution of all approaches. Therefore, there is no "flagship" method for France on which everything depends, but rather the possibility of using the full range of methods and adopting a "portfolio" approach.

Bottom-up analysis

Analysing the availability of the various resources needed for CDR is very useful. In France, there are few unused resources. Deploying CDR at scale thus means freeing up new volumes of resources so as not to compete with current uses. Sobriety is the first way to free up volumes of all resources. But beyond that, we need to assess the extent to which a resource can be further developed. For example, France has significant potential for additional production of low-carbon energy, but the prospects for increasing biomass production are limited. For the geological storage of CO_2, France has a high theoretical potential, but the time needed to develop the identified reservoirs is gradually turning into a bottleneck.

The reference and ambition scenarios are therefore based on the implementation of **proactive policies, not only to create the framework and support necessary for CDR sectors, but also in all the related sectors that produce necessary resources for CDR.** The conservative scenario, on the other hand, represents precisely the opposite situation, the status quo, where these changes do not take place, or too late.

The scenarios were constructed in two stages. The theoretical potential represents the achievable capacities if all available resources were used as a priority for CDR. It represents abstract conditions, such as if a "wartime effort" was launched to stabilise the climate as quickly as possible. The three final scenarios, on the other hand, are based on the potential achievable under conditions close to the present. **More than one order of magnitude separates the theoretical potential from the achievable potential, reflecting the much more cautious or close-to-current conditions assumptions that underpin the final scenarios.**

It is also important to bear in mind that there **are margins for error in both directions**. The deployment of certain methods could face obstacles that delay or prevent the achievement of the objectives. But other methods, such as ocean alkalinisation, could accelerate their maturation and come into play sooner than expected. It is also possible that new energy sources will become operational, such as tidal or osmotic energy for renewables, or SMR for nuclear power.

Social geography

The targeted interviews with stakeholders and the citizens' panel largely confirmed known trends in French society with regard to CDR.

Firstly, a lack of information and partial knowledge of the subject. Very little content is available in French to explain the ins and outs of CDR.

There is a clear preference for nature-based solutions, which are perceived to be safer and to have more co-benefits. As for the other methods, there are concerns about their real effectiveness and safety, particularly those that affect open systems such as the oceans. A consensus is emerging on the need to pay more attention to these methods, and to conduct research to optimise them and study their impact, but their deployment is problematic. These positions are very much in line with mainstream media coverage of CDR, which often equates CDR with other methods such as CCS, CCU or even solar radiation management, under the contentious term of "geo-engineering".

Finally, there is a clear need for participation and control, expressed in particular by the rejection of projects decided centrally and imposed on local populations.

Key messages

This study has shown that, without modifying significantly current conditions or questioning the current uses of resources, **France can secure its goal of net zero by 2050** by adopting proactive policies to develop CDR. It could even **become net negative before 2050** if it sticks to its decarbonisation trajectory and deploys the means to achieve the ambition scenario. France can mobilise a wide variety of methods: in the reference and ambition scenarios it relies less on natural sinks and **respects the principle of equivalence between the origin of residual emissions and the level of permanence of CDR methods used** to offset them (like for like principle).

When the scenarios were constructed and compared, it became clear that **the capacity for geological storage of CO_2, the availability of additional decarbonised energy and the level of remuneration for carbon storage practices** were the main factors limiting the deployment of CDR in France.

Finally, although the main objective of this study was to assess the technical feasibility of an ambitious deployment of CDR, a quick estimate of the **costs to be anticipated** is given on the basis of the data published by the IPCC. This estimate, of between €8 billion and €19 billion a year by 2050 (i.e. between 0.3% and 0.7% of GDP in 2021), provides a useful order of magnitude for comparison with other items of government expenditure, particularly for the ecological transition. There are two important points to note about these figures. Firstly, these costs will be shared between private and public players, depending on the implemented regulations. Secondly, they do not include the amounts needed in research and support for innovation to ensure that CDR methods progress and are capable of meeting targets.

As for emission reductions, setting a CDR target is no guarantee that it will be achieved. Given the diversity of resources mobilised, it seems clear that the deployment of CDR must be supported by public authorities, for example by building a **dedicated strategy** that would make it possible to link the development of various technical components, deployment incentives and regulation. A draft roadmap has been established as part of this project and is published with this report.

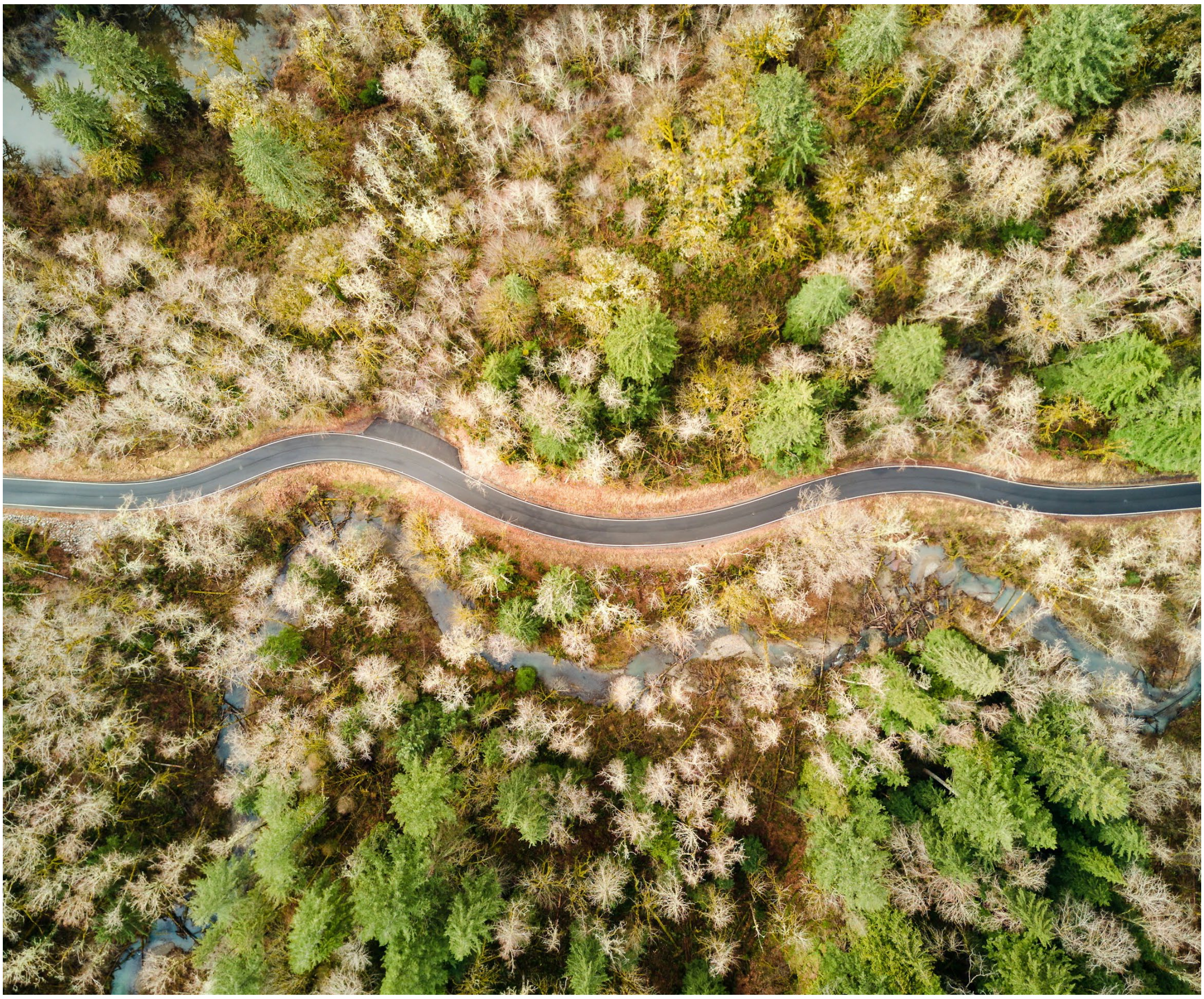
Relying too heavily on the large-scale deployment of CDR to achieve net zero would be risky and foster mitigation deterrence. This scenario must be avoided at all costs, and Carbon Gap has proposed a series of measures to this end in its report "*How to avoid carbon removal delaying emissions reductions*".

Conversely, developing CDR in a structured and ambitious way to achieve net zero sooner and seek a net negative phase that would restore the carbon budget is a necessary and unifying project.

This report should serve as a stepping stone for France to adopt a robust strategy for the third pillar of climate action, CDR, as soon as possible.

Note:
The exercise carried out in this report, i.e. estimating a potential, is based on assumptions that the authors have sought to show in a transparent way, but also on technical and economic parameters, such as the cost of implementing CDR methods, their consumption of energy or other resources. These parameters are likely to evolve quickly, as the methods are matured and deployed on a larger scale to reduce costs. However, improvements should be incremental, and not drastically change the results presented in this report, in the short term.

It is also important to note that a number of key documents are in the process of being updated or drafted at the time of writing this report, in particular the third version of the SNBC and the associated publication of the PPE. These documents are therefore not considered in the report.



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This document presents a quantified estimate of France's potential for the deployment of carbon dioxide removal (CDR) methods. As most of the technologies assessed in this report are still in the early stages of development, the assessment includes uncertainties: some methods may not prove viable, while others that are set aside here may develop quicker than expected. To reduce these uncertainties, it is essential to accumulate more data, in particular by building demonstrators to test the methods in real conditions. This report aims to inform political decision-makers and stakeholders involved in the development of CDR in France.

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Bibliography

1. *Sustainability limits needed for CO_2 removal.* **Alexandra Deprez, Paul Leadley, Kate Dooley, Phil Williamson, Wolfgang Cramer, Jean-Pierre Gattuso, Aleksandar Rankovic, Eliot L. Carlson, Felix Creutzig.** s.l. : Science insights, 2014.

2. *Climate Change 2022: Mitigation of Climate Change.* **GIEC, Working Group 3.** Cambridge : GIEC, 2022.

3. **François de Rochette, Eli Mitchell-Larson, Sylvain Delerce, Benjamin Tincq, Liam St Louis, Greg De Temmerman.** *Elimination du dioxyde de carbone atmosphérique: introduction aux proécédés a émissions négatives.* s.l. : Carbon Gap, 2022.

4. **European Scientific Advisory Board on Climate Change.** *Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050.* 2023. 978-92-9480-584-3.

5. *Reducing the risks of climate overshoot.* **Climate Overshoot Commission.** 2023.

6. *Integrated Assessment of Carbon Dioxide Removal.* **W. Rickels, F. Reith, D. Keller, A. Oschlies, and M. F. Quaas.** s.l. : Earth's Future, 2018, Vol. 6.

7. *Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe.* **Lorenzo Rosa, Daniel L. Sanchez and Marco Mazzotti**. s.l. : Energy & Environmental Science, 2021.

8. *Biomass residue to carbon dioxide removal: quantifying the global impact of biochar.* **David Lefebvre, Samer Fawzy, Camila A. Aquije, Ahmed I. Osman, Kathleen T. Draper and Thomas A. Trabold.** 65, s.l. : Biochar, 2023, Vol. 5.

9. **Negem, project.** *Member State specific pathway for NETP.* 2023.

10. **IRENA.** renewables readiness Assessment. [Online] www.irena.org/Energy-Transition/Country-engagement/RRA.

11. **NASA Earth Observatory.** The carbon cycle. [Online] 2011. https://earthobservatory.nasa.gov/features/CarbonCycle.

12. **INRAE.** *Stocker du carbone dans les sols français, Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût ?* 2020.

13. **ADEME.** *Engrais azotés et N_2O.*

14. **SDES.** *Bilan environnemental de la France - Edition 2022.* 2022.

15. *The influence of particle size on the potential of enhanced basalt weathering for CDR.* **R. Thomas, C. von Hagke.** 15, s.l. : Journal of Cleaner Production, 2021, Vol. 315.

16. **IEA.** *Direct Air Capture, a key technology for net zero.* 2022.

17. **Frontier.** Fontier project applications. Github. [Online]
https://github.com/frontierclimate/carbon-removal-source-materials/tree/main/Project Applications.

18. **RTE.** *Futurs énergétiques 2050.* 2022.

19. **ADEME.** *Récupération de chaleur fatale, état des réalisations et évolutions du gisement à fin 2020.* 2022.

20. **ADEME.** *Transitions 2050.* 2021.

21. **Commissariat Général du Dévelopement Durable.** *Les milieux humides et aquatiques continentaux.* 2018.

22. **Conservatoires d'espaces naturels.** *Pourquoi restaurer les tourbières ?*

23. **Observatoire du littoral.** [Online]
https://observatoires-littoral.developpement-durable.gouv.fr/chiffres-cles-r9.html.

24. **EFESE.** Les écosystèmes marins et côtiers. 2018.

25. *Mangrove ecological services at the forefront of coastal change in the French overseas territories.* **E. Trégarot, A. Caillaud, C. C. Cornet, F. Taureau, T. Catry, S. M. Cragg, P. Failler.** s.l. : Science of the Total Environment, 2020.

26. **ROM : Réseau d'Observation des Mangroves.** [Online] 2022.
www.pole-tropical.org/2022/07/les-mangroves-a-travers-le-temps/.

27. **IPBES.** *The global assessment report on biodiversity and ecosystem services.* 2019.

28. **IFRECOR.** *Etat de santé des récifs coralliens, herbiers marins et mangroves des outre-mer français.* 2021.

29. *Les herbiers de phanerogames marines de l'outre-mer français.* **C. Hily,J. Duchêne, C. Bouchon, Y. Bouchon-Navaro, A. Gigou, C. Payri, F. Védie**. s.l. : Conservatoire du littoral, 2010.

30. *Seagrass Meadows distribution and trajectories of change.* **Telesca.** 2015.

31. **EFESE.** *La séquestration de carbone par les écosystèmes en France.* 2019.

32. **BRGM.** *Mémento roches et minéraux industriels Carbonates calciques et magnésiens et produits dérivés à usage industriel et agricole.* 2000.

33. **BRGM.** *Carbonates calciques et magnésiens Mémento.* 2017.

34. **BRGM.** *Mémento roches et minéraux industriels* : *l'olivine et la dunite.* 2000.

35. **BRGM.** *Mémento roches et minéraux industriels l'olivine.* 1988.

36. **BRGM.** *Mémento roches et minéraux industriels dolomie, magnésite et produits dérivés à usage industriel et agricole.* 1989.

37. *Silicate production and availability for mineral carbonation.* **P. Renforth, C.-L. Washbourne, J. Taylder, and D. A. C. Manning.** s.l. : Environmental Science & Technology, 2011.

38. **France Ciment.** *Le ciment en chiffres.* 2022.

39. *Caractérisation et utilisation de poussières de four de ciment CKD dans la stabilisation/solidification des déchets de l'unité BCR.* **F. Khouan.** 2016.

40. *Valorisation des déchets de four à ciment (CKD) de la cimenterie de Ain-Al-Kebira (Algérie) dans le Mortier.* **G. Amar, A. Merdas.** 2019.

41. **BRGM.** *Panorama du marché français des matériaux de carrière et produits dérivés.* 1999.

42. **BRGM.** *Mémento roches et minéraux industriels Wollastonite.* 1991.

43. **Réseau CO_2 GeoNet.** *Que signifie vraiment le stockage géologique de CO_2 ?* 2008.

44. *Carbon dioxide storage through mineral carbonation.* **S. Ó. Snæbjörnsdóttir, B. Sigfússon, C. Marieni, D. Goldberg, S. R. Gislason, E. H. Oelkers.** s.l. : Nature Reviex Earth Environment, 2020, Vol. 1.

45. *Annales des Mines, responsabilité et environnement.* **LAVERGNE, Dominique AUVERLOT et Richard.** Janvier 2022, Vol. 105. 1268-4783.

46. *Captage et Stockage du CO_2 : le puits de carbone géologique.* **Czernichowski-Lauriol, Isabelle.** 4-5, s.l. : Comptes rendus Géosciences, 2020, Vol. 352.

47. **Ministère de la transition écologique et solidaire.** *Stratégie nationale bas-carbone.* 2020.

48. **CATF.** *Unlocking Europe's CO_2 storage potential.* 2023.

49. **ADEME**. *Avis technique: le captage et le stockage du CO_2 (CSC) en France.* 2020.

50. **BRGM.** *Premières estimations du potentiel de stockage du CO_2 sous forme d'hydrates de gaz dans les formations sédimentaires du Golfe de Gascogne et de la Mer Celtique (offshore profond).* 2014.

51. **Ministère de la transition écologique et solidaire.** *Consultation : Stratégie CCUS Capture, stockage, et utilisation du carbone.* 2023.

52. **Terega.** Projet PYCASSO. [Online] https://assets.ctfassets.net/ztehsn2qe34u/7eY6OvPXsVPuF4cN07Kf35/7623a6d261947c84fa0eb780724065f8/TEREGA_plaquette_pycasso_FR.pdf.

53. **BRGM**. *Planning a Notable CCS Piltot-Scale Project: A Case Study in France, Paris Basin - Ile-de-France.* 2022.

54. **BRGM.** *Projet VASCO, Identification des sites potentiels de stockage de CO_2 et première estimations des capacités.* 2012.

55. **Club-CO_2.** [Online] www.club-co2.fr/fr/content/transporter-le-co2.

56. **Zero Emissions Platform.** *Description of the candidate projects in the thematic area of cross-border carbon dioxide transport and storage networks.* 2022.

57. **Ministère de la Transition Ecologique et Solidaire.** *Ajustements technique des budgets carbone.* 2022.

58. **SGPE.** *La planification écologique: synthèse du plan.* 2023.

59. **European Commission.** *Why do we need carbon capture, use and storage?* 2022.

60. **Agreste.** *Statistique agricole annuelle 2021 - Chiffres définitifs.* 2022.

61. **Jean Pisani-Ferry, Selma Mahfouz.** *Les incidences économiques de l'action pour le climat.* s.l. : France Stratégie, 2023.

62. **Cour des comptes.** *Apprécier la contribution de la dépense publique à la transition écologique.* 2023.

63. **Gouvernement.** *Rapport sur l'impact environnemental du budget de l'Etat.* 2022.

64. **Institut Rousseau.** *2% pour 2°C, Les investissements publics et privés nécessaires pour atteindre la neutralité carbone de la France en 2050.* 2022.

65. **ADEME.** *Feuilleton, Les effets macroéconomiques.* 2022.

66. **SDES.** *Opinions des Français sur l'environnement en 2022.* 2023.

67. *Discourses of climate delay.* **William F. Lamb, Giulio Mattioli, Sebastian Levi, J. Timmons Roberts, Stuart Capstick, Felix Creutzig, Jan C. Minx, Finn Müller-Hansen, Trevor Culhane and Julia K. Steinberger.** s.l. : Cambridge University Press, 2020.

68. **SGPE.** *La planifcation écologique de l'industrie.* 2023.

69. *Le principe de précaution devant le Conseil constitutionnel.* **Denoix De Saint Marc, Renaud.** 2014.

70. **Réseau Action Climat.** *Fausses solutions - Captage et stockage du CO_2.* 2022.

71. **GreenPeace.** *Ce que GreenPeace propose.* s.l. : www.greenpeace.fr/sauver-climat-greenpeace-propose/, 2017.

72. **Confédération Paysanne.** *Méthanisation : la Confédération paysanne demande un moratoire.* s.l. : www.confederationpaysanne.fr/actu.php?id=10996, 2021.

73. **France Energie Eolienne.** *Observatoire de l'éolien 2022 - Analyse du marché, des emplois et des enjeux de l'éolien en France.* 2022.

74. **SGPE.** *La planification écologique de la forêt.* 2023.

75. *Temperature extremes of 2022 reduced carbon uptake by forests in Europe.* **Auke M. van der Woude, Wouter Peters, Emilie Joetzjer, Sébastien Lafont, Gerbrand Koren, Philippe Ciais, Michel Ramonet, Yidi Xu, Ana Bastos, Santiago Botía, Stephen Sitch, Remco de Kok, Tobias Kneuer, Dagmar Kubistin, Adrien Jacotot, Benjamin Loubet**,. s.l. : Nature, 2023.

76. **Campbell et al**. *Geochemical Negative Emissions Technologies: Part I. Review.* 2022.

77. **IGN.** Communiqué de presse 12 octobre 2023. [Online] www.ign.fr/files/default/2023-10/cp_ign_memento_2023.pdf.

78. **Smith, S. M., Geden, O., Nemet, G., et al.** *The State of Carbon Dioxide Removal - 1st edition.* 2023.

79. **SHOM.** *Superficies des espaces maritimes de souveraineté et de juridiction de la France.* 2023.

80. **Telesca, Luca.** *Seagrass meadows (Posidonia oceanica) distribution and trajectories of change.* 2015.

81. **WWF.** [Online] www.wwf.fr/especes-prioritaires/posidonie.

82. **National Academies of Sciences, Engineering, and Medicine**. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* 2019.

83. **IGN.** *Quel rôle pour la filière forêt bois française dans le changement climatique.* 2017.

84. **ADEME.** *Feuilleton Sols : Quels enjeux pour une gestion durable des sols à l'horizon 2050 ?* 2022.

85. **CITEPA.** *Rapport Secten Edition 2020 - Utilisation des Terres, Changement d'Affectation des Terres et Forêt.* 2022.

86. **ADEME.** *Un mix 100% renouvelable ? Analyses et optimisations.* 2015.

87. **Roustan, Michel.** *Eau : données et statistiques. s.l. : Techniques de l'Ingénieur,* 2023.

88. **CEREMA.** *La mesure de l'étalement urbain.* 2015.

89. **AGRESTE.** *L'occupation du sol entre 1982 et 2018.* 2021.

90. **(SOeS), Le service de l'observation et des statistiques.** *Atlas régional de l'occupation des sols en France.* 2016.

91. **IGN.** *Le mémento Inventaire forestier - La forêt en chiffres et en cartes - Edition 2014.* 2014.

92. **EFESE.** *Les milieux humides et aquatiques continentaux.* 2018.

93. **ONRB.** *Évaluation des ressources agricoles et agroalimentaires disponibles en France.* 2020.

94. **AgroLeague.** *Fonctionnement, avantages et inconvénients du semis direct.* 2022.

95. **ADEME.** *Un mix de gaz 100% renouvelable en 2050 ?* 2018.

96. **SDES.** *Bilan énergétique de la France.* 2022.

97. **EDF.** *Le nucléaire en chiffres.* https://t.ly/mD_rj

98. **INSEE.** *Part des énergies renouvelables dans la consommation finale brute d'énergie par filière renouvelable.* s.l. : www.insee.fr/fr/statistiques/4469376#tableau-figure1, 2022.

99. **al, Campbell et.** *Geochemical Negative Emissions Technologies: Part I. Review.* 2022.

100. **ADEME.** *Forêts et usages du bois dans l'atténuation du changement climatique.* 2021.

101. **INSEE.** Population 2050. [Online] https://t.ly/NQjue.

102. **AGRESTE.** *Récolte de bois et production de sciages en 2021.* 2023.

103. **SGPE.** *La planification écologique dans l'énergie.* 2023.

104. **SNEB.** *Les spécialistes de la fertilisation.* [Online] www.sneb-engrais.fr/amendements/20-dolomie.html.

105. **Concawe.** *E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050.* 2022.

106. **INSEE.** *surface agricole en France.* [Online] www.insee.fr/fr/statistiques/5039859?sommaire=5040030#:~:text=En.

107. **ONRB.** *Les Etudes de FranceAgriMer.* 2016.

108. **Réserve régional des tourbières des Saisies Beaufortain Val d'Arly.** *Qu'est-ce qu'une tourbière ?* s.l. : www.reserve-regionale-tourbiere-des-saisies.com/tourbiere/.

109. **L'Info Durable.** *Municipales : ces grandes villes qui passent au vert.* 2020.

110. **La Gazette.** *2,8% des Français ont un maire écolo.* 2020.

111. **Info Compensation Carbone.** *Etat des lieux de la compensation carbone en France - Edition 2022.* 2022.

112. **Le Monde.** *Eoliennes : les raisons du retard de la France en matière de production et d'installation.* 2022.

113. **Ministère de l'Environnement, de l'Energie et de la Mer.** *Atlas régional de l'occupation des sols en France.* 2016.

114. **Ministère de la Transition Ecologique et Solidaire.** *Programmation Pluriannuelle de l'Energie.* 2018.

115. **Ministère de la Transition Ecologique et Solidaire.** *Stratégie nationale bas-carbone.* 2020.

116. **Running Tide.** [Online] www.runningtide.com/carbonremoval.

117. **INRAE.** *Drainage des tourbières pour l'agriculture : estimation des émissions de carbone sur le dernier millénaire.* 2021.

118. **MTES.** *Gisement de chaleur fatale à proximité de réseaux de chaleurs.* [Online] www.ecologie.gouv.fr/chaleur-recuperation-des-processus-industriels.

119. *Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050.* **Change, European Scientific Advisory Board on Climate.** 2023. 978-92-9480-584-3.

120. *Reducing the risks of climate overshoot.* **Commission, Climate Overshoot.** 2023.

121. **Gap, Carbon.** *How to avoid carbon removal delaying emissions reductions.* 2023.

122. **BRGM.** *Carbonates calciques et magnésiens et produits dérivés à usage industriel et agricole.* 2000.

123. *Assessing the capacity of Seagrass meadows for carbon burial : Current limitations and future strategies.* **Carlos M. Duarte, Hilary Kennedy, Núria Marbà, Iris Hendriks**. s.l. : Ocean & Coastal Management, 2013, Vol. 83.

124. *Toward a coordinated global observing system for seagrasses and marine macroalgae.* **J. Emmett Duffy, Lisandro Benedetti-Cecchi, Joaquin Trinanes.** s.l. : Frontiers in Marine Science, 2019, Vol. 6.

125. **CDR Primer.** *The Building blocs of CDR systems.* s.l. : https://cdrprimer.org/read/chapter-2, 2021.

126. *Substantial role of macroalgae in marine carbon sequestration.* **Dorte Krause-Jensen, Carlos M. Duarte**. s.l. : Nature Geoscience, 2016, Vol. 9.

127. *Silicate Production and Availability for Mineral Carbonation.* **P. Renforth, C.-L. Washbourne, J. Taylder, and D. A. C. Manning**. s.l. : Environmental Science & Technology, 2011.

128. *Negative CO_2 emissions via enhanced silicate weathering in coastal environnement.* **Filip J. R. Meysman and Francesc Montserrat.** s.l. : Biologgy letters, 2017.

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10. Appendix

10.1. Chemical reactions involved in on-land enhanced weathering and ocean alkalinisation

The document "*Geochemical Negative Emissions Technologies: Part I. Review*" by Campbell et al (2022) lists all the rocks used in Enhanced rock weathering and chemical alkalinisation of the oceans, and the associated chemical reactions. It classifies the chemical reactions into two categories:

- **Aqueous carbonation:** This process involves the reaction of CO_2 with minerals in the aqueous phase to form soluble carbonates.
- **Solid carbonation:** In this case, the CO_2 reacts with the minerals in the open air, with humidity acting as a catalyst for these reactions.

These reactions are presented below. The words highlighted in yellow in the figures below correspond to the rocks whose deposit has been estimated in this report.

Minéraux	Formule chimique	Réaction chimique
		Carbonation – aqueous
Calcite	$CaCO_3$	$CaCO_3 + CO_2 + H_2O \text{ --> } Ca^{2+} + 2HCO_3^-$
Chrysotile	$Mg_3Si_2O_5(OH)_4$	$Mg_3Si_2O_6(OH)_5 + 6CO_2 + 5H_2O \text{ --> } 3Mg^{2+} + 6HCO_3^- + 2H_4SiO_4$
Dolomite	$CaMg(CO_3)_2$	$CaMg(CO_3)_2 + 2CO_2 + 2H_2O \text{ --> } Mg^{2+} + Ca^{2+} + 4HCO_3^-$
Hydromagnesite	$Mg_5(CO_3)_4(OH)_2.4H_2O$	$Mg_5(CO_3)_4(OH)_2.4H_2O + 6CO_2 \text{ --> } 5Mg^{2+} + 10HCO_3^-$
Ikaite	$CaCO_3.6H_2O$	$CaCO_3.6H_2O + CO_2 \text{ --> } Ca^{2+} + 2HCO_3^- + 5H_2O$
Magnesite	$MgCO_3$	$MgCO_3 + CO_2 + H_2O \text{ --> } Mg^{2+} + 2HCO_3^-$
Monohydrocalcite	$CaCO_3.H_2O$	$CaCO_3.H_2O + CO_2 \text{ --> } Ca^{2+} + 2HCO_3^-$
Nesquehonite	$MgCO_3.3H_2O$	$MgCO_3.3H_2O + CO_2 \text{ --> } Mg^{2+} + 2HCO_3^- + 2H_2O$
Sodium carbonate	Na_2CO_3	$Na_2CO_3 + CO_2 + H_2O \text{ -> } 2Na^+ + 2HCO_3^-$
Thermonatrite	$NaHCO_3$	$Na_2CO_3.H_2O + CO_2 \text{ -> } 2Na^+ + 2HCO_3^-$
Anorthite	$CaAl_2Si_2O_8$	$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \text{ --> } Ca^{2+} + 2HCO_3^- + Al_2Si_2O_5(OH)_4$
Diopside	$MgCaSi_2O_6$	$MgCaSi_2O_6 + 4CO_2 + 6H_2O \text{ --> } Ca^{2+} + Mg^{2+} + 4HCO_3^- + 2H_4SiO_4$
Forsterite	Mg_2SiO_4	$Mg_2SiO_4 + 4CO_2 + 4H_2O \text{ --> } 2Mg^{2+} + 4HCO_3^- + H_4SiO_4$
Jennite	$Ca_9Si_6O_{18}(OH)_6.8H_2O$	$Ca_9Si_6O_{18}(OH)_6.8H_2O + 18CO_2 + 10H_2O \text{ --> } 9Ca^{2+} + 18HCO_3^- + 6H_4SiO_4$
Larnite	Ca_2SiO_4	$Ca_2SiO_4 + 4CO_2 + 4H_2O \text{ --> } 2Ca^{2+} + 4HCO_3^- + H_4SiO_4$
Rankinite	$Ca_3Si_2O_7$	$Ca_3Si_2O_7 + 6CO_2 + 7H_2O \text{ --> } 3Ca^{2+} + 6HCO_3^- + 2H_4SiO_4$
Tobermorite	$Ca_5Si_6O_{12}(OH)_{10}.5H_2O$	$Ca_5Si_6O_{12}(OH)_{10}.5H_2O + 10CO_2 + 7H_2O \text{ --> } 5Ca^{2+} + 10HCO_3^- + 6H_4SiO_4$
Wollastonite	$CaSiO_3$	$CaSiO_3 + 2CO_2 + 3H_2O \text{ --> } Ca^{2+} + 2HCO_3^- + H_4SiO_4$
Brucite	$Mg(OH)_2$	$Mg(OH)_2 + 2CO_2 \text{ --> } Mg^{2+} + 2HCO_3^-$
Lime	CaO	$CaO + 2CO_2 + H_2O \text{ --> } Ca^{2+} + 2HCO_3^-$
Periclase	MgO	$MgO + 2CO_2 + H_2O \text{ --> } Mg^{2+} + 2HCO_3^-$
Portlandite	$Ca(OH)_2$	$Ca(OH)_2 + 2CO_2 \text{ --> } Ca^{2+} + 2HCO_3^-$
CAH10	$CaAl_2O_4.10H_2O$	$CaAl_2O_4.10H_2O + 2CO_2 \text{ --> } Ca^{2+} + 2HCO_3^- + 2Al(OH)_3 + 6H_2O$
C2AH8	$Ca_2Al_2O_5.8H_2O$	$Ca_2Al_2O_5.8H_2O + 4CO_2 \text{ --> } 2Ca^{2+} + 4HCO_3^- + 2Al(OH)_3 + 3H_2O$
C3AH6	$Ca_3Al_2(OH)_{12}$	$Ca_3Al_2(OH)_{12} + 6CO_2 \text{ --> } 3Ca^{2+} + 6HCO_3^- + 2Al(OH)_3$
C4AH13	$Ca_4Al_2O_7.13H_2O$	$Ca_4Al_2O_7.13H_2O + 8CO_2 \text{ --> } 4Ca^{2+} + 8HCO_3^- + 2Al(OH)_3 + 6H_2O$

Figure 65 - List of rocks involved in an aqueous carbonation reaction that can be used for Enhanced rock weathering and ocean alkalinisation by mineral means (76)

The minerals involved in a **solid carbonation** reaction are listed below. The words highlighted in yellow also correspond to the rocks whose deposits have been studied in this report.

Minéraux	**Formule chimique**	**Réaction chimique**
		Carbonation—solid
Anorthite	$CaAl_2Si_2O_8$	$CaAl_2Si_2O_8 + CO_2 + 2H_2O \rightarrow CaCO_3 + Al_2Si_2O_5(OH)_4$
Diopside	$MgCaSi_2O_6$	$MgCaSi_2O_6 + 2CO_2 + 4H_2O \rightarrow CaCO_3 + MgCO_3 + 2H_4SiO_4$
Forsterite	Mg_2SiO_4	$Mg_2SiO_4 + 2CO_2 + 2H_2O \rightarrow 2MgCO_3 + H_4SiO_4$
Gehlenite	$Ca_2Al_2SiO_7$	$Ca_2Al_2SiO_7 + 2CO_2 + 5H_2O \rightarrow 2CaCO_3 + 2Al(OH)_3 + H_2SiO_4$
Jennite	$Ca_9Si_6O_{18}(OH)_6.8H_2O$	$Ca_9Si_6O_{18}(OH)_6.8H_2O + 9CO_2 + H_2O \rightarrow 9CaCO_3 + 6H_4SiO_4$
Larnite	Ca_2SiO_4	$Ca_2SiO_4 + 2CO_2 + 2H_2O \rightarrow 2CaCO_3 + H_4SiO_4$
Lime	CaO	$CaO + CO_2 \rightarrow CaCO_3$
Merwinite	$MgCa_3Si_2O_8$	$MgCa_3Si_2O_8 + 4CO_2 + 4H_2O \rightarrow 3CaCO_3 + MgCO_3 + 2H_4SiO_4$
Rankinite	$Ca_3Si_2O_7$	$Ca_3Si_2O_7 + 3CO_2 + 4H_2O \rightarrow 3CaCO_3 + 2H_4SiO_4$
Tobermorite	$Ca_5Si_6O_{12}(OH)_{10}.5H_2O$	$Ca_5Si_6O_{12}(OH)_{10}.5H_2O + 5CO_2 + 2H_2O \rightarrow 5CaCO_3 + 6H_4SiO_4$
Wollastonite	$CaSiO_3$	$CaSiO_3 + CO_2 + 2H_2O \rightarrow CaCO_3 + H_4SiO_4$
Brucite	$Mg(OH)_2$	$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$
Portlandite	$Ca(OH)_2$	$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$
Periclase	MgO	$MgO + CO_2 \rightarrow MgCO_3$
		Amorphous silica precipitation*
		$H_4SiO_4 \rightarrow SiO_2 + 2H_2O$

Figure 66 - List of rocks involved in a solid carbonation reaction and usable for Enhanced rock weathering and ocean alkalinisation by mineral means (Campbell et al 2022)

10.2. Description of the sources used to estimate biomass feedstocks

Broadly speaking, the methodology used to estimate the biomass feedstock was as follows for each type of biomass:

1) Identify the total volume of biomass produced annually
2) Remove constrained volumes (technical constraints and volumes not relevant to CDR)
3) Withdraw volumes allocated as a priority to other uses (food, better soil management, etc.)
4) Allocate the remaining volumes between the various uses (anaerobic digestion, combustion, recycling, materials), which can be directed towards CDR methods
5) Sum the volumes per use for CDR methods (combustion and anaerobic digestion for BECCS, materials and recycling for bio-sourced products, and biochar).

The methodology is summarised in Figure 67.

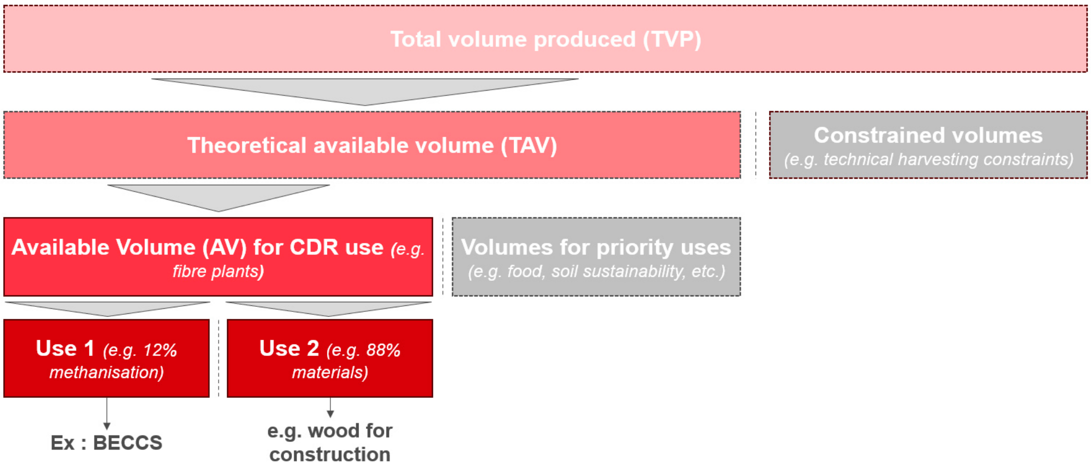

Figure 67 - Methodology for estimating the capacities for CDR methods associated with a biomass input

This methodology is broken down according to the type of biomass, depending on available data. Details are given in the table below. The main sources used in the table below are:

- ONRB: National Observatory of Biomass Resources
- Modecom database (2017)
- SINOE database, managed by ADEME (2021)
- IGN forest inventory (2012 - 2020)
- ADEME, "*Un mix de gaz 100% renouvelable en 2050?*" (2018).
- Agreste database (2021)

These sources were used to estimate biomass feedstocks for the following types of biomasses.

Category	Type of biomass	Source
Biomass from non-food agriculture	Dedicated crops	ONRB
	Intermediate crops	France Stratégie
	Agricultural waste	ONRB / France Stratégie
	Livestock manure	ONRB
	Fibre plants	ONRB
	Perfume plants	ONRB
Municipal waste	Green urban waste	ONRB / Modecom
	Used edible oils	France AgriMer
	Paper and cardboard waste	Modecom
	Wood waste	Modecom
	Sewage sludge	SDES
	Household waste	Modecom
Co-products of the agri-food industry	Oilseed crushing	ONRB
	Sugar beet	ONRB
	Fruit-vegetables transf.	ONRB
	Vinification	ONRB
	Meat industries	ONRB
	Egg products	ONRB
	Fishing and aquaculture	ONRB
	Wine distillation	ONRB
	Cider	ONRB
	Potato	ONRB
Forest biomass	Hedgerows and agroforestry	France Stratégie
	Forest harvesting	Agreste/IGN

Table 14 - Sources used to estimate the feedstock by type of biomass

ONRB

The ONRB (National Observatory of Biomass Resources) provides data on the total volumes produced, those with technical constraints and the priority uses of biomass for the types of biomasses mentioned in the table above.

SDES

For sewage sludge, data comes from the SDES database of volumes treated in wastewater treatment plants. The database gives the volumes and uses of urban wastewater collected in 2016. For this waste, the volume collected by the treatment plants is considered to be directly the VTD (Volume théorique disponible - Theoretical Available Volume). To estimate the available volume (AV), the agronomic uses of this sludge (land application, composting, etc.) were given priority.

Modecom

The Modecom-2017 database was used to estimate the volumes of the following waste collected annually:

- Green urban waste (garden waste)
- Paper and cardboard waste
- Wood waste
- Food waste

This database comes from the waste characterisation campaign carried out by ADEME in mainland France. The data from this campaign covers conventional collection waste (household and similar waste) and waste from waste collection centres. This study enables a precise grouping of types of waste collected according to the four categories listed above for the year 2017. The SINOE database, managed by ADEME, provides data for 2021 but with less precise waste categories than those used in Modecom. The breakdown of waste by category in Modecom has been applied to the SINOE collection data for 2021 to obtain an approximation of the volumes treated in each category in 2021 and to deduce the available theoretical volumes.

Secondly, no priority uses were identified for these categories, so the entire VTD was considered to be available for uses that allow carbon capture and storage. The Available Volume (AV) is therefore equal to the Theoretical Available Volume (TAV).

IGN / ADEME / Agreste

IGN, ADEME and Agreste can be used to determine the amount of wood harvested from forests and the biomass available from agroforestry. Wood is found in both forest biomass and agroforestry.

Forest biomass

For forest biomass, the total volume produced (TVP) is considered to be the annual biological production of forests estimated by the IGN forest inventory. This volume is an annual average calculated over the years 2012-2020 and gives the volume of wood produced biologically each year that could be harvested without deforestation.

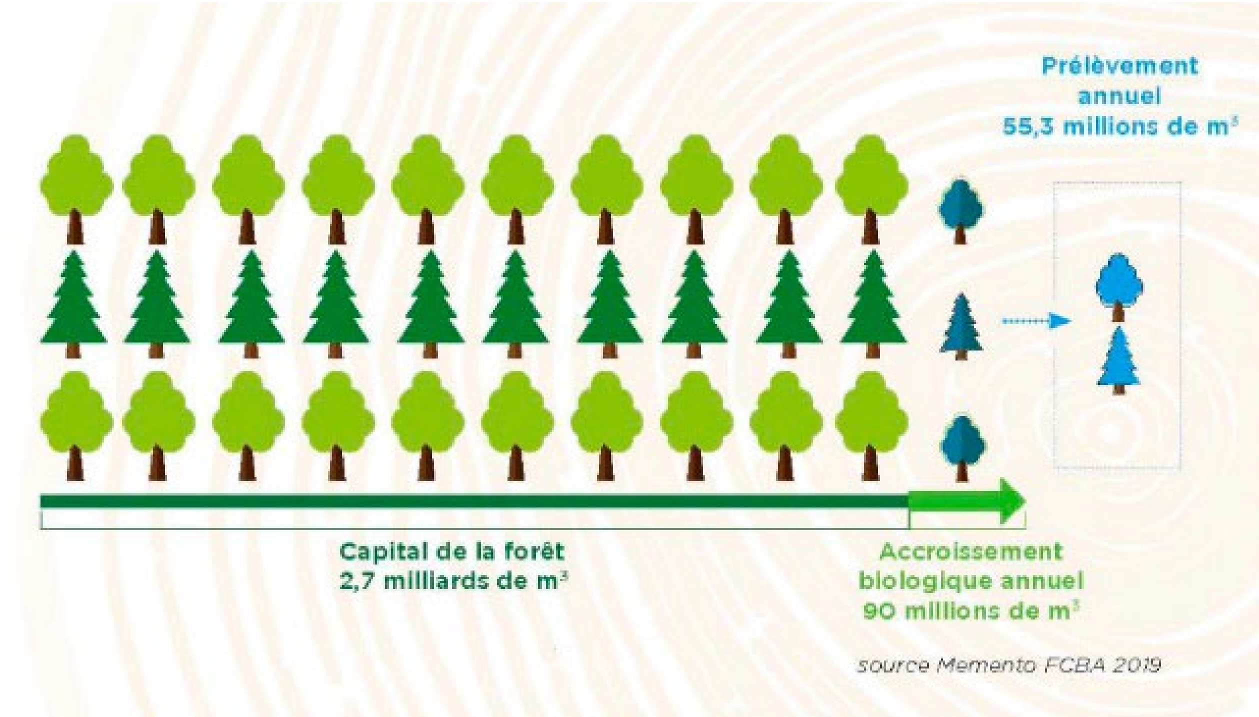

Figure 68 - Forest growth dynamics in 2019

In "*Transitions 2050*", ADEME describes two forestry scenarios: a "constant forestry" scenario, in which the annual harvest in 2050 would be equal to the current harvest of around 55 Mm^3/year, and a "dynamic forestry" scenario with an annual harvest in 2050 of 91 Mm^3/year.

The scenario chosen in this report is that of constant forestry, given the latest IGN studies. This shows a fall in annual biological production from 91.5 Mm^3/year between 2005 and 2013 to 87.8 Mm^3/year between 2013 and 2021. At the same time, mortality is expected to rise sharply (+80%) over the same period, to 13.1 Mm^3/year between 2013 and 2021, compared with 7.4 Mm^3/year between 2005 and 2013. (77).

The Theoretically Available Volume (TAV) of forest biomass corresponds to the volume of wood harvested that could, in theory, be fully used for CDR.

The available volume (AV) of forest biomass has been estimated from the Agreste database. This gives the volumes marketed and their breakdown into main uses (timber/wood industry and wood energy) for the year 2021.

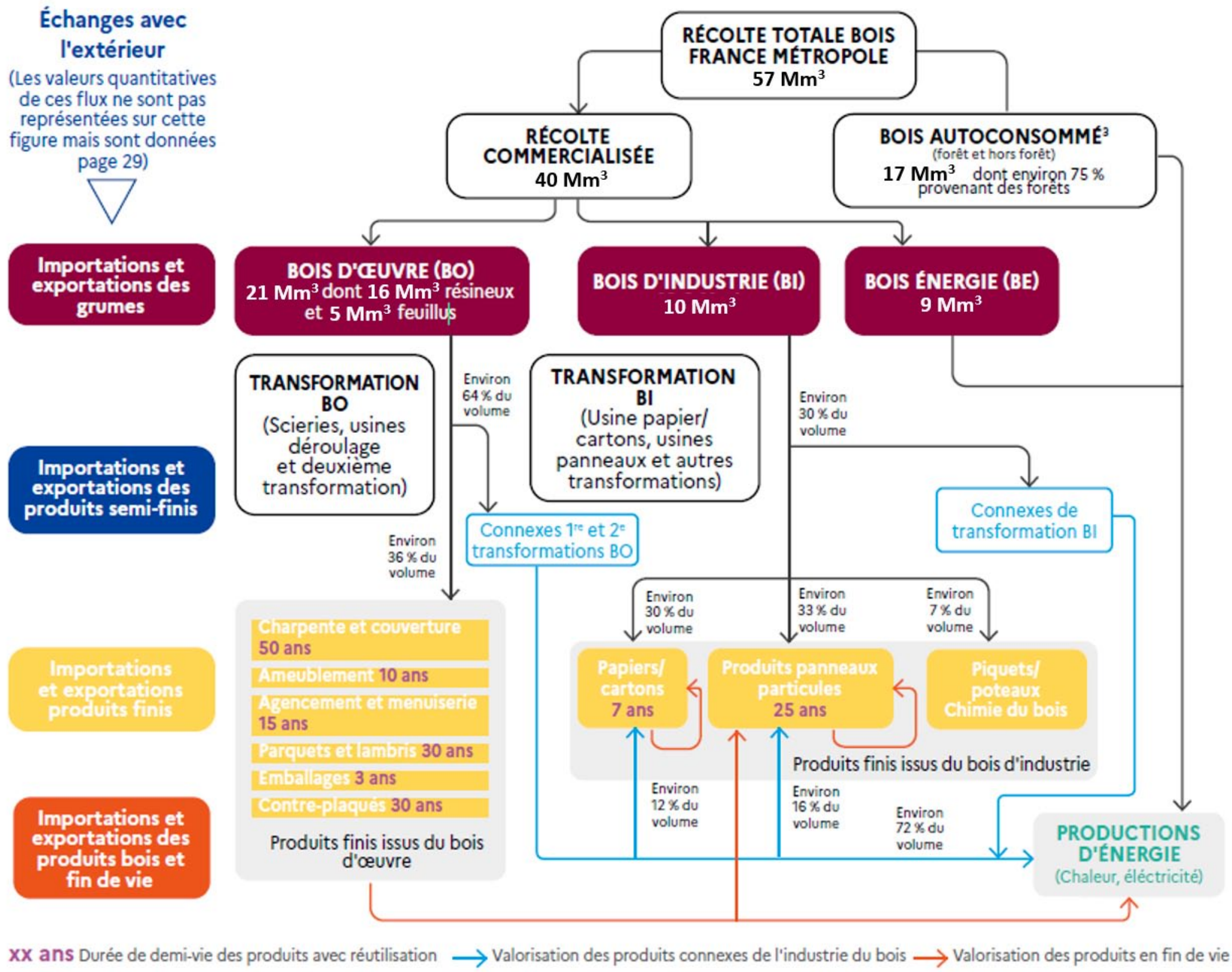

Figure 69 - Wood industry flows in 2021

The wood harvested is either commercialised or self-consumed (mainly by private individuals). Only commercialised wood is considered for CDR purposes.

In addition, packaging and paper/cardboard have not been included in the volume of wood that can be recovered for CDR because their lifespan is inferior to 10 years.

Wood consumption for packaging production was estimated from the 2019 report of the "*pole emballage bois*". This estimate was used to determine the proportion of timber dedicated to packaging in 2019, which was then applied to the 2021 timber volumes given by Agreste.

Finally, the volume of wood available for CDR is obtained by subtracting from the volume of wood harvested, the self-consumed volume and the volume dedicated to wood products with a lifespan inferior to 10 years.

Agroforestry biomass

The data for agroforestry comes from the France Stratégie report. The assessment of the resource availability is based on the estimate of the total volume produced (TVP) of wood from agroforestry carried out by ADEME in 2014. The constrained volumes are then applied, i.e. the profitability of exploiting the resource. In the case of agroforestry, France Stratégie has not considered any agronomic constraints relating to the return to the soil. Applying these constraints enables us to estimate the volume theoretically available (VTA). No priority uses have been identified that are incompatible with CDR methods (e.g. BECCS). The volume available (AV) is thus equal to the volume theoretically available (VTA).

France AgriMer
The France AgriMer source is used to define the volumes of used edible oils available for CDR. In this source, data on the total volume produced and collections of used edible oils are estimated for 2014.

In principle, there are no constrained volumes in the used oil feedstock, so the volume theoretically available (VTA) is equal to the total volume produced (TVP) of used edible oils.

Furthermore, there is no priority use for used oils other than the production of biofuel, so the volume available (AV) is equal to the volume theoretically available (VTA).

10.3. Criteria used by INRAE to estimate the surface area of carbon storage practices

Carbon storage practices	Description	Criteria used by INRAE to estimate the area available for implementing practices
	Agricultural land	
Development of agroforestry in cultivated plots	Introducing trees in cultivated agricultural plots	• Minimum lot size of one hectare • Soil depth greater than 1 m • Non-hydromorphic soil • Exclusion of vineyards and orchards • Exclusion of permanent grassland
Including or extending temporary grassland in crop rotations	• Insertion of temporary grassland in crop rotations without grassland, replacing forage maize crops	• Intermediate grassland included only in crop rotations containing fodder maize, replacing it
	• Extending the number of years of temporary grassland in crop rotations that already include temporary grassland	• Only temporary grassland less than five years old has been considered (otherwise it becomes permanent grassland)
Inserting intermediate crops and extending existing crops	Insert intermediate crops with high nitrogen uptake between the harvest of a main crop and the sowing of the following crop	• Installation of ICs outside Nitrate Vulnerable Zones (ZVN) • Not taking account of derogations in NVAs (late-harvest derogations and clay derogations) • Inserting ICs in short summer intercropping and after-grain maize • Destroy IC as late as possible (1 month before sowing the main spring crop or a few days before sowing the main autumn crop) • Minimum intercropping period of two months • No limit to the establishment of ICs depending on the % of clay in the soil • Comparison with a reference scenario with criteria on duration, main crops, etc.
Switch to direct seeding and abandon tillage	Sow directly into the residues of a previous crop (plant cover, previous main crop, etc.), without tilling	• Exclusion of waterlogged soils • Exclusion of areas on which species are grown that are very difficult to cultivate using direct seeding while maintaining a good yield (sugar beet, monoculture grain maize, sunflower, potato)

››

Carbon storage practices	Description	Criteria used by INRAE to estimate the area available for implementing practices
	Agricultural land	
Spreading new organic resources	Spreading organic resources (livestock manure, urban sewage sludge, digestate from anaerobic digestion, compost, and industrial effluent) on cultivated land	• Lack of available new organic resources (NOR) • Restriction to agricultural land with wheat and oilseed rape for compost spreading, and to land with maize and sunflower for digestates.
Planting hedges	Planting hedges (shrubs and tall trees) around agricultural areas	• Soil depth greater than 50 cm • No hedges to be planted around plots of less than eight hectares. • Hedges may not be planted in the middle of a single plot • Exclusion of vineyards and orchards • Permanent grassland excluded
	Vineyards	
Year-round grass coverage of vineyard inter-rows	Sow, maintain and care for plant cover (grass) between the rows of vines all year round	• Severe loss of yield due to permanent grass cover in some vineyards • High soil stoniness (presence of large stones in vineyard soils) • Exclusion of vineyard areas in departments not associated with vineyards • Exclusion of areas where these practices are already in use
Grass coverage between vineyard rows in winter only	Sow, maintain and care for plant cover (grass) between the rows of vines in winter only	• Exclusion of vine areas in departments not associated with vineyards • Exclusion of areas where these practices are already in use
	Permanent meadows	
Substituting mowing for grazing	Increase the amounts of harvested grass by grazing instead of mowing	• Only permanent grassland managed using farming methods 8, 9, 10 and 20.
Moderately increase mineral nitrogen fertilisation of permanent grassland	Increase the amount of mineral nitrogen fertiliser given to permanent grassland areas	• Only permanent grassland managed using farming methods 1, 2, 4, 12, 15, 21 and 24.

Table 15 - Methodology used by INRAE to estimate the storage capacities generated by agricultural, winegrowing and grassland-related carbon storage practices (12)

10.4. Converting biomass into energy

In the table below, an energy potential has been calculated for all relevant biomass categories, in particular for feedstocks that are used in the form of combustion or anaerobic digestion. In total, this represents a potential of 225 TWh of thermal energy that could be produced.

Biomass	Usage	Unit	Volume	Conversion factor [Mtoe/Mt or Mm³]	Energy potential [TWh]
Agricultural biomass					**123**
Dedicated crops	Combustion	MtDM	0,070	0,4	0,4
Intermediate crops	Anaerobic digestion	MtDM	4,4	0,2	10,6
Agricultural waste	Combustion	MtDM	7,3	0,4	33,3
Agricultural waste	Anaerobic digestion	MtDM	10,5	0,2	24,2
Livestock manure slurry	Anaerobic digestion	MtDM	1,6	0,18	3,3
Livestock manure	Anaerobic digestion	MtDM	23,1	0,19	50,8
Fibre plants	Combustion	MtRM	0,1	0,4	0,3
Perfume plants	Combustion	MtDM	0,014	0,4	0,1
Perfume plants	Anaerobic digestion	MtDM	0,011	0,2	/
Municipal waste					**20,4**
Green urban waste	Anaerobic digestion	MtDM	5,122	0,2	11,5
Used edible oils	Biofuels	MtRM	0,08	0,5	0,4
Wood waste	Combustion	MtRM	0,49	0,4	2,1
Sewage sludge	Anaerobic digestion	MtDM	0,16	0,1	0,2
Household waste	Anaerobic digestion	MtRM	4,91	0,1	6,2
Co-products of the agri-food industry				**9,9**	
Oilseed crushing	Biofuels	MtRM	0,64	0,9	7,0
Sugar beet	Anaerobic digestion	MtRM	0,15	0,2	0,3
Vinification	Anaerobic digestion	MtRM	0,06	0,1	0,1
Meat industry	Biofuels	MtRM	0,19	0,9	2,1
Fishing and aquaculture	Biofuels	MtRM	0,04	0,9	0,4
Forests					**59,3**
Hedgerows and agroforestry	Combustion	Mm³	3,09	0,207	7,4
Wood harvesting	Combustion	Mm³	21,5	0,207	49,9
Pre-total					**210**
Seaweed	Anaerobic digestion	/	/	/	15
Total					**225**

Table 16 - Biomass energy conversion factors for BECCS and theoretical maximum potential for total biomass energy recovery available for BECCS in 2050

10.5. Limiting factors for establishing the reference scenario

The table below shows the maximum theoretical feedstocks (from part 5) and the resource feedstocks used in the reference scenario.

Resource	CDR method	Maximum theoretical resources	Use of resources (without CO2 storage constraints)	Use of resources (with CO2 storage constraints)
Electricity	Electrochemical DACCS	185 TWh_e	15 TWh_e	10 TWh_e
	S-DACCS (low-temp)	185 TWh_e	2.7 TWh_e	1.7 TWh_e
	Accelerated deterioration	185 TWh_e	0.5 TWh_e	0.5 TWh_e
Heat	S-DACCS (low-temp)	53 TWh_{th}	14 TWh_{th}	9 TWh_{th}
	Enhanced weathering	53 TWh_{th}	3 TWh_{th}	3 TWh_{th}
Area of new land (forests, peat bogs, sea grass beds, mangroves)	Reforestation / Afforestation	+2.9 Mha	+0.9 Mha	+0.9 Mha
	Increase in peatland area	+0.01 Mha	+ 0 Mha	+ 0 Mha
	Increase in seagrass and mangrove areas	+ 0.008 Mha	+ 0 Mha	+ 0 Mha
Surfaces for carbon storage practices	Storage practices	Depending on practices	Depending on practices	Depending on practices
Biomass	BECCS	212 TWh_{th}	28 TWh_{th}	18 TWh_{th}
	Biobased products	9.5 Mt	1.5 Mt	1.5 Mt
	Biochar	1.6 Mt	0.8 Mt	0.8 Mt
Rocks and minerals	Enhanced weathering Mineral alkalisation of the oceans	Limestone: 5.2 Mt, Dolomite: 0.18 Mt, CKD: 0.12 Mt, Olivine: 0 Mt	Limestone: 3.1 Mt, Dolomite: 0.09 Mt, CKD: 0 Mt, Olivine: 0 Mt	Limestone: 3.1 Mt, Dolomite: 0.09 Mt, CKD: 0.12 Mt, Olivine: 0 Mt
Forest area	Natural forest carbon sink	19.8 Mha	17.8 Mha	17.8 Mha

Table 17 - Maximum theoretical resource deposits (part 5) and use of resources (with or without constraints on geological storage of CO_2) in the reference scenario

10.6. The like-for-like principle, whereby the permanence of the CDR method used to offset residual emissions needs to match their origin

The UNFCCC's "*Race to Zero*" campaign defines comparable ("like-for-like") CO_2 removals as "*when an emissions source and emissions sink match in terms of warming impact and in terms of time scale and sustainability of carbon storage*". This definition indicates that CO_2 from permanent storage, such as fossil fuels, must be returned to permanent storage. At the same time, CO_2 released from a low-permanence storage, such as forests or soils, can be put back into the same type of storage (i.e. offsetting land-use change through reforestation). It also means that short-lived greenhouse gases, such as methane, could be neutralised by storing CO_2 with the same lifetime as methane (adjusting volumes to account for global warming potential). The like-for-like principle derives from the structure of the natural carbon cycle and prevents, for example, an oil company from continuing to produce fossil fuels and releasing CO_2 from the long carbon cycle, while offsetting its emissions by planting trees and storing carbon in the short carbon cycle. The like-for-like principle should always be used when offsetting residual emissions with negative emissions to help achieve sustainable carbon neutrality.

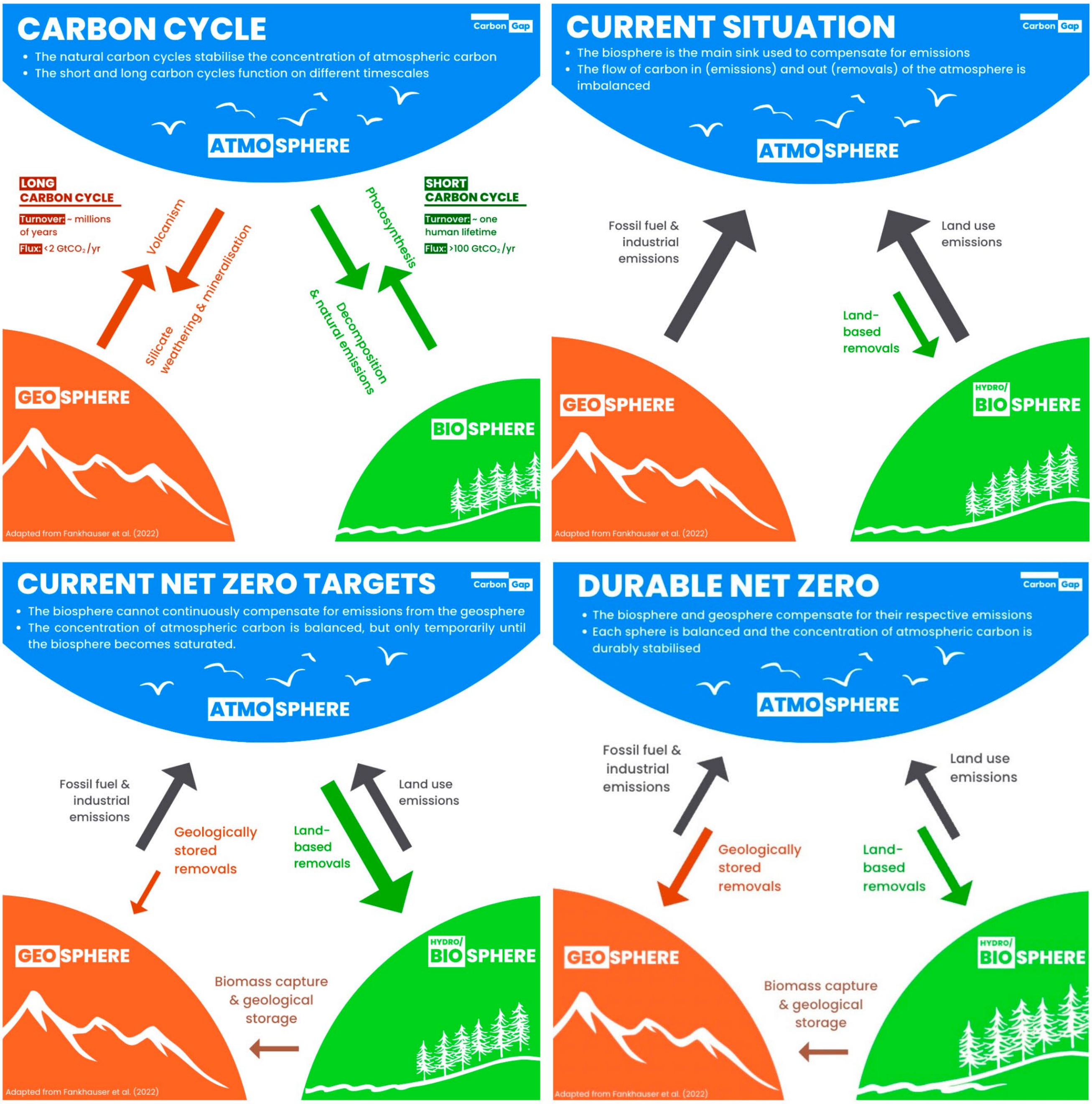

Figure 70 Illustration of the like-for-like concept by comparing different states of equilibrium of carbon flows with the atmosphere

10.7. Conversion factors for INRAE carbon storage practices

The CO_2 elimination potentials of carbon storage practices per hectare are taken from the INRAE report "*Stocker du carbone dans les sols français*" (2020). The report presents estimates of the GHG balance of stocking practices over the entire soil profile. This GHG balance is made up of two effects:

- A reduction in CO_2 in the atmosphere by eliminating and storing carbon **in the soil**
- Effects **other than the storage of carbon in soils**, such as emissions of other greenhouse molecules (nitrogen and methane), the elimination of carbon in the trees and hedges **biomass** (not just soils) and **indirect emissions** linked to certain practices (reduction or increase in the use of fertilisers and herbicides).

In this report, the INRAE values for CO_2 equivalent elimination potential (full GHG balance) have been used, as they consider major effects such as carbon storage in the trees and hedges biomass in the case of agroforestry and hedge planting practices. They also make it possible to exclude practices that store carbon but have a positive GHG balance (emitter), such as nitrogen fertilisation of permanent grassland.

Carbon storage practices	Additional carbon storage per ha (on the whole profile) (kgC/ha/year)	CO2 removed from the air with additional storage of carbon (on the whole profile) (kgCO2/ha/year)	Main modified emission sources	CO2 removed from the air by modification of other emission sources (kgCO2e/ha/year)	CO2 removed from the air taking into account the full GHG inventory (kgCO2e/ha/yr)
Prolongation of intermediary crops	-215	-788	↗ CO2 fuels ↘ N_2O indirect	52	-736
New organic resources	-98	-359	↗ N_2O indirect (volatilisation, leaching) ↘ CO_2 fertilizers production	35	-324
Inclusion and prolongation of temporary grasslands	-192	-703	↘ N_2O indirect (volatilisation, leaching) ↘ CO_2 fertilizers production	-201	-903
Intra-plot agroforestry	-391	-1 432	↗ Storage C biomass	--3 874	-5 306
Hedgerows	-31	-115	↗ Storage C biomass	-1 121	-1 236
Moderate intensification of temporary grasslands	-213	-781	↗ N_2O direct and indirect ↗ CO_2 fertilizers production	791	10
Mowing replaced by grazing	-362	-1 328	↗ N_2O	343	-986
Permanent grassing in vineyards	-464	-1 701		167	-1 534
Winter grassing in vineyards	-300	-1 100		13	-1 087

Table 18 - Calculation of the GHG balance of carbon storage practices (over the entire soil profile) in 2020 according to INRAE

10.8. Allocation of electricity in the ambition scenario

The 30 TWh of electricity available in the **ambition** scenario breaks down into ~2 TWh for enhanced weathering (Limestone + Basalt), 3 TWh for S-DACCS (low temp), leaving 25 TWh for electrochemical DACCS.

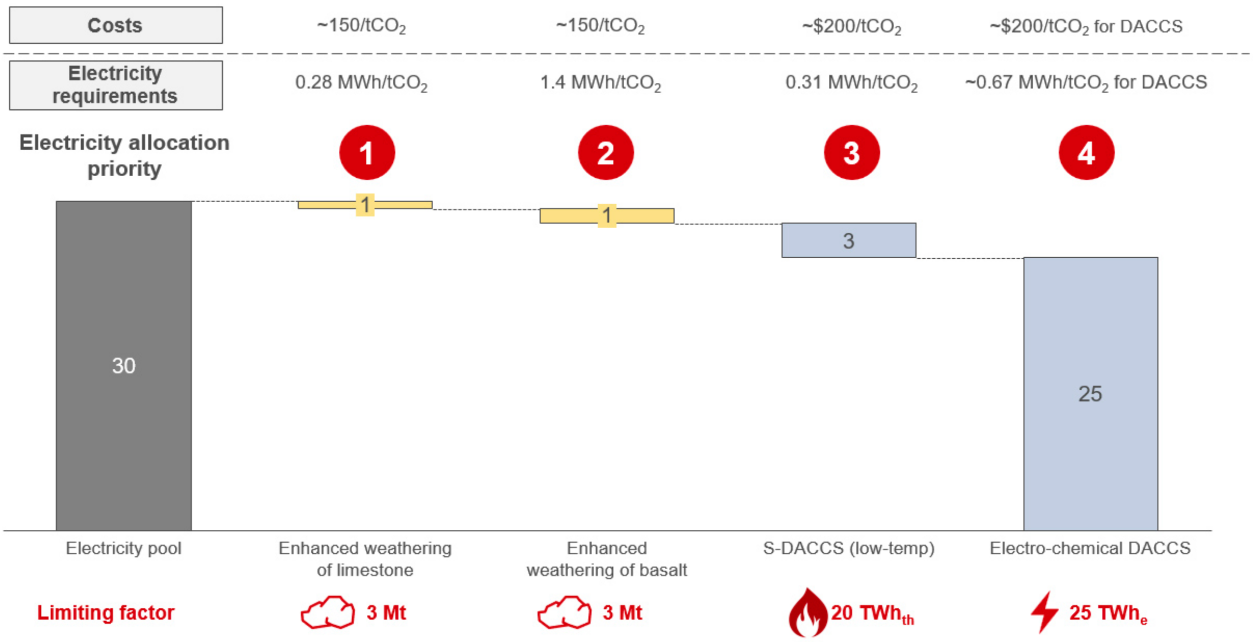

Figure 71 - Distribution of the electricity feedstock among the various CDR methods consuming electricity in the ambition scenario in 2050 [TWh/year]

10.9. Biogenic CO_2 requirements for shipping

For the maritime sector, the biogenic CO_2 requirement for the production of sustainable fuels has been estimated at 5.7 $MtCO_2$/year. This estimate is based on data from the roadmap for decarbonisation of the maritime sector (2022). This roadmap presents seven scenarios for decarbonising the maritime sector in France. Scenario 3, known as "S3", is described as the "reference" scenario in this roadmap and has therefore been used to estimate the need for biogenic CO_2.

The volumes of electro-fuels, e-ammonia, hydrogen, methane, and methanol were estimated based on their respective shares in the energy mix of cargo ships, given that the overall cargo volume in 2050 in scenario S3 is 46.4 TWh. These shares were obtained by reading the graph with the following elements.

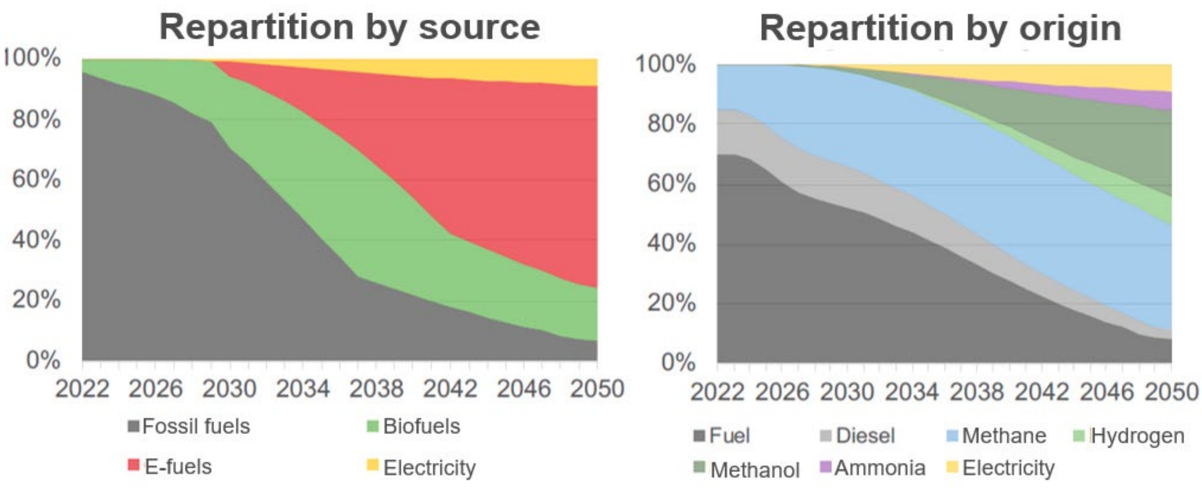

Figure 72 - Evolution of the fuel mix in scenario S3 of the maritime sector decarbonisation roadmap

In detail, the roadmap estimates the need for electro fuels in the "reference" scenario in 2050 at ~32 TWh, including ~24.6 TWh of e-methane and e-methanol (the rest being hydrogen and e-ammonia). The roadmap does not directly specify the volume of e-methane and e-methanol, so an estimate was made based on the share of methane and methanol in the total estimated volume of these fuels (LNG, biofuels, and e-fuels).

In total (LNG, biofuels, and e-fuels), the volume of methane and methanol represents ~29.7 TWh, of which ~59% is methane and ~41% is methanol. Applying this ratio to the volume of e-methane and e-methanol (~24.6 TWh), the volume of e-methane and e-methanol is estimated at ~14.6 TWh and ~10 TWh respectively.

Using the conversion factors 1 TWh = 85.9 ktoe, methane (0.84 tonnes/toe) and methanol (2.10 tonnes/toe), and bearing in mind that the production of e-methane and e-methanol requires around 3 and 1.4 tonnes of CO_2 per tonne of fuel respectively according to the Concawe report, the biogenic CO_2 requirement is estimated at ~3.2 and ~2.5 $MtCO_2$/year for e-methane and e-methanol respectively, i.e. a total of ~5.7 $MtCO_2$/year (Concawe 2022).

10.10. Volume of BECCS in 2050 in the ambition scenario

In the **ambition** scenario, BECCS potential is **18 $MtCO_2$/year** after deducting the need for electro fuels but before considering the constraints linked to the storage of biogenic CO_2. As in ADEME S4 scenario, it assumes strong development of CO_2 transport and storage infrastructures throughout the country, as well as widespread use of biomass for energy. The need for biogenic CO_2 is still estimated at 7.4 $MtCO_2$/year for air transport and 5.7 $MtCO_2$/year for maritime transport.

However, unlike ADEME S3 scenario, ADEME S4 scenario anticipates a volume of electricity of 18 TWh for the production of sustainable aviation fuels in 2050. This corresponds to a volume of around 1.5 Mt/year of biogenic CO_2 in 2050, which is therefore **already included** by ADEME.

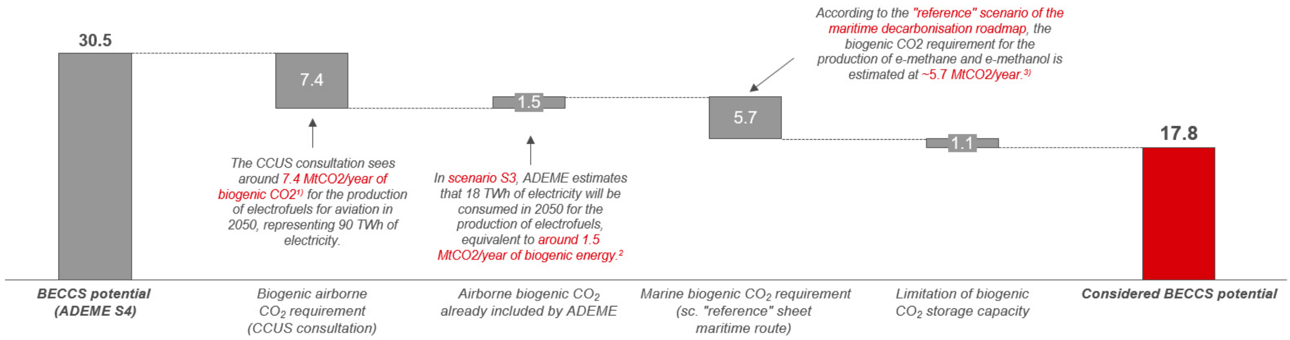

Figure 73 - Reduction in ADEME BECCS potential (S4) considering competition for biogenic CO_2 with air and sea transport

10.11. Capture costs for different CDR methods

CDR methods	Unit	Value	Source
BECCS	€/tCO_2	200	Average value of state of CDR
Biochar	€/tCO_2	200	Average value of state of CDR
Biobased products	€/tCO_2	200	Average value of state of CDR
Afforestation and Reforestation	€/tCO_2	120	Average value of state of CDR
Total carbon storage practices	€/tCO_2	30 – 40 -120	Depending on the scenario
Enhanced limestone weathering	€/tCO_2	125	Average value of state of CDR
Electrochemical DACCS	€/tCO_2	200	Average value of state of CDR
S-DACCS low temperature	€/tCO_2	200	Average value of state of CDR

Table 19 - Capture costs at maturity for the different CDR methods according to State of CDR (78)

About us

Carbon Gap

Carbon Gap is a philanthropy-funded non-profit organisation focusing on scaling up just and effective carbon dioxide removals (CDR) in Europe. Founded in 2021, its dual mission is to:

- **Accelerate** the development of carbon dioxide removal (CDR) removal capacity in Europe.
- **Monitor** how CDR methods are deployed, to ensure maximum climate benefit, full transparency, and that the necessary safeguards are in place.

Carbon Gap is working with scientists, NGOs, decision-makers, investors, and entrepreneurs to catalyse the emergence of a robust CDR sector that will enable Europe to secure its climate objectives and plan a net negative phase, while creating economic benefits locally.

In just two years, Carbon Gap has established itself as a reference CDR organisation in Europe, with a pragmatic, constructive and inclusive vision for developing a full range of effective and safe CDR methods.

Carbon Gap is the main project leader and coordinator of this report. The Carbon Gap team led the project, designed the methodology, contributed to the analyses, and wrote the report.
www.carbongap.org

RMI

RMI is an independent, non-governmental organisation, founded in 1982 as the Rocky Mountain Institute. It aims at transforming the world's energy systems through market-based solutions to align with a 1.5°C future and secure a clean, prosperous, carbon-neutral future for all. RMI works in the world's most strategic geographies and with businesses, policymakers, communities, and non-governmental organisations to identify and scale up energy system interventions that will reduce greenhouse gas emissions by at least 50% by 2030. RMI has offices in Basalt and Boulder, Colorado; New York; Oakland, California; Washington DC; and Beijing.

RMI contributed to the compilation of the database on the resource requirements of CDR methods and to the analysis for the allocation of available resources.
www.rmi.org

E-CUBE

E-CUBE Strategy Consultants is a strategy consultancy dedicated to energy, mobility and climate issues. Founded in 2008 and employing around fifty consultants, the firm is at the heart of the challenges of energy transition and sustainable development. Thanks to its commitment, E-CUBE has established fruitful partnerships with more than 300 customers, demonstrating its expertise through the completion of more than 800 projects to date.

E-CUBE's work covers the full range of General Management issues: strategic analysis, 'data' strategy, decarbonisation strategy and impact on business models, redefinition of energy supply strategies, regulatory and techno-economic studies, organisational change and improving operational performance.

E-CUBE's work focuses on three areas:

- **Energy and Environment:** helping energy companies (electricity and gas producers, oil companies, renewable energy players) to anticipate and take account of changes in their market, regulatory, competitive, and technological environment. Assisting private and public sector players in re-evaluating their strategy in order to integrate the challenges and opportunities of a 'new deal' in energy and the environment.
- **Mobility:** supporting players in the automotive, rail, air transport, shipping, and logistics sectors in their strategic, regulatory, and operational projects. Helping industry leaders re-evaluate their strategy to take account of the challenges of digital technology and the opportunities presented by a new energy and environmental deal.
- **Decarbonisation:** helping industrial and service sector players to understand the impact of the energy and environmental transition on their activities and business models, supporting and challenging their decarbonisation strategy, and helping them to overhaul their energy supply and logistics strategies.

E-CUBE carried out the data research and analysis, conducted the stakeholder interviews, wrote the report, and led the roadmap design workshop.
www.e-cube.com