THE CONTRIBUTION OF CARBON CAPTURE & UTILISATION TOWARDS CLIMATE NEUTRALITY IN EUROPE

A SCENARIO DEVELOPMENT AND MODELLING EXERCISE

CO2 VALUE EUROPE

EUROPE WILL NOT REACH CLIMATE NEUTRALITY WITHOUT CARBON CAPTURE & UTILISATION

CO_2 VALUE EUROPE

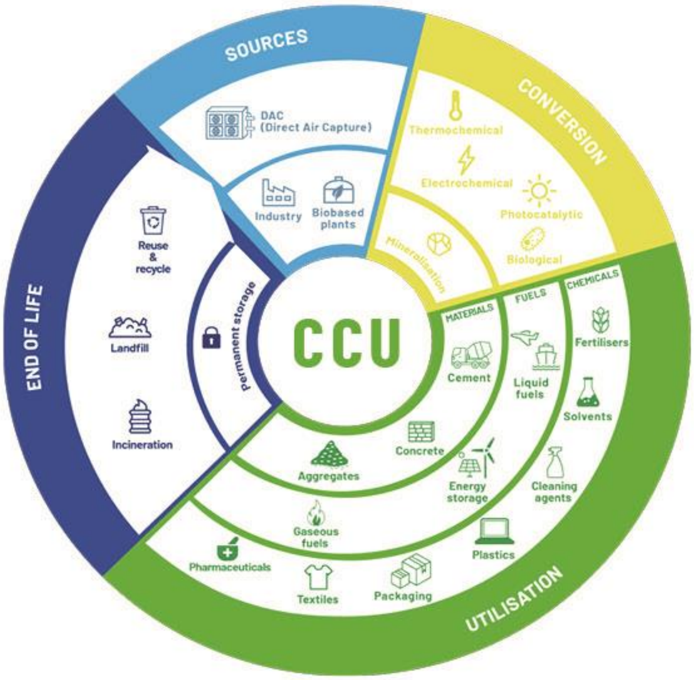
Numerous sectors and services will still rely on carbon by 2050. **The use of captured carbon as feedstock to answer unavoidable demands in fuels, chemicals and materials is crucial** to transition to a fossil-free circular economy and reach EU's climate targets.

Carbon Capture & Utilisation (CCU) represents an array of technologies able to capture carbon at point sources or from the air and use it to produce essential products. CCU reduces and avoids emissions, in certain cases removes CO_2 from the air, and eliminates the need to use virgin fossil feedstock.

By 2050, the EU will be able to **capture at least 320 MtCO_2** mainly from biogenic, atmospheric and process emission sources, and convert 55% of it into products, while the rest will be stored underground.

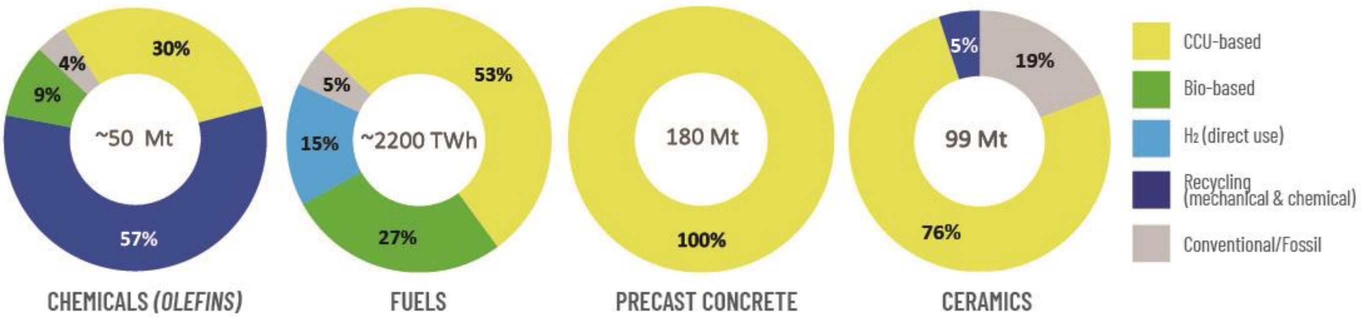
CCU represents approx. 21% of the overall GHG emission reduction that can be achieved through technological solutions in the EU. Per sector, this represents:

% GHG emission reduction through CCU per sector in 2050



Share of CCU Products in 2050

CCU products will have a major contribution to replace fossil-based products in the industry and transport sectors. **Some CCU technologies are already deployed at commercial scale while others will achieve commercial production before 2030. A combination of domestic production of CCU fuels & chemicals and limited (compared to current situation) imports will strengthen EU's energy sovereignty.**



What's Needed?

1. **Clear recognition in EU policies of the importance of carbon circularity and the use of captured carbon to substitute fossil carbon.**
2. **Explicit target setting for CCU's role in EU climate goals 2030, 2040, 2050.**
3. **Synchronised action at EU and national level in financing and strategic prioritisation of CCU.**

Disclaimer

Authors

CO_2 Value Europe (CVE) is the non-profit Association representing the CCU Community in Europe with more than 90 members along the CCU value chain from various economic sectors and the academia, from large companies to start-ups and from industrial clusters to university groups. Our mission is to promote the development and market deployment of sustainable industrial solutions that convert captured carbon into valuable products, in order to contribute to the net reduction of global CO_2 emissions and to substitute fossil carbon. We believe that CCU technologies offer a large panel of solutions for carbon intensive sectors where no or very few other alternatives exist.

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Executive Summary

For several decades, exponential growth in the use of fossil carbon has created drastic climate disturbances. To mitigate climate change, all uses of virgin fossil carbon must, urgently, be phased out. Many transport sources and industrial processes can easily be electrified and should be where possible. But some sectors like chemical, materials (e.g. lime and steel), aviation and maritime transport will continue to use carbon and the virgin fossil used today will need to be substituted to meet climate neutrality targets.

CO_2 Value Europe (CVE) is advocating for the "defossilisation" of these sectors by promoting the creation of a circular carbon economy based on the principle of Carbon Capture and Utilisation (CCU). CCU represents a large set of technologies able to capture carbon at point sources or in the atmosphere and use it as feedstock to produce non-fossil fuels, chemicals and building materials. Depending on the context, these technologies can reduce or avoid greenhouse gas emissions; and, in some circumstances, generate negative emissions via Carbon Dioxide Removal (CDR) when CO_2 from the air or from biogenic processes is sequestered permanently in products in a way that it is not reemitted under normal use and end-of-life of the product.

CVE has developed the first quantitative assessment on the crucial role CCU will play in reaching climate neutrality in Europe. This two-year exercise has been carried out with international industrial, technological, economical, and academic experts on CCU and related subjects to understand and quantify the potential of CCU, but also to describe the main parameters and key uncertainties associated with the upscaling of these technologies. The key messages of this report are summarized below.

a. **The contribution of CCU as a climate-mitigating solution**

- The EU will not reach climate neutrality without CCU. Currently in place economics and regulatory measures represent only 34% of the effort required to reach climate neutrality. These measures must therefore be significantly reinforced by additional measures including societal changes (30%) and technological development (37%). By 2050, more than 21% of GHG reduction from technologies will come from CCU reducing CO_2 emissions by about 250Mt in the EU.
- **In 2050, about 320 $MtCO_2$ will need to be captured in the EU, 55% will be utilized and the rest stored underground**. 46% will come from Direct Air Capture (DAC), 23% from remaining process emissions, 23% from biogenic emissions, 2% from CCU fuel combustion and only 6% from the remaining fossil fuel emissions. To substitute fossil-based products and ensure a sufficient non-fossil carbon supply in the coming decades, a faster ramp-up of carbon capture in industries with high process emissions and of DAC is crucial, especially to reach the demand for fuels and chemicals in the late 2040s.
- From the 173 $MtCO_2$ utilized, 50% will be used to produce CCU fuels, 42% for chemicals production and 8% will be mineralised in building materials.

b. **The role of CCU in different sectors**

- **CCU plays a crucial role "defossilising" industry and reducing by at least 20% its greenhouse gas emissions**. The use of captured carbon as feedstock will reduce emissions by 11% in the chemical industry, by 7% using CCU fuels and by 2% capturing CO_2 permanently in building materials via mineralisation. To reach net zero, residual emissions e.g., from process emissions will need to be compensated by CDR.
- By 2050, two thirds of the primary production of the main chemical building block, olefin, will be produced using captured carbon as feedstock via synthetic ethanol and methanol routes. This represents 30% of the total olefin production and is the main pathway to produce olefin ahead of other primary routes such as biogenic and remaining fossil production and the secondary routes (chemical and mechanical recycling).

- **CO_2 can be stored permanently in building materials via mineralisation processes. By 2050, at least 14 $MtCO_2$** (10% of the total CO_2 stored) could be channelled in building materials. These numbers are constrained notably by product demand and the availability of wastes and minerals as feedstock for the reaction but could be significantly higher when adding more mineralisation pathways into the model. CO_2 mineralisation has the potential to perform CDR when the CO_2 sources captured come from DAC or biogenic sources.
- **In the transport sector, CCU technologies are a key solution to reduce emissions for aviation, maritime and long-haul vehicles**. By 2050, 11% (111 $MtCO_2$) of emission reductions in transports will be coming from CCU fuel use. Greenhouse gas emissions from the maritime, aviation and inland transports (including heavy duty and long-haul vehicles as well as inland waterways) sectors will be reduced by 35, 38 and 2% respectively.

c. **The contribution of and challenges for the production of CCU fuels & chemicals**

- **CCU fuels are drop-in solutions as they do not require changes in infrastructure.** By 2050, they will represent 1161 TWh of the energy mix in the EU, including 474 TWh for aviation and marine transports, 509 TWh to replace fossil fuels in the industry and 178 TWh in heavy-duty road vehicles. The EU has the potential to produce at least 55% of the demand for CCU fuels, the rest will need to be imported.
- The domestic production of CCU fuels and chemicals for the transport and industry sectors will require up to 1187 TWh of low-carbon electricity in 2050 (including DAC, carbon capture at point sources, production of H_2 and final product generation). This represents approximately 22% of the modelled low-carbon electricity production in the EU by that year.

OUR RECOMMENDATIONS

1. A key building block for reaching climate neutrality in Europe will be **scaling up carbon capture**. Until 2030, achieving carbon capture – regardless of whether it is meant for utilisation or storage – at wide-scale will be paramount, in order to further achieve climate objectives in 2040 and 2050. The EU institutions should support the **deployment of carbon capture and utilisation as a standalone activity, by considering it as strategic, by including it systematically in policy instruments, and by encouraging the building of capture infrastructures**.
2. To support the deployment at large scale of CCU products, the EU should **better recognise the concept of carbon circularity** with the reuse of unavoidable carbon or carbon coming from the atmosphere as a key lever – for now, there is no incentives under EU law for **using captured carbon as feedstock** for chemicals for example. It is crucial such incentives are swiftly put in place to move away from fossil carbon use. The EU should refer explicitly and systematically in relevant policy initiatives (Industrial Carbon Management Communication, Net Zero Industry Act, EU climate targets for 2040, future European Climate Law, etc.) to the three core CCU pathways, i.e., fuels, chemicals and mineralisation, and accordingly **set targets for 2030, 2040 and 2050 to drive down the use of fossil resources**.
3. The EU and Member States should **frontload public funding instruments** like the Innovation Fund, the Recovery and Resilience Facility, the Important Projects of Common European Interest with increased budget especially during the next 2-3 years so that plants at industrial scale become operational already until 2030. Accordingly, Member States should be encouraged to **include elements of the CCU chain systematically in their National Energy and Climate Plans** (including, for example, CO_2 transport

infrastructure, renewable hydrogen backbone development, renewable energy grid capacity expansion, industrial symbiosis and upscaling).

4. The EU regulatory framework should ensure that **all stakeholders along the CCU chain find incentives to invest and implement CCU solutions** (e.g. regarding CO_2 accounting). The current rules are counterproductive as they deter the use of captured carbon to replace carbon from fossil resources, for example to create chemical building blocks. To unleash the potential of CCU across sectors, additional rules need to be set to **recognise the value of reusing unavoidable carbon into products of both permanent and non-permanent storage** and for climate benefits to be shared along the CCU value chain.
5. Future EU regulations should imperatively create new legal obligations to use alternative carbon feedstock, including captured carbon, for the production of chemicals and mandate incorporation targets for renewable materials in a wide variety of everyday products (e.g. packaging, textiles, etc.).
6. Mineralisation should continue to be promoted as one of the levers to mitigate emissions, both for industrial CO_2 which can lead to zero emissions processes, as well as for biogenic/DAC CO_2 which can lead to CDR. **Market uptake mechanisms (e.g. public procurement) and strong certification frameworks should be put in place to incentivise mineralisation projects** while ensuring their long-lasting positive climate impacts.
7. The role of CCU fuels (both RFNBOs and RCFs) should be recognised as contributing to the transition of aviation, maritime and long distance/heavy duty land transport. Mandatory incorporation targets in ReFuelEU Aviation should be revised regularly; more ambitious quotas in FuelEU Maritime should be set; and CCU fuels should be recognised as one of the levers to decrease the carbon footprint of heavy-duty vehicles in the short to medium term. Regulations stipulating conditions for RCF and RFNBO production should better reflect the realities of scaling up at industrial levels.
8. The EU will need to complement domestic production of CCU fuels and chemicals with imports outside Europe. There is therefore a need to **complete the current EU regulatory framework to provide legal certainty for CCU fuels producers in and outside Europe** (e.g. concerning eligibility of CO_2 sources, definitions of carbon pricing mechanisms); at the same time, **international cooperation is required for the development of compliance mechanisms** that will take due consideration of specificities at non-European level.

Contents

List of abbreviations

CCU	Carbon Capture and Utilisation
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CVE	CO_2 Value Europe
DAC	Direct Air Capture
GHG	Greenhouse Gases
IPCEI	Important Projects of Common European Interest
NZIA	Net Zero Industry Act
PPA	Power Purchase Agreement
RCF	Recycled Carbon Fuels
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
TRL	Technology Readiness Level
WtE	Waste-to-Energy

1. Introduction

The European Green Deal has put forward ambitious legal obligations for Europe to reduce GHG emissions by at least 55% by 2030 (compared to 1990 levels) and reach carbon neutrality by 2050. Many technological solutions will be needed to achieve this goal; it will require actions at a political level (e.g. goal setting in policy instruments); societal responses (e.g. choices towards more circularity and sobriety); and economic measures (e.g. investments in mitigation measures) to happen simultaneously to help us achieve those goals. Among the technology-based solutions that can be implemented, Carbon Capture and Utilisation (CCU) is a crucial climate mitigating solutions for sectors hard to decarbonise such as the maritime and aviation transports and some process industries. CCU does not only provide a way to reduce emissions, but it also generates added-value products to substitute fossil-based ones facilitating the eventual phase out of virgin fossil carbon.

1.1. Background

1.1.1. What is CCU?

CCU represents a large set of technologies in which carbon is captured and used to produce essential products. Carbon is usually captured from concentrated industrial waste gases in the form of carbon dioxide (CO_2) or, sometimes carbon monoxide (CO). CO_2 can also be captured from the air in a process known as direct air capture (DAC). The captured carbon can then be converted into different types of products that have traditionally been made from virgin fossil carbon sources, such as building materials, synthetic fuels and chemicals (Fig.1).

CCU is recognized by the IPCC as a climate-mitigating solution to carbon-intensive sectors e.g., process industry, aviation, maritime and construction where no or very few alternatives exist to reduce emissions and move away from fossil resources. These solutions should not substitute large-scale efforts to prevent greenhouse gas emissions especially when more energy-efficient solutions are available, but they should be seen as significant opportunities to reduce emissions in sectors that will continue to be reliant on carbon-based feedstock and fuels. Moreover, to ensure real emission reductions over their entire value chain, the climate-mitigation potential of CCU technologies should be based on a full life-cycle analysis.

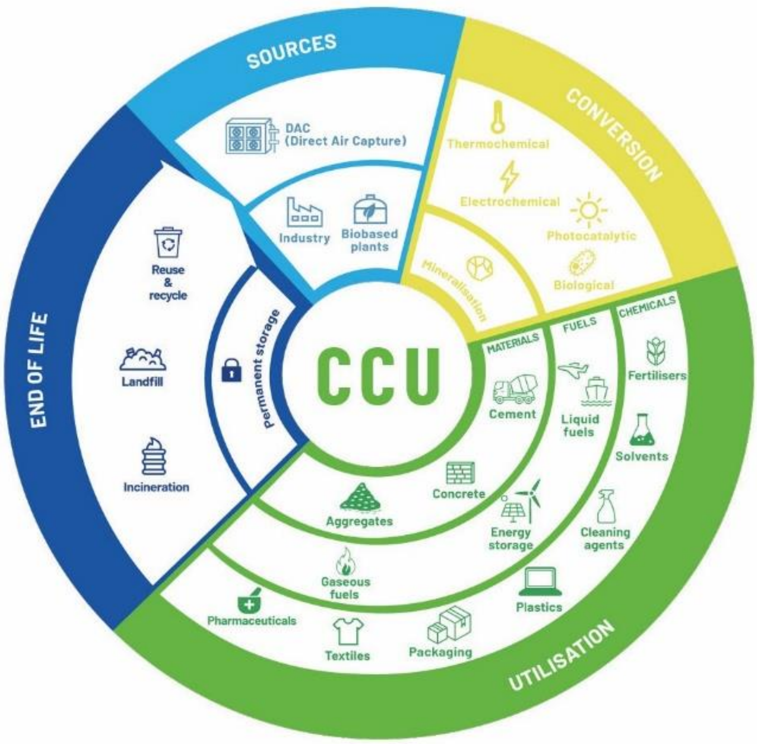

FIGURE 1. **The concept of CCU**

Numerous CO_2 conversion technologies exist and are at different stages of development including some that are already commercialized. They can mainly be divided into two categories:

1. The production of fuels and chemicals by using renewable/recycled H_2 and captured carbon to produce hydrocarbons which substitute for fossil equivalents. H_2 can be produced by water electrolysis using renewable or low carbon electricity (i.e. the Power-to-X approach), or recycled from industrial processes, and reacts with captured carbon to produce all commonly used hydrocarbons. Liquid and gaseous fuels and chemicals can be generated using these different types of processes (e.g. biological, thermochemical, electrochemical, photocatalytic, etc.). Some processes under development aim at bypassing the production of H_2 as intermediate and react captured carbon directly with water. When the energy carrier of CCU products is of renewable origin (other than biomass) then this type of products is referred to as Renewable Fuels of Non-Biological Origin (RFNBO); when the energy is already present in the recycled streams then they are referred to as Recycled Carbon Fuels (RCF).
2. The mineralisation of CO_2 is also referred to as carbonation and is a natural phenomenon sequestering CO_2 on geological time-scales in rocks. Ca (calcium)- or Mg (magnesium)-containing minerals react with CO_2 to produce carbonates ($CaCO_3$ or $MgCO_3$). Respectively, these are known as limestone or dolomite and form one of the most abundant rock types found on the Earth's surface. The carbonation reaction can be accelerated to take only a few minutes in a managed processes called "accelerated carbonation". The latent reactivity of minerals found in solid waste can be readily reacted with dissolved CO_2 to form building materials (e.g., aggregates, concrete blocks etc.) where CO_2 is permanently stored. All mineralisation processes discussed in this report are "accelerated carbonation" technologies.

1.1.2. Science

CCU technologies have existed for several decades, such as in the production of urea, but only started to be seriously considered as a potential solution to mitigating climate change in the last decade. In recent years, there has been an exponential technological evolution and recognition – although there remains a lack of understanding of their benefits challenges and opportunities.

To date, no exhaustive quantification exists on the global climate mitigation potential of CCU technologies, because of the uncertainties in the evolution of renewable electricity availability and cost and because of the low granularity of models to simulate the complexity of the different CCU options.[1,2,3] One challenge is that CCU is often assessed in a linear way[4] only considering its decarbonisation potential, while the main objective of these large set of technologies is not only to reduce emissions, but mainly to move away from fossil carbon by substituting fossil feedstock with renewable carbon[5,6] by creating a circular carbon economy. This is crucial for reaching climate targets as stated in the last IPCC reports.[7]

However, several peer-reviewed scientific studies have shown the efficiency of CCU applications e.g. by calculating the quantity of CO_2 that could be reused[8,9] or by performing full Life Cycle Assessment (LCA) on various CCU routes.[10-13] LCAs show that depending on the context, the climate mitigation potential of CCU varies. These technologies can lead to:

- *Net reduction of CO_2 emissions* with respect to conventional pathway (use of fossil feedstock) to produce the same final product, but with renewable carbon feedstock.
- *Net zero CO_2 emissions* when CO_2 emissions used as feedstock for the production process are stored durably in products (e.g. through mineralisation), or when they are re-emitted at the end-of-life of the product but then recaptured and recycled, or when CO_2 is captured from the atmosphere and returned to it at the product's end-of-life.
- *Net CO_2 removal* when CO_2, which is captured from the atmosphere or from the treatment of biomass, is durably stored in products via mineralisation processes.

Several studies[e.g.7,14-16] show that CCU can reduce CO_2 emissions independently from the duration of CO_2 storage in a product, the long-term goal should be to close the loop (prevent CO_2 to finally reach the atmosphere), move away from fossil fuel and create net-zero emission processes. A key gap in current actions to achieve this is the omission of waste disposal within emissions trading schemes. The potential of CCU is recognized by the climate community and discussed in the last report of the IPCC[7] as a major opportunity for climate change mitigation, energy transition and a reinvention of the industrial sector, benefiting society as a whole.

1.1.3. Policy

Progress in terms of legislative support for CCU has been ambivalent. On the one hand, at EU level, a wide range of far-reaching legislations have been adopted recently which have started to recognise the key role of CCU in "defossilising" the economy, and this sets the scene for future progress. But on the other hand, the EU approach remains for now contradictory, inconsistent and lacking an overarching supporting framework for CCU: rules adopted have also been consistently creating extra hurdles and conditions for CCU projects to really take-off, and in some areas like CCU chemicals, there are no real incentives or market-pull mechanisms in place yet to move away from a fossil-based economy. More ambitious, adapted and coherent legislations will be absolutely necessary to really incentivise industries to invest into CCU as a way to "defossilise" their emissions. Some of the latest EU legislations adopted include:

- The **Emission Trading Scheme (ETS) revision**, which as of 2023 has become the official EU law, where EU authorities recognised the role for CCU for example by binding CO_2 permanently in construction products via mineralisation, and avoiding double counting of CO_2 for other CCU processes. However, it leaves out important pathways such as CCU chemicals, and create little incentives for original emitters that would invest into CCU routes. The rules around **ETS aviation** create financial mechanisms to support the transition of aviation towards sustainable aviation fuels.

- The Carbon **Border Adjustment Mechanism (CBAM)** aims to mirror the ETS rules for raw materials and energy carriers produced outside of Europe, and ensure to limit carbon leakage and encouraging third countries to adopt ETS-like systems. Further work is expected in the revision of the ETS to account for CCU products that do not lead to permanent binding and for the inclusion of the Waste-to-Energy sector that could lead to a further CO_2 source to be used for CCU applications.

- The latest revision of the **Renewable Energy Directive (REDIII)** sets a target for 42.5% of the final energy consumption in Europe to be renewable energy by 2030, and CCU fuels are given a dedicated role to contribute to those targets in specific sectors. In transport, the legislation makes it mandatory for 5.5% of the energy in transport to come either from advanced biofuels or RFNBOs, and it mandates for at least 1% of the total energy to come from RFNBOs alone. REDIII also allows Member States to include recycled carbon fuels meeting agreed criteria to count towards transport targets. In industry, REDIII imposes to EU Member States that at least 42% of the hydrogen used in the industry comes from RFNBOs by 2030 and 60% by 2035.

- The new legislation on **ReFuelEU Aviation** obliges EU airports and fuel suppliers to ensure that starting from 2025 at least 2% of aviation fuels will be sustainable, with this share increasing every five years: 6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045 and 70% in 2050, including via RFNBO and RCF. In addition, a specific proportion of the fuel mix (0.7% in 2030, 1.2% in 2032, 5% in 2035 and progressively reaching 35% in 2050) must comprise synthetic aviation fuels.

- The recent **FuelEU Maritime** mandates that shipping above a gross tonnage of 5.000t will need to gradually reduce GHG emissions in the energy they use by 2% as of 2025 to 80% as of 2050 compared to 2020 levels. The new rules also set a 2% renewable fuels usage target as of 2034 if the Commission reports that in 2031 RFNBOs amount to less than 1% of fuel mix.

In order to implement those legislations, EU countries will need to adopt national legislations mirroring those targets. At EU level, complementary legislations (known as “delegated acts” and “implementing acts”) will continue to provide further details and methodologies on how to account for the production of CCU products and how they will contribute to the overall target of moving away from fossil resources – but already some of the adopted rules are very stringent in terms of use of industrial ETS CO_2, which could put in jeopardy CCU projects on existing emissions, whereas for CCU to deploy we need rules that foster the scale-up of projects. For example, the REDII Delegated Act on GHG Methodology, which sets the criteria for fuels to be considered renewable or recycled mandates that ETS CO_2, when captured and reused, will not be considered as avoided after 2040: this creates much uncertainty for investments in projects that will run for decades. Similar caveats are the stringent rules in additionality, temporal and geographical correlation for the determination of full renewability of RFNBO; the non-inclusion of the Waste-to-Energy (WtE) sector as an eligible CO_2 source for RFNBO; or the inability of RCF producers to use renewable PPA for the displaced electricity. Already many CCU projects in industries with unavoidable emissions (e.g. cement, steel) are struggling to plan ahead with such rules in place.

In addition to those final legislations, a number of new proposals are still under legislative discussions at EU level. They include the following proposals:

- In its proposal for a **Certification Framework for Carbon Removals**, the European Commission includes in the definition of removals the permanent binding of atmospheric or biogenic CO_2 in products, e.g. via mineralisation.

- In the **Sustainable Carbon Cycles Communication**, the Commission refers to CCU, CCS and carbon removals, as "innovative clean technologies" and calls for "at least 20% of the carbon used in the chemical and plastic products should be from sustainable non-fossil sources by 2030", but as of yet, this aspirational target has not been translated into actionable and binding legal provisions in EU legislations. This is an absolute must in order to support the use of alternative carbon feedstock.
- The European Commission announced the publication by early 2024 of **a Communication on Industrial Carbon Management,** specifically to explore the role of **CCU, CCS, and CDR pathways** and highlight the importance of those technological value chains to help decrease emissions from hard to abate sectors. It is an important opportunity to focus on all pathways for carbon capture and suggest quantified targets for the role of CCU pathway.
- In its proposal for a **Net Zero Industry Act,** the Commission identifies CCU as one of the net zero technology that will help the EU industry to reach its climate goals. In the original proposal, CCU was not recognised as a strategic net zero technology, which, if not corrected in the final legislation, is inconsistent to some of the aforementioned instruments and could send contradictory signals to investors, companies, national authorities, and civil society on the importance of CCU to reach net zero targets. This is a clear example of the ambivalent approach taken on CCU at EU level: on the one hand, companies are bound or encouraged to use CCU technologies (in aviation, in maritime, in energy-intensive industries); and on the other hand, CCU is only partly recognised as important and not defined as strategic.

The EU is now close to having a first set of complete legislative frameworks for CCU fuels and for CO_2 mineralisation. The continent has yet to adopt binding provisions around the production and uptake of CCU chemicals: for example, no reference to alternative carbon feedstock has been put forward in any of the recent EU legislations around chemicals and plastics such as the Packaging and Packaging Waste Regulation, which is a clear missed opportunity. For CCU technologies in general, the foundations of a true EU regulatory framework are now in place for fuels and mineralisation, but much more focus is needed to create a proper policy framework for CCU chemicals and the recognition of captured carbon as a circular carbon feedstock. More coherent and consistent actions on all three pathways will be required to scale-up and systematise the uptake of CCU products by EU consumers and businesses. To that end, additional legislative actions will be crucial to transform "defossilisation" objectives into a reality.

1.1.4. Projects

When it comes to the implementation of CCU, a series of facilities are operational in industrial environments (e.g. the George Olah facility in Iceland; Steelanol in Ghent, Belgium; Solarbelt in Wertle, Germany or CO_2ntainer in Montalieu, France).

A large number of projects with a combined output of hundreds of thousands of tons of CCU products per year are expected to be operational by 2030. These projects are distributed all over Europe showcasing the inherent geographical flexibility of CCU and are also supported by different public funding mechanisms at the European and national levels (e.g. Innovation Fund, IPCEI). A non-exhaustive list can be seen in Table 1 and further examples can be consulted at CO_2 Value Europe's public CCU project database.

TABLE 1. Examples of CCU projects in the EU expected to be operational before 2030.

Project	Country	Product	Estimated product capacity (t/a)
Carbon2Business	Germany (Lägerdorf)	Fuels & chemicals	350.000
HySkies	Sweden (Forsmark)	Fuels & chemicals	90.000
AIR	Sweden (Stenungsund)	Fuels & chemicals	200.000
eM-Rhône	France (Roussillon)	Fuels & chemicals	150.000
Green MEIGA	Spain (Caldas de Reis)	Fuels & chemicals	100.000
TRISKELION	Spain (Mugardos)	Fuels & chemicals	40.000
Flagship ONE/TWO	Sweden (Örnsköldsvik/Sundsvall)	Fuels & chemicals	45.000/130.000
E-fuel pilot	Norway (Porsgrunn)	Fuels & chemicals	8.000
Green Fuels for Denmark	Denmark (Copenhagen)	Fuels & chemicals	250.000
Norsk e-fuel	Norway (Mosjøen)	Fuels & chemicals	40.000
Power-to-Methanol	Finland (Lappeenranta)	Fuels & chemicals	25.000
Vordingborg	Denmark (Vordingborg)	Fuels & chemicals	80.000
E-fuel	Germany (Frankfurt)	Fuels & chemicals	2.500
AGGRECACO2	Spain (Muskiz)	Materials	56.000
CO2NCREAT	Belgium (Hermaille-sous-Huy)	Materials	130.000
CAP2U	Germany (Lengfurt)	Chemicals & Materials	70.000*
C2PAT	Austria (Mannersdorf)	Chemicals	160.000
Columbus	Belgium (Wallonia)	Fuels & Chemicals	330 GWh/y
REUZE	France (Dunkirk)	Fuels & Chemicals	100.000
HyNetherlands	Netherlands (Delfzijl)	Fuels	100 MW **
Hynovera	France (Meyreuil)	Fuels & Chemicals	100 MW **
LIPOR	Portugal (Meia)	Fuels & chemicals	32.000
Finnfjord	Norway (Finnfjord)	Fuels & chemicals	100.000

**capture capacity, ** electrolytic capacity*

Even more projects are advancing in the TRL scale and are expected to reach demonstration scale within the next 5 years, for example projects for the production of materials (e.g. HERCCULES, Carbon4minerals, Accsess), chemicals (e.g. Concencus, CO2SMOS, VIVALDI, INITIATE, Carbon2x, PyroCO2, Threading-CO2) and fuels (e.g. ECO2FUEL, TAKE-OFF , MariSynFuel, Vantaa Electrofuel).

These examples showcase the stakeholder interest into scaling up the respective CCU technologies at industrially relevant scales and the confidence in the potential of CCU to reach emission reductions and substitution of fossil-based products. At the same time, they highlight how crucial the period to 2030 will be for putting in place the necessary policies and incentives to foster the deployment of CCU and realise this potential.

1.2. Objectives

The decision to quantify the contribution of CCU on the road to carbon neutrality by 2050 was motivated by the following factors*:*

- Because of its multi-faceted approach and high granularity, CCU technologies have been so far largely neglected in the development of climate and energy models, and as a result its contribution is not visible in future energy and climate projections.
- Although there are estimations in literature about the potential of specific CCU technologies to contribute to climate mitigation, it has not been so far integrated in contextualized studies that include a more holistic examination of different options (technological and not) and the role they can play in different sectors to reach climate neutrality in the EU.
- While policy instruments try to include CCU more in their scope over the last years, there is a lack of a foundational estimation of its potential that prevents policy making in developing concrete pathways to see CCU deploy in an accelerated way.
- Practically speaking, the calendar of the development of this CCU quantitative assessment report coincided with the development of the Communication of the Industrial Carbon Management Strategy so that it can feed its elaboration and the discussions among the CCUS Forum.

2. CCU's Developments by 2050

The process of developing this quantitative exercise was based on the collective experience of more than 30 expert stakeholders of the CCU value chain that were gathered during three physical workshops. It was composed of two main exercises: (i) the scenario development exercise where experts identified scenarios of what could happen ("Contrasted scenarios") and what would be desirable to happen ("Vision scenario") in terms of CCU deployment and (ii) a modelling exercise to yield quantitative information about the role of CCU by 2050.

2.1. CVE's Vision scenario development methodology

The development of CVE Expert Vision scenario 2050 towards climate neutrality was conducted as a bottom-up exercise to determine the context within which CCU could operate and to have a view on multiple possible or desirable futures under today's knowns and uncertainties. The sequence to construct the CVE Expert Vision Scenario is illustrated in (Fig. 2) and described stage by stage below:

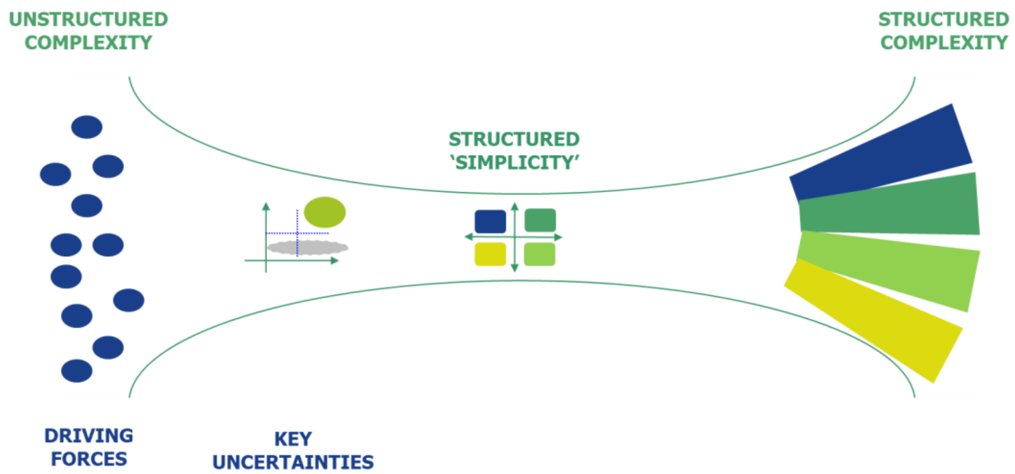

FIGURE 2. **Scenario development process**

Identification of the major driving forces for the future deployment of CCU. These driving forces could be of societal, technological, economic, ecological or political nature. All driving forces identified were group under the following 9 major ones: *regulatory framework; availability of resources; economic growth; overall CO_2 value; social acceptance; level of investment in CCU; level of infrastructure; availability of skills; technological breakthroughs.*

Identification of key uncertainties. The driving forces were placed on a XY axis "impact vs uncertainty" and the ones with the highest impact and the highest uncertainty were considered as "key uncertainties". After consolidation, two key uncertainties were considered: *level of economic activity* and *level of support in CCU* and they were placed on a new XY axis (i.e., the scenario framework) leading to four contrasted scenarios.

Development of contrasted scenarios. The experts were separated into four groups, each in charge of one scenario. They were asked to determine the characteristics and build the storyline of their respective scenario: description of the global & European context in terms of geo-political, socio-economic and environmental developments and events; identification of potential, opportunities and threats for CCU deployment within the defined context. Four contrasted scenarios were thus identified as shown in Fig. 3 and Fig.4.

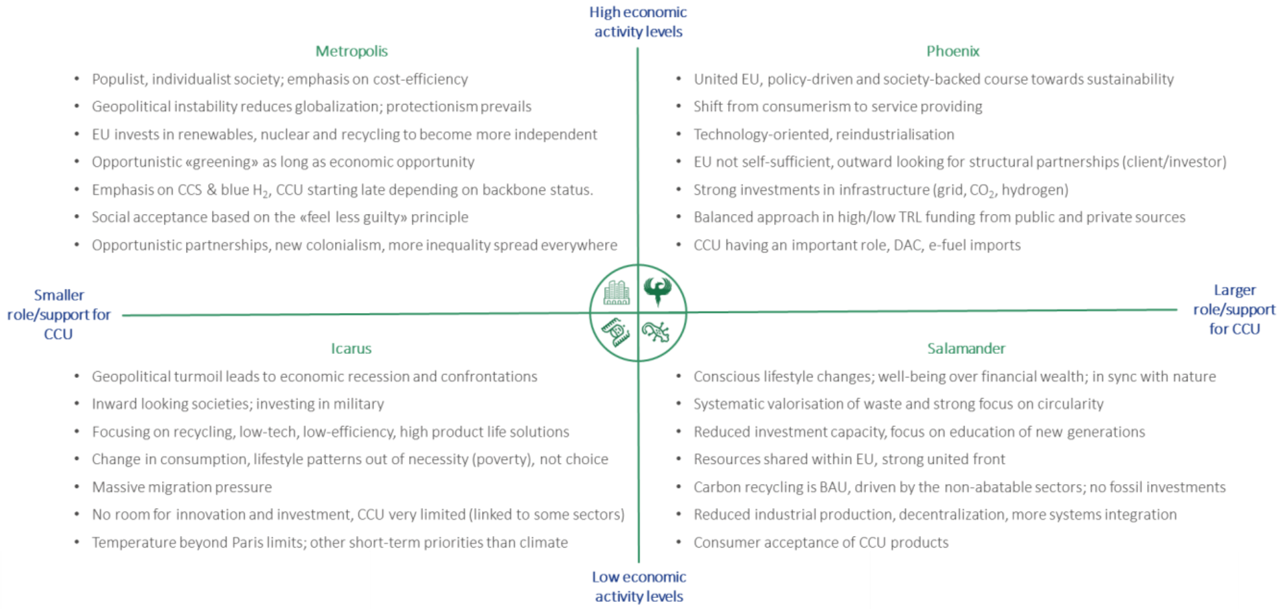

FIGURE 3. **Description of four contrasted scenarios**

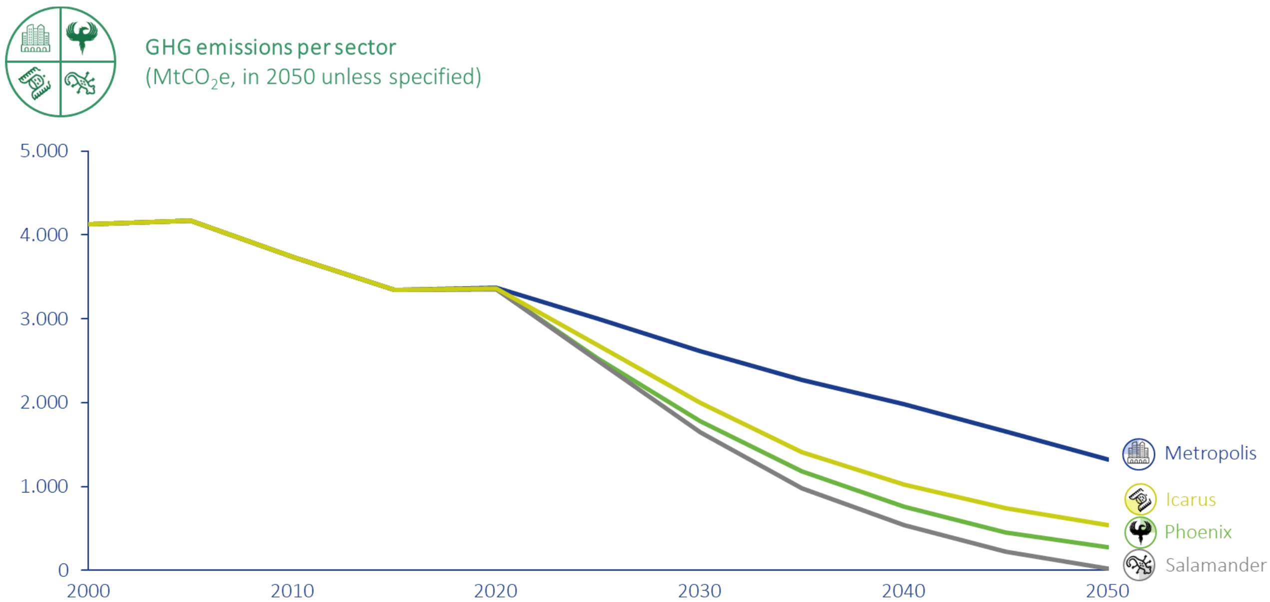

FIGURE 4. **Net GHG emissions of the contrasted scenarios**

Identification of representative CCU pathways. The experts have collectively identified some representative CCU pathways and their technical information (in terms of material and energy inputs, product outputs, emissions, etc.) were included in the Pathways Explorer model (see Annex II for more information on the model); *namely e-methane, Fischer-Tropsch liquid synthetic fuel, e-methanol, CO_2 to olefins, concrete curing with CO_2 and CO_2 mineralisation in industrial waste)*.

<u>Description of the “CVE Expert Vision” scenario</u>. The four contrasted scenario were analysed to frame a balanced and scientifically credible CVE expert vision. The objective was to reach the highest values possible in term of GHG emission reduction, amount of non-(virgin-)fossil carbon available for utilisation and the percentage of CCU product penetration in the market while reducing as much as possible the impact on planetary boundaries including the use of water, land and raw materials, hence the amount of energy[17,18] (Table 2). Combining information on societal changes and technological levers of the representative CCU pathways, the “CVE Expert Vision” scenario has been modelled using the CLIMACT Pathway Explorer 2050 and the results of this exercise are discussed in the following sections. Please note that assumptions used as model inputs are detailed in Annex I.

TABLE 2. CVE Expert Vision Scenario vs. the four contrasted scenarios

	EU Emission reduction (vs 2022)	Final energy demand	Societal changes	Technology level	Carbon demand for CCU	% of CCU penetration	Electricity consumption (CCU/Total)	Water consumption	Material consumption	Impact on planetary boundaries	EU energy sovereignty
Salamander	-99%	7100 TWh	High	Medium	123 Mt CO_2	Fuels:9% Chemicals: 5% Concrete: 20%	22% 858 TWh/3970 TWh	Low	Low	Low	High
Phoenix	-85%	10300 TWh	Medium	High	305 Mt CO_2	Fuels:12% Chemicals: 28% Concrete: 20%	26% 1658 TWh/6360 TWh	High	High	Medium	High
Metropolis	-31%	14600 TWh	Low	Medium	5 MtCO2	Fuels: 0% Chemicals: 0% Materials 0%	2.5% 181 TWh/7440 TWh	High	High	High	Low
Icarus	-75%	7240 TWh	High	Low	9 Mt CO2	Fuels: 1% Chemicals : 0% Materials: 0%	5% 130 TWh/2420 TWh	Low	High	Medium	Medium
Vision	-100%	8868 TWh	Medium-high	High	173 MtCO_2	Fuels 10% Chemicals 30% Concrete 20% Ceramics 76%	22% 1187TWh/5328 TWh	Medium	Medium	Low-Medium	High

2.2. The CLIMACT 2050 Pathways Explorer webtool

CO_2 Value Europe has collaborated with the consulting company CLIMACT to develop an open-access web tool to quantify the climate-mitigating contribution of CCU as part of a more holistic model integrating both technological and behavioural elements. This model, the 2050 Pathways Explorer, is a step-by-step solution supporting organisations with a robust analytical foundation and enabling the development of energy transition scenarios based on credible and transparent assumptions. In this exercise, the assumptions are mainly based on the CVE Vision scenario 2050 built during the scenario development process (see Annex I).

The Pathway Explorer is an open-source web-based tool which enables to explore possible futures and assess the implications and trade-offs of their choices. Simulations can be performed in real time, offering a direct understanding of the key levers of the low carbon transition. The exploration scope encompasses the energy system and its dynamics, all GHG emissions, and the associated resources and socio-economic impacts.

This is the first time that CCU is included in such a holistic climate & energy model and as such, not only the results of the modelling but also the tool itself are important outcomes of this exercise. We consider this exercise as the beginning of a continuous development of this publicly accessible web-tool. More CCU pathways will be included in the future and further inputs (e.g. costs) will be continuously added or refined, reflecting the dynamic character of the tool and the opportunity it provides for every user to explore the contribution of CCU in different points in time. Further details on how to use and navigate through the 2050 Pathways Explorer can be found in Annex 2.

2.3. Modelling Results

2.3.1. Can CCU contribute to reach climate neutrality by 2050?

"The EU will not reach climate neutrality without CCU as climate-mitigating solutions. These technologies play a significant role by reducing greenhouse gas emissions and by providing alternative carbon feedstock to produce essential products and substitute virgin fossil carbon use in several key sectors of the EU economy."

The road to net zero emissions by 2050 in the EU has been modelled using the CLIMACT pathways explorer. The results confirm the widely reported emission reduction gap between climate objectives and the stated policy measures[19] and show that approximately 2/3 of the effort will have to come from new measures including deeper societal changes (~30%) and further technology development (~37%) including the implementation of CCU solutions representing 8% of total emission reduction in the EU and 21% of the technological effort to reach climate neutrality (Fig 5).

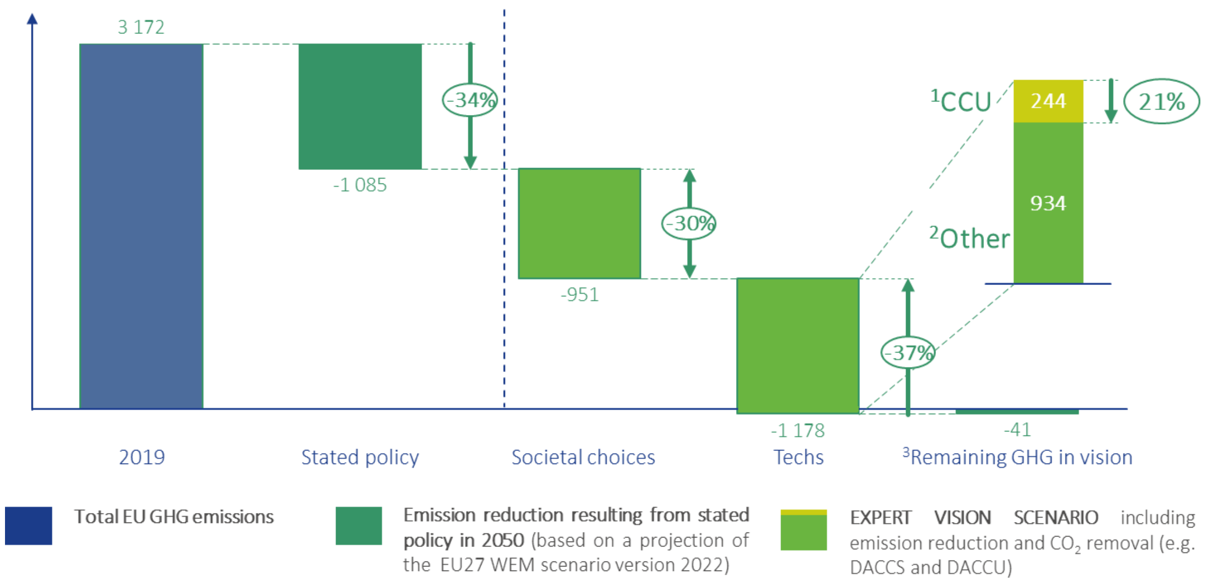

FIGURE 5. **Impact of categories of actions to reduce overall GHG emissions in the EU until 2050.***
[1]This includes the benefits of CCU-fuels imported from outside the EU;
[2]Others: Aggregated benefits of actions on low carbon electrification, technology switch, efficiency improvements, fuel switches and CCS;
[3]Final value of remaining GHG emissions in 2050 is sensitive to small changes in the modelling and may vary from +/-50 Mt due to high sensitivity of results for land-use carbon sinks.

2.3.2. How can CCU contribute to reducing greenhouse gas emissions in the EU?

"By 2050, CCU will play a significant role to reduce EU emissions in transports (-11%) and industries (-20%) through the use of captured carbon to produce CCU fuels, chemicals and building materials."

In the EU industry sector, the largest reduction of greenhouse gas emissions (-60%) will come from higher investments in technological development and large-scale improvements in energy efficiency. However, CCU will also play a significant role reducing emissions by at least 20%, including 11% in the chemical industry, 7% by using CCU fuels and

[*] Data calculated with the CLIMACT 2050 Pathways Explorer Model

2% by capturing CO_2 permanently in building material via mineralisation (Fig. 6). More than the net greenhouse gas emission reduction it achieves, CCU is crucial to substitute the use of virgin fossil carbon, i.e. "defossilise" the EU industry, create more feedstock sovereignty and ensure access to renewable fuels for sectors that cannot be electrified on the required timescale. Moreover, to reach net zero, residual emissions, e.g. from process emissions, will need to be compensated by Carbon Dioxide Removal (CDR).

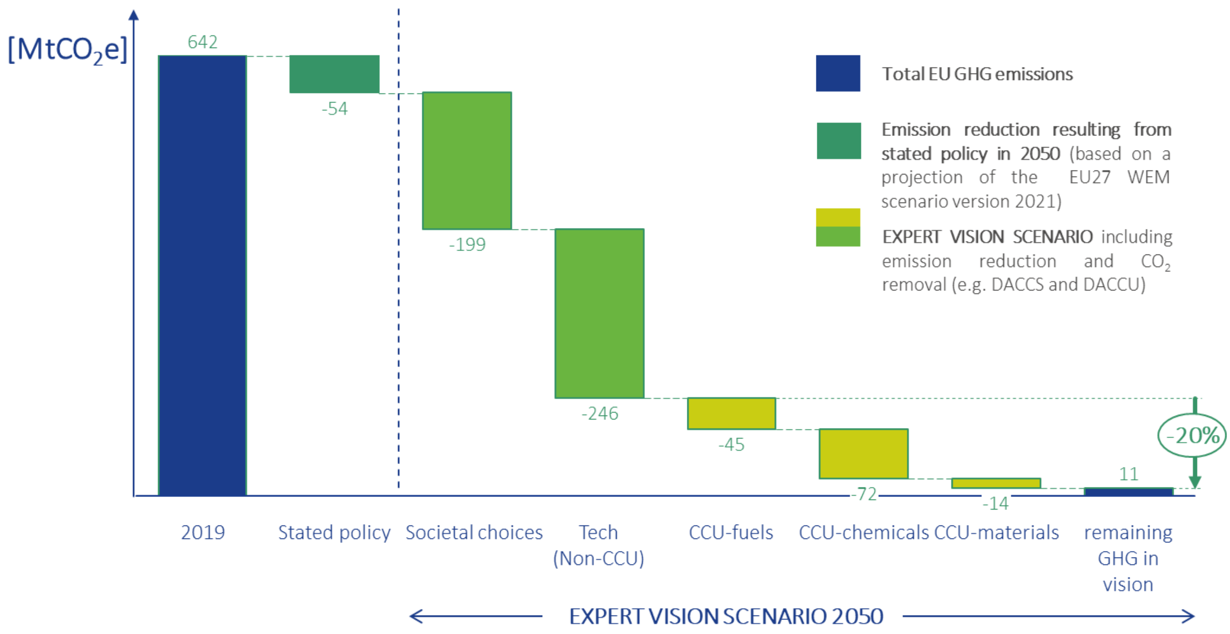

FIGURE 6. **Impact of categories of actions to reduce GHG emissions in the EU industry until 2050.***

In the transport sector, existing policy measures will only induce 26% of the required emission reductions (REF). Therefore, added measures are urgently required to lowering the demand for fuels, increasing electrification and further deploying renewable energy systems. Moreover, a switch to non-fossil fuels especially for sectors that cannot be easily electrified on short timescale, i.e. the aviation, maritime, heavy duty and long-haul transports is crucial. Considering the emergency to decrease emissions from transports worldwide, alternative fuels that do not require massive changes of infrastructure and present drop-in solutions should be more widely used today. This potential can be acquired by both biofuels and CCU fuels produced using captured carbon and renewable, recycled or low carbon hydrogen as feedstock. Biofuels present limited opportunity due to feedstock availability constraints and blending limitations. Hence, CCU fuels are essential to answer the residual fuel demand by 2050 and substitute as much as possible fossil fuels. As described in our vision CCU-fuels will represent 60% of the fuel demand in the aviation and maritime sector and 10% of fuels used for inland transports by 2050. By 2050, CCU-fuels emissions will be captured to close the loop and avoid emissions from these sectors.

By 2050, 11% of emission reductions in transports will be coming from CCU fuel usages. Greenhouse gas emissions from the maritime, aviation and inland transports (including heavy duty and long-haul vehicles as well as inland waterways) sectors will be reduced by 35, 38 and 2% respectively (Fig. 7).

*Data calculated with the CLIMACT 2050 Pathways Explorer Model.

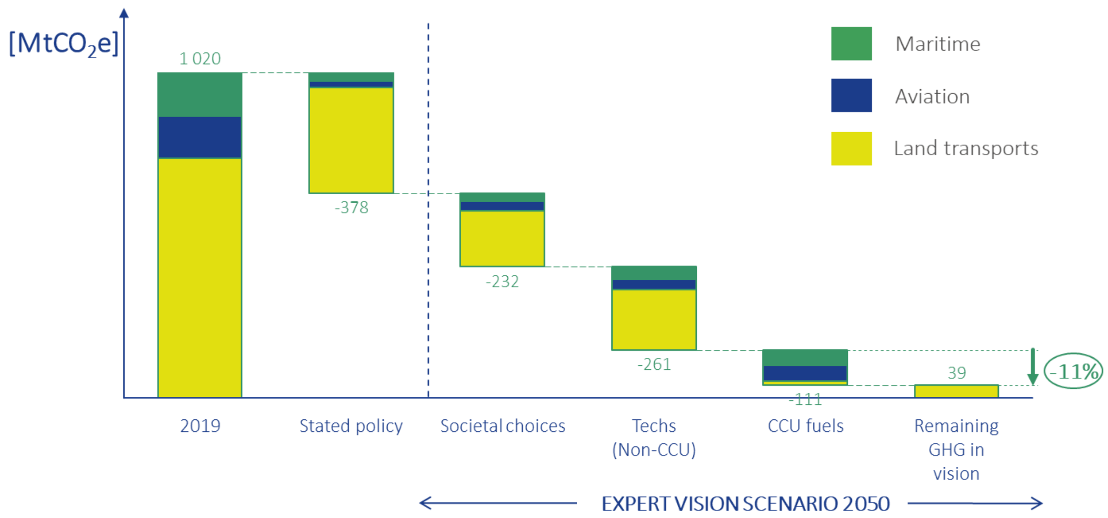

FIGURE 7. **Impact of categories of actions to reduce greenhouse gas emissions in transport until 2050. Land transport includes heavy duty and long-haul road transport as well as inland waterways.***

2.3.3. Where will the captured carbon come from?

"In 2050, the main sources of carbon captured will be direct air capture and industries with unavoidable process emission, but some level of point source capture of fuel combustion (CCU fuels, biofuels and residual fossil fuels) and upgrading of biogas will remain."

Most the of the carbon will be captured at point sources until 2035 while DAC is brought to scale. Then, DAC will need to pick up to supply enough CO_2 for all the desired CCU applications. To reach climate neutrality in the EU, 320 $MtCO_2$ will need to be captured by 2050. Modelling assumes that 46% will come from DAC, 23% from process emissions, 23% from biogenic sources, 2% from CCU fuel combustion and 6% from the residual fossil fuel emissions. Industries with unavoidable process emissions (e.g. lime plants), will remain together with DAC, the principal suppliers for captured carbon used in CCU products, but the emissions from hard-to-abate sectors is assumed to decrease over time as the production methods change (Fig. 8).

Based on our modelling assumptions, a fast ramp-up of carbon capture in industries with high process emissions and of DAC is crucial to answer the CCU product demand by 2030 and start substitute fossil-based products.

[*] Data calculated with the CLIMACT 2050 Pathways Explorer Model.

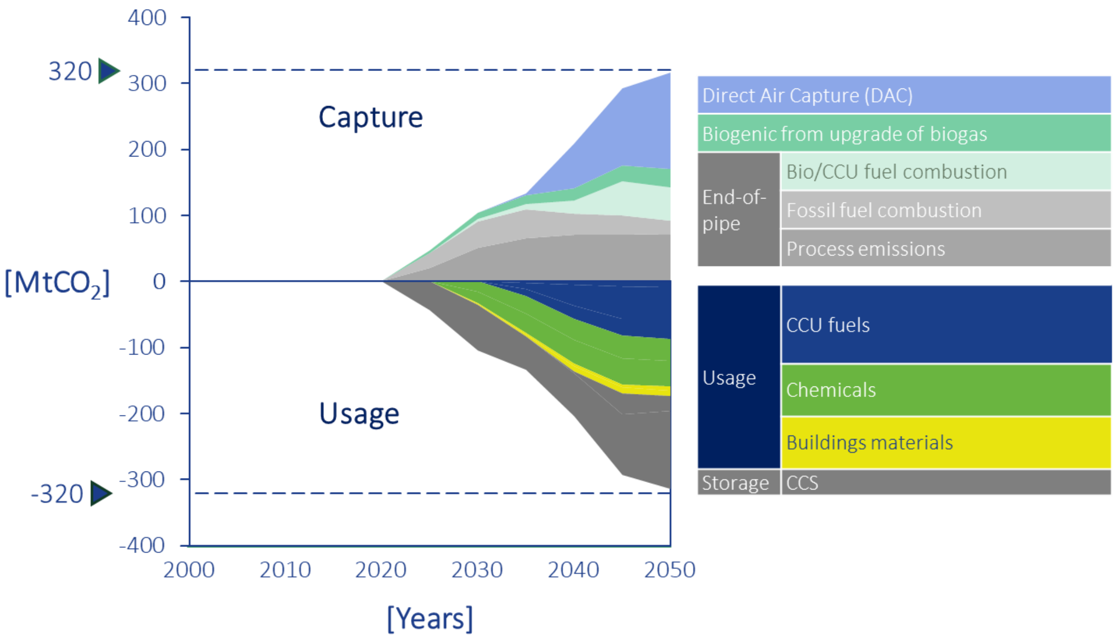

FIGURE 8. **Carbon Capture, Usage and Storage applications based on the CVE expert vision scenario 2050***

2.3.4. How will the captured carbon be used?

"In 2050, 55% of the captured carbon will be used as feedstock to answer the non-fossil carbon demand and the rest will be stored underground via CCS. From the 173 MtCO₂ utilized, 50% will be used to produce CCU fuels, 42% for chemicals production and 8% will be mineralised in building materials."

Fuels: They will provide 1161 TWh by 2050 and use the largest amount of CO_2 among CCU applications (50%). 474 TWh will be produced for international aviation and maritime transports, 178 TWh in inland transport (including heavy duty road vehicles and inland waterways) and 509 TWh to replace fossil fuels in industries. It represents a share of CCU fuel per sector of 69%, 21% and 18% respectively (Fig. 9). The EU has the potential to produce at least 55% of the demand of CCU fuels, the rest will need to be imported. Domestic and imported CCU fuels are considered in our quantification and the CO_2 capture outside Europe to answer CCU fuel demand in the EU is accounted for in Fig.5,6 and 7.

* The results are from the CLIMACT 2050 Pathways Explorer Model.

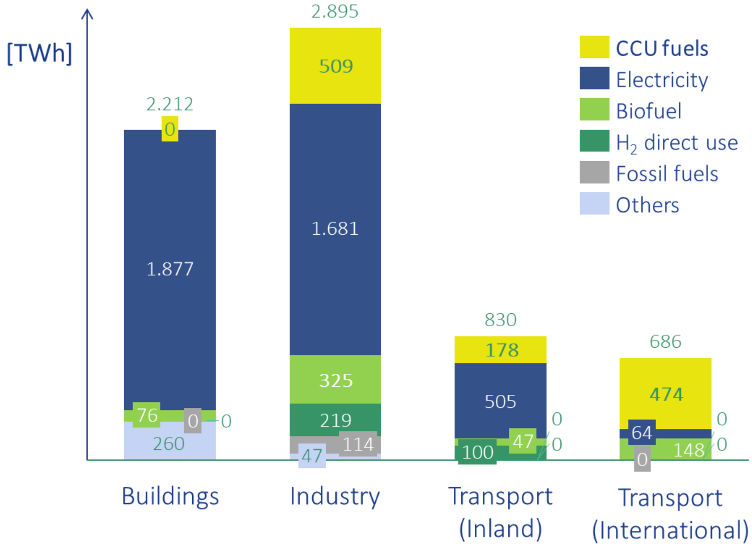

FIGURE 9. **CCU fuel usages per sector represented by the final energy consumption by energy carrier [TWh]. Land transport includes heavy duty and long-haul road transport as well as inland waterways. International transport includes mainly aviation and maritime transports.***

Chemicals: Olefins represent key components of the chemical industry and their production, depending today on virgin fossil gas and oil, is expected to increase because of an increasing global population and rising living standards. In the CVE Expert Vision, the olefin demand decreases from 65 Mt to 50 Mt by 2050, because of increased material efficiency and circularity. We show that CCU has the potential to become a key alternative to virgin fossil carbon use and contribute to at least 70% of the primary production of olefins by using renewable energy and captured carbon as feedstock. This represents 30% of the total olefin production (including the secondary routes) (Fig. 10).

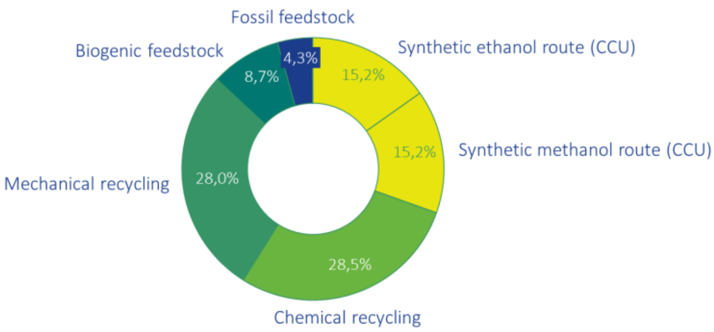

FIGURE 10. **Contribution in 2050 of the different pathways to produce olefins, a widely used chemical building block [Mt].***

Building materials: CO_2 can be stored permanently in building materials via mineralisation. This process has the potential to sequester permanently at least 4% of the carbon captured. It can produce about 76% of total ceramics

* Data calculated with the CLIMACT 2050 Pathways Explorer Model.

production (99Mt) and 100% of precast concrete can be CO_2 cured which represents 20% of the total EU concrete production (900Mt) (Fig. 11).

By 2050, at least 14 $MtCO_2$ (10% of the total CO_2 stored) could be channeled in building materials using carbonation of industrial wastes and CO_2 curing. CO_2 mineralisation does not only reduce CO_2 emissions, it has also the potential to perform CDR when the CO_2 captured comes from DAC or biogenic sources is stored permanently in building materials.

This share would be higher if more technologies such as Substitute Cementitious Material (SCM) or recycled concrete would be included in the model. This will be the next improvement step of our model approach.

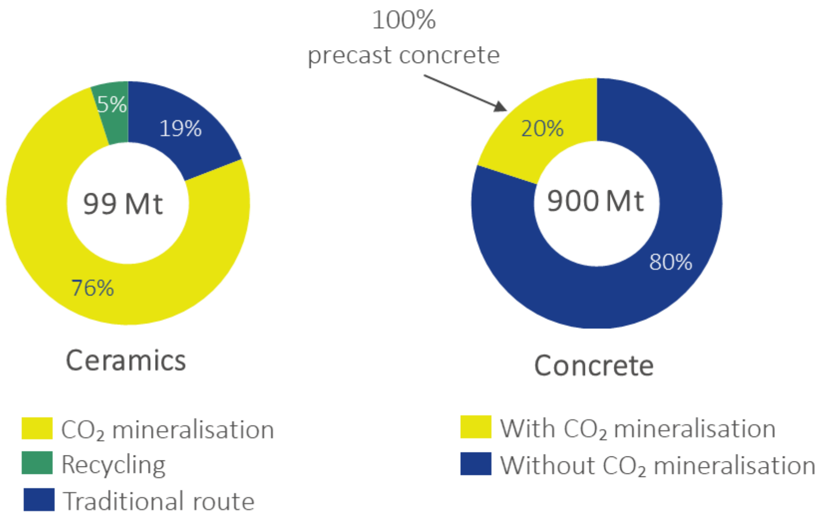

FIGURE 11. **Production of building materials [Mt] in 2050.***

2.3.5. What will be the electricity consumption of CCU technologies in 2050?

"CCU related technologies required a significant amount of low carbon electricity, but the EU has the potential to produce more than half of the CCU fuels demand by 2050 to move away from fossil fuels, increasing energy sovereignty and reducing greenhouse gas emissions".

The domestic production of CCU fuels and chemicals for the transport and industry sectors will require up to 1187 TWh (including DAC, carbon capture at point sources, production of H_2 and fuel production) in 2050 which represents approx. 22% of the modelled low carbon (i.e., renewable and nuclear) electricity production in the EU by that year (Fig. 12).This share can be reduced by reducing CCU fuels demand, by improving energy and material efficiency of CCU technologies, by optimizing the deployment of renewable systems and recycling energy from industrial processes or by importing higher share of CCU fuels (45% imports for now) or hydrogen (30% for now). In our assumptions, CCU fuels imports are assumed to be produced by low carbon electricity hence significant constrains exist as well on the amounts of products that can be imported, and they are taken into account in EU GHG reduction calculations.

* Data calculated with the CLIMACT 2050 Pathways Explorer Model.

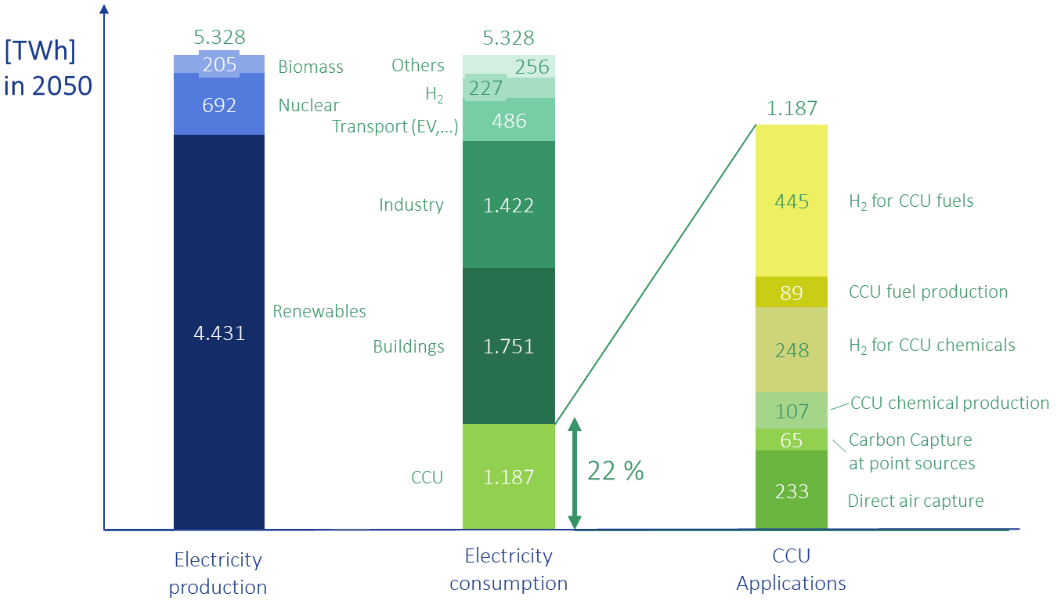

FIGURE 12. **Electricity consumption of CCU related technologies (right) compared to other sectors (middle) and electricity production mix in the EU (left).***

2.3.6. What is the role of CCU fuels to ensure energy sovereignty in the EU?

IPCC[7] and IEA[20] scenarios show that phase-out of fossil fuel extraction is required to reach global climate targets by 2050. The EU has the potential to decrease primary energy consumption by combining energy efficiency improvements, technological breakthroughs, and societal changes. Despite the need for some imports of CCU fuels and H_2 to answer the demand of non-fossil carbon feedstock, CCU fuels, together with renewable energy developments and electrification will therefore help strenghtening EU energy sovereignty and decrease import of primary energy from 60% (today) to 10% (by mid-century). (Table 3).

TABLE 3. Evolution of EU energy sovereignty between 2021 and 2050 based on our CVE expert Vision. *

EU energy sovereignty (TWh)	2021	Vision 2050
Primary energy consumption	15248	8850
Imports of fossil fuels	9443	277
Imports of CCU fuels and H_2	negligible	698
Energy dependency	> 60%	11%

* Data calculated with the CLIMACT 2050 Pathways Explorer Model.

2.3.7. What are the next steps?

This exercise is the first stage of long-term process to monitor and quantify the role of CCU to contribute to climate neutrality in the EU. One of the main results is the creation of the first-of-a-kind open-access CCU model to explore and put in context the contribution of the different CCU pathways in the EU.

The next stages will focus on adding more CCU technological pathways in the model as well as developing cost information. Also, new developments should soon allow better quantifying of the impact of technological developments on planetary boundaries.

Further elements that could be considered in future versions of this exercise are related to e.g. CO_2 infrastructure, public acceptance, and products standardisation.

3. Recommendations

The modelling results of CVE Vision scenario have provided quantified answers to a series of questions on the role that CCU can play towards reaching to EU's climate and circularity goals, with a focus on the 2050 carbon neutrality milestone. To fulfil this role and allow CCU to realise its potential, a series of actions are needed.

The following recommendations are focusing on the policy level but further elements from a social (e.g. consumer and public acceptance), technical (securing consistent funding along the TRL scale) and economic point of view (e.g. integrating public and private financing) will need to be addressed. Basing on the results of the current exercise, CVE will develop a holistic set of recommendations to see CCU deploy in an accelerated pace.

RECOMMENDATIONS on EU policies for an accelerated CCU deployment

- **Refer explicitly and systematically in relevant EU instruments (Net Zero Industry Act, EU climate targets for 2040, future ETS revision, Industrial Carbon Management Communication, future European Climate Law, etc.) to the three core CCU pathways, i.e., fuels, chemicals and mineralisation**, and their different impacts and roles to "defossilise" the EU economy.
  - **Set clear distinctions between different options of industrial carbon management**, i.e., rather than referring to "CCUS", the EU should refer distinctly to CCU, CCS and CDR respectively, whilst acknowledging that specific CCU pathways can be considered CDR (e.g. biogenic CO_2-to-mineralisation, DAC-to-mineralisation). We ask EU policy-makers to consider CCS, CCU and CDR pathways not as competing, but rather as different levers needed.
  - Acknowledge the contribution of CCU in emission reduction and carbon removals by **including ambitious targets for 2030, 2040, 2050 for all strands of CCU products** (following the example of ReFuel EU Aviation and REDII, expand to CCU fuel targets for maritime transport under FuelEU Maritime, to the role of CCU fuels in the emission standards of HDV and long-haul transport, to CO_2-based carbon content in chemicals and plastics and to mineralisation products). This will be equivalent to explicit targets for hydrogen under the RePowerEU or for CCS under the NZIA.
    - Our exercise has revealed targets for CCU products with a focus on a 2050 horizon. Intermediate goals for 2030 and 2040 can be derived in further concertation with European stakeholders and aligned with the modelling exercise currently undertaken by the EU for the 2040 targets.
  - **Set as a clear target of the EU Industrial Carbon Management Communication the definition in future EU regulations of new legal obligations to use alternative carbon feedstock, including captured carbon**, for the production of chemicals and mandate incorporation targets for renewable materials in a wide variety of everyday products (e.g. packaging, textiles, etc.). The inclusion of such targets will be central to make alternative carbon feedstock and carbon circularity a reality. **This will materialise and translate into mandatory target the aspirational 20% goal** for non-fossil carbon that has already been announced **through Sustainable Carbon Cycles Communication** as a way to move away for fossil resources.

- **Support the deployment and strong upscaling of carbon capture** by considering it strategic as a standalone activity. Regardless of the finality (utilisation or storage), capturing carbon is the first step and as such crucial to reach climate goals through CCU, CCS and CDR.
    - We recommend for the EU to **distinguish clearly the unavoidable** fossil emissions (e.g. from process emissions such as lime or cement production) from fossil emissions from the use of fossil fuels which could be substituted. By doing so, the EU will ensure that capture of carbon focuses on the hardest to abate sectors.
    - We recommend for the European Commission to provide a detailed impact **assessment on the availability of CO_2 sources** (atmospheric, biogenic, fossil) to inform future policy-making decisions, reviewing also the phase-out date for the use of unavoidable CO_2 after 2040, and to possibly foresee shortage of supply of CO_2 for CCU, CCS and CDR targets by 2050.
    - It is important to consider **CO_2 transport infrastructure network** in the future development of infrastructure scenarios (e.g. Ten Year Network Development Plan) and that this consideration is done in conjunction to further infrastructural issues that will determine CCU deployment, like the development of a hydrogen backbone and the expansion of the renewable electricity grid capacities.
    - Our exercise has shown the **importance of Direct Air Capture** for the provision of sufficient CO_2 into the downstream activities. Further funding support adapted to this technology is necessary (e.g. including DAC better into the Innovation Fund scope).

- **Lay out the ground for strengthening the EU legislations to incentivise further CCU and CDR projects,** building on the latest progresses made at EU level:
    - The new ETS legislation asks for an assessment by 2026 to **account for CCU products that are not permanently binding CO_2 into a product**. This will be a crucial milestone for deployment of CCU for chemicals in particular. It is important that this accounting ensures that all emissions are accounted for, that no double counting takes place and that all stakeholders along the CCU chain find an incentive to invest and implement CCU solutions – and that the use of captured carbon is rewarded rather than maintaining rules that penalise it compared to using additional fossil resources as is the case now. Future rules also need to create a clear interest for emitters to invest into CCU technologies, as is the case for other low carbon solutions. The inclusion of the waste-to-energy sector in ETS will also be crucial to drive more CCU projects in incineration.
    - The adaptation of the Delegated Acts of REDII to provide legal certainty for the **production of RFNBO and RCF domestically and abroad** (e.g. with an appropriate definition of a carbon pricing mechanisms and reflection on the deadline of CO_2 eligibility from unavoidable industrial emissions after 2040). Our results show that energy sovereignty can be strengthened with a significant (55%) domestic production, but that imports will be still needed. Internal cooperation and coordination will therefore be crucial so that compliance with EU rules is considerate of specific circumstances at different geographies.

- **Ensure synergy between actions at EU level and transposition at Member State level**
    - **Support the inclusion of CCU deployment in national climate and energy legislations and schemes** (e.g. National Energy and Climate Plans or National Recovery and Resilience Plans) mirroring the work undertaken in the EU Temporary Crisis & Transition Framework but in a more long-term perspective.
    - **EU regulations should drive State Aid support and investments** towards net zero technologies such as CCU, as one of the levers of energy sovereignty.
    - **Accordingly manage public funding instruments at EU and MS level like the Innovation Fund or Important Projects of Common European Interest** with frontloading with increased budget especially during the following 2-3 years so that plants at industrial scale can be operational already within the 2030 milestone.

4. References

[1]Detz RJ and B van der Zwaan. Transitioning towards negative CO_2 emissions, Energy Policy 2019; 133:110938.

[2]Breyer C, Fasihi M, Bajamundi C, Creutzig F. et al. Direct Air Capture of CO_2: A key technology for ambitious climate change mitigation, Joule 2019; 3:2053-2057.

[3]Sapart et al., Climate Change Mitigation: The contribution of Carbon Capture and Utilisation (CCU), GHGT 16, 2022; SSRN-id4286792.

[4]De Kleijne K, Hanssen S V, van Dinteren L, Huijbregts M A J, van Zelm R, de Coninck H. Limits to Paris compatibility of CO_2 capture and utilization, One Earth 2022; 5:168-185.

[5]Global CO_2 Initiative (GCI), Implementing CO_2 Capture and Utilization at scale and speed: The path to achieving its potential, 2022, available at: https://deepblue.lib.umich.edu/handle/2027.42/174095.

[6]Mertens et al., CCU: More than Hiding CO_2 for some time, Joule 2023; 7: 442-449.

[7]IPCC AR6 WG3. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

[8]Hepburn C, Adlen E, Beddington J, Carter E A, Fuss S, Mac Dowell, N, Minx J C, Smith P, Williams C K. The technological and economic prospects for CO_2 utilization and removal, Nature 2019; 575:87-97.

[9]Koytsoumpa E I, Bergins C, Kakaras E. The CO_2 economy: Review of CO_2 capture and reuse technologies, The Journal of Supercritical Fluids 2018; 132:3–16.

[10]Artz J, Müller T E, Thenert K, Kleinekorte J, Meys R, Sternberg A, Bardow A, Leitner W. Sustainable conversion of carbon dioxide: an integrated review of catalysis and life cycle assessment, Chemical Reviews 2019; 118, 2:434-504.

[11]Kätelhön A, Meys R, Deutz S, Suh S, Bardow A. Climate change mitigation potential of carbon capture and utilization in the chemical industry, PNAS 2019; 116 (23):11187-11194.

[12]Di Maria A, Snellings R, Alaerts L, Quagheber M, van Acker K. Environmental assessment of CO_2 mineralisation for sustainable construction materials, International Journal of Greenhouse Gas Control 2020; 93: 102882.

[13]Ostovari H, Müller L, Skocek J, Bardow A. From unavoidable CO_2 Source to CO_2 sink? A cement industry-based on CO_2 mineralization, Environmental Science & Technology 2021; 55 (8):5212–5223.

[14]Gong J, English N J, Pant D, Patzke G R, Protti S, Zhang T. Power-to-X: lighting the path to a net-zero-emission future, ACS Sustainable Chemistry & Engineering 2021, 9 (21):7179-7181.

[15]Farfan J, Fasihi M, Breyer C. Trends in the global cement industry and opportunities for long-term sustainable CCU potential for Power-to-X, Journal of Cleaner Production 2019; 217:821-835.

[16]Breyer C, Tsupari E,Tikka V, Vainikka P. Power-to-Gas as an emerging profitable business through creating an Integrated value chain, Energy Procedia 2015; 73:182-189.

[17]Meng, C. and co-authors, Planet-compatible pathways for transitioning the chemical industry, PNAS 2023, 120 (8), e2218294120.

[18]Bachmann, M., Zibunas, C., Hartmann, J., Tulus, V., Suh, S., Guillén-Gosálbez, G., & A. Bardow. Towards circular plastics within planetary boundaries, Nature Sustainability 2023; 6, 599–610.

[19]UNEP, UN Emissions Gap Report 2023, available at: https://www.unep.org/resources/emissions-gap-report-2023.

[20]International Energy Agency (IEA), Net Zero Emissions by 2050 Scenario, 2023, available at: https://www.iea.org/reports/global-energy-and-climate-model/net-zero-emissions-by-2050-scenario-nze.

Annex 1 – Vision scenario assumptions

The Pathways Explorer employs more than 180 levers of societal and technological nature among different economic sectors (buildings, transport, industry, energy, etc.). As explained in Annex II, the values and trajectories behind these levers can be consulted easily and in a transparent way in the web-based tool. Table A1 provides only an excerpt of some parameters and assumptions that have been considered for the development of the Vision scenario.

TABLE A1. Examples of assumptions on model input variables – Vision scenario

Societal
Stabilization of average housing temperature at 19°C
Stabilization of the living floor area per capita
Shift towards more active transport (urban) and public transportations
High increase of the car sharing economy (shared vehicles, self-driving…)
Significant reduction of air transport (-25%)
Shift towards a sharing economy for goods
Development of circular behaviours (Reduce, Reuse & Recycle)
Shift towards a healthier diet (reduction of average calories)
Reduction of meat consumption
Technological
High renovation rates & depth (limited new constructions)
Massive switch towards heat-pumps and district heating
Electrification of the road fleet (+H_2 for some heavy vehicles)
Increased energy efficiency for cars (lighter & more efficient)
Massive electrification of the industry, H_2 for some heavy industries (steel,…)
Development of circular economy
Massive investment in renewables and grid infrastructure
Stabilization of current nuclear production
High investment in carbon capture from industries with high unavoidable process emissions
After potential electrification and efficiency investment, carbon capture is used in sector where it is more difficult to decarbonize fully
CO_2 potential from industrial sources tend to decrease over time as the production methods change (e.g.: H-DRI steel)
CCU products
Building materials: CO_2 can be stored permanently in building material via mineralisation processes. A maximal estimated potential of CO_2 used is assumed, i.e. about 75% for the production of ceramics and 20% for concrete production (estimated potential for prefabricated concrete). However, it is to be noted that other technologies have not been taken into account in the current exercise. Hence additional and larger sequestration potential is likely, but still needs to be evaluated.
Chemicals: Captured carbon can be used as feedstock with low renewable hydrogen to produce chemical building blocks. 70% of the production of primary chemical olefin, a widely used chemical building block, is based on CO_2-based chemicals (35% e-methanol and 35% e-ethanol). In this assumption, the primary demand for chemicals is reduced from 65 Mt to 50 Mt by 2050, because of increasing material efficiency and circularity.

Fuels: based on the development of regulations for quotas in the use of CCU fuels in the EU, the assumptions are as follows for the use of CCU fuels in 2050:

- **60% of aviation will be powered by CCU fuel (7% electric and 33% biofuel)**
- **60% of maritime will be powered by CCU-methanol (10% electric, 15% biofuel and 15% green NH_3)**
- **10% of land transport, mostly long-haul and heavy-duty vehicles, will be powered by CCU fuels**

Annex II – The Climate 2050 Pathways Explore model

The [Pathways Explorer](), developed by CLIMACT since 2011, serves governments and companies and NGOs in the development of energy transition scenarios at global, continental, national, regional, city, sectoral level. It provides a step-by-step support solution, creating a robust analytical foundation, enabling the development of energy transition scenarios based on credible and transparent assumptions. Behind the process is an open-source web-based tool enabling the exploration of possible futures and assessing the implications and trade-offs of their choices (Fig. A1). Simulations can be performed in a user-friendly way and in real time, offering a direct understanding of the key levers of the low carbon transition. The exploration scope encompasses the energy system and its dynamics, all GHG emissions, and the associated resources and socio-economic impacts. The user can make assumptions on socio-demographic evolutions as well as societal, technological and economic parameters and the model provides quantified outputs for KPI like GHG emissions per sector, energy use per sector, product demand and activity levels, etc.

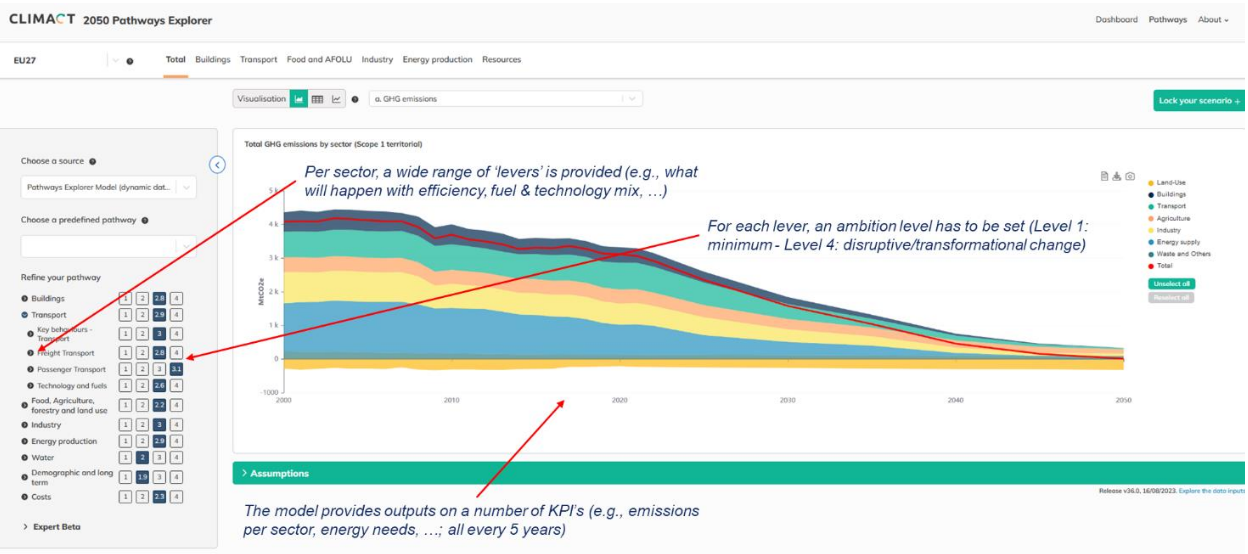

FIGURE A1. Snapshot example of the 2050 Pathways Explorer interface

What can the Pathways Explorer provide?

- A fully comprehensive and dynamic model, covering all energy sectors, direct and indirect emissions
- Assessment of the resources impact (minerals, materials, air quality, water, land-use)
- Modelling of technological, societal, cultural, behavioural choices
- Insights from large amounts of expert consultations
- An open-source model, with a real-time online webtool for reach and use

What does it not provide, and when to use other solutions ?

- High resolution in space and time. In some sectors, this additional level of resolution is useful to operationalise the Pathways (e.g., specify where and when energy is produced and consumed)
- Cost-optimization. The Pathways Explorer is a simulation model, bespoke to explore the solution space. Cost-optimization models are useful to find an optimum under constrains (e.g., assess which technologies should be deployed when, assess how a new tax impacts the optimum).
- Forecasted scenarios. No probability or specific likelihood is associated to each Pathway with this methodology.
- Macro-economic analysis. For example, jobs and GDP are not provided by the Pathways Explorer. However, the model results feed several macro-economic models.

How does it work?

The Pathways Explorer provides simulations of the energy system and takes into account a set of assumptions defined by the users as well as potential interactions between the modelled sectors. A short summary of the model inputs and outputs is described in Table A2.

TABLE A2. Type of inputs/outputs of the Pathways Explorer model

Inputs		Outputs	
Socio-demographic evolutions	(e.g., population growth, household size, urban vs. non-urban population, ...)	**GHG emissions and removals**	(per sector, per technology)
Behavioural evolutions	(e.g., mobility demand and modes, housing surfaces & renovation rates, diets, product use and lifetime, land management, ...)	**Energy use**	(per carrier, per sector, per technology, ...)
Technological evolutions	(e.g., energy mix, energy efficiency, production technologies, carbon capture rates, ...)	**Product demand** and **activity levels**	(e.g., Demand for steel, cement, construction materials, plastics, ... and how much is produced via each technology route)
Economic parameters	(e.g., price trajectories for fuels, materials and technologies, import/export rates, ...)	**Costs** *(not yet included in the current exercise)*	(CAPEX, OPEX) NOTE: Costs are calculated *ex post* (not an optimization)

This systemic approach aims at modelling coherent pathways, considering the ties between different sectors. Figures A2 and A3 illustrate the coverage and interactions among different modules of the model, respectively.

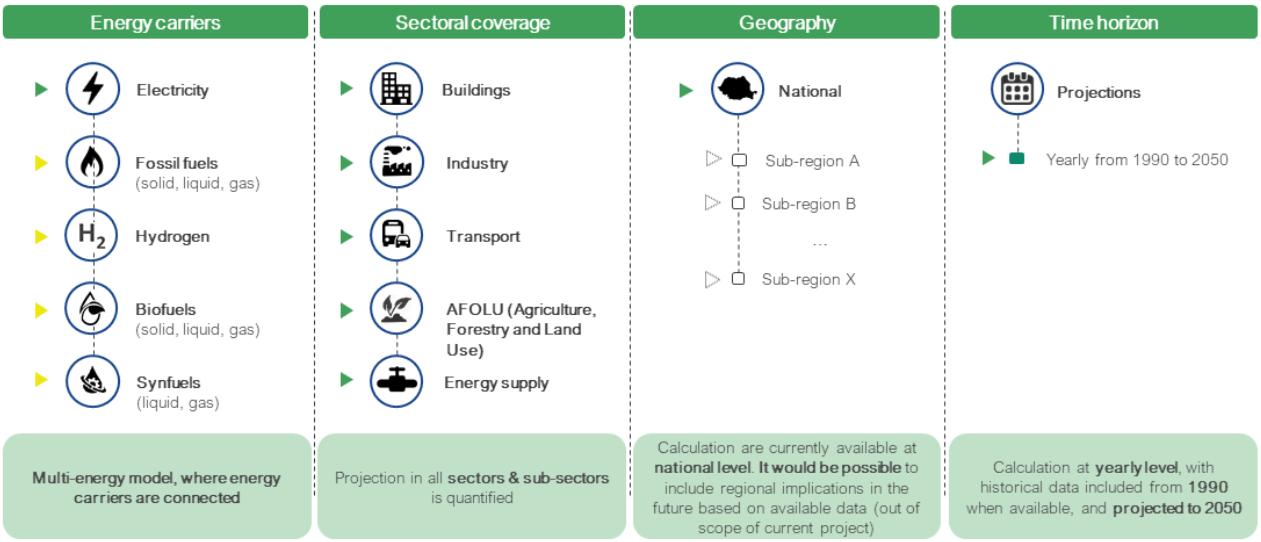

FIGURE A2. Coverage of the Pathways Explorer model

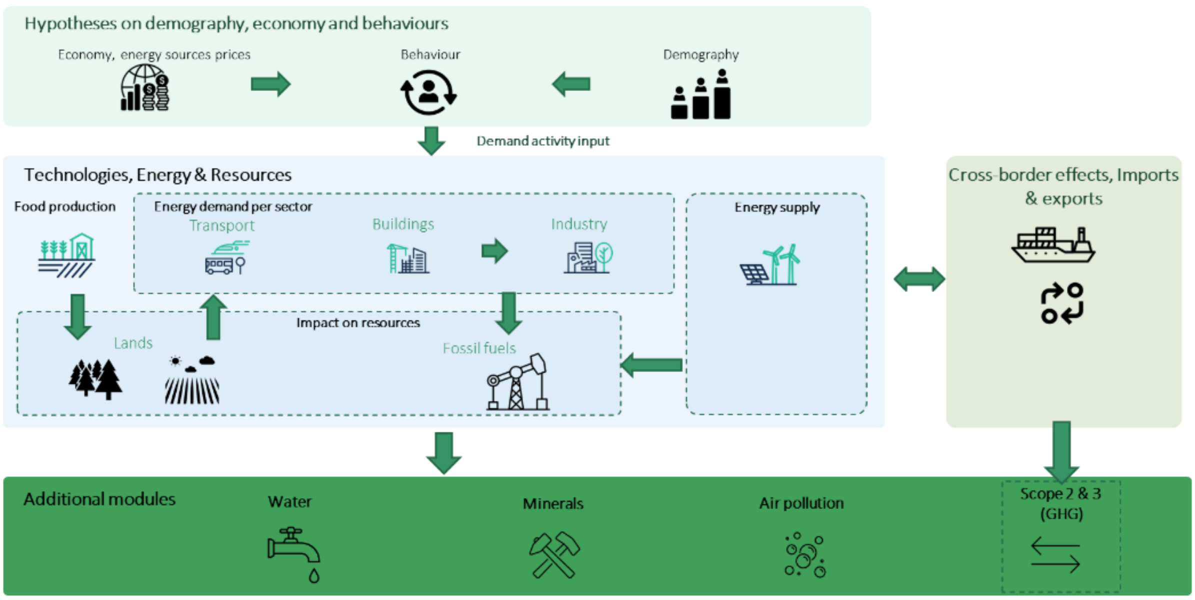

FIGURE A3. Interactions among modules of the underlying model

The technological pathways considered in this exercise are included in Table A3, however, more pathways can be implemented in the future when technical information as well as a proper assessment of product demands are available.

TABLE A3. Modelled technological pathways

Groups		Technology			
		Name	Description	Container	Replacement
Usage	CCU-Fuels	E-Methane	through methanation ⚡+H_2+☁→ CH_4	in synthetic methane	replaces natural gas
		Fischer-Tropsch process	through Fischer-Tropsch process ⚡+H_2+☁→ Synthetic fuel	In synthetic liquid fuel	replaces liquid fossil fuels
		e-Methanol	through methanol synthesis ⚡+H_2+☁→ Synthetic methanol	In synthetic methanol	replaces maritime fuels
	Chemicals	e-MTO	MTO with synthetic methanol ⚡+H_2+☁→ Synthetic methanol → Olefins	In Olefins	Fossil based olefins
		e-Dehydration	Dehydration of synthetic ethanol ⚡+H_2+☁+CO_2→ ⚡+Synthetic ethanol → Olefin	In Olefins	Fossil based olefins
	Buildings materials	Cement CO_2 curing	Curing to store carbon in the concrete Cement+☁→ Concrete	In concrete	Concrete with water based curing
		Mineralisation in waste fractions	Carbon bricks ⚡ + ☁ + Ca/Mg+...→ Ceramic	In ceramics	Ceramic bricks
Storage	Industry	CCS	Capture of industrial emissions	stored	/
	Energy supply	CCS	Capture of energy supply emissions	stored	/

Legend	
⚡	Power
☁	CO_2
H_2	Hydrogen

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