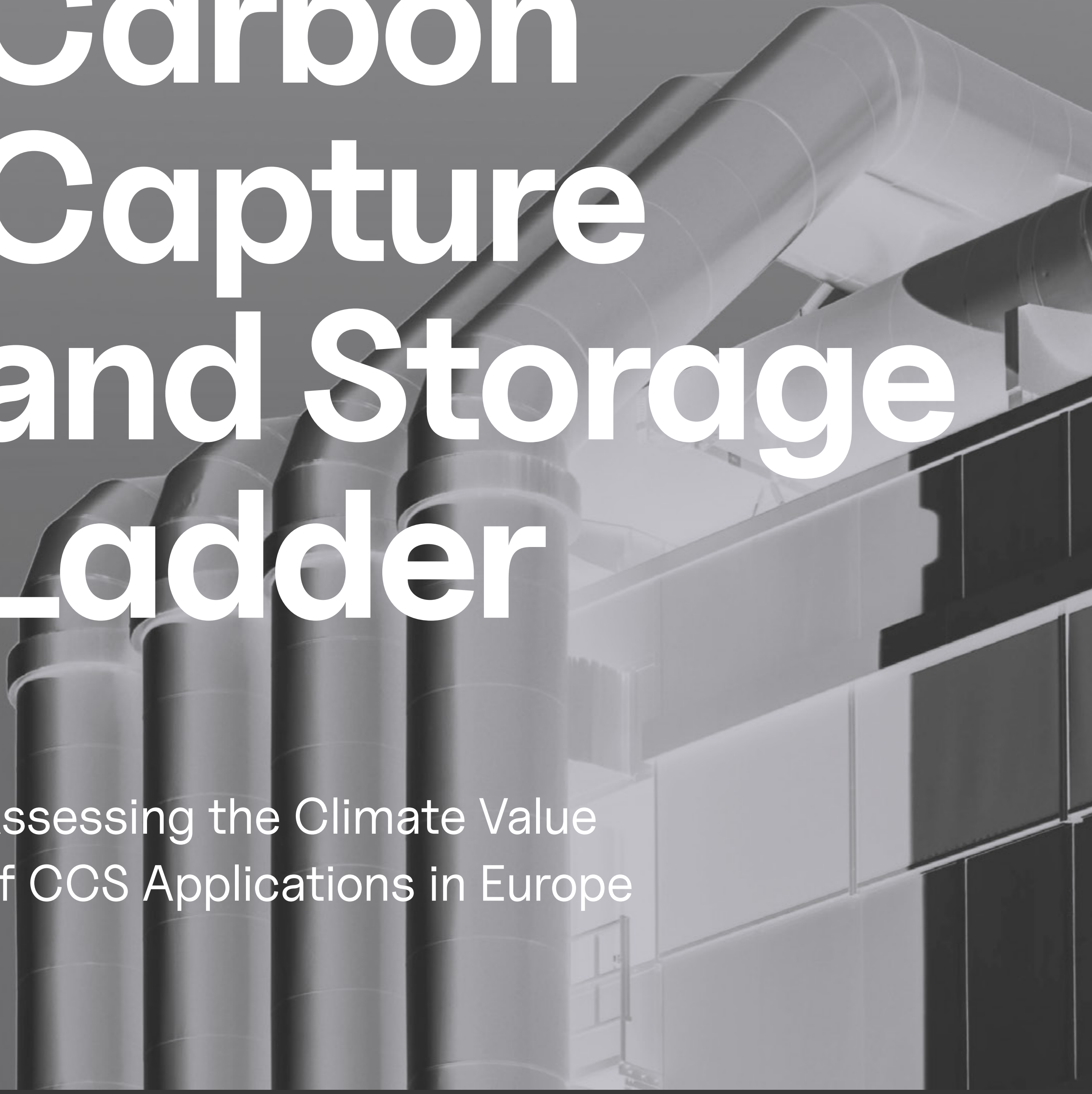
E3G BELLONA

Carbon Capture and Storage Ladder

Assessing the Climate Value of CCS Applications in Europe



Criteria and Methodology

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Criteria and methodology

At the heart of our methodology lies a multicriteria assessment that can help determine the climate value of carbon capture and storage (CCS) applications in Europe. While CCS technologies are traditionally assessed based on their emission reductions to investment ratio, we argue that determining CCS's climate credentials in the context of deep decarbonisation requires a more comprehensive approach. To do so, we need to establish the factors that facilitate the evaluation of how apt CCS is for different industrial processes.

Criteria: facilitating CCS climate assessment

We propose four key criteria to assess the climate value of CCS applications. Before discussing how we utilise these criteria to score CCS applications in the methodology section that follows, it is worth breaking the four criteria down in full and the elements that were considered in each.

1. **Competition from alternative technologies**
    - *Are there alternative low-carbon technologies, currently or soon to be available, on a scale that could produce the same good/material in a manner compatible with climate neutrality and bring forward defossilisation, without reliance on CCS? Are related feedstocks/resources such as clean energy available in sufficient quantities?*
2. **Mitigation potential**
    - *To what extent can CCS deployment reduce overall emissions and contribute to European climate goals? This covers both a system dimension (i.e., overall emission reductions potential) and single plant/good dimension (i.e., how much can the application of CCS lower its total life-cycle emissions?).*
3. **Feasibility of carbon capture**
    - *How feasible is CCS deployment in this sector? What is the techno-economic feasibility of upscaling its deployment? This considers spatial distribution and proximity to clusters (infrastructure needs), individual source sizes etc., which can all impact the system costs of CCS deployment.*
4. **Source of CO_2**
    - *What is the source of CO_2 being captured? Is there a risk of lock-in to fossil fuels by deploying CCS or other negative side-effects such as from biomass production?*

Our review of primary data availability, secondary data sources, and sectoral knowledge ultimately led us to employ these four central criteria as the best proxies for evaluating the climate value of CCS applications. We contend that these are the criteria which can best ascertain the climate value of CCS deployments for different sectors via a reasonably rigorous quantification process that scores applications on a 1–5 scale.[1] However, we do not suggest that these criteria and this broader methodology are perfect. Rather, we hope these criteria can serve as a robust starting point for future quantitative scoring exercises. More detailed justifications for each criterion selection immediately follow.

Firstly, it is important to note that, like all technologies, CCS does not have zero impact on the climate and environment. Facilitating CCS requires building considerable CO_2 transport and storage infrastructure for the captured emissions. The use of CCS can effectively lock-in fossil fuel usage – except in cases where industries have process emissions[2] – and, in doing so, also implicitly locks in the associated negative ecological, environmental and health impacts surrounding fossil fuel extraction and combustion. Consequently, if **alternative decarbonisation options** are available to decarbonise and defossilise applications, then these should typically be favoured over CCS deployments where viable. This criterion therefore effectively evaluates whether a given industrial process has a feasible alternative technological route that can decarbonise production effectively – such as electrification of heat sources – or whether industries can pivot to alternative decarbonised products that provide the same value.

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[1] See the 'Methodology: operationalising the criteria' section for further details.

[2] Defined as emissions resulting from chemical or physical transformations other than fuel combustion during the production process (IEA, 2020, The challenge of reaching zero emissions in heavy industry).

Furthermore, **the mitigation potential** of a given CCS application must be evaluated to determine the extent to which CCS can robustly facilitate decarbonisation agendas. Mitigation potential involves the analysis of a whole host of factors. These include, for example, the volume of CO_2 emissions both in terms of the overall size of sectors and their gross mass of CO_2 emissions – the larger the volume of carbon dioxide emissions, the greater the mitigation potential. Further associated factors concern the capture rates of CCS on given applications. In effect, the mitigation potential concerns the system-wide potential of a sector – that is, the (percentage) amount of their emissions that can be alleviated through CCS deployments.

The **feasibility of carbon capture** to reduce emissions at scale in a sector is also a crucial element to incorporate when considering the climate value of CCS applications. At a micro level, there may be project-specific physical constraints regarding building a CCS unit on a certain plant due to environmental issues, space and/or planning restrictions, as well as technology limitations for applying CCS to a particular industrial process such as the concentration of CO_2 in the flue gas. A holistic appraisal of such factors – and subsequent remedial actions – must be included in costing exercises for building CCS applications which may ultimately make it too expensive a decarbonisation option for emitters. Such matters would need to be evaluated on a case-by-case basis, however, and cannot be meaningfully incorporated into a robust assessment framework. Nonetheless, macro-level feasibility considerations can be included in the evaluation matrix. One notable example of this is geographical limitations. Any decarbonisation technology solution – whether CCS or otherwise – has to incorporate land-, resource- and energy-use constraints when appraising the feasibility of the solution for achieving climate aims. For example, in some sectors emitters are widely dispersed throughout Europe thereby creating practical constraints for CCS to reach its (theoretical) mitigation potential. This is because there will likely not be the necessary transport and storage infrastructure available for those polluters. In other words, industries that are less concentrated and more dispersed geographically have lower feasibility for effective sector-wide CCS.

The **CO_2 source** is the fourth and final pivotal factor that should be incorporated into any multicriteria assessment as not all sources of CO_2 are equal. For instance, an industrial process that utilises a CO_2 fuel source but is considered easy to electrify should not, on this criterion alone, be treated as an equal candidate for access to CO_2 transport and storage infrastructure as an industry that has (significant) process emissions. This is because those that can avoid their carbon dioxide generation have an obligation to do so in alignment with net zero goals, whereas those sectors with process emissions – the cement and lime industries being two prime examples – have no other options to fully decarbonise at the present time. In other words, this criterion effectively differentiates between those sectors that can decarbonise through other means – such as via technological solutions and electrification of industrial processes – and those that cannot, like cement and lime. Evaluation of the CO_2 sources therefore helps to address the risk of fossil fuel lock-in and the range of harmful effects that the fossil fuel industry has on the climate and environment.

In short, despite not having an extensive academic literature to draw upon, we contend that these four factors are the most critical components that can be suitably operationalised to determine the climate value of CCS. Ultimately, no set of feasible criteria can be fully exhaustive.[3]

In summary then, based on our criteria we argue that CCS is most valuable for instances in which all the following conditions are met:

1. There are no or limited alternatives for deep decarbonisation.
2. CCS has a significant emissions reduction potential.
3. CCS has (relatively) limited feasibility challenges constraining its scaling related to the costs, location or size of individual CO_2 sources.
4. There are limited or no negative side effects such as a substantial risk of fossil fuel lock-in.

The remainder of this methodology document is dedicated to illustrating how these criteria were deployed within our analyses.

Methodology: operationalising the criteria

This section provides further detail on how we used the four established criteria to construct the ranking matrix and resultant Ladder.

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[3] Further criteria such as the systemic and societal value of goods/materials were tested with stakeholders when developing this methodology. However, such criteria were hard to substantiate robustly without ad hoc qualitative judgements and their inclusion produced disparate and inconclusive results.

A non-exhaustive list of 26 CCS applications[4] was compiled covering a wide range of sectors. For some sectors (e.g., primary steel or hydrogen production) several production routes were included to show that the climate value of CCS can differ within an individual sector. These applications were ranked across the four criteria on a scale of 1 (lowest) to 5 (highest) using quantitative data supplemented by qualitative assessments. This was done by the authors of this briefing and tested externally through several stakeholder workshops.

From this, a multicriteria matrix is produced which can evaluate the priority need of CCS applications in accordance with climate goals, assuming long-term geological storage of CO_2 as the default. Scores across the four criteria were then averaged to give an overall numerical ranking for each CCS application. A temporal dimension was also included within this work, with scores given for industrial processes for two separate years – 2030 and 2050. These dates are aligned with the likes of the EU's 55% emissions reduction target by 2030 and its 2050 climate neutrality objective.

Accordingly, this work seeks to understand the temporal dynamics of CCS, drawing out the implications of how the changing decarbonisation landscape over the coming decades can affect the value of CCS in the near- and long-term. Indeed, implicit herein is the fact that other decarbonisation options will develop in parallel to CCS and be correspondingly pushed via policies. These include increased electrification, substitution, efficiency and circularity, as well as considerable scale-up of renewables and resulting availability of green hydrogen by mid-century. The chronological development of such solutions impacts our criteria scoring in various ways at different points in time, hence the need to rank the climate value of different CCS applications in the near- and long-term.

These rankings were thus employed to construct a CCS Ladder for both 2030 and 2050. The applications were split into a ranking classification from 'A' to 'F' based on their aggregate scores.[5] When producing the overall ranking, we aggregated the individual criterion scores without weighting. Several Ladder iterations with differently weighted criteria were developed during the testing stage and the results of these exercises produced broadly similar rankings to those present in the version ultimately presented. Consequently, the decision was taken not to weigh any criteria since the aim of this ranking exercise is to provide a systematic and transparent yet simple and straightforward evaluation of CCS applications.

Criterion #1: Competition from alternative technologies

We explored whether CCS is essential for decarbonisation in a sector or whether credible low-carbon alternative decarbonisation technologies exist. Recent studies have suggested that the value of CCS is greatest in areas where low-carbon alternatives are least well-developed.[6] Therefore, we should target the deployment of carbon capture applications where there is the least competition from alternatives. In evaluating this dimension, we considered:

1. The strength of competition from alternatives, based on their technology readiness levels (TRL) and likely cost of deployment – relative to carbon capture applications.
    - The greater this competition, the lower applications are ranked.
2. The level of process emissions associated with the production of the good/material
    - For example, in cement production roughly 60% of the emissions are process emissions related to calcination. These emissions cannot be avoided by fuel-switching and will require CCS until novel chemistries can be developed to avoid these process emissions.
    - The greater the level of process emissions that will require capture, the higher applications are ranked on this dimension.

Criterion #2: Mitigation potential

We explored the contribution that carbon capture could make in achieving European climate targets. In evaluating this dimension, we incorporated:

1. The mitigation potential at a given plant.
    - Carbon capture is often likely to be a low- but not zero-carbon option due to imperfect capture rates and upstream emissions from fossil fuel extraction.

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[4] More detail on the criteria and the 26 illustrative CCS applications can be found in this document's Annex.

[5] Category 'F' represents the bottom of the scale, incorporating processes with aggregate scores less than two while the 'A' category represents the top of the scale with processes that have aggregate scores of more than four. The intermediate categories span increments of 0.5 on the aggregate score scale.

[6] Grant et *al.*, 2021, Cost reductions in renewables substantially erode the value of CCS in mitigation pathways.

    - We therefore explored how close to a zero-carbon operation CCS could be for a given technology by evaluating the share of emissions that could be avoided by CCS relative to overall life-cycle emissions both upstream and downstream.[7]
    - The greater the process-specific mitigation potential, the higher applications are ranked on this dimension.
2. The system-wide mitigation potential of CCS on this application in 2030 and 2050.
    - This considers the process-specific mitigation potential and the likely scale of the industry itself – and related emissions – in 2030 and 2050.

Criterion #3: Feasibility of carbon capture

We assessed the feasibility of deploying CCS to reach its mitigation potential at sectoral level in Europe. While this feasibility is dependent on a whole host of factors (including plant-level abatement costs), we consider four underlying criteria which will impact the techno-economic feasibility of CCS on a system-level:

1. The size of individual sources – greater volumes of CO_2 streams are better.
2. The concentration of CO_2 gas in the exhaust stream – more highly concentrated CO_2 streams increase mitigation potential.
3. The spatial distribution of CO_2 sources – fewer, more spatially concentrated sources enhance the feasibility of CCS to deliver emission reductions at scale.
    - Assuming that all the other feasibility sub-criteria remain constant, a sector that is highly dispersed receives a score 1 point lower in 2030 compared to its scoring for 2050.
    - This is because it is presumed that there will be a (more extensively) developed CO_2 transport and storage infrastructure by 2050 that would be accessible to those industries which are highly dispersed.
4. Whether industrial sources tend to be clustered with other industrial emitters or not.

Criterion #4: CO_2 source

We considered whether CCS deployments could have substantial negative impacts. While the range of possible adverse impacts from CCS deployments is large – which is also the case for other large-scale infrastructure projects – we focus on two significant possible side effects: risk of fossil fuel lock-in and broad environmental sustainability concerns. CCS deployments where these two risks are high should thus be deprioritised against other applications which do not have such impacts.

These risks largely stem from the source of CO_2 being captured. Deciding on the relative merits of different CCS projects therefore requires a careful assessment of the CO_2 source CCS is applied to. For instance, this is particularly relevant when CCS is coupled with biomass which could, under very limited circumstances, lead to the net removal of CO_2 from the atmosphere.[8] However, a growing body of evidence suggests that the level of biomass that can be sourced sustainably for these bioenergy with carbon capture and storage (BECCS) activities is very limited.[9] For biomass to be compatible with a climate-neutral future, it must be sourced with close to zero upstream emissions from where it is produced, and in a way which protects biodiversity, soil health, freshwater reservoirs, food security, air quality, and the livelihoods of local communities who use the land.[10] As such, any use of BECCS should have very clear guardrails to protect against the possible negative impacts that the technology can have.

The Ladder values process emissions the most by scoring them as the highest value CO_2 source because such CO_2 generation is typically associated with material extraction and chemical reactions incurred during production processes of certain materials. This is not a zero-impact operation, but since the goods in question cannot avoid

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[7] A detailed assessment of feasible capture rates and overall life-cycle emissions would need to include an assessment of the energy consumption required to achieve certain capture rates, there being – in the absence of use of additional renewables capacity – an inverse relationship between increasing capture rates and decreasing overall life-cycle emissions. However, doing so is beyond the scope of this work at present.

[8] Many computational models that map decarbonised futures (e.g., integrated assessment models produced by the IPCCC) often rely on large amounts of BECCS.

[9] Energy Transitions Committee, 2021, Bioresources within a Net-Zero Emissions Economy.

[10] CEPS, 2020, Biomass and climate neutrality.

the generation of CO_2 during the production process, this source of CO_2 is deemed as less regressive than fossil/bioenergy production. The Ladder views these process emissions as effectively unavoidable if there is no other sufficiently viable path to fully avoid the process altogether by switching to alternative (technology) routes. As such, applications with process emissions are scored higher due to a lack of alternative solutions to mitigate them at present – beyond reducing their overall quantity through substitution, material efficiency, circularity, and so on.

In the aid of transparency, we have therefore ranked the four main sources of CO_2 emissions as follows:

1. **Lowest ranking** (1): **Fossil CO_2**.
    - Applications which capture fossil CO_2 can lock in dependency for fossil fuels.
    - Given the wider impacts of fossil fuel extraction and combustion such as air pollution, this source of CO_2 ranks lowest.
    - The decision was taken not to differentiate between different fossil fuels such as coal, oil, and natural gas to not encourage lock in of any one of these energy sources.
    - All industrial processes utilising fossil fuels as the primary power source for their operations were therefore scored '1'.
2. **Low-medium ranking** (2): **Part process emissions (> 15%) and general fuel mix**.
    - Applications with a small but significant share of process emissions but using a mix of mainly fossil fuels as an energy source are scored higher than those exclusively using fossil fuels.
3. **Medium ranking** (3): **Sustainable biomass**.
    - One key feature of any bioenergy operation should be that the operating plant utilises sustainably sourced biomass[11] as opposed to mass-scale artificial (i.e., short-rotation plantation) biomass.[12]
    - Deploying CCS with biomass is only compatible with climate goals if the biomass comes from sustainable sources – sources that have not been cultivated specifically for bioenergy purposes. Unsustainable biomass can even perform worse than natural gas, for example, when accounting for deforestation emissions. Not all biomass consumed by bioenergy applications is, at present, sustainably produced – we assume this is no longer the case by 2030 onwards.
    - Sustainable biomass sources are nonetheless better sources of CO_2 than fossil CO_2 as they are renewable. However, biomass cultivation and consumption is not zero-impact due to the land requirements and the resulting air pollution from combustion. Therefore, sustainable biomass receives a medium ranking of '3'
4. **Medium-high ranking** (4): **Majority process emissions and general fuel mix**.
    - Applications where the majority of emissions are process emissions complemented by a mix of fossil fuels as an energy source score relatively high.
    - Process emissions are deemed largely unavoidable due to a lack of alternative solutions at present (barring unforeseen technological breakthroughs).
    - As such, they receive a high but not a maximum score due to the fossil emissions embedded in their fuel mix.
5. **High ranking** (2030: 4; 2050: 5): **Pure unavoidable process carbon dioxide generation**.
    - Operations with pure process emissions infer that these operations are powered by electricity. As electricity generated from renewables is the cleanest form of energy, these applications with pure process emissions are scored the highest due to a lack of alternative solutions at present (barring unforeseen technological breakthroughs).
    - However, due to considerable scope 2 emissions still likely to be present in Europe's energy mix

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[11] For example, biogenic waste resulting from sustainable materials at the end of their lifecycles or biomass cultivation that is integrated into landscape diversification and habitat restoration strategies (e.g., perennial grasses; paludiculture harvested from wetland restoration).

[12] Artificial biomass is conceptualised as biological materials grown in short-rotation (monoculture) plantations specifically for the purpose of being consumed by BECCS plants with little-to-no regard for the environment.

by 2030, electricity is unable to receive a maximum ‘5’ and is therefore given a score of ‘4’.

- Only applications with pure process emissions by 2050 are scored the maximum ‘5’ as, by mid-century, it is assumed that Europe’s electricity grid is almost exclusively powered by renewables.

The incorporation of sustainable biomass[13] offers an excellent case-in-point for the value that the CO_2 source criterion has for ranking the climate value of different CCS applications. As there is likely **not enough sustainable biomass available to meet the demand for all the bioenergy processes considered**, its use must be targeted to the highest-value applications. Ideally, this would require a separate sustainable biomass ladder which applies similar considerations like those adopted for the CCS Ladder to determine the best allocation of supply for feeding into bioenergy CCS applications. Such a tool does not exist presently[14] and, therefore, discussions around the prioritisation of sustainable biomass use is beyond the scope of this analysis. Consequently, although multiple bioenergy applications might rank highly as CCS applications, further decisions would need to be taken to decide which – if any – of these applications would ultimately be valuable uses of sustainable biomass.

Methodology: exercise boundaries

We defined the parameters for this CCS Ladder as follows. Firstly, **in terms of geographic scope, we have focused on Europe – primarily the EU and neighbouring European countries** (including EFTA states). This means we have been cognisant of the need both for meeting short-term (2030) climate targets as well as climate neutrality by mid-century.

We have also assumed that carbon capture applications are **fitted on plants using the present dominant fuel mix of that plant/energy grid, inclusive**. For instance, CCS applied to an integrated steel mill would be capturing both emissions from the blast furnace and from other sources such as its auto-generation plant.

Removals in the CCS Ladder – BECCS and direct air capture (DAC)

In the initial matrix and Ladder that we produced, removals ranked relatively highly. In fact, DAC ranked as one of the highest applications on the Ladder, as did some BECCS options (e.g., hydrogen production via biomass gasification). Used to compensate for emissions which are very difficult to fully eliminate and contribute to achieving negative emissions, technological removals will play a key – but limited – role in decarbonisation.

Take BECCS, for instance. Confining BECCS operations to sustainably sourced biomass inputs alone likely limits the overall amount of biological matter able to be fed into these plants. Doing so will help minimise the possible negative environmental consequences associated with BECCS operations as well as the contention around the technology’s usage. Accounting for these climatic, ecological and social criteria therefore significantly restricts the potential of biomass for delivering net-zero ambitions.

Given the substantial challenges in upscaling carbon dioxide removals (CDR) due to the nascent nature and costs of the technology, it cannot be relied upon as an oven-ready solution today. In other words, removals should not presently be depended on to deliver at scale. **Cutting emissions – fast and deeply – must remain the priority.** Regardless, it would be amiss not to include CDR technologies within the Ladder.

As removals cannot be a substitute for ambitious emissions cuts, we have taken a nuanced approach to removals. BECCS applications utilising only sustainably sourced biomass are included in the Ladder due to the technological readiness of these applications. DAC CDR is treated separately within the Ladder visualisations to make clear that CDR should not be conflated with industrial CCS, nor distract from the need for CCS applications to facilitate ambitious emission reductions since the technology remains in its infancy.

For clarity, the high value of removals in the Ladder is not a call to expand CDR deployment at the expense of emissions cuts. Nonetheless, CDR’s inclusion supports a call to encourage R&D into removals in the hope of developing viable technological solutions while simultaneously cutting emissions, assuming large-scale CDR will not be achieved. Ideally, to complement this work, a separate ladder to rank different CDR applications would need to be devised.

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[13] Only utilising sustainable biomass as the supply inputs for BECCS activities should safeguard against the production of large-scale artificial biomass.

[14] CCC, 2018, Biomass in a low-carbon economy.

Annex

CCS applications considered

For the first iteration of the CCS Ladder, 24 illustrative CCS applications were chosen, covering both the energy sector and energy-intensive industries. This list of applications can be found in →[Table 1] below, delineated according to three aspects: **input**; **process**; **product**.

List of applications by input, process, and product

Sector	Application	Input	Process	Product
Aluminium	CCS applied to smelter	Bauxite and electricity (electrolysis) and fossil fuels (refining)	Bayer high-temperature high-pressure	Alumina
Cement	CCS applied to process emissions (electrified kiln)	Limestone and electricity	Decalcification and sintering	Cement clinker
Cement	CCS applied to combustion + Process emissions	Limestone and coal/biomass fuels	Decalcification and sintering	Cement clinker
Ceramics	CCS applied to kiln	Raw materials and fossil/biomass input	Ceramics kiln	Ceramics
Chemicals	Steam cracking for HVCs (fossil-based feedstocks)	Naphta, ethane, other fossil-based feedstocks	Steam cracking	High Value Chemicals (HVCs)
Chemicals	CCS with chemical recycling (pyrolysis or gasification)	Plastic waste	Pyrolysis or gasification, collection of side product	Syngas or pyrolysis oil
Chemicals	Ammonia	Fossil fuels	Haber-Bosch	Ammonia
Glass	CCS applied to furnaces	Raw materials and mainly natural gas	Furnace + flat glass deposit	Glass
Hydrogen	Biomass gasification	Sustainable biowaste	Biomass gasification	Hydrogen
Hydrogen	Blue hydrogen via ATR	Natural gas	Autothermal reforming (ATR)	Hydrogen
Hydrogen	Blue hydrogen via SMR	Natural gas	Steam methane reforming (SMR)	Hydrogen
Hydrogen	Black hydrogen via coal gasification	Coal	Coal gasification	Hydrogen
Lime	CCS applied to combustion + Process emissions	Limestone and coal/biomass fuels	Decalcification	Lime
Liquid fuels	Biofuel produced with CCS	Sustainable biomass	Fischer-Tropsch	Liquid hydrocarbons
Paper	CCS applied to main and recovery boiler	Mix of biomass, electricity, gas and coal	Kraft pulp mill	Paper
Power	Biomass power plant	Sustainable biomass	Incineration	Baseload electricity/heat
Power	Gas-fired power	Natural gas	Incineration	Baseload electricity/heat
Power	Coal-fired power	Coal	Incineration	Baseload electricity/heat
Refineries	Fluid catalytic cracking	High-weight fraction of crude oil	Fluid catalytic cracking	Gasoline, HVCs, other petroleum products
Steel	CCS applied to DRI-EAF	Iron ore and natural gas	Direct reduced iron and electric arc furnace	Steel
Steel	CCS applied to BF-BOF	Iron ore and coking coal	Blast furnace and basic oxygen furnace	Steel
Steel	Hisarna	Iron ore and coking coal	Cyclone Converter Furnace and Smelting Reduction Vessel	Steel
Waste	Waste incineration	Waste	Incineration	Electricity/heat
Removals	Direct air capture	Low/high temperature heat and electricity	Solid sorbent/liquid sorbent Direct Air Capture	Carbon Dioxide Removal (CDR)

Notes:

1. If installations can run on different fuels – for example, coal, substitute fuels or biomass in the case of cement kilns – we assumed that the general fuel mix would likely change over time alongside Europe's decarbonisation trajectory. That is, coal use being phased down while alternative (renewable) energies are scaled up and made more widely available.
    - Likewise, electrified installations are assumed to be powered by (nearly) 100% renewable electricity by 2050 for the purpose of this exercise.