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FINAL REPORT

Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios

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Executive summary

This report reviewed the role of CCS and CCU in Europe in decarbonisation scenarios consistent with the 1.5°C and 2°C global temperature targets. The scenarios provide insights on the combinations of technologies that could be compatible with the climate targets under different conditions. They were produced by a range of global and Europe-scale models, between which the representation of CCS and CCU technologies varies.

Published scenarios indicate that CCS is essential for Europe to reach net zero CO_2 emissions by 2050, which is consistent with the 1.5°C global target. Under a 2°C target, most scenarios suggest a prominent role for CCS, although a small number suggest low levels of deployment.

This implies that Europe needs a large-scale CCS industry to meet future targets. In the 1.5°C scenarios, the median CO_2 captured by CCS is 230-430 $MtCO_2$/yr in 2030, increasing to 930-1200 $MtCO_2$/yr by 2050. In the 2°C scenarios, the median CO_2 captured by CCS is lower with 35-100 $MtCO_2$/yr in 2030, increasing to 600-930 MtCO2/yr by 2050. There is a significant range across these scenarios, implying some key uncertainties as to the actual level that might be required.

CCS enables CO_2 removal when combined with bioenergy, provided biomass is sourced sustainably. Bioenergy with CCS (BECCS) plays a key role in the modelled scenarios for Europe. In the 1.5°C scenarios, the median CO_2 captured by BECCS is 30 $MtCO_2$/yr in 2030, increasing to 400 $MtCO_2$/yr by 2050. In the 2°C scenarios, the median CO_2 captured by BECCS is lower with 1-5 $MtCO_2$/yr in 2030, increasing to 150-230 $MtCO_2$/yr by 2050.

Scenario design strongly influences the amount of CCS deployed in both the 1.5°C and 2°C scenarios. Assumptions such as high future energy demands or low levels of renewable deployment lead to higher levels of CCS deployment, and vice versa. European-scale models were found to suggest lower levels of CCS deployment. More research is needed to understand what drives these differences.

Models indicate significant annual investments are needed in CCS in Europe until 2050 in both 1.5°C and 2°C scenarios. These amount to $14 billion (median) in scenarios consistent with 1.5°C and $11 billion (median) in 2°C scenarios.

This review does not give a clear consensus if and how CCU can play a role in European decarbonisation. Some studies foresee a significant role while others do not consider it.

Further research priorities were identified, which would provide additional important insights on the role of CCS and CCU in Europe. These include modelling to examine the optimal sectoral deployment of CCS, and to better quantify the role for CCU. This requires enhanced representation of CCU options and decarbonisation options for industry and transport in the models. A synthesis of the research, and potentially updated research, on the spatial layout of CO_2 infrastructure and the system cost implications of CCS and CCU would be beneficial. More analysis is also needed on the role of CCS in Europe in scenarios of low future energy demands, and on the risks associated with CCS failing to scale up.

1 Introduction

In the Paris Agreement adopted in December 2015, governments agreed to keep the global average temperature to well below 2°C relative to pre-industrial levels, aiming at limiting the increase to 1.5°C, as this would significantly reduce the risks and impacts of climate change (IPCC 2018). The EU and its member states formally ratified the agreement in October 2016, committing through its Nationally Determined Contribution to reduce its greenhouse gas (GHG) emissions by 40% by 2030 relative to 1990 levels. The EU's goal to achieve an 80% GHG emission reduction by 2050 is considered broadly in line with the 2°C global goal of the Paris Agreement. However, after the publication of the IPCC Special Report on 1.5°C, it became obvious that much more stringent climate targets were necessary. In November 2018, the EU set out its vision to become climate-neutral. This implies raising the GHG emission reduction target to 55% in 2030, and to 100% or net-zero by 2050. As part of the European Green Deal, in March 2020 the Commission proposed the first European Climate Law[1] to legislate for the 2050 climate target.

Numerous scenarios have been published describing European decarbonisation pathways in line with the Paris Agreement targets. These scenarios represent different ways the energy and broader economic systems could transition to low carbon (i.e. 80% reduction in GHG emissions as compared to 1990 levels) or net zero GHG emissions by 2050. They explore how the energy system would change, or need to change, under different combinations of assumptions, e.g. low biomass availability or high deployment of renewable electricity technologies, under specific climate targets. They provide insights on the combinations of technologies and policies that could be compatible with the climate targets under different conditions. The role of Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) technologies in global decarbonisation scenarios was recently examined in depth by the IEAGHG (2019). However, there is no similar review study for EU decarbonisation pathways. This study fills that gap by reviewing the role CCS and CCU play in modelled EU decarbonisation pathways in line with the Paris Agreement targets.

1.1 Objectives and structure of this report

Understanding the potential role of CCS and CCU technologies is critical for European stakeholders, as policy is developed to bring about a low carbon transition. This set of technologies has been shown to play a prominent role across many scenarios. This report seeks to establish, based on modelled scenarios, what could be their role, and some of the underlying drivers associated with different outlooks.

Specifically, this report reviews the ranges of CO_2 mitigation delivered by CCS and CCU technologies across different scenarios of European decarbonisation published to date. This includes:

- Ranges of CO_2 mitigation foreseen for different sectors and countries in the published scenarios
- Analysis of the determinants of these ranges
- The role of biomass, CCU, and low carbon hydrogen
- Infrastructure and cost considerations relevant to CCS and CCU technologies.

It is important to note from the outset that the scenarios presented by energy system models are exploratory and are therefore not forecasts or predictions of future CCS deployment. The ranges of results across multiple models and scenarios aim to provide insights on the approximate ranges of CCS and CCU deployment that could be feasible and required to meet decarbonisation goals.

[1] https://ec.europa.eu/clima/policies/eu-climate-action/law_en

The report is structured as follows: Section 2 describes the approach taken in this review, followed by the description of the criteria used for model selection in Section 3. Section 4 describes the identified ranges of CO_2 captured by CCS and CCU technologies, with further assessment of the sectoral uses of CCS and drivers of CCS deployment in the selected models. Section 5 reviews the role of CCU in European decarbonisation pathways. The last two sections describe insights gained on the infrastructure (Section 6) and costs (Section 7) of CCS and CCU in European decarbonisation analyses.

2 Approach taken

To deliver the objectives, a focused literature review on modelling studies was undertaken, examining EU decarbonisation scenarios using both global and EU-level models. Studies which present the results from individual models and model inter-comparison projects were screened to identify those which report CO_2 emissions mitigated and/or removal by CCS and CCU at the EU-level. Publicly available studies were selected based on the following criteria:

i) Geographic resolution: must report EU level results. For this review only decarbonisation scenarios reporting specific EU results were selected. Global scenarios which report the EU as part of OECD were excluded, as the level of CCS and CCU deployment in the EU could not be evaluated.
ii) Climate targets: must report scenarios compatible with the EU targets of 80% reduction and/or Net Zero CO_2 by 2050. Depending on the age and purpose of the scenario analysis, the published EU scenarios may represent narratives of no climate action, or NDCs. For this review the focus was kept strictly on decarbonisation scenarios compatible with the Paris Agreement targets.
iii) Technology specification: must report results for CO_2 mitigation or removal by CCS and/or CCU. This means scenarios exploring pathways where CCS and CCU are deliberately restricted (e.g. because they were too costly or not accepted by the public) are included but studies exploring 100% renewable electricity systems or futures with explicitly no negative emissions technologies may not be. Comments from the wider literature are provided on this where relevant in the report.

The databases and studies selected in this screening are detailed in the appendices of this document, Annex 1 and Annex 2.

Based on the selected studies and databases, a quantitative review of the ranges of CCS and CCU found in the literature was undertaken. For this, the relevant data from both databases and individual studies were collated and analysed, consolidating findings across different scale models and over time. This literature was examined further to identify drivers of CCS and CCU deployment in these scenarios, with particular emphasis on:

i) Key elements of scenario definition
ii) The level of climate ambition (carbon budgets)
iii) Assumptions related to biomass availability, and
iv) Insights on hydrogen, especially when linked to CCS and CCU deployment.

Where available, this review highlighted the level of CCU technology deployment and uses in different sectors. To contextualise these findings, the review was expanded to include certain additional studies on CCU. The selection criteria in this narrower review were based on geographical scope (EU), and inclusion of at least one of the following: ranges of costs, CO_2 mitigation efficiency, TRL for different technologies, and bottlenecks in CCU uptake and scaling at the EU level.

Finally, insights on costs, infrastructure requirements and stranded assets were collated from the reviewed studies and summarised. Priority areas for further study on these topics are identified.

3 Model selection

Section 3: Key findings

Global model scenarios

- A large number of the global model scenarios that are publicly available do not report EU level results so were not included in this study. The EU region is typically reported as part of a larger aggregate region.
- From the publicly available scenarios that do report EU level results, most of these scenarios focus on climate policy goals consistent with limited warming to 2°C, equivalent to the EU target of an 80% reduction of CO_2 emissions by 2050. A more limited set of scenarios consider 1.5°C, commensurate with a net-zero CO_2 emission goal in 2050.
- Most scenarios also include CCS technologies, including BECCS. Very few explicitly include CCU technology pathways.

EU model scenarios

- These scenarios are fewer in number compared to the global scenarios. They also differ in that more of these scenarios include CCU pathways and provide more detail on sector implementation. They are similar in providing both 80% and net-zero scenarios.

Many models are currently used for analysing future scenarios of decarbonisation at national, regional and global levels. Of these, the most prominent are the Integrated Assessment Models (IAMs) which underpin the Intergovernmental Panel on Climate Change (IPCC) assessment reports. The majority of these IAMs are global in scope and the European Union is represented as a single region or as two sub-regions.[2] In addition to these models, there are also other global models hosted by the IEA, IRENA, EC-JRC (POLES), and other research institutes such as UCL (TIAM-UCL) and CIRED (Imaclim). There are also energy system models with a European focus i.e. PRIMES hosted by E3MLab/ICCS at the NTUA, JRC TIMES,[3] TIMES-EE/EG hosted by IER Germany, and our in-house European energy system model ETM-UCL.

To identify EU-level results from the global IAM models, the publicly available results held in databases hosted by IIASA[4], the International Institute for Applied Systems Analysis, were reviewed. These present the results of several major model-inter-comparison projects, in which multiple models were run by diverse research groups with inputs that are somewhat harmonised in order to explore sensitivities to different policy and technology dimensions. As described above, models and scenarios were selected if they provided results for the amount of CO_2 captured by CCS or CCU technologies in the EU for scenarios compatible with the Paris Agreement. This includes both 1.5°C and 2^{o}C-compatible scenarios, which if equally allocated to the EU broadly translate into decarbonisation targets between 80% CO_2 emission reduction from 1990 levels and Net Zero GHG emissions in 2050.

EU-level results are not provided in scenarios used in the IPCC AR5 (SSP and RCP databases) or the IPCC Special Report on 1.5°C (SR1.5 scenario database). However, six model inter-comparison project databases meeting the selection criteria described in Section 2 were identified. The names and main characteristics of these

[2] https://www.iamcdocumentation.eu/index.php/IAMC_wiki
[3] https://www.researchgate.net/profile/Alessandra_Sgobbi2/publication/270278897_The_JRC-EU-TIMES_model_-_Assessing_the_long-term_role_of_the_SET_Plan_Energy_technologies/links/55d1b48808ae95c3504d58fc.pdf
[4] https://iiasa.ac.at/web/home/research/researchPrograms/Energy/Databases.en.html

databases are described in Table 1 below and in Annex 1. In addition, studies using a single global IAM and EU-level models which met the criteria specified in Section 2 were identified; these are described in Annex 2.

As shown in Table 1, the model intercomparison projects examine different sets of scenarios. While 2°C scenarios are available in all databases, 1.5°C scenarios are available only in the recent inter-comparison exercises published in 2020, specifically CD-LINKS and NFGS.

The two earliest databases (EMF28 and GEA) include scenarios that specifically exclude or restrict CCS deployment in order to explore how the energy system could be sufficiently decarbonised without those technologies. Later projects focused more on the impact of different levels of climate policy, represented as earlier and later mitigation action across the energy system, carbon budgets and ways of sharing the burden of climate mitigation between geographic regions.

Most scenarios in databases and individual studies include CCS technologies applied both to fossil- and bio-plants. CCS is usually applied to electricity generation, and sometimes to industrial plants, liquid fuels and hydrogen. CCU technologies are only available in European-scale models. The full list of studies is Table 1described in Annexes 1 and 2.Table 1Table 1Table 1

Table 1. Summary of global model inter-comparison databases providing EU level results for decarbonisation pathways compatible with the Paris Agreement, i.e. 1.5°C and 2°C compatible scenarios.

Database (year of publication)	Global models	European models	Scenarios	
EMF28 (2012)	POLES, TIAM-UCL, TIMES Pan EU, TIMES-VTT, WITCH, WorldScan	CCTSMOD, PET, PRIMES	80% GHG emission reduction by 2050 (2°C)	Scenarios of energy efficiency policies, technology development, carbon markets. Includes one with restricted CCS
GEA (2012)	IMAGE, MESSAGE		2°C	Scenarios of energy demands, transport technologies, various restrictions on electricity generation technologies. Includes one with restricted CCS
AMPERE (2014)		TIMES Pan EU, PRIMES	80% GHG emission reduction by 2050 (2°C)	Scenarios of delayed action, high renewables, restricted transport electrification. Includes one with restricted CCS
LIMITS (2016)	GCAM, IMAGE, MESSAGE, REMIND, TIAM-ECN, WITCH		2°C	Scenarios of more and less stringent mitigation policy, and methods of burden sharing
CD-LINKS (2020)	COFFEE, DNE21+, IMAGE,	PRIMES	2°C and 1.5°C	Scenarios of specific mitigation policies (current policies, NDCs) and different carbon budgets after 2030

	MESSAGE, REMIND		
NGFS (2020)	REMIND-MAgPIE, GCAM, MESSAGE-GLOBIOM	2°C and 1.5°C	Scenarios of delayed vs immediate mitigation action, and levels of Carbon Dioxide Removal (CDR) deployment, including BECCS.

Table 1Table 1Table 1Table 1

4 Ranges of CO_2 captured and stored by CCS technologies

Section 4: Key findings

- Published scenarios indicate that CCS is essential for Europe to reach net zero CO_2 emissions by 2050, which is consistent with the 1.5°C global target. Under a 2°C target, most scenarios suggest a prominent role for CCS, although a small number suggest low levels of deployment.
- In the 1.5°C scenarios, the median CO_2 captured by CCS is 230-430 $MtCO_2$/yr in 2030, increasing to 930-1200 $MtCO_2$/yr in 2050.
- In the 2°C scenarios of the more recent databases, the median CO_2 captured by CCS is slightly lower with 35-100 $MtCO_2$/yr in 2030, increasing to 600-930 $MtCO_2$/yr in 2050. (For reference, the EU net CO_2 emissions in 2018 were 3,151 $MtCO_2$[5].)
- These medians represent central values from the set of scenarios, implying some key uncertainties as to the actual level that might be required. From these more recent databases, the CO_2 captured in 2050 ranges from 389 to 2,575 $MtCO_2$/yr in the 2°C scenarios and from 324 to 2,230 $MtCO_2$/yr in the 1.5°C scenarios.
- Note the ranges in the full set of models is larger: the 2°C scenarios show a range from almost no deployment in 2050, up to 3,850 $MtCO_2$/yr.
- Additionally, there is a difference between the results from global and European-scale models. Scenarios from EU models show a lower range, rising to just over 1000 $MtCO_2$/yr by 2050.
- These ranges of results reflect uncertainty in a large number of factors, including CCS-specific assumptions, the role of other mitigation options, and the assumed drivers of economic growth. Sources of uncertainty around CCS deployment needs to be reduced to ensure a more definitive path and role for these technologies.
- A small set of global scenarios (whose results could not be included in this review) have indicated that a 1.5°C target can be achieved with little or no CCS in any region, through very high levels of energy efficiency improvements, renewables uptake and reduction of energy demands.
- BECCS is shown to be important, accounting for approximately one third of total CCS, in both the 1.5°C and 2°C cases.
- All the 1.5°C scenarios deploy some BECCS by 2030.
- Information on CCS use by sector is only available from Europe-scale modelling studies. The available data is not conclusive concerning which sectors deploy CCS the most, with significant variability across the studies.

[5] Table ES. 4 in https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2020

Ranges of CO_2 sequestration were identified at European level across a wide spectrum of models and scenarios compatible with 1.5°C and 2°C. To examine the ranges and effect of key drivers, the CO_2 sequestration at European level was recorded along with characteristics of each model and scenario, for each 10-year time period between 2020 and 2050. The total amount of CO_2 captured and stored in geological storage was recorded as "Total CCS". Further disaggregation of Total CCS results is sometimes possible by technology type and fuel. Where possible, the CO_2 captured by all CCS technologies was split into BECCS and fossil-CCS, and separated by the power and industry sectors.

4.1 Total CCS ranges

Ranges from full dataset

The CO_2 captured and sequestered in geological storage at European level (Total CCS) is publicly available in the databases listed Table 1. Covering 20 different IAMs and 28 scenarios, the full set of mitigation pathways under 1.5°C and 2°C scenarios is illustrated in Figure 1 and Table 2. Note that decarbonization pathways under 2°C are available in all databases, while 1.5°C scenario results are available only in the most recent two databases (CD-LINKS and NFGS), hence the reduced number of 1.5°C compatible scenarios in Figure 1 (right hand panel).

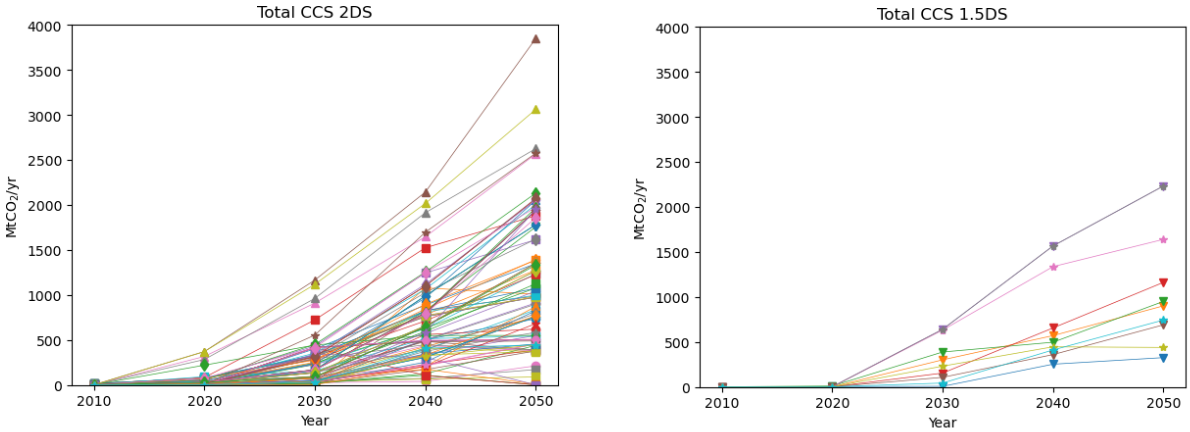

Figure 1. Ranges of CCS deployed in the EU across 2°C (left) and 1.5°C scenarios (right). Each coloured line represents a scenario from a model intercomparison project database. Each database is represented by a different marker: EMF-28 (square), GEA (triangle), AMPERE (filled circle), LIMITS (diamond), CD-LINKS (inverted triangle), NGFS (star).

As illustrated in Figure 1, different model-scenario combinations suggest quite a range of CCS deployment pathways up to 2050 for both 2°C and 1.5°C scenarios. Some models suggest that it is possible to reach a global target of 2°C without any deployment of CCS (see Figure 1, left hand panel, showing scenarios which are on the x-axis showing 0 $MtCO_2$/yr removal in 2050.) For the same climate target, other model-scenario combinations suggest an exponential increase of CCS deployment. Scenarios from earlier studies show this growth starting from as early as 2010 (see the GEA pathways marked with triangle markers in Figure 1, left hand panel.)

These differences are caused by a combination of drivers, which are discussed further in Section 0.

It is interesting to note that in the 1.5°C scenarios, all model-scenario combinations plotted in Figure 1, right panel, need some level of CCS deployment from 2030 onwards. Note that a small number of global scenarios have been modelled which achieve 1.5°C with zero or very low levels of negative emission technologies (e.g. Grubler *et al* 2018, van Vuuren *et al* 2018). These scenarios are global in scope and don't report European results, hence their exclusion from the results presented in this review. Those few scenarios envisage large changes in the energy system (both related to how energy is produced and consumed) and wider life-style changes, e.g. much lower meat consumption and less flying. Figure 1, right, and Table 2 below show that, except for those no-CCS global scenarios, the minimum CCS deployment in Europe is 5 $MtCO_2$/yr in 2030, increasing to 324 $MtCO_2$/yr in 2050.

Table 2. Ranges of Total CCS deployed in Europe in 2030 and 2050 under 1.5°C and 2°C scenarios. Note that Total CCS refers to CO_2 captured and stored in geological storage (i.e. it does not include CCU).

Total CCS [$MtCO_2$ /yr]	**2030**	**2050**
2°C scenarios	0 to 1,164	0 to 3,850
1.5°C scenarios	5 to 640	324 to 2,230

As mentioned above, 1.5°C scenarios are only included in the most recent databases. For the 2°C scenarios, the range of CCS deployment has clearly changed in the studies over time and understanding what has led to this is useful for understanding the results and for policy decision making.

Figure 2 illustrates the variation of CCS deployment within databases and between databases. The boxplots represent the distribution of model-scenario results in each database. The main body of each boxplot indicates the 1st and 3rd quartiles, with the orange horizontal line showing the median value of Total CCS in each database. The whiskers (vertical lines) show the highest and lowest results reported in the databases. Please note that this simply shows the results of the range of scenarios included in the databases. They do not represent an uncertainty analysis or probability of future CCS deployment.

The earlier studies, i.e. in the GEA database (published in 2012), show both the largest CCS range and the highest median value of CCS deployed in 2050. The GEA, EMF-28 and AMPERE projects include scenarios which explore the possibility that CCS technologies are not available at all – therefore zero CCS is deployed. Scenarios without CCS were not explored in the later projects.

At the higher end of the ranges are GEA scenarios with a combination of high energy demand and limited availability of renewables. In the EMF-28 database (published in 2014) the high CCS deployment is present in scenarios considering fragmented carbon markets. The lower ranges in AMPERE (published in 2014) are partially explained by the fact that the only models reporting EU CCS results were European-scale models, which typically appear to report lower deployment of CCS (see further discussion in section 5.3).

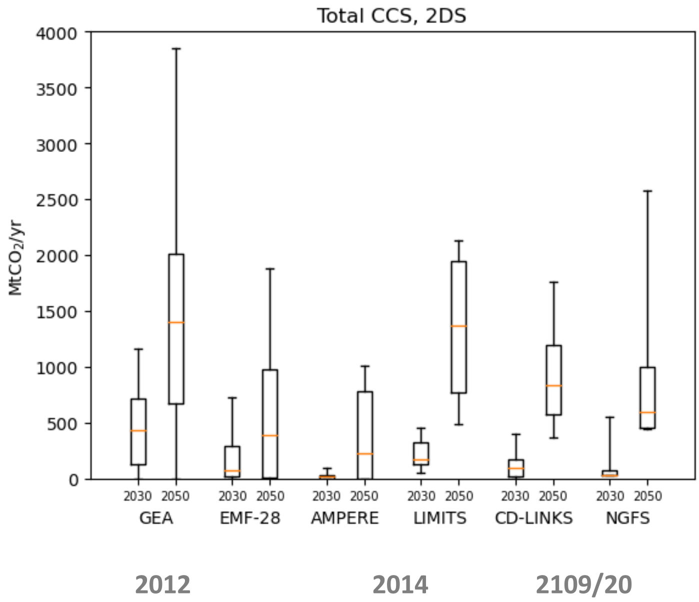

Figure 2. European CCS in 2°C scenarios in 2030 and 2050. The dates below the x-axis show the year of publication of each database. These box plots show the distribution of scenarios in each database. The orange line shows the median value, while the box and whiskers show the quartiles and full range of results across the scenarios. They do not represent a central estimate with error bars, or the probability of CCS deployment.

Results from recent studies

Based on the more recently published databases, CD-LINKS and NGFS (published in 2019/20), which incorporate the most up-to-date assumptions on the drivers of emission mitigation, the data suggest that the ranges of CCS deployment in newer databases is narrower than in the older databases (**Error! Reference source not found.**). These results indicate that CCS plays a role in all scenarios compatible with 1.5°C and 2°C, i.e. the minimum deployment of CCS is 5 $MtCO_2$/yr in 2030 and 324 $MtCO_2$/yr in 2050.

Low carbon hydrogen

Where available in the studies covered in this review, we have highlighted references to the role of hydrogen, particularly where it is produced in combination with CCS. A more in-depth review of the role of hydrogen in energy system decarbonisation pathways would be possible.

In the studies covered in this review (which generally focus on the role of CCS), the specific role of blue versus green hydrogen is not thoroughly discussed.

The study presented by Sgobbi *et al* (2016) used the JRC-EU-TIMES model to examine the role of hydrogen in EU decarbonisation scenarios. This analysis found that a key driver for the uptake of hydrogen is the requirement for net negative emissions through the use of BECCS. This hydrogen production pathway was found to be key in providing decarbonisation options for transport and industry, as well as providing flexibility for the whole system. Cost factors and the stringent CO_2 budget mean most fossil fuel-based hydrogen production is not preferred in the decarbonisation scenarios; biomass and coal gasification are used for almost 70% of hydrogen production by 2050. The study notes that this is sensitive to the capture rate assumed for BECCS – if it is lower, electrification and coal gasification and methane steam reforming with CCS become preferable. Further, the study found that the role of hydrogen is not dependent on the availability of CCS. In fact, a delay in the availability of CCS, and a large increase in its costs, strengthened the role of hydrogen (with electrolysers) because it would be needed even more to decarbonise the system in the medium term.

Blanco et al (2018) used the JRC-EU-TIMES model to examine specifically the role of Hydrogen and Power to Liquid (H_2 + CO_2 -> liquid fuels) in meeting future demands in the transport, heat and power sectors under European target of 80-95% emission reduction. In this extensive sensitivity analysis, 15 parameters were varied to create 50 model runs, the results of which are aggregated and displayed as a set of indicative scenarios. The parameters that were varied include: the emissions reduction target, CO_2 storage availability, biomass availability, PtL performance, PEM performance and potential for variable renewables. 23 hydrogen production processes are studied including reforming, gasification and electrolysis with a range of fuels, at a range of scales, with and without CCS. Following storage and delivery, the model represents several end-uses of H_2, some of which involve blending with natural gas, for use in space heating, industry (steel), transport (cars, buses and trucks) and combination with CO_2 for fuel synthesis. This is in the context of the wider energy system. CO_2 sources include industry (steel, ammonia, glass and paper manufacturing), power stations and other fuel production (BtL, biogas, H_2 production). In most scenarios, the model selected to produce H_2 through gas reforming with CCS and the preferred CO_2 sink was underground. They suggest a H_2 demand increase to 20–120 mtpa (2.4–14.4 EJ/yr), mainly used for PtL (up to 70 mtpa), transport (up to 40 mtpa) and industry (25 mtpa). Scenarios were also examined in which CO_2 storage was not possible due to a political ban or poor social acceptance. In these scenarios (and only these), 90% of the required H_2 was produced by electrolysis and CO_2 use for PtL became more attractive. In these scenarios the price of H_2 is driven by CO_2 price and fuel prices.

Drivers of CCS deployment*Table 3. Ranges of CCS deployed in 2030 and 2050 in the EU under 1.5°C and 2°C scenarios in all and selected databases*

Total CCS [$MtCO_2$ /yr]	**2030**	**2050**
2°C, all databases	0 to 1,164	0 to 3,850
2°C, CD-LINKS and NGFS	10 to 552	389 to 2,575
1.5°C, CD-LINKS and NGFS	5 to 640	324 to 2,230

In the newer databases, **Error! Reference source not found.**2°C scenarios appear to deploy slightly less Total CCS than the 1.5°C scenarios Figure 3**Error! Reference source not found.**. **Error! Reference source not found.Error! Reference source not found.**In the 1.5°C scenarios, the median CO_2 captured by CCS is 230-430 $MtCO_2$/yr in 2030, increasing to 930-1200 $MtCO_2$/yr by 2050. In the 2°C scenarios, the median CO_2 captured by CCS is lower, 35-100 $MtCO_2$/yr in 2030, increasing up to 600-930 $MtCO_2$/yr by 2050. This is partially explained by the stringency of the 1.5°C target, which demands immediate and aggressive mitigation, as compared to the 2°C scenarios which allow for a slower mitigation and potentially lower CCS deployment.

Under the 1.5°C target, there is also quite a wide range of CCS deployment, from 5 to 640 $MtCO_2$ in 2030, and 324 to 2,230 $MtCO_2$ in 2050 (**Error! Reference source not found.** and **Error! Reference source not found.**). The scenario with the highest levels of CCS, (which reaches 2,230 $MtCO_2$ in 2050) is from the MESSAGE-GLOBIOM model. In this scenario, climate mitigation starts immediately and proceeds in an orderly way, i.e. CCS is developed and deployed early. In the equivalent scenario where Carbon Dioxide Removal (CDR) is allowed to take only a limited and climate action is disorderly with sudden disruptions, CCS plays a smaller role.

The 2°C NGSF scenarios show a lower median level of Total CCS as compared to the CD-LINKS scenarios (**Error! Reference source not found.**, left panel). This is partially explained by the fact that NGFS explores 2°C scenarios with delayed mitigation action, i.e. decarbonisation, including CCS deployment happens latter, while CD-LINKS explores only scenarios with immediate mitigation.

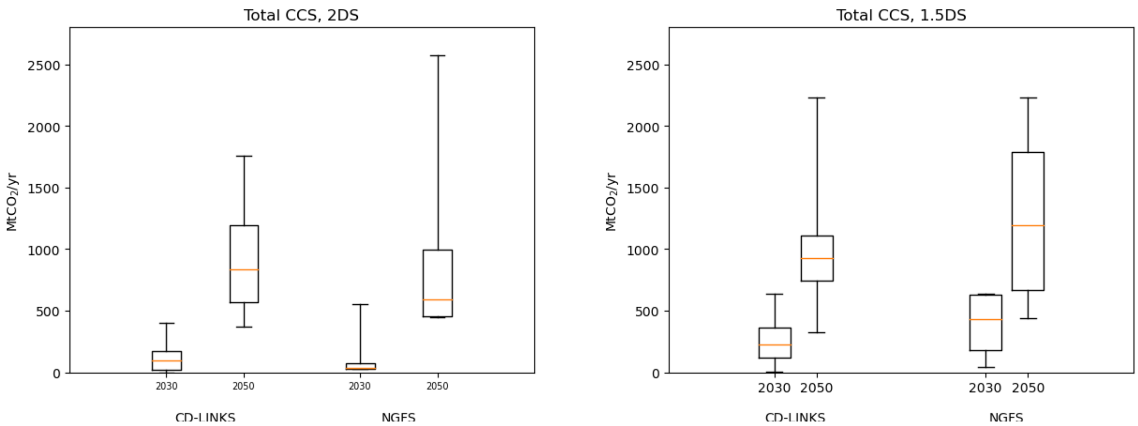

Figure 3. Distribution of model results in terms of Total CCS under 1.5°C scenarios in CD-LINKS and NGFS databases. These box plots show the distribution of scenarios in each database. The orange line shows the median value, while the box and whiskers show the quartiles and full range of results across the scenarios. They do not represent a central estimate with error bars, or the probability of CCS deployment.

4.2 BECCS ranges

Within the total amount of capture by CCS, this review also found a wide range of capture by BECCS. The capture by BECCS, shown in **Error! Reference source not found.**, is a subset of the above Total CCS numbers. CO_2 removal by BECCS accounts for approximately a third of Total CCS capture in both 2°C and 1.5°C scenarios. This could be due to a combination of factors, such as availability of alternative CDR options leading to a smaller role for BECCS, but also may indicate new constraints on biomass availability. These factors are further investigated below.

Table 4. Ranges of BECCS deployed in 2030 and 2050 in the EU under 1.5°C and 2°C scenarios

BECCS [$MtCO_2$ /yr]	**2030**	**2050**
2°C scenarios	0 to 215 (from 0 to 1,164 Total CCS)	3 to 1,336 (from 0 to 3,850 Total CCS)
1.5°C scenarios	0.5 to 190 (from 5 to 640 Total CCS)	105 to 795 (from 324 to 2,230 Total CCS)

In contract to Total CCS, only three out of the six model inter-comparison databases report CO_2 captured by BECCS, namely CD-LINKS, LIMITS, and NGFS (Figure 4). The range of BECCS deployed in the LIMITS scenarios is very wide, with a median value of approximately 100 $MtCO_2$/yr in 2030, and 750 $MtCO_2$/yr in 2050. The main reason behind this variation is the model specification, but also the scenario design. The highest BECCS deployment in LIMITS occurs in TIAM-ECN scenarios, which assume that biomass resources are tradable between all regions. At the opposite end, the lowest deployment occurs in WITCH, which considers BECCS deployment only for electricity production and limits bioenergy deployment to the regions which produce biomass. As a result, BECCS deployment mainly happens in Latin-America, and much less in other regions, including Europe.

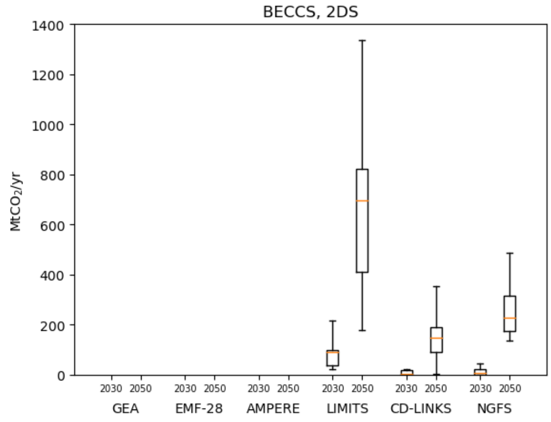

Figure 4. Distribution of model results in terms of BECCS under 2°C scenarios across all databases. Note that only LIMITS, CD-LINKS and NGFS report BECCS ranges. These box plots show the distribution of scenarios in each database. The orange line shows the median value, while the box and whiskers show the quartiles and full range of results across the scenarios. They do not represent a central estimate with error bars, or the probability of CCS deployment.

As shown in Figure 5, 2°C compatible pathways are possible with no BECCS deployment until 2040, while 1.5°C start deploying BECCS from 2030. It is also interesting to note that 1.5°C scenarios seem to deploy less BECCS than 2°C scenarios. This may be biased by the fact that the 2°C scenarios illustrated in Figure 5 (left hand panel) include the LIMITS scenarios (diamond markers), which report the highest BECCS deployment, as explained above.

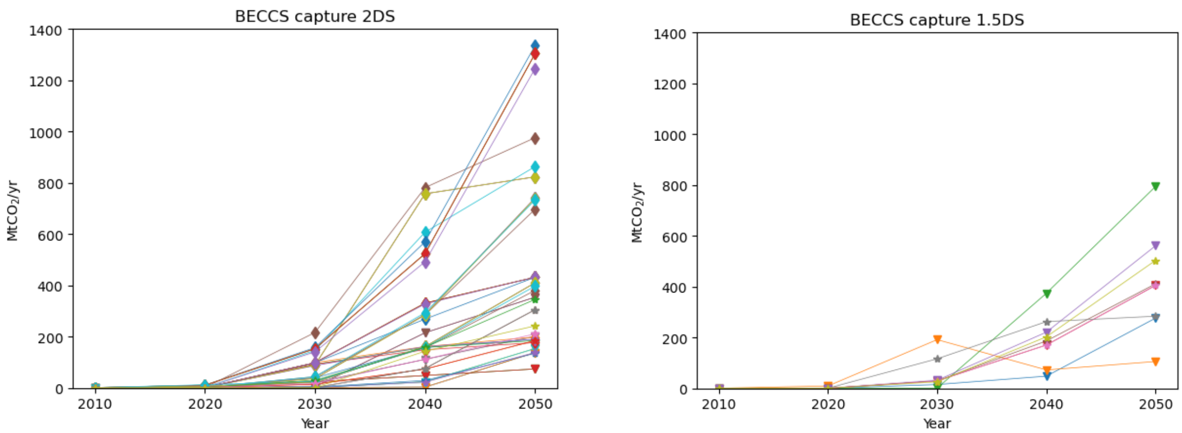

Figure 5. Ranges of BECCS deployed in the EU across 2 (left) and 1.5°C scenarios (right). Coloured lines indicate combinations model & scenario. Each model inter-comparison database is represented by different marker: LIMITS (diamond), CD-LINKS (inverted triangle), NGFS (star).

To investigate differences in BECCS deployment in 1.5°C vs 2°C scenarios, it is helpful to focus on the newest databases (CD-LINKS and NGFS), which are the only databases reporting both 1.5°C and 2°C compatible scenarios (Figure 6). Looking at BECCS deployment in these newer scenarios we see similar patterns in the scenario results as for Total CCS, with the 2°C scenarios utilizing less BECCS than the 1.5°C scenarios.

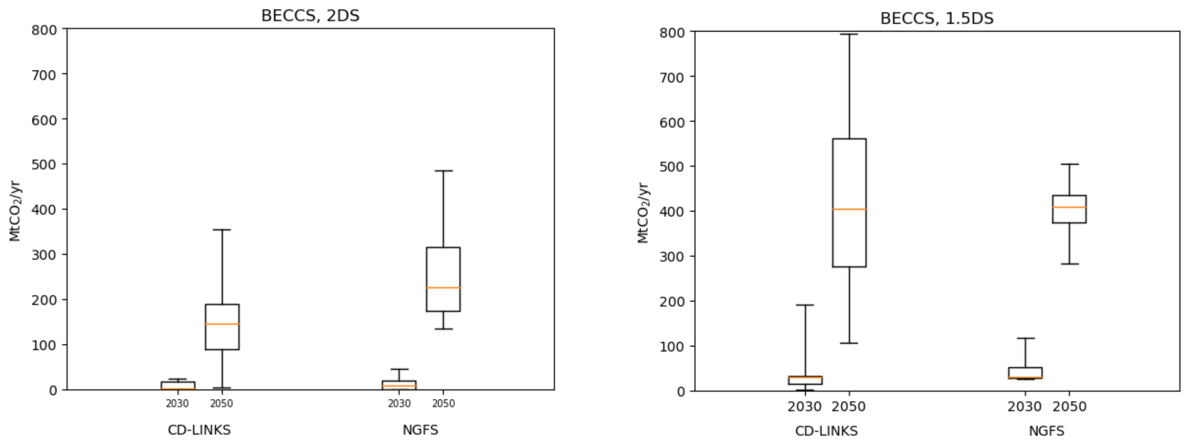

Figure 6. Distribution of model results in terms of BECCS under 1.5°C scenarios in CD-LINKS and NGFS databases. These box plots show the distribution of scenarios in each database. The orange line shows the median value, while the box and whiskers show the quartiles and full range of results across the scenarios. They do not represent a central estimate with error bars, or the probability of CCS deployment.

It is interesting to note that both NGFS and CD-LINKS broadly agree on the median amount of BECCS deployed under 1.5°C scenarios (i.e. 30 $MtCO_2$/yr BECCS in 2030 and 400 $MtCO_2$/yr BECCS in 2050. See Figure 6, right hand panel), although there is a much wider spread of BECCS deployment in CD-LINKS. Looking at the 2050 values, at the lower end of the BECCS deployment in the CD-LINKS range sit the scenarios from the DNE21+ V.14 and PRIMES_V1 models, which do not report scenarios in the NGFS project The models reporting scenarios in both databases, MESSAGEix 1.0 and REMIND-MAgPIE 1.7-3.0, report similar BECCS removal in both databases, i.e. 405 and 561 $MtCO_2$/yr respectively in 2050 in CD-LINKS, and 405-411 and 283-503 $MtCO_2$/yr respectively in 2050 in NGFS[6]. Whilst different assumptions on how the transition to 1.5°C could happen (e.g. with orderly decarbonisation with CDR developed early versus a disorderly transition with delayed CDR availability) affects MESSAGE-GLOBIOM results very little (29 $MtCO_2$/yr BECCS in 2030, and 405-411 $MtCO_2$/yr in 2050), it does affect REMIND-MAgPIE results (25- 116 29 $MtCO_2$/yr BECCS in 2030, and 283-503 $MtCO_2$/yr in 2050).

In the 2°C scenarios, Figure 6 left, both CD-LINKS and NGFS report lower BECCS deployment as compared to the 1.5°C scenarios, Figure 6 right. In CD-LINKS this is explained by scenario design, as immediate action under 1.5°C scenarios leads to fossil-CCS being displaced by BECCS, while in the 2°C scenarios fossil-CCS can be still used, hence the lower need for BECCS. NGFS 2°C scenarios consider delayed action, hence less removal by BECCS is needed pre-2050.

4.3 Sectoral use of CCS

The previous sections describe the emissions captured by fuel (bioenergy and fossil fuels). Some models also provide a breakdown of emissions captured by sector, primarily for the power and industry sectors (see Annex 3 for a full representation of results in each database). Figure 7 shows this breakdown, in a range of individual studies and databases for scenarios consistent with the global 2°C and 1.5°C targets.

[6] In CD-LINKS each model report results for one scenario, i.e. NPi2020_400 for the global scale models (REMIND, MESSAGE, IMAGE, and DNI21+) equivalent to NPi2020_verylow scenario for PRIMES (EU scale model). In NGFS both REMIND and MESSAGE report two scenarios compatible with the 1.5 °C target, i.e. Immediate 1.5 °C with limited CDR (Disorderly, Alt) and Immediate 1.5 °C with CDR (Orderly, Alt), see Section 5.1 for further scenario description.

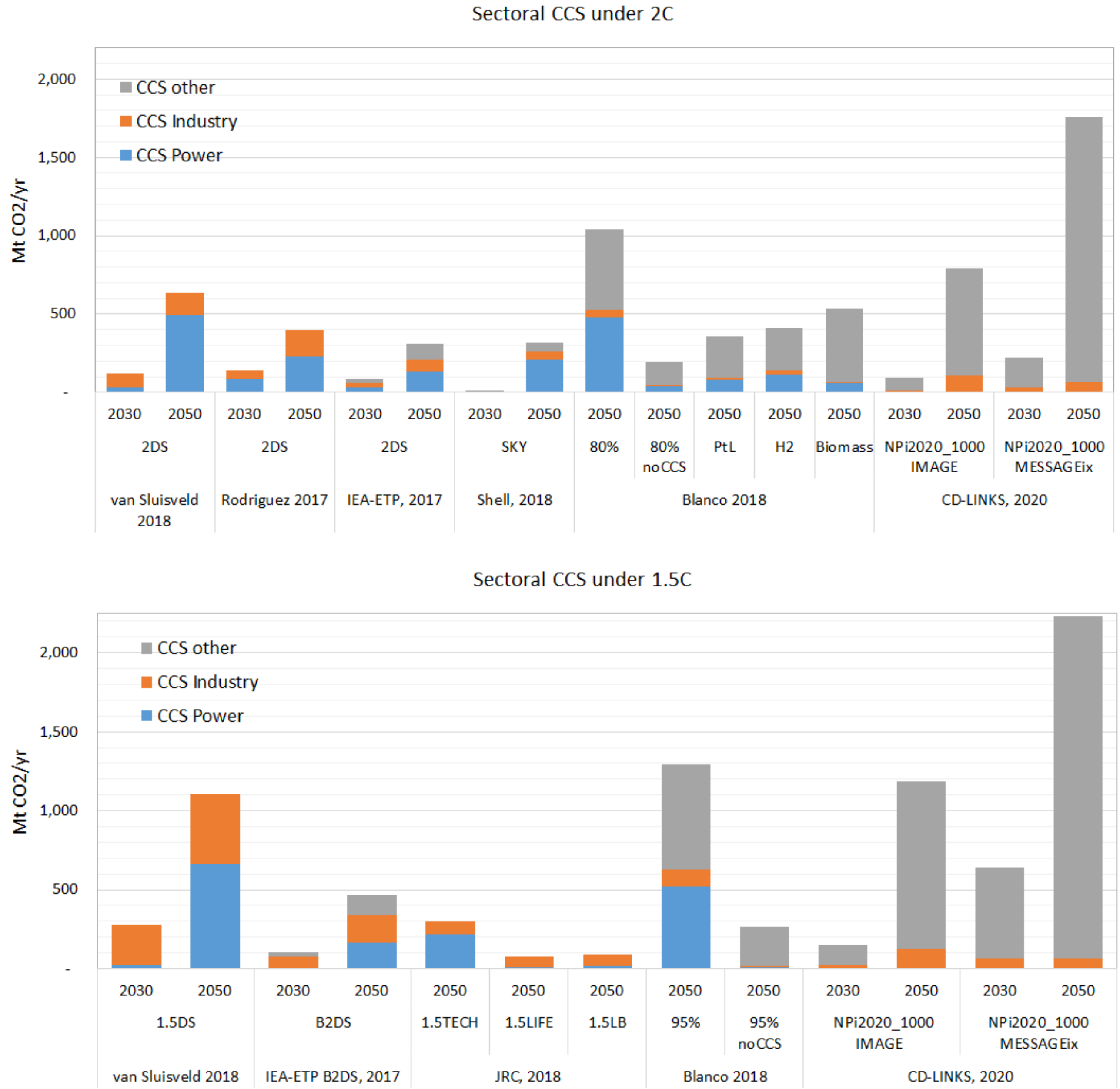

Figure 7. Sectoral use of CCS in 2030 and 2050 across different studies in 2°C and 1.5°C scenarios.

Levels of sectoral representation, transparency of assumptions and the ways that results are reported were found to vary significantly between studies. For example, industrial CCS can denote the capture of emissions generated by on-site electricity and heat production, by industrial processes, or both. Even within a single study, this can vary between industrial sectors. For example, in some studies report industrial emissions and aggregate all other CCS simply as "other", e.g. CD-LINKS. Other studies report a much more detailed breakdown of sectoral use of CCS, e.g. Shell SKY scenarios report CCS from Heavy Industry, Agriculture & Other Industry, Liquid Hydrocarbon Fuels, Gaseous Hydrocarbon Fuels, Electricity – Commercial, Hydrogen, and Heat – Commercial. To allow some comparison in Figure 7, CO_2 captured by CCS in Heavy Industry was allocated to "CCS Industry", CCS on "Electricity – Commercial" was allocated to "CCS Power", and the reminder to the category "CCS other".

One of the more detailed studies examining the decarbonisation of EU industry is found in van Sluisveld *et al* (2018), which employed the global IMAGE integrated assessment model linked with the WISEE energy system model. The study found that in the cost optimal energy system transition, very little CCS is deployed in Europe before 2030 under either the 2°C or 1.5°C target. From 2030 onwards, both the Total CCS deployed and the technologies used in different sectors were found to depend on the level of climate ambition. In the 2°C scenario, European industry CO_2 emissions are reduced by 60% by 2050 relative to 2015, with the total amount of CO_2 captured in industry being approximately 200 $MtCO_2$/yr. In the 1.5°C scenario, the industry sector almost reaches net zero by 2050, with approximately 250 $MtCO_2$/yr being captured. In the 2°C scenario, it is not economic to deploy BECCS in industry, and coal-CCS in iron and steel plants is the main option for industry decarbonisation. In contrast, in the 1.5°C scenario, industry applies CCS more in combination with biomass than with fossil fuels in order to achieve negative emissions and there is a significant uptake of BECCS in pulp and paper, which captures 291 $MtCO_2$/yr per year, playing a large role in the sector reaching net zero.

In the study by Solano Rodriguez et al (2018), the role of CCS in capturing industrial process emissions is highlighted. In the "Policy Success" scenario, which is consistent with 2°C, the model finds it economically preferable to substantially reduce the use of coal in industry, increasing the shares of natural gas, electricity, oil products and other heat. However, it is the deployment of CCS from 2025 onwards to capture industrial process emissions (particularly for iron and steel) which most significantly affects the sector's emissions. CCS captures approximately half of industry's CO_2 emissions by 2050. (Note that this study used the European TIMES model, in which the industry sector is disaggregated for Chemicals, Iron & Steel, Non-Ferrous Metals, Pulp & Paper, and 'Other' Industry but unfortunately the results are not presented for each sub-sector.)

In their study on the potential for hydrogen and Power-to-Liquid (PtL) processes, Blanco et al (2018) used the JRC-EU-TIMES model to examine a range of scenarios. In each, a particular technology or set of technologies was constrained or actively prioritised. In this study, the 'other' category plotted in Figure 7 includes CO_2 captured through BECCS-hydrogen, Biomass to Liquid (BtL) processes and other hydrogen production. Under the 2°C target, in the "Hydrogen" scenario, CCS is not allowed and variable renewables are high, leading to high use of electrolysis for hydrogen, so less CCS overall but still a significant portion in the 'other' category. In the "Biomass" scenario, underground CO_2 storage is not allowed but biomass potential is high. The figure shows that in both the 2°C and 1.5°C scenarios, when CCS is restricted, there is still a small amount of CO_2 captured in the 'other' sectors.

Low carbon hydrogen

Where available in the studies covered in this review, we have highlighted references to the role of hydrogen, particularly where it is produced in combination with CCS. A more in-depth review of the role of hydrogen in energy system decarbonisation pathways would be possible.

In the studies covered in this review (which generally focus on the role of CCS), the specific role of blue versus green hydrogen is not thoroughly discussed.

The study presented by Sgobbi *et al* (2016) used the JRC-EU-TIMES model to examine the role of hydrogen in EU decarbonisation scenarios. This analysis found that a key driver for the uptake of hydrogen is the requirement for net negative emissions through the use of BECCS. This hydrogen production pathway was found to be key in providing decarbonisation options for transport and industry, as well as providing flexibility for the whole system. Cost factors and the stringent CO_2 budget mean most fossil fuel-based hydrogen production is not preferred in the decarbonisation scenarios; biomass and coal gasification are used for almost 70% of hydrogen production by 2050. The study notes that this is sensitive to the capture rate assumed for BECCS – if it is lower, electrification and coal gasification and methane steam reforming with CCS become preferable. Further, the study found that the role of hydrogen is not dependent on the availability of CCS. In fact, a delay in the availability of CCS, and a large increase in its costs, strengthened the role of hydrogen (with electrolysers) because it would be needed even more to decarbonise the system in the medium term.

Blanco et al (2018) used the JRC-EU-TIMES model to examine specifically the role of Hydrogen and Power to Liquid (H_2 + CO_2 -> liquid fuels) in meeting future demands in the transport, heat and power sectors under European target of 80-95% emission reduction. In this extensive sensitivity analysis, 15 parameters were varied to create 50 model runs, the results of which are aggregated and displayed as a set of indicative scenarios. The parameters that were varied include: the emissions reduction target, CO_2 storage availability, biomass availability, PtL performance, PEM performance and potential for variable renewables. 23 hydrogen production processes are studied including reforming, gasification and electrolysis with a range of fuels, at a range of scales, with and without CCS. Following storage and delivery, the model represents several end-uses of H_2, some of which involve blending with natural gas, for use in space heating, industry (steel), transport (cars, buses and trucks) and combination with CO_2 for fuel synthesis. This is in the context of the wider energy system. CO_2 sources include industry (steel, ammonia, glass and paper manufacturing), power stations and other fuel production (BtL, biogas, H_2 production). In most scenarios, the model selected to produce H_2 through gas reforming with CCS and the preferred CO_2 sink was underground. They suggest a H_2 demand increase to 20–120 mtpa (2.4–14.4 EJ/yr), mainly used for PtL (up to 70 mtpa), transport (up to 40 mtpa) and industry (25 mtpa). Scenarios were also examined in which CO_2 storage was not possible due to a political ban or poor social acceptance. In these scenarios (and only these), 90% of the required H_2 was produced by electrolysis and CO_2 use for PtL became more attractive. In these scenarios the price of H_2 is driven by CO_2 price and fuel prices.

5 Drivers of CCS deployment

Section 5: Key findings

- Scenario design strongly influences the amount of CCS deployed in decarbonisation under both 1.5°C and 2°C scenarios. It is clear that assumptions such as high future energy demands or low levels of renewable deployment can lead to higher levels of CCS deployment.
- New methods of implementing climate targets in the models appear to affect the total amount and of CCS in the energy system and how it is used, with additional restrictions on the timing of emissions leading to higher Total CCS.
- It is also evident that the model structure and set-up itself can also be an important driver of CCS deployment, based on very different deployment rates under harmonised scenario assumptions.
- The geographical scope and resolution of the model influences CCS ranges. European-scale models were found to suggest lower levels of CCS deployment. More research is needed to understand what drives these differences.
- Assumptions around the availability and use of biomass appear a key driver in the deployment of BECCS, but not in total CCS deployment.

The deployment of CCS and CCU technologies for European decarbonisation under different mitigation scenarios is influenced by a multitude of factors. These include the ways in which CCS and CCU technologies are represented and parameterised in the models, the alternative technologies available in the models (e.g. new types of thermal power station, or potential maximum levels of wind and solar power deployment), and the model assumptions about the future, e.g. demographic and economic projections, discount rates, energy demands, etc.

This section reviews model assumptions and results across the following categories:

- Scenario definition under 1.5°C and 2°C scenarios (Section 5.1),
- Level of climate ambition, including carbon budget assumptions (Section 5.2),
- Model scope, i.e. global models with representation of the EU vs EU-scale models (Section 5.3), and
- Assumptions about the availability of biomass and the role of bioenergy (Section 5.4).

5.1 Scenario definitions

Each scenario in these modelling studies represents a self-consistent storyline, within which the model plots the transformation of the energy system. The scenarios are implemented as a set of constraints on the model, for example a level of climate change mitigation ambition (2°C or 1.5°C, or a specific carbon budget), maximum rates of deployment of renewable electricity technologies, and maximum biomass availability. Due to uncertainty over the future availability of CCS, older databases (EMF-28, GEA, and AMPERE) considered scenarios in which CCS was explicitly restricted, while more recent inter-comparison projects (LIMITS, CD-LINKS and NGFS) examined scenarios with delayed action and sensitivities to carbon budgets. Table 5 summarises the scenarios/sensitivities studied in each project database.

Table 5. Summary of scenario design and climate target settings in the model inter-comparison projects

Database	Scenarios	
EMF-28 (2012)	80% GHG emission reduction by 2050 (2°C)	High efficiency Pessimistic re tech Green Fragmented C markets Restricted CCS
GEA (2012)	2°C	Combinations of: 3 demand levels, conventional/advanced transport tech, supply side tech restrictions (nuc/CCS/bio/RE)
AMPERE (2014)	80% GHG emission reduction by 2050 (2°C)	All options Delayed action High renewables No transport electrification Restricted CCS
LIMITS (2016)	2°C	Combinations of: reference/stringent mitigation policy, methods of burden sharing
CD-LINKS (2019)	2°C and 1.5°C	Combinations of: current policies, NDCs and different carbon budgets after 2030
NGFS (2020)	2°C and 1.5°C	Combinations of: delayed/immediate mitigation action, high/low CDR

2°C compatible scenarios

As illustrated in Table 5, all databases report pathways compatible with a global 2°C target. The majority of scenarios explore uncertainties across decarbonisation options. These include: more optimistic or pessimistic assumptions about efficiency improvements (in EMF-28); more optimistic or pessimistic assumptions around the evolution of nuclear, CCS, bioenergy and renewables (GEA); restricted CCS deployment, high/low renewables deployment (AMPERE); or an overall delay in mitigation action (CD-LINKS). Some scenarios explore uncertainties in the demand-side decarbonisation options, e.g. different demand levels (GEA), restricted electrification of transport (AMPERE). Others explore policy options, e.g. fragmented vs global carbon markets (EMF-28) or different approaches to how the burden of climate mitigation is shared between geographic regions (LIMITS).

In terms of CCS, the earlier databases – GEA, EMF and AMPERE – explored scenarios which actively excluded CCS. This was done to test futures in which CCS was not available, either due to high costs, technical difficulties, social acceptability, or a lack of political support. Note that in these scenarios the non-availability of CCS is an input assumption to the models, i.e. it is a deliberate choice of the modeler. This is to be differentiated from model scenarios which allow CCS technologies, but for whatever reason, e.g. high renewable availability and low cost, CCS is not picked up as cost-effective mitigation option. In the EMF database, the level of global co-operation appears to be a key driver, as the scenarios with a single global carbon market have higher CCS deployment than those with fragmented carbon trading. In the GEA database, CCS deployment is high (e.g. more than 2,000 $MtCO_2$/yr in 2050) when energy demands are high (and emissions are higher). When energy demands are set lower, CCS deployment is much lower (e.g. mostly under 1,000 $MtCO_2$/yr) except when biomass and other renewable technologies are restricted.

Across all the EMF-28 scenarios, restricting renewables is the driver that leads to the highest levels of CCS deployment (more than restricting nuclear or carbon sinks). The AMPERE study shows the same relationship between CCS and renewables deployment: the scenarios with higher renewables deployment result in less CCS deployment in 2050. It is not possible to check this relationship in newer databases, as their scenario design did not explore different levels of renewables. The EU "Clean Planet for All" also suggests that higher renewable availability reduces the role of CCS, although CCS technologies are seen necessary for carbon reduction in energy intensive industries.

1.5°C compatible scenarios

As discussed previously, the number of scenarios compatible with a global target of 1.5°C is much lower than those compatible to 2°C. Given the urgency of the 1.5°C, the newer scenario design focuses on the timing of climate mitigation and presence of CDR options. These scenarios explore pathways in which aggressive climate mitigation is implemented from 2020 (these are termed "immediate scenarios") versus scenarios in which only NDCs are implemented until 2030, but no further actions (termed "delayed scenarios"). Regarding CDR alternatives, while all models include at least two options, namely BECCS and afforestation/reforestation, some scenarios look at constraints on CDR, including maximum injection rates for geological sequestration, constraints on land available for afforestation/reforestation and BECCS (Bertram *et al* 2020).

1.5°C scenarios without CCS were not identified in this review. This is consistent with the wider literature indicating that models find it very difficult to identify 1.5°C -consistent pathways without the use of CCS. The review presented by (Rogelj *et al* 2018b) indicated that scenarios consistent with the global 1.5°C target include "upscaling of bioenergy and renewable energy technologies, shifting away from freely emitting fossil-fuel use, and the deployment of CDR, such as Bioenergy with Carbon Capture and Sequestration (BECCS) or large-scale afforestation". Grubler et al (Grubler *et al* 2018) presented a scenario consistent with 1.5°C with no CCS or any other negative emissions technologies, which is achieved through dramatic reduction in global energy demands. Van Vuuren et al (2018) found that in scenarios which include large-scale lifestyle change, additional reduction of non-CO_2 greenhouse gases and more rapid electrification of energy demand based on renewable energy, the role of CDR could be to be significantly reduced but not fully eliminated. Others have described ways to achieve 100% renewable electricity systems, e.g. Bogdanov *et al* (2019), though it is noted that these do not address the need to balance residual emissions from other sectors.

Among the 1.5°C scenarios, there is a wide variation in the deployment of CCS between models, even when examining supposedly the same scenario. For example, the five models that provided results for the "NPi2020_400" scenario in the CD-LINKS database range from 689 to 2,232 $MtCO_2$/yr in 2050. This suggests that model structure and set-up is also an important factor in determining the role for CCS, given that variation is observed even where scenario design and input assumptions of the models are harmonized to some degree.

This review did not find any studies that tested the relationship between CCS deployment and renewables expansion in 1.5°C scenarios. As mentioned above, global studies exploring 1.5°C-consistent pathways with limited CCS suggest that a wide deployment of renewables coupled with fast electrification of end-use sectors reduces the need for BECCS, but does not eliminate it (van Vuuren *et al* 2018). More studies considering whole energy system decarbonisation are needed to explore the relationship between renewables and CCS at EU level.

5.2 Level of climate ambition

Table 6 shows the global climate targets and European level carbon reduction targets for the scenarios in the model inter-comparison projects.

Overall, the level of climate mitigation ambition being assessed has increased over time, and the carbon budget has become more stringent accordingly. For example, the 2°C scenarios in the LIMITS project (2016) and NGFS project (2020) are calibrated for a 70% and 67% chance of keeping to 2°C respectively, whereas in the GEA project, the target was consistent with only a 50 % chance of 2°C. The trend towards higher ambition is also seen by comparing the carbon budgets used in AMPERE versus those in CD-LINKS.

Table 6 Summary of climate targets in the model inter-comparison projects

Database	EU Carbon budget/ climate target	Global climate target	Source
EMF-28 (2012)	80% reduction of EU27 GHG emissions by 2050	"Consistent with global 2°C"	EMF-28 publication, Holz et al. (2013)
GEA (2012)		"Limit temperature change to below 2°C (with a probability of >50%)"	GEA Web Technical Summary for Policy makers
AMPERE (2014)	EU27 123.6 $GtCO_2$ (over 2010-2050) or 78.9 (2020-2050) excluding LULUCF	Carbon budget of 1400 $GtCO_2$ over 2011-2100 including land use	AMPERE study protocol
LIMITS (2016)		2.8 W/m2 giving a likely to very likely (>70%) chance of reaching the 2°C target	LIMITS Study protocol
CD-LINKS (2019)		Carbon budget of 1000 $GtCO_2$ over 2011-2100 including land use (2DS) Carbon budget of 400 $GtCO_2$ over 2011-2100 including land use (1.5DS)	CD-LINKS project protocol

NGFS (2020)	Limit global warming to 2˚C with a 67% chance (2DS) Limit global warming to 1.5˚C with a 67% chance (1.5DS)	NGFS study protocol

Only the most recent two databases, CD-LINKS and NGFS, include scenarios consistent with limiting global temperature rise to 1.5°C as well as 2°C. As explained in section 4, the urgency and stringency of the 1.5°C target induces higher levels of CCS in scenarios which do not explicitly exclude this set of technologies. The stringency of the 1.5°C target has also lead to advances in the design of climate targets, which, instead of considering only cumulative carbon budgets, also include the timing and level of the peak emissions and behaviour of the global temperature after the peak in emissions is reached (Rogelj *et al* 2018a). These changes have a significant effect on the level and use of CCS deployment, in particular for BECCS. For instance, in CD-LINKS, in which the 1.5°C target is modelled with a fixed carbon budget of 400 $GtCO_2$ over the period 2011-2100, BECCS is used to displace fossil-CCS directly. In NGFS, where the new scenario design is utilised, BECCS is used in addition to fossil-CCS to offset its residual emissions, resulting in overall higher total CCS deployment (see the median values of total CCS in Figure 3, right).

5.3 Model scope (global vs European scale models)

This review shows that Total CCS ranges are lower in the results of European-scale models than in Global IAMs, for both 1.5°C and 2°C scenarios (Figure 8 and Figure 9). In the 2°C scenarios, the range of CO_2 captured by CCS in 2050 is 1-3,850 $MtCO_2$/yr in the global models, but only 0-1,300 $MtCO_2$/yr in the European-scale models.

This is due to various factors, including different technology options being available; European-scale models include different demand assumptions, and additional options for CCU technologies. See further discussion on the role of CCU in section 6. Another key issue is the target setting at different spatial and administrative levels; global modelled scenarios will typically not have specific EU targets but will explore where it is most cost-effective ways to undertake emission reductions in line with the global target. This might mean that the implicit EU target in a global scenario is higher or lower than that used in a European model.

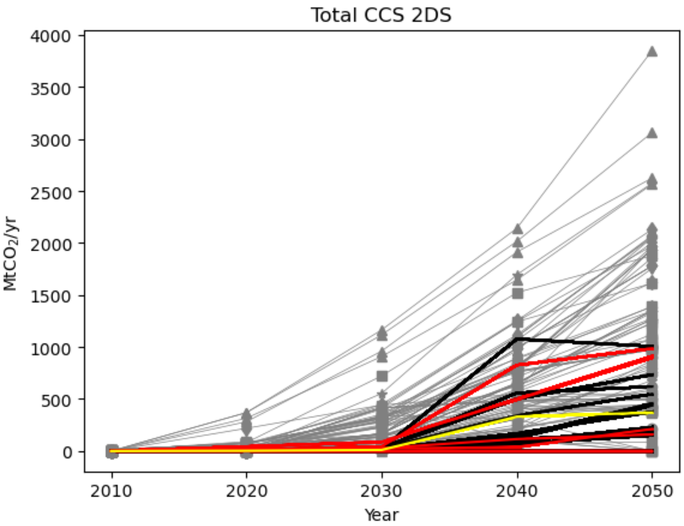

Figure 8. Comparison between the ranges of EU Total CCS under 2°C scenarios reported by global scale models (left, grey lines and markers) vs results reported by European-scale models (left, in bright and bolder colours: PRIMES (black), PRIMES_V1 (yellow), TIMES-PanEU (red). Note, it was not possible to plot BECCS as this was not reported in the databases for the European-scale models.

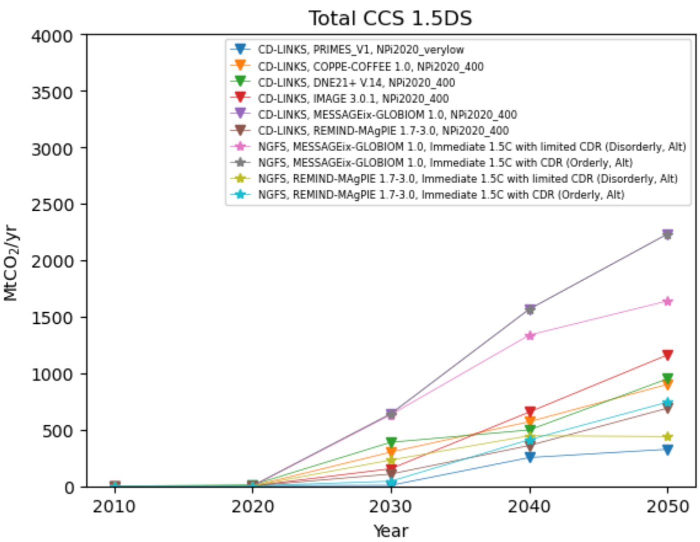

Figure 9. Comparison between the ranges of EU Total CCS under 1.5°C scenarios reported by global scale models vs results reported by PRIMES_V1, European-scale model (blue line and markers). Note, it was not possible to plot BECCS as this was not reported in the databases for the European-scale models.

5.4 Role of biomass

This section reviews the available information on the importance of biomass assumptions in driving the deployment of CCS in the models and the role of bioenergy. Unfortunately, the biomass availability assumptions are not transparently reported for many of the studies or databases included in the review, so insights are also drawn from the wider literature.

Primary biomass used

The biomass input assumptions were generally not stated in the study protocols or journal papers. Plotting the amount of biomass used in the reviewed model scenarios and the amount of CO_2, Figure 10 shows the correlation between the CO_2 captured and the amount of primary biomass consumed across both the 1.5°C and 2°C scenarios. (Each point represents the results for one scenario for 2050.) There is clear correlation between the amount of CO_2 captured by BECCS and the primary biomass consumed. There is no clear correlation between the primary biomass and the total CO_2 (Figure 10, left).

The scenarios of the LIMITS database generally use more primary biomass than those in the CD-LINKS project (See Figure 10). Both databases include scenarios which use up to 20 EJ in the EU by 2050 but in different ways, with quite different levels of BECCS deployment. In LIMITS scenarios, almost all the biomass is used in BECCS technologies, while in CD-LINKS a larger portion of the biomass is used in technologies without CCS. This could be due to the inclusion of additional CDR options (such as afforestation) in the CD-LINKS scenarios (which are not in the LIMITS scenarios) which reduces the need for BECCS in the model.

Figure 10 (right) shows that both databases include scenarios with high CCS and low biomass consumption, particularly in CD-LINKS. This should not be interpreted as meaning that fossil-CCS can reduce the need for BECCS, as in these scenarios there is land-based CDR to compensate for residual emissions including from the fossil-CCS. See Annex 3 for further comparison of the levels of Fossil-CCS and BECCS in each model scenario.

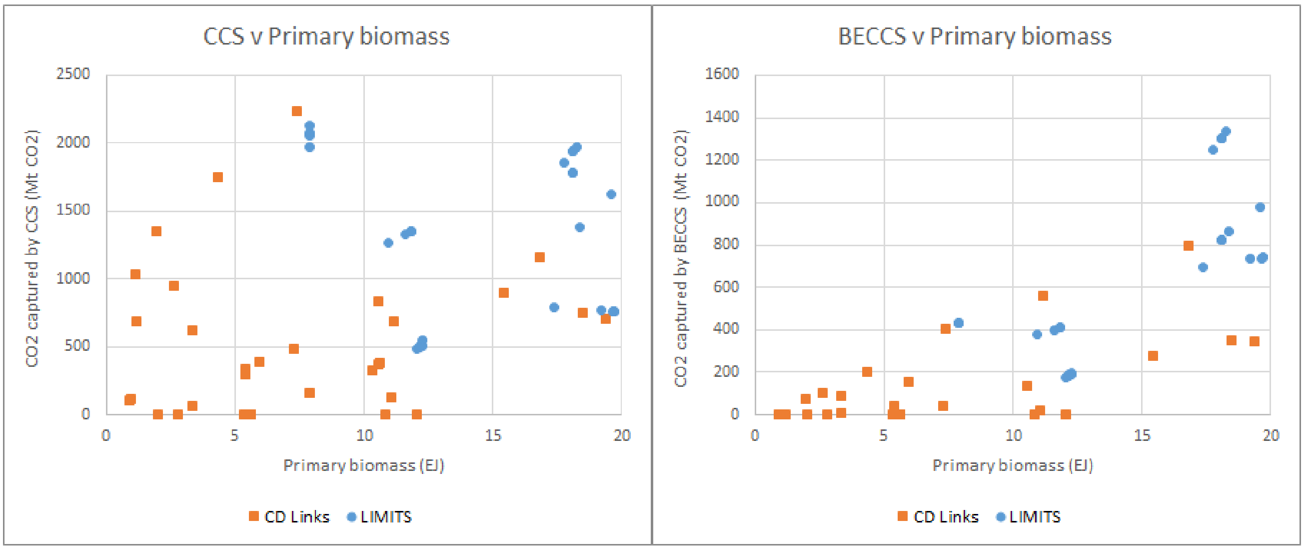

Figure 10 Primary biomass and CO_2 captured by Total CCS (left) and BECCS (right) in the LIMITS and CD-LINKS databases.

Low biomass scenario

The only study covered in this review with a specific low-biomass scenario is the EU 2018 – A Clean Planet for All study. All the scenarios in this study use substantial amounts of biomass in the EU: 7.1-10.5 EJ/yr, which is within the range identified by Mandley et al 2020 (see below). Restricting the biomass availability changes how it is used in the energy system. In the base 1.5°C scenario (in which primary biomass is 8.8 EJ/yr in 2050), approximately 40% of the total biomass is used in electricity generation, while the rest is used for transport biofuels, industry and other end uses. When biomass availability is limited (to 7.1 EJ/yr in 2050), approximately 75% of it is used for electricity. This is due to there being a much higher use of hydrogen and electricity in industrial heat, residential heat and transport. (Note this differs from other studies examining the optimal use of biomass, which tend to suggest that when biomass availability is restricted (and other technologies kept the same), the biomass is used preferentially in the hard to decarbonise industry and transport sectors. For example Vrontisi et al (2019) found that biomass - in particular new lignocellulosic crops - is more effectively used in transport than in power supply or other end uses.) The level of capture from fossil-CCS is almost the same in the two scenarios (74-77 $MtCO_2$), but in the low biomass scenario capture by BECCS is higher and additional DAC is deployed (capture by DAC is 186 $MtCO_2$ vs 123 $MtCO_2$ in 2050 when biomass is not constrained). This results in higher total CO_2 captured when biomass availability is limited. The additional captured CO_2 is largely used in synthetic fuels, as the lower biomass availability leads to a relatively high reliance on synthetic fuels for transport rather than advanced biofuels.

Sustainable biomass potential

Currently, the EU uses 5.6 EJ/yr of bioenergy, of which 4% is imported (Mandley *et al* 2020). Mandley et al (2020) provide a comprehensive and up to date review of the role of bioenergy in the EU up to 2050, summarising biomass resource estimates from studies that use supply-based, demand-based and hybrid methods.

"Supply-based" projections are bottom-up resource assessments, which estimate the potential production of biomass based on available land area and technical assumptions around crop production, e.g. achievable yield. Across these, the review found that the technical potential[7] for domestic production of bioenergy in the EU is estimated at 8.6-25 EJ/yr in 2050. (It is noted that studies conducted since 2010 employ a smaller range of biomass availability assumptions: 8.6-20 EJ/yr by 2050.) The range is mainly due to differences/uncertainties in the land area available for dedicated energy crops, the rate of yield improvements for energy crops, the amount of forest biomass available, which are affected by harvest rates and collection of residue fractions.

"Demand-based" bioenergy assessments use cost-supply curves in models of the energy system or wider economy. These are the models which examine the transition of the energy system, so are scenarios of how much bioenergy is used in a simulated or optimised pathway, rather than what is technically available. The biomass use is lower in these assessments as some of the technical potential is judged to be not economically competitive with other fuels or not preferred when compared to energy efficiency gains in the power sector or other flexibility options. The estimated biomass use is 5-19 EJ/yr in the "demand-side" projections.

Biomass feedstocks

Interestingly, the energy system models described above tend to include biomass resources from purposely cultivated energy crops and forestall and/or agricultural residues. This is somewhat in contrast with the latest JRC analysis of synergies and issues in delivering clean energy technologies in the EU (Carlsson *et al* 2020), which suggests that biomass resources include food crops, and non-food and non-feed biomass e.g. agricultural and forestry residues and municipal solid waste (MSW) and aquatic biomass. The only scenario explicitly mentioning bio-waste is the new SKETCH[8] scenario from Shell. SKETCH depicts an EU in which biofuel use would triple between 2020 and 2050, consuming 1.5 EJ/yr by 2030 and approximately 3 EJ/yr primary biomass by 2050 (fig 3 in (Shell 2020)). Their scenario explores the use of advanced biofuels for the sectors requiring high density liquid fuels, i.e. long-haul aviation and chemicals. Waste-related biofuels are expected to help transition to scale deployment especially for aviation fuels.

[7] "Technical potential" denotes theoretical potential for biomass production, which has not been constrained by socio-economic factors, e.g. establishment of new supply-chains, public acceptance of energy crop production.
[8] https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/scenario-sketches/new-sketch-a-climate-neutral-eu.html

Biomass trade

Biomass trade is commented on in Mandley *et al* (2020) as well as Jewell *et al* (2014) and Calvin *et al* (2013), which both analysed results of the LIMITS database. Whether biomass trade is allowed and economically preferable affects the potential biomass used in different regions, and therefore the potential for BECCS.

Jewell *et al* (2014) and Calvin *et al* (2013) noted that trade in biomass commodities is allowed in some models and not in others. In the LIMITS scenarios, trade of primary biomass is allowed in the IMAGE, TIMES-ECN and REMIND models, while trade in biofuels is allowed in MESSAGE, IMAGE and TIMES-ECN. Under the 2°C scenario, in the ReMIND model the EU exports approximately 400 EJ of bioenergy (due to peaking population, high yields and good transport infrastructure) whereas in IMAGE the EU imports approximately 500 EJ of bioenergy (Jewell *et al* 2014). Clarification on the extent to which biomass may be traded internationally in the future would assist further modelling efforts.

As would be expected, when global trade in bioenergy is allowed in the models, regional patterns of bioenergy use reflect global patterns, whereas when trade is restricted, regions with high potential to produce biomass generally consume more than regions with low production potential (Calvin *et al* 2013). In the models where feedstocks can be traded globally, bioenergy production potential does not limit the consumption of bioenergy on a regional basis, whereas towards the end of the century, the injection rate for captured CO_2 to underground storage is a binding constraint in several regions (Calvin *et al* 2013).

Mandley *et al* (2020) found that the EU is likely to be able to meet its own demand for biomass with domestic production in terms of technical potential, however notes that models tend to project a significant increase in biomass from outside the EU (from the current 4% rising to 13-76%) due to those imported resources being better quality or more economically favourable as the models do not foresee meaningful reduction in domestic biomass production costs.

6 The role of CCU

Section 6: Key findings

- CCU technologies feature in decarbonisation pathways from European scale models, but not global scale models. This likely reflects the lack of available CCU options in global models.
- The scale of CCU deployment in EU decarbonisation pathways is between 47 and 800 $MtCO_2$/yr by 2050. In some cases, this contribution is as high as 50% of the captured CO_2.
- There is relative agreement across the studies as to the contribution from CCU for materials (47 to 80 $MtCO_2$/yr by 2050), but not for liquid transport fuels (150 to 800 $MtCO_2$) and chemicals (up to 300 $MtCO_2$).
- Spatial analysis of CO_2 sources and utilization industries identified regions with high potential for CCU: Germany (Dusseldorf and Cologne), Belgium (Antwerp Province and East Flanders), Spain (Cataluna) and Poland.
- The main drivers of CCU deployment in the models are climate credits (e.g. CO_2 captured and permanency of storage). This is variable across the studies because it is dependent on the source of CO_2, supply chain emissions, and what the synthetic materials and fuels substitute.
- Currently there is an active debate on the role CCU options could play in climate mitigation.
- LCA studies suggest that CCU for transport fuels lead to positive (not zero) emissions supply chains, while CCU for chemicals may lead to carbon neutral supply chains. More research is needed to understand the contribution of CCU to climate mitigation, when CCU is implemented at continental or global scales.

6.1 Availability of CCU as a mitigation option

To investigate the role CCU technologies could play in the European decarbonisation, this study scrutinised all the models providing decarbonisation pathways compatible with 1.5°C and 2°C global scenarios. A first finding is that the global IAMs which provide EU ranges for CCS technologies as reviewed in Section 3, do not report CCU deployment. For instance, the IAMC wiki[9], which provides an overview of similarities and differences across global IAMs, lists a rich portfolio of CCS technologies available in global scale IAMs, but there is no mention of CCU.

The absence of CCU technologies from global IAMs is also highlighted in the wider literature, see e.g. Detz and van der Zwaan (2019), who argue that including CCU technologies in global IAMs would provide far more opportunities for reaching global net zero by 2050. Depending on the source of CO_2 captured, Detz and van der Zwaan (Detz and van der Zwaan 2019) suggest that CCU technologies could deliver net zero emissions or even negative CO_2. However, this is strongly debated by Mac Dowell et al. (2017), who suggest that from the perspective of mitigating anthropogenic CO_2 emissions, CCU "is highly unlikely to ever be a realistic alternative to long-term, secure, geological sequestration." These authors suggest that CCU could at best supplement CCS to a small extent, and mainly through CO_2 Enhanced Oil Recovery (CO_2-EOR), the only CCU technology they estimate can be developed at the required scale.

Several global energy systems models, e.g. TIAM-UCL (Anandarajah *et al* 2011), TIAM-FR (Selosse and Ricci 2017), include CO_2-EOR as a geological storage technology. Consequently, CO_2-EOR is reported as CCS, not CCU. However, as suggested by several studies, e.g. MacDowell *et al* (2017), Hepburn *et al* (2019), the sequestration potential of CO_2-EOR depends on the source of CO_2. When the injected CO_2 is equal to the CO_2 released by burning the extracted oil, if the utilised CO_2 comes from a fossil-CCS plant, then there is no net CO_2 removal from the atmosphere and the CO_2-EOR is a net emitter of CO_2. This suggests that CO_2-EOR should not be considered a CCS technology, which implies storage of CO_2 over centuries. However, recent studies, e.g. Núñez-López *et al* (2019) suggest that with careful selection of operational choices, CO_2-EOR could achieve a net negative carbon throughout most of its life cycle. The assumptions around and role of CO_2-EOR in decarbonisation pathways may need further investigation, especially as several countries explicitly mention CO_2-EOR in their NDCs. [10]

6.2 Confusion related to the term "CCUS"

Carbon Capture Utilisation and Storage (CCUS) is highlighted as key technology in the IEA's "Transforming Industry through CCUS" report (IEA 2019). As the IEA opted for discussing CCU and CCS together, it is not straightforward to differentiate how much of this is CCU (without geological, or long-term CO_2 storage), how much is CCUS (CO_2 utilisation followed by geological storage, e.g. CO_2-EOR), and how much is purely CCS (without utilisation). In the IEA Clean Technology Scenario, compatible with the Paris Agreement climate targets, "CCUS" contributes almost one-fifth of the emission reduction of the global industry sector, being deployed for the production of synthetic low carbon fuels, including low carbon hydrogen, and to remove CO_2 from the atmosphere in combination with biomass (IEA 2020b). While the first set of technologies might fit under the CCU definition used in this report, bioenergy with CO_2 removal from the atmosphere and sent to

[9] https://www.iamcdocumentation.eu/index.php/IAMC_wiki

[10] All countries NDCs available at http://www4.unfccc.int/ndcregistry/Pages/All.aspx. Also see (Campbell *et al* 2018) for a summary of countries mentioning CO_2-EOR in their NDCs.

geological storage would classify as CCS. However, the IEA study doesn't specify the potential for European CCU and CCS deployment in 2030 and 2050, nor does it make a clear difference between CCU and CCS.

The term "CCUS" is also mentioned in the Shell Sketches scenario, compatible with EU net zero by 2050[11], although BECCS is mentioned separately and net CO_2 removal option, along with natural sinks. Shell estimates that 50 $MtCO_2$/yr in 2030 and up to 600 $MtCO_2$/yr in 2050 need to be stored, complemented by sequestration of up to 300 $MtCO_2$/yr in 2050 in natural carbon sinks (equivalent to reforesting 5% of EU area). They found that "CCUS" is critical for achieving net zero in the EU by 2050, especially in high emitting industries, e.g. cement, and power through BECCS. Shell acknowledges that using captured CO_2 for fuels and chemicals is important for the transition, but as this form of CCU results in net emissions, in the long-term CCU should be restricted to permanent or near-permanent uses, e.g. building materials.

6.3 Role of CCU options

A key role for CCU for synthetic fuels is indicated by several studies exploring futures fuelled by 100% renewable electricity. Teske (2019) suggests that synthetic fuels from captured CO_2 and renewable electricity could play an important role not only for providing low carbon transport fuels, but also for the long-term storage of renewable power and balancing the renewable energy across borders. Khalili *et al* (2019) investigate the transition of the global transport system to net zero by 2050, suggesting renewable electricity, hydrogen, and renewable fuels such as synfuels (fuelled by renewable electricity) and biofuels (limited by sustainability constraints) as key components in the transition. Again, synthetic fuel storage is seen as key for providing the needed system flexibility in electricity systems that are close to 100% renewable. Bogdanov *et al* (2019) describe a 100% renewable electricity system in which synthetic fuels from captured CO_2 and renewable electricity play a critical role in storing and converting renewable electricity. They also note that this role is not seen in global IAM modelling pathways compatible with 1.5°C as IAMs do not have enough temporal resolution of the power system (as they usually use annual energy balancing), and therefore lack insights for storage needs, grid demand, demand response, and variable renewables complementarity. Furthermore, several studies have highlighted the underestimation of renewable energy potentials in IAMs, e.g. (Creutzig *et al* 2017, Krey *et al* 2019), because of high cost assumptions, no representation of country-level renewables policies, and partial modelling of system integration.

Some of the limitations discussed above for the inclusion of CCU in global IAMs are addressed in EU-scale models. Using an EU scale energy system model, JRC-EU-TIMES, Blanco et al (2018) investigated the role of hydrogen and Power-to-Liquid (PtL) in a low carbon EU, i.e. meeting between 80 and 95% CO_2 reduction by 2050 (vs. 1990). Their results suggest a deployment of CCU between 200 and 500 $MtCO_2$/yr, increasing up to 800 $MtCO_2$/yr when biomass potential is high. This amounts to approximately 40% of captured CO_2. They found a preferential CO_2 utilisation for PtL, which can reach a deployment of up to 800 $MtCO_2$/yr, and chemicals utilising up to 290 $MtCO_2$/yr. 85% of CO_2 for utilisation across different categories comes from biomass to ensure neutrality of liquids. They found that the main driver of CCU is transport, as the other sectors can be decarbonised by using low carbon hydrogen or electricity. They also found the parameters with the largest influence on CCU are the stringency of the CO_2 target, the availability of CO_2 underground storage, and the biomass potential. PtL becomes economically attractive only when there is a ban on underground geological storage (the lowest cost storage option). The authors highlight key challenges for PtL, including the sources of CO_2, competition with biofuels, electricity and H_2 sources, and system conditions which make the technology attractive. Among BtL processes, biojet fuels are usually favoured. However, when biomass

[11] https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/scenario-sketches.html

availability is high, there is enough biomass to produce biodiesel directly, making more CO_2 available to be used in PtL for biojet fuel.

Using the same EU-scale energy system model, JRC-EU-TIMES, integrated with Life Cycle Analysis (LCA), Blanco *et al* (2020) investigates the role of Power-To-Methane (PtM) in decarbonizing the European energy system in scenarios achieving between 80 and 95% of GHG emission reduction as compared to 1990. In this study PtM is methane production from electricity and captured CO_2. The resulting methane is used both the variable renewables integration and decarbonisation of heating. The GHG profile of this CCU option is directly influenced by the profile of the electricity and the captured CO_2. They conclude that for PtM to be less carbon intensive than natural gas, the emission factor of electricity used for PtM should be 123–181 gCO_2eq/kWh when the CO_2 comes from air or biogenic sources. However, the authors highlight that PtM becomes attractive only when geological storage is not possible, hence preventing BECCS for power to deliver negative emissions.

CCU is also identified as a key technology in the EU 2018 report "A Clean Planet for All". PRIMES (EU scale energy system model) scenarios compatible with 1.5°C and 2°C suggest that by 2050 between 47 and 80 $MtCO_2$ are stored in materials, and 154 - 372 $MtCO_2$ are utilised for synthetic fuels production. In these scenarios only CO_2 from BECCS or DAC can be used for synthetic fuels and materials (i.e. not CO_2 from fossil fuel CCS), to ensure carbon neutrality. The level of CO_2 utilisation in this study is approximately 50% of the total CO_2 captured. This report also specifies assumptions around CCU technologies TRL and start time: synthetic fuels (power to gas/liquid) TRL = 6, expected market entry 2025, vs advanced biofuels (TRL = 9 in 2020), CCS (TRL = 8-9 in 2025) and renewable H_2 (TRL = 7 in 2020).

Note that all the studies using energy system models for exploring future decarbonisation pathways provide insights on the CO_2 abatement potential of CCU technologies from a bottom up perspective and in the context of least-cost decarbonisation scenarios. This may explain the fact that they suggest an important role of CCU for synthetic fuels (between 150 to 800 $MtCO_2$/yr by 2050). Other studies, e.g. Shell Sketches, see only a transitional role for CCU for fuels, suggesting that on the long term the focus should be on CCU options which lead to long-term CO_2 storage. A more holistic vision for the role of CCU is described by Carlsson *et al* (2020, who identify several synergies between CCU, CCS and biomass (termed CCUS) in both materials (chemicals, plastics, building materials) and transport fuels, e.g. H_2 from biomass or coal gasification with CCS, CCS on advanced biofuels, captured CO_2 combined with H_2 serving as energy storage. JRC-EU-TIMES scenario results used in Carlsson et al (2020) suggest ranges between 80 and 96 $MtCO_2$/yr stored in materials by 2050 and between 56 and 399 $MtCO_2$/yr by 2050 CCU, mainly production of diesel or kerosene by combining hydrogen and CO_2.

With spatial analysis, Patricio et al (2017) identified the regions within Europe that have the greatest potential to deploy CCU. Note, this method differs significantly from the other studies included in this review, as it is a snapshot spatial analysis, rather than the simulation or optimization of a transition pathway. 9 CCU technologies with promising technology readiness levels were considered. The potential sources of CO_2 were mapped using emissions data collected by the European Commission (these are mainly thermal power stations and industrial combustion processes) and the potential uses of CO_2 were mapped using historic activity data for those utilization processes. Based on this analysis, the study found that the 9 CCU technologies could potentially utilize up to 72.9 $MtCO_2$ in Europe each year. The highest potential is for concrete curing and horticulture production which account for up to 22.5 and 22.2 $MtCO_2$/year respectively, followed by lignin production (8.4 $MtCO_2$/yr) and ethylene and propylene polymers (8.3 $MtCO_2$). The results indicate that Germany, UK and France, followed by Spain, Italy and Poland have the greatest potential for CCU due to the co-location of potential sources and receiving processes. The study specifically highlights the following sub-country regions where CCU could be developed: in Germany (Dusseldorf and Cologne), Belgium (Antwerp Province and East Flanders), Spain (Cataluna) and Poland (S'la˛skie). Further promising regions are in Poland (Łódzkie), Finland (Etelä-Suomi and Helsinki-Uusimaa), Italy (Lombardia) and The Netherlands (South Holland

and North Braband). The authors note that the CO_2 sources and receiving processes have large potential in the UK and France but are not co-located at the sub-country level.

6.4 CCU climate merits from an LCA perspective

It is interesting to note that energy system modelling studies have a preference for CCU for synthetic fuels, especially in combination with biomass resources to ensure carbon neutrality of the resulting fuels. Life Cycle Assessment (LCA) has an established methodology for assessing the environmental impacts of materials and fuels. A clear message from the LCA literature, also in agreement with other studies, e.g. Hepburn *et al* (2019), is that CCU cannot be considered "by default" as leading to lower GHG emissions, as their life cycle carbon emissions are highly case-dependant (e.g. Müller *et al* 2020, Kätelhön *et al* 2019, Artz *et al* 2018).

Regarding the climate merits of CO_2 utilisation for synthetic fuels, several LCA studies suggest that these result in net emissions of CO_2, for example: Blanco *et al* (2020) demonstrated net positive emissions for PtM; Artz *et al* (2018) demonstrated it for gas-to-liquid diesel and jet fuels produced by CO_2-based Fischer−Tropsch processes fed with CO_2 captured from fossil plants, or other unsustainable sources; Thonemann (2020) for CO_2-based production of kerosene; and Liu *et al* (2020) for CO_2-based production of diesel, with CO_2 captured by DACS. Note that these LCA studies do not necessarily use biomass as feedstock. Biomass is usually considered as carbon neutral in IAMs (Butnar *et al* 2020b), and hence utilised with CCU to produce carbon neutral products and/or with CCS as a CDR option. However, there are multiple examples in the LCA and wider literature challenging the assumption of biomass neutrality, for example see Lamers and Junginger (2013) and Röder *et al* (2019), hence also challenging the assumption that CCU would lead to carbon neutral fuels.

CCU options leading to carbon neutral products include utilisation of captured CO_2 for chemicals production, but not for transport fuels. Several LCA studies suggest CCU options may lead to carbon neutral chemicals, e.g. CO_2-based oxymethylene ethers produced with wind electricity and biogas CO_2 (Deutz *et al* 2018), plastics or chemicals from concentrated industrial de-fossilised CO_2 sources (Artz *et al* 2018).

The LCA literature also highlights that low TRL technologies might have overestimated emissions, as they are not optimised. For example, Müller *et al* (2020) suggests that industrial scale utilisation of CCU would bring with it process optimisation of both materials and energy efficiency. CCU would also benefit from economies of scale and established supply chains. They also highlight that as CCU will be deployed in the future, their merits should be compared against their counterfactuals in the future, and not to the current technology base, as usually done in LCA studies assessing CCU (Müller *et al* 2020). This is even more relevant for the use of CCU for mitigating GHG emissions from the chemical industry where the climate change mitigation potential of CCU is not determined by the amount of carbon stored in the chemical, nor by the amount of CO_2 utilised, but what the resulting product substitutes (Kätelhön *et al* 2019). Kätelhön *et al* (2019) caution that while LCA studies demonstrated GHG emission reduction for individual CCU technologies, more research is needed for understanding the climate merits of CCU implementation at larger continental or global scales.

7 Infrastructure and costs

Section 7 Key findings

- Areas with a high density of industrial sites present the best opportunities for commercially viable development of CCS clusters. Scattered deployment of CCS could significantly increase the cost per unit of CO_2 transport and storage.
- Possibilities for onshore storage will drive storage cost reduction.
- Important drivers determining economic CCS infrastructure deployment include: the evolution of capture sites' distribution over time (i.e. where capture sites are located), the capacity and potential injection rates of storage sites, climate policy, fossil fuel prices.
- Spatial modelling of the suggested EU pathways to net zero is needed to understand implications for CO_2 storage options, including cross-sector synergies.
- Costs of parts of the CCS process (globally) are estimated as follows: capture $/t$CO_2$ 20–110, transport 1.3-15.1 $/t$CO_2$/250 km, storage 1.6-31.4 $/t$CO_2$.
- Global IAMs generally use the following post-capture cost assumptions: transport 10 $/t$CO_2$, storage 5-10 $/t$CO_2$.
- Models indicate that average annual investments for CCS in Europe between 2016 and 2050 would be $11 billion/yr in scenarios consistent with 2°C, and $14 billion/yr in scenarios consistent with 1.5°C.

Where available in the studies covered in this review, the infrastructure requirements and costs associated with CCS deployment were recorded. Where available, regional opportunities for shared infrastructure are also recorded.

7.1 Infrastructure

The EU 2018 report "A Clean Planet for All" notes that areas with a high density of industrial sites present opportunities for commercially viable development of CCS clusters. Sites already in development include the ports of Rotterdam, Antwerp and Marseilles and Tees Valley. The following papers completed spatial network analysis on the pipelines and infrastructure that could be needed based on where storage sites are located. These papers are a few years old, and do not reflect findings on the volumes of captured CO_2 reported under EU pathways to net zero. New spatially explicit research on CO_2 infrastructure compatible with net zero EU pathways is needed to cover this gap.

Kjarstad et al. (2013a) combined techno-economic modelling of the electricity system (Chalmers Electricity Investment model) with cost-optimisation analysis of bulk CO_2 pipelines to assess how the CO_2 transport network could develop over time considering the locations of power plants and storage sites. The study found that evolution of capture sites' distribution over time (I.e. where capture sites are located) as well as the capacity and potential injection rates are all important drivers for the optimal lay-out and timing of pipelines. Further, the study found that permitted aquifer storage is a key driver of transport costs: costs would more than double if onshore storage were excluded. The authors noted that uncertainties in when capture equipment will be installed and storage reservoir characteristics could limit the construction of CO_2 transportation networks in Europe.

Oei et al (2014) focused on the costs of CCS and CO_2 transport and found that more scattered deployment of CCS could significantly increase the cost per unit of CO_2 transport and storage – by as much as 30% or more. It should be noted that energy system models can also provide insights on the potential economic use of particular storage sites in long-term decarbonisation pathways (e.g. Selosse and Ricci 2017). The literature on specific storage sites is not extensively covered in this review. However, an example can be seen in Strachan *et al* (2011), which used energy system optimisation models at multiple scales (country and European level) to examine the potential role of the Utsira geological formation as a shared CO_2 storage site for the countries bordering the North Sea, and whether different network layouts might influence the cost and deployment of CCS and the Utsira site. The study found that climate policy is a key driver of CCS deployment as well as fossil fuel prices, that Utsira played an important role in the electricity decarbonisation pathways examined, and that national level policies and regional commodity trading led to differences in the contributions from different countries.

The IEA Special report on CCUS (IEA 2020a) estimates that around 68% of key emission points in Europe (power plants and factories) are located within 100 km of potentially available geological storage. However, they point out that much of the European storage is located onshore, where storage projects are likely to get public opposition. Modelling studies such as Selosse and Ricci (2017) suggest that CCS based decarbonisation pathways would be significantly impacted by limited onshore storage. But this is due to higher offshore storage costs assumed in the study, rather than to the available storage capacity.

7.2 Costs

Detailed analysis of the costs of CCS was outside the scope of this review, however some limited information on this was found in the modelling studies covered. Further research focusing specifically on CCS and CCU costs in the wider literature could be beneficial for expanding on and contextualising our findings.

A recent assessment of CCS costs, barriers and potential is provided in Budinis *et al* (2018), with a global focus. The authors note that cost estimates for CCS vary widely, and depend on the process type, separation technology, CO_2 transport technique and storage site, but that there is a notable lack of cost data for specific processes and technologies. The review showed that the capture step is the most expensive part of the CCS process with costs ranging \$2015/tCO_2 20–110. The cost to transport cost CO_2 depends on the location and length of the pipeline, ranging 1.3-15.1 \$2015/tCO_2/250 km. Storage cost depends on the type of storage site (including whether existing facilities can be reused) and is 1.6-31.4 \$2015/tCO_2.

In a review of the assumptions employed in global IAMs, Butnar *et al* (2020b) found that that these models generally assume CO_2 transport costs to be approximately 10 \$/tCO_2 (but can range 1-30 \$/tCO_2) and geological storage costs to range 5-10 \$/tCO_2. The upper limits of these ranges are slightly lower than those identified by Budinis *et al* (2018); more information on specific technologies and regional costs is needed.

Some discussion was found in the studies regarding the impacts of costs on the deployment of CCS in the models. Oei et al (2014) focused on the impact of different CO_2 prices on the optimal CCS deployment and CO_2 transport network in Europe. In this analysis, the costs were such that different sectors would install CCS technologies at different carbon prices: it would be economically preferable for iron and steel at 50 euro/tCO_2, cement at 75 euro/tCO_2 and electricity at 100 euro/tCO_2. Note this analysis was published in 2014 so the costs may be outdated. The variable costs of CO_2 capture were found to be more important in driving the level of CCS deployment than investment costs. Budinis *et al* (2018) added to this with their review of the barriers to CCS deployment, concluding that in the short to medium term, cost is the most significant barrier to greater CCS deployment, but that CCS is thought to become cost effective when compared with other mitigation options in the long-term, and so then the residual emissions from CCS facilities becomes the key factor limiting uptake in modelled scenarios.

Investment requirements for CCS were examined in McCollum *et al* (2018) using a set of the global IAMs. This analysis indicates rapid decline in investments in unabated fossil fuel infrastructure, to be replaced with increased investments in renewables, nuclear and demand-side energy efficiency (and to a lesser extent fossil fuel power plants with CCS). Under current policies, average annual investments in CCS in Europe between 2016 and 2050 are expected to be zero (the range across the models is \$0-2 billion/yr). If current NDCs are implemented in the models, average annual investments rise to \$2 billion/yr (0-8 billion). Under scenarios consistent with 2°C, they are increased to \$11 billion/yr (1-23 billion) and under 1.5°C they are increased to 14 billion (2-24billion). Carlsson *et al* (2020) provide further detail on technology-specific investment requirements for Europe from modelling with JRC-EU-TIMES. This report suggests that for a scenario consistent with net zero by 2050, high investments are required for biofuel production (with re-use of all carbon), fuel cells and DAC. In particular, this study notes a deployment of DAC of up to 350 MtCO_2/yr by 2050 which would require on average 6 bn€/yr. Detailed analysis of the relationship between CCS deployment (or restrictions) and system costs, or wider economic impacts, was not available in the literature covered in this review. As mentioned above, no scenarios were identified in this review that are consistent with net zero in the EU by 2050 without the use of CCS. Further cost analysis may be found if the scope of a future review were focussed on this question. However, some initial insights were identified.

Griffin *et al* (2014) analysed scenarios from the EMF27 project and POLES model to investigate the potential for achieving decarbonisation consistent with 2°C without CCS (and/or nuclear power). Using cost assumptions that were reasonable at the time of publication, the study found that it appeared possible to replace nuclear generation with renewable power at "realistic" costs (calculated as total abatement costs and final user prices to households), however the exclusion of CCS caused "unbearable economic costs", indicating that CCS could represent a critical technology. In this analysis, the marginal abatement cost in 2050 was 830 \$/tCO_2eq in the 'All technologies' scenario, and 4130 \$/tCO_2eq in the scenario without CCS. The model was not able to identify a pathway consistent with 2°C when both CCS and nuclear power were excluded. We note that the cost of renewable electricity, and projected future costs, have fallen considerably since the publication of this analysis, so this assessment may be outdated. More updated analysis on this would be valuable.

The availability of other particular technologies (which are used in combination with CCS) could also impact system costs significantly. For example, Blanco *et al* (2018a) found that expanding H_2 and PtL would contribute to energy security and independence, while reducing energy related import costs for Europe from the current €420 billion/yr to 350 or €50 billion/yr for 95% CO_2 reduction with and without CO_2 storage.

A recent analysis of the stranded assets problem with relation to the European energy system transition is presented by Loffler *et al* (2019). This studied employed the GENeSYS-MOD with limited foresight to examine the unused capacities and stranded assets that could arise. While, many of the models used for energy system modelling have full view of the demands, costs and technical parameters over the modelling horizon, the limited foresight feature leads the model to represent imperfect knowledge and shorter-term planning. This study found that that even in the base case with perfect foresight, the rapid transition required under the 2°C target leads to the underutilization of existing fossil fuel plants. Approximately 85 GW of capacity would be stranded, corresponding to investment losses of approximately €50 billion. In the scenario with limited foresight, there is even more over-construction of conventional generation plants in the 2020s, leading to €150 billion of investment losses. The POL scenario also includes constraints which represent certain political boundaries, thus representing how policy-makers often have to compromise with multiple objectives and influences. In this scenario, conventional power plants have their lifetimes extended (due to concerns over energy security and jobs) and national targets for renewable capacity are not exceeded; up to 260 GW total capacity could be stranded by 2035, leading to investment losses of €200 billion, with significant shares in the coal and gas sectors. This difference between these scenarios indicates how the risk of stranded assets is compounded when short term priorities are prioritized over the long-term goal, and leads the authors to call for "strong, clear signals from policy makers arises in order to combat the threat of short-sighted planning and investment losses".

No detailed analysis of stranded assets associated with CCS, or no-CCS scenarios, was found.

8 Summary and discussion

- This section discusses the main findings of the review. It also highlights remaining research and data gaps. CCS is highly prevalent across the scenarios reviewed, suggesting that it is a key technology needed for future decarbonisation. This is particularly true where specific sectors exist that would be hard-to-mitigate.
- While earlier published scenarios explored pathways that excluded CCS, such scenarios are now less prevalent due to increasing climate ambition in recent years. Notably, in the most ambitious 1.5°C cases, BECCS is particularly important, as a CDR option, to offset other sectors where emissions may continue.
- This review also highlights that CCS options are highly cost-effective in many modelling analyses because they allow for continued use of fossil fuels and provide a system-wide offset mechanism via BECCS.
- Published scenarios indicate that CCS is essential for Europe to reach net zero CO_2 emissions by 2050, which is consistent with the 1.5°C global target. Under a 2°C target, most scenarios suggest a prominent role for CCS, although a small number suggest low levels of deployment.
- This implies that Europe needs a large-scale CCS industry to meet future targets. In the 1.5°C scenarios, the median CO_2 captured by CCS is 230-430 $MtCO_2$/yr in 2030, increasing to 930-1200 $MtCO_2$/yr by 2050. In the 2°C scenarios, the median CO_2 captured by CCS is lower with 35-100 $MtCO_2$/yr in 2030, increasing to 600-930 $MtCO_2$/yr by 2050. There is still a significant range across these scenarios, implying some key uncertainties as to the actual level that might be required.
- CCS enables CO_2 removal when combined with bioenergy, provided biomass is sourced sustainably. BECCS plays a key role in Europe, based on the modelled scenarios. In the 1.5°C scenarios, the median CO_2 captured by BECCS is 30 $MtCO_2$/yr in 2030, increasing to 400 $MtCO_2$/yr by 2050. In the 2°C scenarios, the median CO_2 captured by BECCS is lower with 1-5 $MtCO_2$/yr in 2030, increasing to 150-230 $MtCO_2$/yr by 2050.
- Scenario design strongly influences the amount of CCS deployed in both the 1.5°C and 2°C scenarios. Assumptions such as high future energy demands or low levels of renewable deployment lead to higher levels of CCS deployment, and vice versa. European-scale models were found to suggest lower levels of CCS deployment. More research is needed to understand what drives these differences.
- Models indicate significant annual investments are needed in CCS in Europe until 2050 in both 1.5°C and 2°C scenarios. These amount to $14 billion (median) in scenarios consistent with 1.5°C and respectively $11 billion (median) in 2°C scenarios.
- The study does not give a clear consensus if and how CCU can play a role in the decarbonisation. Some studies foresee a significant role while others do not consider it.
- However, large uncertainties remain as to the role of CCS, as represented by the scenario set reviewed in this study. Policy makers will need to assess how to manage such uncertainties.
- Critical uncertainties identified in this review include the level of sustainable biomass that will need to be diverted to BECCS, the level of future energy demand, performance of CCS e.g. capture rates, and the role of CCU.
- Other key uncertainties include the extent to which other strategies are taken. A stronger focus on renewables and storage may limit the need for CCS in power generation, and there may be questions about the role of hydrogen, and its use of CCS depending on production e.g. electrolysis. Hence the importance of whole system thinking for this type of strategic thinking.

- While CCS has been shown to be prevalent across models, there has been limited focus on demand side efforts in many models. Two scenario exercises showed that CCS could have a limited role if large reductions were made in energy demand, through efficiency measures and reductions in demand for energy services.
- There are a number of areas for further research including; which sectors are best to deploy CCS, and what is the role for CCU. For the latter case, this reflects that many models do not often include CCU. Some of the European models, which have more detailed specification, show an important role for CCU, albeit not at the levels for CCS.

Key research gaps for modelling include:

- Enhanced representation of CCU. In particular, global models do not appear to have included the types of options included in Europe-only models.
- Improved consideration of spatial factors relating to infrastructure, particularly that which concerns transport and storage, and proximity to sources of CO_2.
- Alternative demand side strategies to explore the role for CCS under lower demand scenarios
- More analysis to highlight risks associated with CCS failing to scale; such risks are rarely embedded in these scenarios.

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10 List of Abbreviations

CCS: Carbon Capture and Storage (total CCS refers to the totality of CO_2 captured and stored in geological storage)

BECCS: Bioenergy with Carbon Capture and Storage

CCU: Carbon Capture and Utilisation

IAM: Integrated Assessment Model

NDC: Nationally Determined Contributions

CDR: Carbon Dioxide Removal

DACS : Direct Air

11 Technical annexes

11.1 Annex 1. Selected public databases for assessing CCS and CCU ranges

Database and last update year	Relevant results to this study*	Models providing EU level results**	Geographic resolution of Europe results	Climate targets	Links and selected references to be reviewed further
AMPERE (2014)	Total CO_2 emissions mitigated by CCS; capacity of CCS technologies (electricity from gas +CCS and coal +CCS)	TIMES Pan EU and PRIMES (both EU models)	EU27	80% GHG emission reduction by 2050 (2°C)	https://tntcat.iiasa.ac.at/AMPEREDB/dsd?Action=htmlpage&page=about (Capros *et al* 2014, Marcucci and Fragkos 2015, Schwanitz *et al* 2015)
CD-LINKS (2020)	Capacity additions, primary energy, secondary energy (hydrogen, electricity, liquids) and investment requirements for techs with (and without) CCS.	IMAGE, MESSAGE, REMIND (all global models)	EU28	NDCs	https://data.ene.iiasa.ac.at/cd-links/# (McCollum *et al* 2018, Vrontisi *et al* 2019)
EMF28 (2013)	CCS results are aggregated (no CCU-specific results) Percentage share of each generation technology, system costs when CCS excluded	CCTSMOD, EMELIE-ESY, EMPS, EPPA, FARM EU, GEM-E3, Global Gas Model, MERGE-CPB, PACE, PET, POLES, PRIMES, TIAM-UCL, TIMES Pan EU, TIMES-VTT, WITCH, WorldScan (various geographic scope)	EU27 level and individual countries France, Italy, Germany, Sweden, UK	80% GHG emission reduction by 2050 (2°C)	https://tntcat.iiasa.ac.at/EMF28publicDB/dsd?Action=htmlpage&page=welcome Special Issue of Climate Change Economics on EMF28/Scenarios for Transforming the European Energy System https://www.worldscientific.com/toc/cce/04/supp01 including (Holz and Von Hirschhausen 2013, Weyant *et al* 2013, Knopf *et al* 2013)
LIMITS (2016)	Installed capacity of fossil and bio-power generation with CCS, bio-liquids with CCS	AIM-Enduse, GCAM, IMAGE, MESSAGE, TIAM-ECN, REMIND, and WITCH (global models)	EU27	LIMITS 450 scenario (2°C)	https://tntcat.iiasa.ac.at/LIMITSPUBLICDB/dsd?Action=htmlpage&page=sectors Special Issue of Climate Change Economics on LIMITS project/ Implementing Climate Policies in Major Economies https://www.worldscientific.com/doi/10.1142/S201000781440003X

					(Tavoni *et al* 2015, 2013)
GEA (Global Energy Assessment Scenario Database, 2013)	Aggregated CCS CO_2 removal/mitigation; installed capacity for fossil- and bio-CCS for electricity, liquids and hydrogen	IMAGE and MESSAGE (global models)	WEU and EEU (EU27)	2°C	https://tntcat.iiasa.ac.at/geadb/dsd?Action=htmlpage&page=regions
The GGI (Greenhouse Gas Initiative) scenario database (2009)	Fossil- and bio- CCS CO_2 emissions mitigation/removal	IIASA IAM framework/ MESSAGE-GLOBIOM (global models)	WEU and EEU (EU27)	450ppm/ 2°C scenarios	https://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=htmlpage&page=about
The Network for Greening the Financial System (NGFS) scenario database (2020)	Coal, gas, oil and bio-CCS, for electricity and industry - installed capacity and CO_2 emissions mitigation/removal by technology	REMIND-MAgPIE 1.7, GCAM5.2 and MESSAGEix-GLOBIOM (global models)	GCAM EU12, EU15, Europe Eastern, Europe NonEU; MESSAGEix-GLOBIOM Eastern Europe, Western Europe; REMIND-MAgPIE EU27	Current policies, NDCs, 1.5°C and 2°C	https://data.ene.iiasa.ac.at/ngfs
Shared Socio-economic Pathways (SSP) database* (2018)**	Fossil- and bio- CCS installed capacity and CO_2 emissions mitigation/removal	IMAGE, MESSAGE-GLOBIOM, AIM, GCAM, REMIND-MAGPIE (global models)	Only OECD results	2°C	https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=10
IPCC 5th Assessment Report AR5 database* (2014)**	Fossil- and bio- CCS installed capacity and CO_2 emissions mitigation/removal	AIM-Enduse, BET, DNE21, EC-IAM, ENV-Linkages, Ecofys Energy Model, FARM, GCAM, GEM-E3-ICCS, GRAPE, GTEMREF32, IEEJ, IGSM, IMACLIM, IMAGE, KEI-Linkages, MARIA23, MERGE-ETL, MERGE, MESSAGE, MiniCAM, POLES, REMIND, TIAM, TIMES-VVT, WHICH, WorldScan, iPETS	Only OECD results	2°C	https://tntcat.iiasa.ac.at/AR5DB/dsd?Action=htmlpage&page=regions
IPCC Special Report on	Fossil- and bio- CCS installed capacity and CO_2	AIM/CGE, C-ROADS, GCAM, GENeSYS-MOD IEA Energy Technology Perspective Model,	Only OECD90+EU results	2°C	https://data.ene.iiasa.ac.at/iamc-1.5°C -explorer/#/workspaces

1.5°C (SR1.5)* (2019)**	emissions mitigation/removal	IEA World Energy Model, IMAGE, MERGE-ETL, MESSAGEix-GLOBIOM, POLES REMIND-MAgPIE, Shell World Energy Model 2018, WITCH-GLOBIOM

* Installed CCS capacity, and CO_2 removal/mitigation ranges

** We are listing only the models which provide EU level results (not the full list of models covered by the database)

*** The rows shaded in red highlight databases which we will not investigate further, as they do not contain EU level CCS results.

11.2 Annex 2. Selected model-specific and review publications for assessing CCS and CCU ranges

Type and scope of publication	Relevant results to this study*	Models providing EU level results**	Geographic resolution of Europe results	Climate targets	Links and selected references to be reviewed further
Multi-model comparison from AME, AMPERE and LIMITS projects	CO_2 captured and stored in geological storage by CCS Shown for each model, aggregated over all technologies.	Global models from AME, AMPERE, and LIMITS. European models from AMPERE. National models for France, Germany, Italy, UK.	EU. Also national models for UK, Germany, France, Italy	Comparison of the most ambitious mitigation scenarios for countries with those of the EU in global 1.5°C and 2°C scenarios.	(Wachsmuth and Duscha 2019) (Duscha *et al* 2019)
JRC review report	Comparison of fossil- and bio-CCS deployed across several EU high ambition scenarios from JRC, ECF, EU, IEA, Navigant, Oeko-Institut, Eurelectric, WndEurope and Teske et al 2019	Various (global/EU models)	EU	Net Zero/ EU scenarios from various sources with more than 50% reduction of emissions in 2030	(Tsiropoulos *et al* 2020)
Review of CCS potential and costs across AMPERE and EMF27 studies	Fossil- and bio-CCS, DACS model assumptions vs reality	N/A	Global results only but relevant for T4	2°C scenarios	(Budinis *et al* 2018b)
REMIND global IAM	Capacity and CO_2 emissions mitigation/removal from biomass to hydrogen (B2H2), biomass integrated gasification combined cycle and biomass to liquid (B2L)	REMIND (global model)	EU	2°C scenarios	(Humpenöder *et al* 2014)
WITCH global IAM*	A range of coal-CCS techs, a generic natural gas-CCS tech, a generic biomass-CCS tech	WITCH (global model)	Eastern and Western EU modelled but only global results presented	2°C scenarios	(Carrara 2018, Vinca *et al* 2017, 2018)
IMAGE global IAM	Fossil- and bio-CCS CCS on electricity and hydrogen production as well as to	IMAGE (global model)	EU or Western EU and Central EU	1.5°C and 2°C scenarios	(Esmeijer *et al* 2018, Koelbl *et al* 2014, Vaughan *et al* 2018, van Sluisveld *et al* 2018)

	steel and cement production in the industry				
GCAM-ZEP	Fossil-CCS (coal, lignite, gas) and bio-CCS used for power generation	GCAM (global model), ZEP (Zero Emissions Platform, power model)	GCAM: Global with EU-12, EU-15, European Free trade Association, Eastern Europe and Europe-non EU; ZEP: Europe (31 countries)	Net Zero Europe by 2050	(ZEP 2014).
AIM-CGE model*		AIM-CGE (global model)	Global with EU25 and the Rest of Europe Only global results	2°C scenarios	(Akashi and Hanaoka 2012)
IEA global model	BECCS for industry, power, biofuel production	IEA global model	EU, Europe	1.5°C and 2°C scenarios	https://www.iea.org/reports/world-energy-outlook-2019 https://www.iea.org/reports/energy-technology-perspectives-2017 (IEA 2010, 2017, IEAGHG 2014, IEA 2008, Kypreos and Lehtila 2014)
POLES (EC-JRC, Infra-CCS tool, JRC GECO2018)	CO_2 captured by and installed capacity of coal-, gas-, bio-CCS and DAC	POLES (global model)	EU28	Assessment of the EU's internal reductions by 2050 in line with 1.5°C and 2°C scenarios	(Griffin *et al* 2014, Keramidas *et al* 2018, EC - JRC; Tchung-Ming 2018)
TIAM-UCL global model	CO_2 captured by and installed capacity of coal-, gas-, bio-CCS used in power, heat, industry and biofuel production; DACS	TIAM-UCL (global model)	Eastern EU, Western EU and the UK	2°C and below 2°C scenarios	(Ekins *et al* 2017, Winning *et al* 2019, 2018, Cronin *et al* 2020, Butnar *et al* 2020a, Pye *et al* 2019)
TIAM-Grantham+ WITCH*	CCS on coal, gas, bio for electricity, heat, industry	TIAM-Grantham+ WITCH (global models)	Global results only	1.5°C and 2°C scenarios	(Realmonte *et al* 2019)
IMACLIM	Coal/gas/oil/bio-CCS for power generation	IMACLIM	EU28	2°C scenarios	(Bibas *et al* 2020)
Shell SKY and SKETCH scenarios	CCUS for chemicals and transport fuels, DACS, CCS on fossil industry and power	Shell model (global model)	Europe	Sky Shell for Paris Agreement global scenarios, Sketch for Net Zero Europe by 2050	(Shell 2018, Shell International B.V. 2020) also interactive tool https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky/interactive-tool.html#iframe=L1dlYkFwcHMvU

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PRIMES	Gas CCS for power generation, industry CCS, CCU for synthetic fuels and materials	PRIMES (EU model)	EU, individual countries	1.5°C and 2°C scenarios	(European Commission 2016, 2018, Vrontisi *et al* 2019, Paroussos *et al* 2016)
JRC-EU-TIMES	Fossil and bio-CCS, CCU in materials, reuse, synfuels	JRC-EU-TIMES (EU model)	EU28 and individual countries	80% reduction, Net Zero	(Simoes *et al* 2017, Blanco *et al* 2018, Carlsson *et al* 2020)
TIMES-EE/EG	Coal/lignite/gas/bio-CCS in power and industry	TIMES-EE/EG (or TIMES Pan EU, EU model) coupled to EcoSense and NEWAGE	EU28 + Norway and Switzerland	80 and 95% reduction of EU emissions	(Schmid *et al* 2019, Korkmaz *et al* 2020)
ETM-UCL (EU energy system model)	Coal-, gas-, bio-CCS in power, industry, heat, H2	ETM-UCL (EU model)	Europe only: 9 regions covering the 28 member states	80% reduction by 2050	(Solano Rodriguez *et al* 2017, McDowall *et al* 2018, Drummond and Ekins 2017)
PLEXOS (European dispatch power model)	CO_2 captured by fossil-, bio-CCS, DACS	PLEXOS (EU model)	Europe	Below 2°C scenarios	(Gaffney *et al* 2020)
Chalmers model suite	Fossil-CCS electricity power plants and CHP only	Chalmers ESOM, ELIN, InfraCCS, Chalmers database on power plants and storage sites (EU model)	Individual countries of EU27 and Norway	2°C scenarios	(Odenberger and Johnsson 2009, 2010, 2011, Kjärstad *et al* 2013b, Odenberger *et al* 2013, Norwood *et al* 2017)
Electricity system model LIMES-EU+	Coal- and gas-CCS	LIMES-EU+ (EU model)	29 European regions	80% GHG emission reduction by 2050	(Schmid and Knopf 2015)

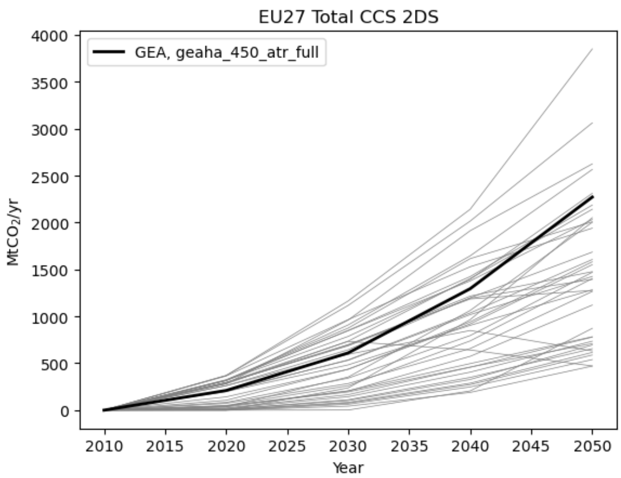
* The rows shaded in red highlight studies which we will not investigate further, as they do not contain EU level CCS/U results.

11.3 Annex 3. Ranges of CCS in individual selected databases

GEA (Global Energy Assessment) Scenarios (2012)

The Global Energy Assessment GEA scenarios (2012)[12] examine the major global challenges and their linkages to energy. It contains 41 pathways to 2°C combining demand, CDR, transportation fuels options.

GEA scenario database[13] documents all GEA scenarios. It reports total CO_2 removal by CCS at EU 27 level, also available for the Eastern European Union (EEU) and Western European Union (WEU).



CCS technologies start in 2010, capturing between 0 and 1,200 MtCO2/yr by 2050 and between 500 and 4,000 MtCO2/yr by 2050.

The highlighted scenario assumes high demand, advanced transport fuels and full availability of CCS (for fossil and bio- technologies).

EMF-28 scenarios (2012)

EMF-28 scenarios[14] examined how changes in an international climate regime and technology choices could affect the European decarbonization strategy and costs through the mechanisms of trade, technology, and innovation. It explored global 2°C scenarios in EU 27.

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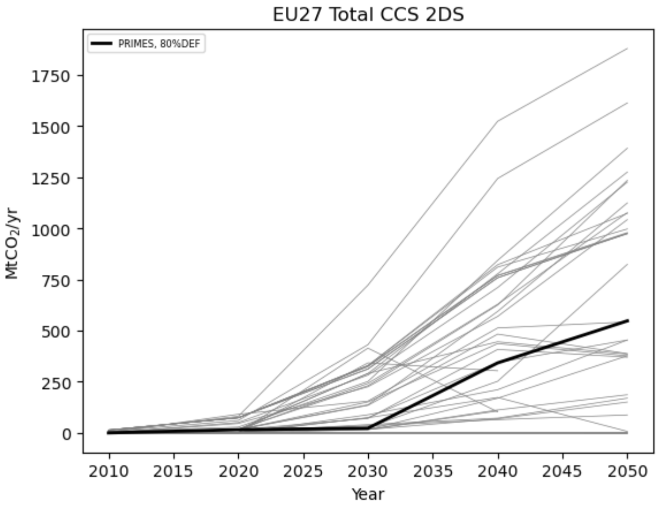
[12] https://iiasa.ac.at/web/home/research/researchPrograms/Energy/Global-Energy-Assessment-Database.en.html
[13] https://tntcat.iiasa.ac.at/geadb/dsd?Action=htmlpage&page=about
[14] https://emf.stanford.edu/projects/emf-28-effects-technology-choices-eu-climate-policy

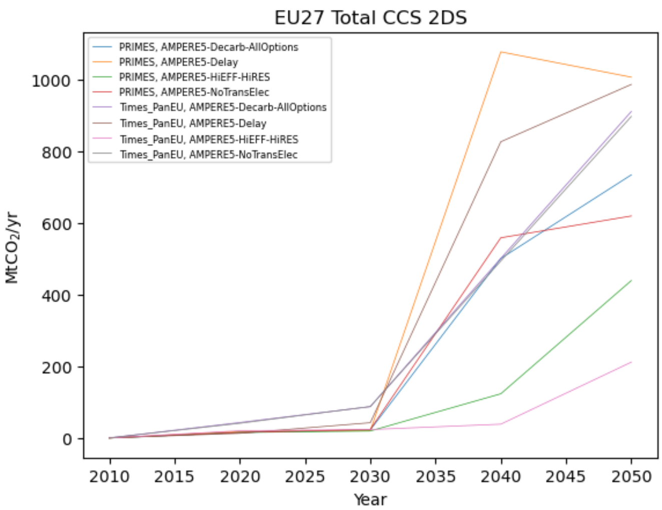


CCS starts in 2010, by 2030 capturing between 0 and 750 $MtCO_2$/yr, and by 2050 between 0 and 1,800 $MtCO_2$/yr total CCS capture.

AMPERE scenarios (2014)

AMPERE scenarios[15] examined cost implications of policy delay, technology availability and unilateral action in a fragmented international policy landscape under a global 2°C temperature target. AMPERE database reports total CO_2 removal by CCS in EU 27.

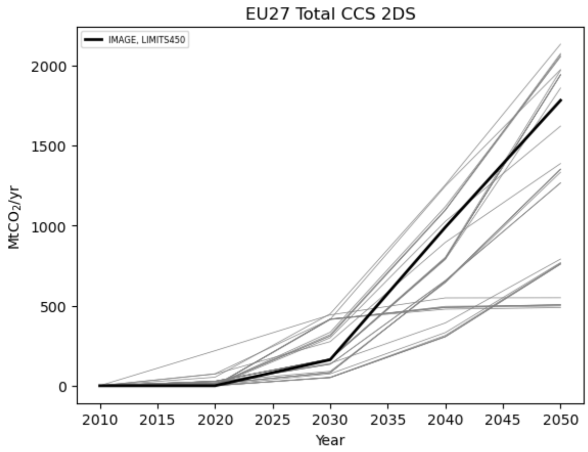
CCS starts in 2010, but the AMPERE scenarios also examine delay of CCS start to 2020 and 2030. By 2030 between 0 and 88 $MtCO_2$/yr captured by CCS, and by 2050 between 200 and 1,000 $MtCO_2$/yr total CCS capture.

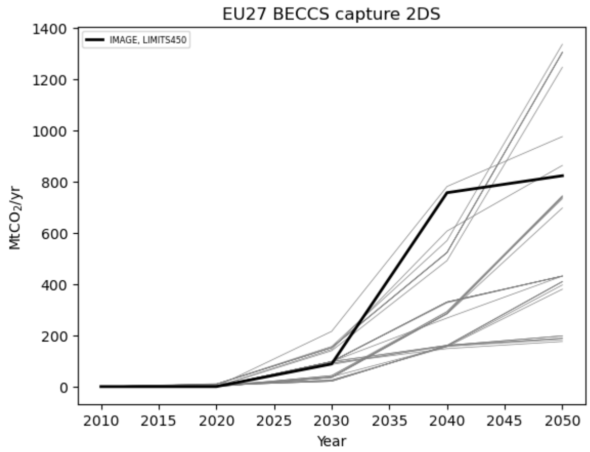


LIMITS scenarios (2014)

LIMITS scenarios examined climate policies consistent with 2°C scenarios. It reports Total CCS and BECCS capture in the EU27.

[15] https://tntcat.iiasa.ac.at/AMPEREDB/dsd?Action=htmlpage&page=about



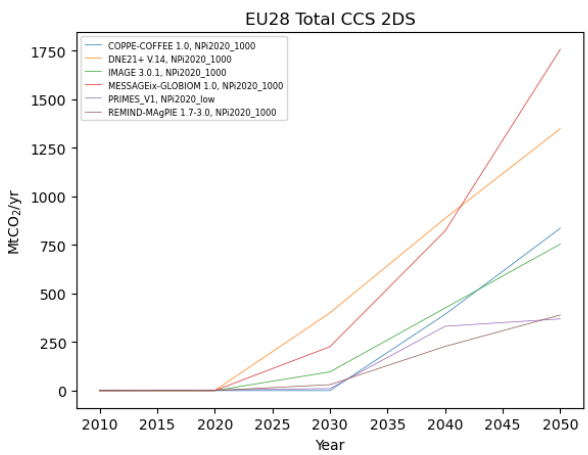


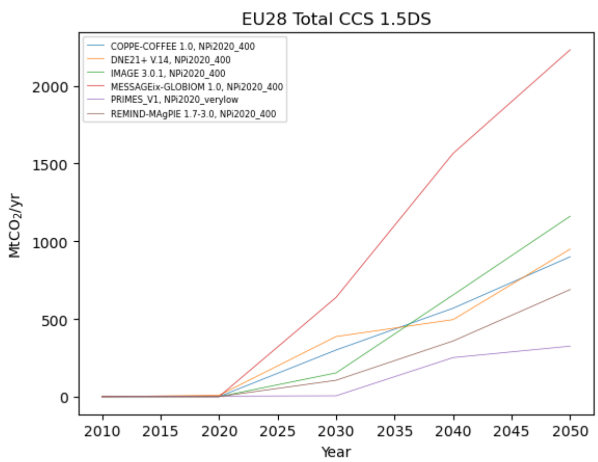
Fossil-CCS starts in 2010, BECCS in 2020. By 2030 between 20 and 450 $MtCO_2$/yr captured by CCS, of which 20 - 220 $MtCO_2$/yr are captured by BECCS. By 2050 between 500 and 2,200 $MtCO_2$/yr total CCS capture, of which 200 – 1,350 $MtCO_2$/yr by BECCS.

CD-LINKS scenarios (2019)

CD-LINKS scenarios[16] explore the interplay between climate action and development. They explore 2°C and 1.5°C based on carbon budgets (1,000 and respectively 400 $GtCO_2$ cumulative over the period 2011-2100.

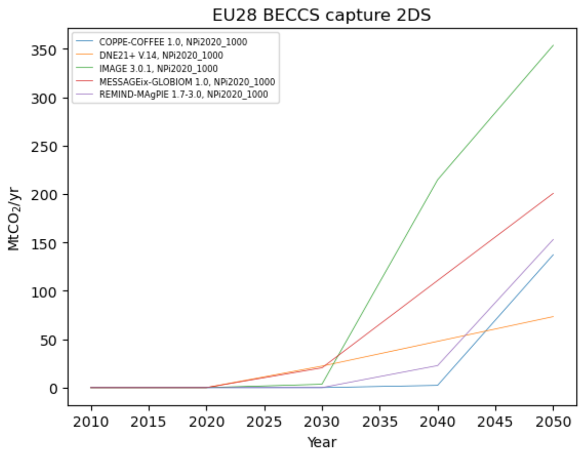
CD-LINKS database reports total CCS, BECCS, fossil-CCS, and CCS in industry deployed in the **EU 28.**

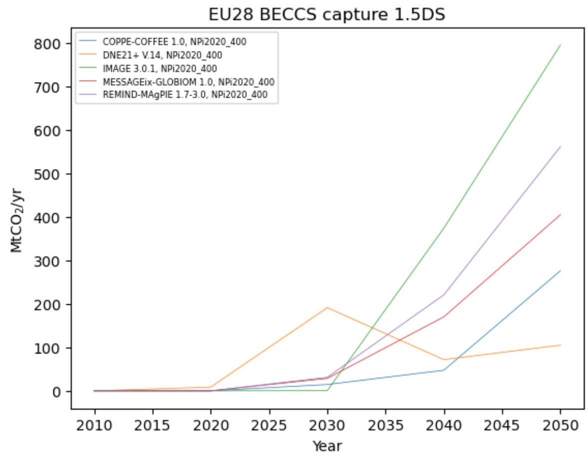




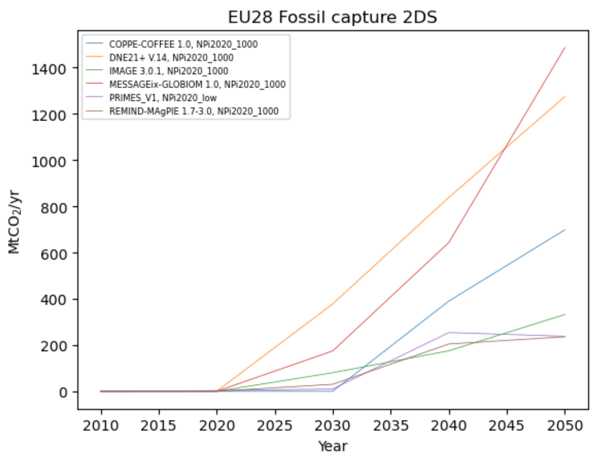
CCS starts in 2020, by 2030 capturing between 0 and 400 $MtCO_2$/yr in 2°C vs 0 to 700 $MtCO_2$/yr under 1.5°C. By 2050 this increases to between 300 and 1,700 $MtCO_2$/yr total CCS capture in 2°C vs 400 to 2300 $MtCO_2$/yr under 1.5°C. Note lower CCS in PRIMES_V1 (European-scale model).

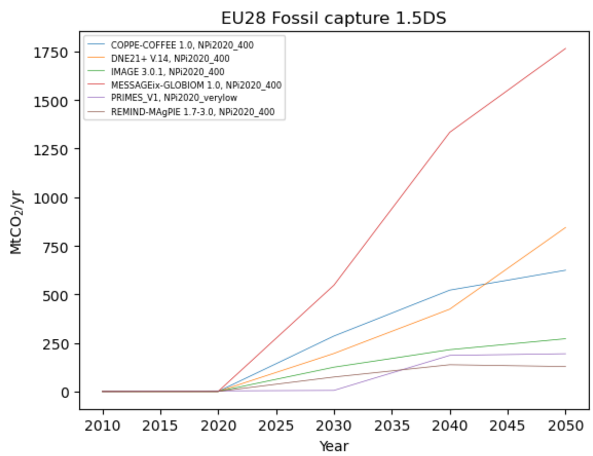
[16] https://db1.ene.iiasa.ac.at/CDLINKSDB/dsd?Action=htmlpage&page=10

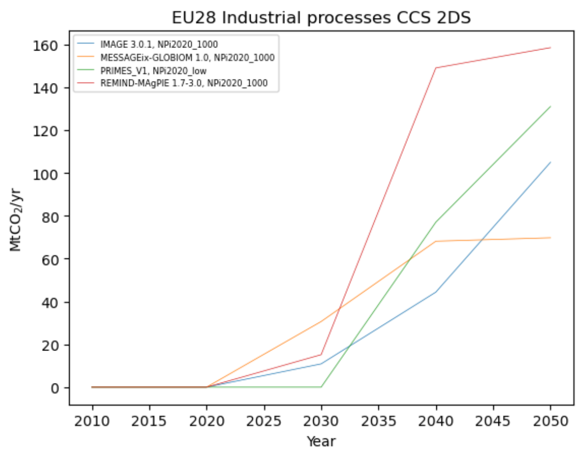


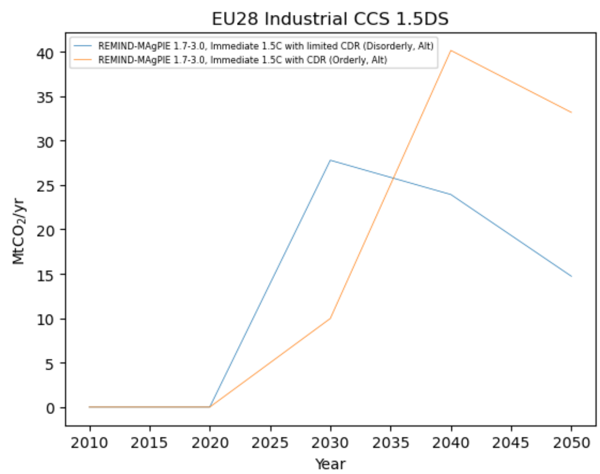


By **2030** up to 23 $MtCO_2$/yr capture by BECCS in 2°C vs up to 200 $MtCO_2$/yr under 1.5°C. By **2050** up to 1,400 $MtCO_2$/yr capture by BECCS in 2°C vs up to 1,750 $MtCO_2$/yr under 1.5°C. Strong fossil removal:







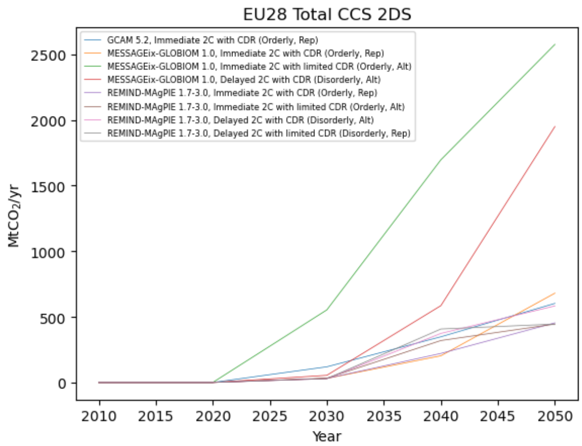


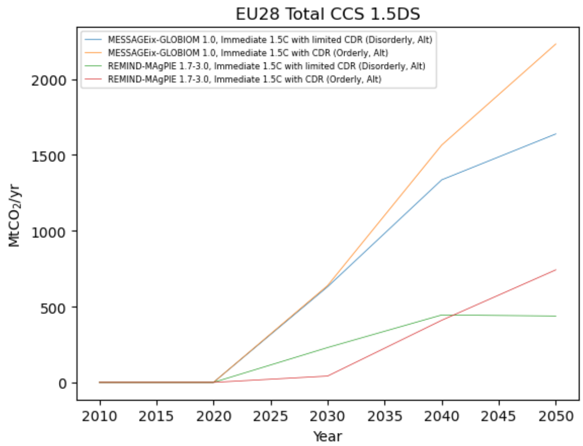
NGFS scenarios (2020)

NGFS scenarios[17] (Network for Greening the Financial System) investigate climate risks to the economy and financial system. They explore both 2°C (for net zero before 2070, equivalent with a 67% chance of 2°C) and 1.5 C scenarios (for net zero by 2050). For both temperature targets the scenarios are defined as:

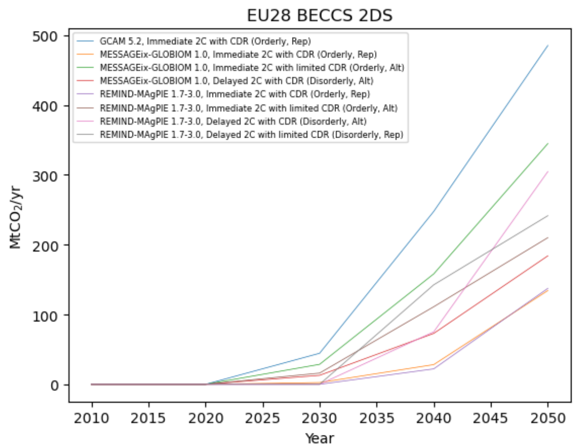
- Orderly: Early, ambitious action to a net zero CO2 emissions economy; CDR limited/not limited
- Disorderly: Action that is late, disruptive, sudden and / or unanticipated; CDR limited/not limited

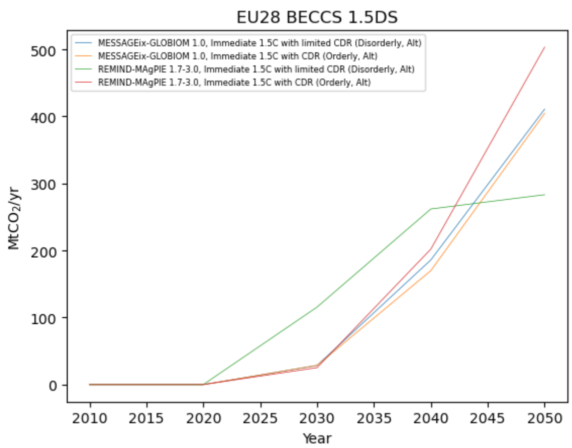
NGFS database[18] reports total CCS, BECCS, BECCS for use for electricity and other supply, CCS in industry (only for 2DS) at EU 28 level, but it also offers results at a more regional detail.





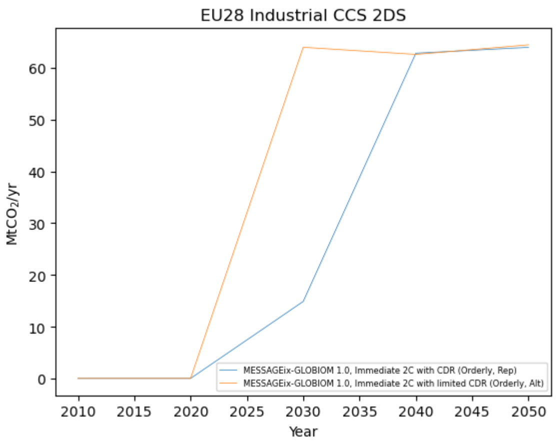
CCS starts in 2020, including BECCS. By 2030 between 0 and 500 $MtCO_2$/yr captured by CCS, including up to 50 $MtCO_2$/yr capture by BECCS. By 2050 except for 2 MESSAGEix-GLOBIOM scenarios, CCS captures between 400 and 600 $MtCO_2$/yr, of which 120 to 480 $MtCO_2$/yr are captured by BECCS.

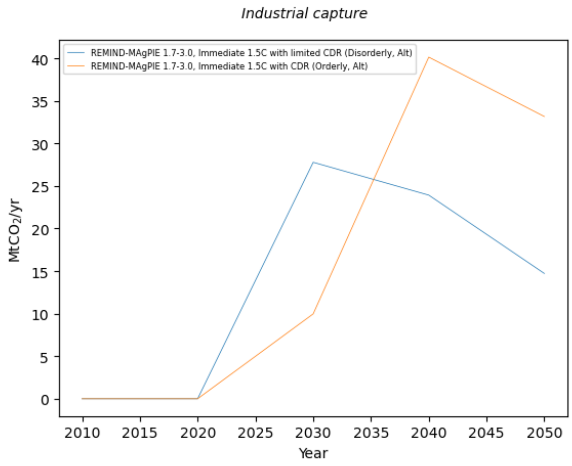




Industrial capture data is patchy.

[17] https://www.ngfs.net/en/publications/ngfs-climate-scenarios
[18] https://data.ene.iiasa.ac.at/ngfs/#/workspaces


EU28 Industrial CCS 2DS
MtCO2/yr
0
10
20
30
40
50
60
2010
2015
2020
2025
2030
2035
2040
2045
2050
Year
MESSAGEix-GLOBIOM 1.0, Immediate 2C with CDR (Orderly, Rep)
MESSAGEix-GLOBIOM 1.0, Immediate 2C with limited CDR (Orderly, Alt)


Industrial capture
MtCO2/yr
0
5
10
15
20
25
30
35
40
2010
2015
2020
2025
2030
2035
2040
2045
2050
Year
REMIND-MAgPIE 1.7-3.0, Immediate 1.5C with limited CDR (Disorderly, Alt)
REMIND-MAgPIE 1.7-3.0, Immediate 1.5C with CDR (Orderly, Alt)