NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

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Executive Summary

To help deliver on net-zero promises, negative emissions technologies and processes (NETPs) which can capture CO_2 from the air, such as direct air capture with CO_2 storage (DACCS) or bioenergy with carbon capture and storage (BECCS), have been developed. For policymakers to anticipate potential deployment trajectories and design effective support mechanisms, reliable economic models projecting cost and upscaling pathways for DACCS and BECCS are needed. These models require two types of inputs, the uncertainty surrounding relevant parameters and the expected best estimates for cost trajectories and the scale of deployment.

Our study investigates future costs and deployment scale uncertainty of DACCS and BECCS technologies in Europe in 2030, 2040 and 2050. Additionally, we explore the links between future policies and uncertainty levels. Quantitative and qualitative insights were gathered from 34 expert elicitations – 21 DACCS experts and 13 BECCS experts were interviewed. Experts were asked to first estimate their 90% confidence intervals for future costs (when possible, breaking down different cost items, such as Capex and Opex) followed by their "best estimates". These assessments provide an empirical basis for the technology learning curves that underpin most projections of future mitigation potential of different options. Experts were then asked to estimate the expected scale of future deployment under two different stylized policy scenarios (again, first confidence intervals and then best estimates). The International Energy Agency's Stated Policies (STEPS) and Net Zero Emissions by 2050 (NZE) scenarios are used as the basis for these stylized scenarios to explore how different policies could influence the deployment of these DACCS and BECCS.

Learning Curves

The experts' best estimates suggest that, by mid-century, costs will fall to an average value of EUR 280/tCO_2 for DACCS and EUR 153/tCO_2 for BECCS (current assumptions are EUR 581/tCO_2 for DACCS and EUR 172/tCO_2 for BECCS – see Tables 2 and 3). However, these 'averages' hide a wide divergence in views among experts, particularly for DACCS. The best estimates for 2030 DACCS costs from several experts are almost an order of magnitude lower than the best estimates provided by other experts. Even more strikingly, experts are so confident in their own estimations, the uncertainty ranges of most experts do not overlap with each other and *no* expert provides a sufficiently large range that overlaps with the range of all other experts. Most DACCS experts do believe that in the future new and better materials as well as economies of scale will reduce the costs of the technology although they differ widely in their assessment of the overall cost implications. By contrast, experts believe that BECCS, while currently significantly cheaper than DACCS, might struggle to scale up given the distinctive characteristics of each plant. For both technologies, the uncertain future of European energy prices is perceived as a hurdle. Overall, experts stress that policymakers must prioritize securing a stable green energy system to reduce uncertainties linked to energy costs for DACCS and revenue streams for BECCS respectively.

Our results indicate that the uncertainty around future costs increases over time for both DACCS and BECCS. For DACCS, experts estimating higher costs were also more uncertain and expecting larger changes over time (from 2030 to 2050). For both technologies, experts providing a cost breakdown (i.e., Capex, Opex, transport/storage costs) also offer narrower, more certain ranges.

Interestingly, our results also indicate some degree of overconfidence in the scalability of DACCS, as the confidence interval actually decreases over time, particularly for the experts that were unable to provide a cost breakdown. This might be because DACCS is still undergoing significant development. The form the technology might take in ten years could differ widely from current configurations, hence encapsulating the full complexity of potential technology trajectories in a single total cost metric can prove to be difficult.

Potential Scalability

Unsurprisingly, a more ambitious global decarbonisation scenario is expected to lead to higher levels of deployment of both DACCS and BECCS although the specific results are less intuitive. In the expert view of what would be deployed in the NZE scenario, the average best estimate for the potential scale of DACCS is 353Mt CO_2/year compared to 39Mt CO_2/year in the STEPS scenario (a ninefold increase). By contrast, despite nominally lower costs, BECCS struggles to achieve similar scales in 2050, reaching an average capture capacity of 131Mt CO_2/year under NZE and 36Mt CO_2/year under STEPS according to this different group of experts (which amounts to less than a fourfold increase). Of course, any comparison of the DACCS and BECCS expert elicitations must be treated with caution since these involve two distinct and independent groups of experts.

The NZE scenario is associated with substantially higher deployment of both technologies, but the average estimated combined capacity of DACCS and BECCS in the expert elicitations for 2050 amounts to only about a quarter of the CO_2 removals the IEA envisions would be needed in its NZE scenario (1.9 GtCO_2). This reinforces the view expressed by several experts that an array of negative emission technologies and practices will be needed to meet net-zero ambitions.

Alongside the higher expected deployment for both technologies under the NZE scenario, the uncertainty associated with these estimates is also higher. Although DACCS experts include the risks that DACCS won't be deployed at all in their most conservative estimates, expert projections suggest that this technology shows promising deployment scale under NZE with the confidence interval maxima reaching up to 1Gt CO_2/year captured in 2050. Experts stated that the deployment levels of both technologies depend on the successful implementation of early plants and that this requires negative emission technologies to be clearly defined in European policy frameworks. For the STEPS scenario, the most conservative estimates (i.e., the minimum of the confidence interval) for BECCS deployment shows a higher potential scalability compared to DACCS. However, BECCS shows a maximum deployment scale that remains limited to around 0.3Gt CO_2/year captured in both scenarios. We found higher uncertainty for the scalability of BECCS, which can be due to the need for one-of-a-kind plants and local supporting infrastructure.

Policy Implications

To conclude, our study can contribute to improving the characterisation of existing economic and techno-economic models of climate change mitigation by providing insights into expert opinions and estimated uncertainty levels for key model parameters such as cost reductions. Our analysis reveals that there is a potential for DACCS and BECCS to play a role (together with other forms of greenhouse gas removal) in reaching net zero. However, there is a high uncertainty regarding future costs and deployment scale. Costs, as well as policy and regulations, are the most relevant limiting factors. Experts believe that policy instruments should reduce the investment burden to promote the deployment of these technologies by integrating them into existing tools such as the emission trading scheme. Without a concrete framework that defines how negative emissions are accounted for, disposed of, and paid for, investors will have limited incentives to provide the initial capital needed to scale-up these technologies.

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Abbreviations

AFOLU	Agriculture, forestry and other land use
AR	Afforestation, reforestation
BE	Best estimate
BECCS	Bioenergy with Carbon Capture and Storage
$Ca(OH)_2$	Calcium hydroxide
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide (lime)
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
COP	Conference of the Parties
DAC	Direct Air Capture
DACCS	Direct Air Carbon and Capture Storage
DOE	US Department of Energy
EOR	Enhanced oil recovery
EOR+	Enhanced oil recovery (with optimal carbon capture)
EU	European Union
EW	Enhanced weathering
FOAK	First of a kind
GHG	Greenhouse gas
IEA	International energy agency
IPCC	Intergovernmental panel on climate change
K_2CO_3	Potassium carbonate
KOH	Potassium hydroxide
kt	Kilo ton
MEA	Monoethanolamine
Mt	Million Ton
MWh	Megawatt-Hour
N_2	Nitrogen
NDC	Nationally determined contributions
NET(Ps)	Negative Emission Technologies (and Practices)
NOR	Norway
NZE	Net Zero Emissions by 2050 Scenario
PIK	Potsdam Institute of Climate Impact Research
ppm	Parts per million
PZ	Piperazine
SMW	Solid municipal waste
SRC	Short rotation crops
STEPS	Stated policies scenario
t	Ton
TSM	CO_2 Transportation, Storage and Monitoring
TWh	Tera watt hour
UK	United Kingdom
USA	United States of America

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1. Introduction

1. 1 Scientific and geo-political history of climate change

Article 2 of the *United Nations Framework Convention on Climate Change (UNFCCC)*, which was adopted at Rio de Janeiro in 1992, calls for the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. [1] However, translating that overall objective into legislative and regulatory action has proven challenging. After the entering into force in 1995, international negotiations followed, and in 1997 during the third Conference of the Parties (COP) to the UNFCCC or COP3, the Kyoto Protocol was signed which legally binds developed parties to emission reduction targets but that agreement ended in 2012 and so the international community needed to find a new basis for cooperation. In 2015, at COP21 in Paris, 196 parties agreed to keep "the increase in the global average temperature to well below 2°C above pre-industrial levels and 'pursue efforts' to limit global temperature rise to 1.5°C. More immediately, under the Paris Agreement countries had to submit their own nationally determined contributions (NDCs), where progress was expected to be made in "implementing and achieving" their NDCs, and all these submissions undergo international review. Moreover, all countries committed to submit new NDCs every five years, with the clear expectation that these new submissions represent a progression over their previous NDC. [6]

Stabilising atmospheric concentrations and keeping below a global temperature target requires that countries shift to focus to carbon neutrality. Sweden became the first country to legislate for a mid-century net zero target [7]. The European Union (EU) set a target of achieving "net zero" greenhouse emissions by 2050 in November 2018. Both the European Parliament and Council, representing the people and the states of the EU respectively, endorsed the *European Green Deal* in the course of 2019. [8] Neighbouring countries to the EU have set similar NDCs. Iceland, Norway, Switzerland, and the United Kingdom have backed the EU NDC by incorporating the same emission reduction levels in their own frameworks. Additionally, Iceland intends to become carbon neutral by 2040 using various carbon storage methods and the UK committed to "reducing GHG emissions by at least 68% by 2030". [9] [10]

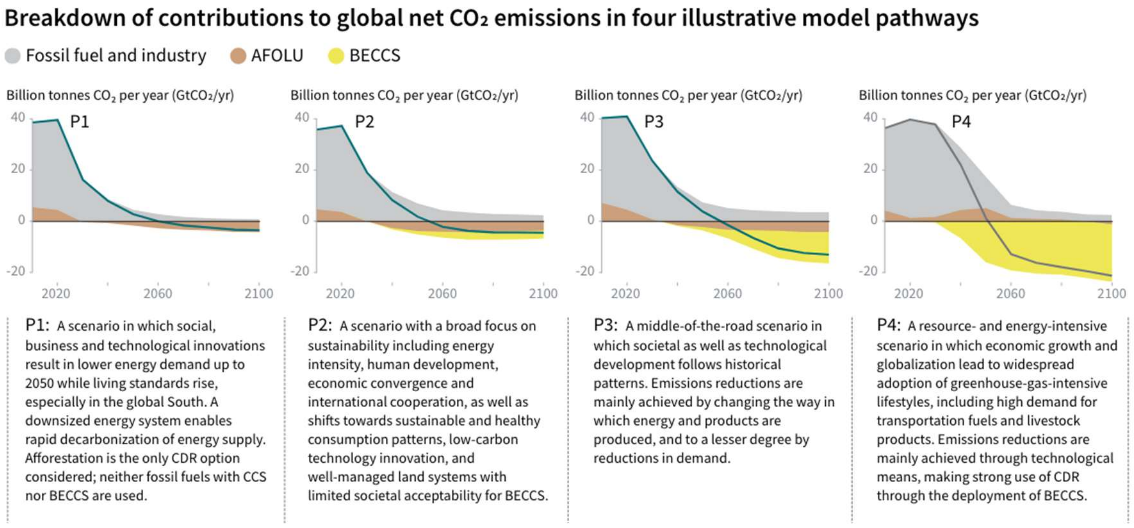
The *European Green Deal* is a climate policy framework defining European energy, transport, and taxation until 2050. The legislative backbone of this deal consists of legally binding objectives set by the European parliament. The three core elements are "no net emissions of greenhouse gases by 2050", "economic growth decoupled from resource use", "no person and no place left behind". With this the EU member states are hoping to become the first net zero continent by 2050. [8] In 2021 the EU adopted an updated regulation known as the *Fit for 55* package. This sets the additional goal to achieve a 55% emission reduction by 2030 compared to 1990 levels. [11] This package includes several amendments to the green deal including some overall more stringent energy and emission targets for 2055. These policy changes reflect policymakers' growing commitment to meeting net-zero targets, which is an important impetus for our research. First, the EU agreed to lower the total allowed emissions in the Emissions Trading Scheme (ETS), a market where emission quotas are allocated to different industries with a certain carbon price and where allocations can be traded. The EU ETS market is particularly interesting in the context of this research as a future negative emissions market could either be integrated into the existing ETS market or be built based on this market. [12] Second, the commission endorsed the goal to remove 310Mt of CO_2 via natural land sinks by 2030. Additionally, the agriculture, forestry, and other land use sector (AFOLU) is meant to become climate neutral from all GHG by 2035. This directive could have a direct influence on the deployment of bioenergy carbon capture and storage (BECCS), one of the studied technologies in this report. [13]

1. 2 The Road to Net Zero

The commitments outlined above show the theoretical targets countries are willing to pursue. Reaching those will be difficult due to the dependence of the energy sector to geo-political and market events. Additionally, getting to Net Zero will require not only a decarbonization of all possible sectors but also the use of CDR technologies to compensate for delays and hard to abate sector emissions.

Political and economic decisions are often made based on projections of technology deployment. The modelling groups contributing to the IPCC assessment report develop different socioeconomic development pathways, compatible with future CO_2 levels that are in line with the *Paris Agreement*. These mitigation pathways include the generation of green electricity and e-fuels, replacing primary chemicals with new fossil-free alternatives, reducing total energy demand, improving energy efficiency, and removing residual emissions from hard-to-abate industries such as steel and cement. [14]

As shown in Figure 1, the four IPCC pathways (P1-P4) used in the IPCC SR1.5 scenarios illustrate major differences in rates of decarbonisation and uptake of CDR for meeting global net zero emissions by 2050. The first pathway assumes drastic innovations in the energy sectors resulting in rapidly falling emissions and a simultaneous increase of global standard of living. Due to the rapid decarbonization of energy sectors, CO_2 uptake through AFOLU is sufficient to meet net negative targets by the end of the century. The other scenarios each show a slower decarbonization curve and the introduction of BECCS in addition to AFOLU to meet the net negative target by the end of the century. The fourth pathway depicts the slowest integration of sustainable practices and a growing dependence on carbon-heavy energy. Despite global emissions being reduced to net zero by 2050, there is a non-negligible overshoot probability of the 1.5°C threshold in the P4 scenario. [14]



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Figure 1: Illustrative mitigation pathways used by the IPCC. The scenarios shows the influence of late decarbonization and intensive energy use on meeting global net zero emissions by 2050 while staying close to the 1.5°C target. [14]

These pathways have two clear messages. First, they show that the later climate action is undertaken, the more radical the transition must be to reach net zero global emissions by 2050. Despite increasing decarbonization, hard-to-abate sectors such as heavy transportation, cement and steel industries will take more time to transition and unless solutions are found, will continue contributing to rising emission levels. This diminishes the plausibility of being able to follow the P1 scenario. Second, these models show the need for negative emission technologies (NETs) to reach global Net Zero. The NETs considered in the previous scenarios are AFOLU and BECCS. There exists, however, a wide range of technologies and nature-based solutions which can capture and store CO_2 from the atmosphere. This study focuses on direct air carbon capture and storage (DACCS) and BECCS.

Such socioeconomic models and mitigation pathways are used by policymakers to support the decision-making for new legislation. To best portray the possible risk ranges associated with each scenario, model developers need to incorporate uncertainty levels associated with the roll-out of NETs. This work focuses on the uncertainty surrounding two model assumptions, namely future costs, and potential scale of DACCS and BECCS technologies. Both of these parameters are essential for estimating the potential role these technologies will play in achieving climate neutrality, in line with NEGEM's goal. In addition, these estimates will be useful in developing and triangulating the models and predictions used by other NEGEM work packages (see Deliverables 2.1, 3.1, 7.2, 7.3, and 8.6).

These two technologies are strong contenders to provide Europe with negative emissions. Their deployment, however, depends on future cost curves and supporting policies. Currently, existing cost and scale data is limited and rarely publicly available as DACCS and BECCS are developed by private companies. To gather knowledge on these two parameters, we carried out expert elicitations with experts from industry, academia, national government bodies and NGOs in the field of DACCS and BECCS technology. Within the wider NEGEM project, the obtained uncertainty levels are fed into the MONET and TIMES-VTT models and the NEGEM scenarios to refine the system assumptions (see Deliverables 7.2, 7.3, and 8.6).

This work contains a literature review of negative emission technologies (Section 2), followed by the description of the project, its aims, research questions, hypothesis and scope and limitations (Section 3. Then, the research methods and analysis tools used are introduced (Section 4). Finally, the results relating to costs, potential scales and enabling policies are presented (Section 5), and reflected on to draw out conclusions, policy implications and recommendations (Section 6).

2. Literature Review

This section provides a short description of existing carbon capture technologies before providing an in-depth introduction to DACCS and BECCS. The engineering, latest developments, and financing of these technologies are discussed.

2. 1 Negative Emission Technologies

Negative emission technologies and natural carbon sinks – also referred to as nature-based solutions – are forms of carbon dioxide removal (CDR). These are defined as: "capturing carbon dioxide from the atmosphere and storing it durably on land, in the ocean, in geological formations, or in products". Additionally, their deployment requires human intervention or, in many cases of nature-based solutions, stopping human intervention. [15] The following six solutions are examples of such NETs:

- Afforestation/Reforestation
- Biochar
- Bioenergy with carbon capture and storage
- Direct air carbon capture and storage
- Enhanced weathering
- Ocean alkalinization

According to the "State of Carbon Removal Report", CDR can be separated into novel technological solutions and conventional CDR. [15] Conventional (sometimes described as 'nature-based') CDR captures and stores the carbon on land. This includes methods such as afforestation and reforestation or biochar. The first stores carbon in the biomass and soils of grown forests while the second stores stable carbon compounds in soils and enhances the absorption of CO_2 on land. [16] [17]

Novel technological CDR solutions (sometimes described as 'engineered removals') store carbon in different topologies such as the ocean, geological formations, or products. Enhanced weathering and ocean alkalinization capture CO_2 via minerals on soil or in the ocean. Finally, DACCS and BECCS, which are described in more detail below, are technological solutions that separate CO_2 from other gases via chemical processes. CO_2 can then be stored underground in geological formations or in products. [15] The following work focusses on DACCS and BECCS that involves long-term geological storage. Storing CO_2 in products (so-called 'carbon utilisation') falls beyond the scope of this research and will not be commented on.

2. 2 State of the Art of DACCS and BECCS Technologies

2. 2. 1 Direct Air Carbon Capture and Storage

2. 2. 1. 1 Technology and latest developments

The underlying principle behind direct air capture (DAC) technology is the absorption or adsorption of CO_2 from an air flow in a liquid or solid medium. The concentrated gas is then released in a second process involving heat, pressure, vacuum, electric or humidity swing. However, to provide a climate solution, DAC needs to be paired with CO_2 storage (hence, DAC with Carbon Storage or DACCS). The captured gas is compressed and transported via containers or pipelines to a storage site where it is stored underground. Atmospheric CO_2 capture is an energy intensive process. The low atmospheric concentration (420 ppm) leads to the process of large air volumes through fans and the desorption process requires energy.

DACCS technologies range from industrial processes based on solid or liquid sorbents, to mimicking nature's natural capture of CO_2 using minerals. In the following the three leading DACCS companies and their technologies are presented. Carbon Engineering, Climeworks and Global Thermostat were chosen based on the maturity of the technology, demonstration pilots and developed projects.

Carbon Engineering, based in Squamish, British Columbia, developed a gas-fired, high temperature liquid sorbent adsorption process as seen in Figure 2. The process uses two chemical loops, the contactor and the calciner loop. In the first loop, CO_2 is captured from the atmosphere. In the contactor air reacts with a liquid solution of potassium hydroxide (KOH) to form water and potassium carbonate (K_2CO_3). There, air and the liquid solvent are in a crossflow configuration with the liquid flowing downwards on a structured packing while air is fed perpendicularly to it. The pellet reactor is a fluidized bed reactor where the potassium carbonate undergoes causticization with the calcium hydroxide ($Ca(OH)_2$) to form calcium carbonate ($CaCO_3$).

In the second loop, CO_2 is released as a pure gas. First, the solid calcium carbonate particles are introduced in the steam slacker unit where lime (CaO) reacts with water to produce heat and steam. This helps pre-heat the calcium carbonate before it enters the calciner unit. The calciner is a fluidized bed reactor in which calcium carbonate is gradually heated up to temperatures of 900°C. At these temperatures it separates into water, CO_2 and CaO. The obtained lime is then cooled and recycled in the steam slacker. Steam and CO_2 are then separated in the condenser. The relatively pure CO_2 gas can be compressed for storage or further use in enhanced oil recovery[1] (EOR+) or e-fuels. [19] [20]

The Carbon Engineering process has the main advantage of using a liquid solvent, allowing for continuous operations. It also uses equipment adapted from well-known industrial processes from the pulp and paper industry or waste-water treatment. This allows Carbon Engineering to have relatively low costs compared to some competitors. A drawback from the process is the high temperature requirement from the calciner unit leading to the use of natural gas. This must be considered in the CO_2 balance of the process. For each tonne of CO_2 removed from the air a total of 1.3 to 1.5 tonnes of CO_2 must be captured by the process to avoid natural gas carbon emissions. This impacts the total efficiency of the process compared to processes using renewable energy sources. The levelized cost of operating a first-of-a-kind (FOAK) plant capturing 1Mt of CO_2 per year is estimated to be USD_{2018} 94 – 232 per ton CO_2 removed. [20]

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[1] Enhanced CO_2 oil recovery (CO_2-EOR) is a tertiary oil-recovery technique by which crude oil is extracted from hard-to-reach geological formations by injecting CO_2 and water into the ground. The interaction of CO_2 with the crude oil is relevant as the CO2 improves oil recovery by lowering interfacial tensions, swelling the oil and reducing the oil viscosity. Combining EOR with long-term CO_2 storage is called EOR+. [18]

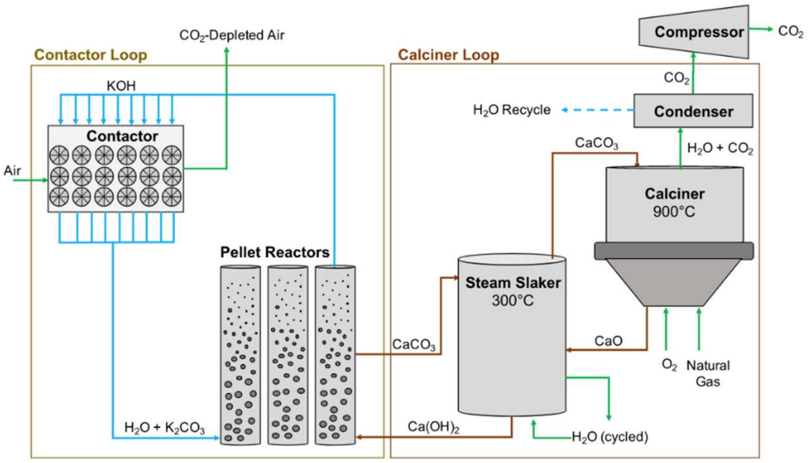


Figure 2: Carbon Engineering direct air carbon capture process. Two chemical loops are represented. Liquids are in blue, solids in brown and gas in green. The liquid solvent (potassium hydroxide, KOH) is regenerated in the pellet reactor and can be re-fed to the contactor. This figure was taken from McQueen et. al. [19]

Climeworks, based in Zürich, Switzerland, developed a modular, low temperature, amine-based, solid sorbent adsorption technology. As seen in Figure 3, their process includes an adsorption and a desorption phase. In the first step, fans push air through the contactor unit. There, CO_2 is adsorbed on a solid amine-based sorbent arranged on a patented filter. [19]

In the second step, a temperature-vacuum-swing process is used for the desorption. The unit is closed, and vacuum is applied to flush out the remaining air. To release CO_2 from the sorbent material, temperatures ranging from 80-120°C and a pressure of ~30 mbar are required. Heat is typically provided by steam from a power plant nearby. In Climeworks' process both waste-incineration plants and thermal power plants can be used. Steam and CO_2 are then separated in the condenser. Finally, in most cases, the relatively pure CO_2 gas can be compressed and sent via pipelines to a storage site nearby. [21] [22]

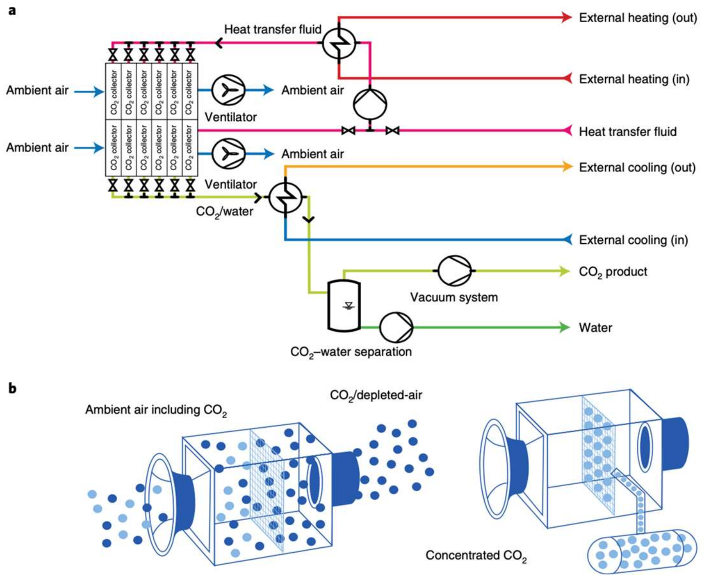


Figure 3: Climeworks' CO_2 capture process showing all material and energy flows for 12 containers or 2 collector units (a) and the temperature-vacuum swing process of a single container (b). The adsorption and desorption processes are shown in (a) in the top and bottom collector unit respectively and in the left and right [23]

The Climeworks process has the main advantage of using modular contactors. A line of six collector units forms a collector container which fits the dimension of standard 40-foot transport containers. This facilitates transport and reduces manufacturing costs as it allows for standardized mass production. Modularity could prove to be an enabling factor in scaling up global DACCS capacity. Finally, looking at the energy requirements, the low temperature needs allow the plant to be located next to a variety of energy sources ranging from geothermal power plants to industrial low-grade waste heat. [21]

The current costs of capturing CO_2 from the atmosphere using the Climeworks process are reported to be around USD_{2017} 500-600 per ton CO_2. [19] [24] [25]

Global Thermostat, a New-York based company uses a low temperature, amine-based, solid sorbent adsorption process which works similarly to the Climeworks process shown in Figure 3. The particularity of the Global Thermostat process is the use of a monolith reactor and a dual module configuration.

The desorption uses a temperature-pressure swing process to release the CO_2. Optimal steam temperature ranges between 105-130°C and can be obtained by coupling with process heat. The obtained gas is then generally compressed and sent for further commercial use or underground storage. The dual modules configuration permits water vapor reuse from one cooling module to a heating module. This internal heat transfer already provides 50% of the energy needed to regenerate the sorbent material, enabling significant energy gains. [26]

The technology patented by Global Thermostat should theoretically lead to significant cost and energy gains. First, the use of mass-produced honeycomb monolith contactor enhances the reaction surface and lowers the pressure drop. This helps reduce the costs of production of the capture unit and lowers the energy required to adsorb CO_2 onto the surface of the sorbent. [19] Second, the dual modules configuration should further enable energy gains. [22] However, due to lack of reliable information around completed projects and actual technology costs, no cost estimates can be provided with certainty.

2. 2. 1. 2 Market Outlook

Since the term direct air capture (DAC) was coined in 1999 by Klaus Lackner, DAC has seen growing interest and commercial developments. The technology saw its debuts in atmosphere control of closed spaces such as submarines and spaceships. [27] Increasing climate concerns and the need to stabilize global atmospheric temperatures led to growing interest and development in the DAC field over the past decades. There are currently 18 DAC plants in operation worldwide. Together they capture around 10’000 tonnes of CO_2 per year. The majority uses the concentrated CO_2 in industrial processes or for carbonated drinks production. There are only two DAC plants permanently sequestrating carbon in geological formations. [28]

Reaching Net Zero targets will require DACCS to scale to the million tons scale before 2030. Models from the IEA Net Zero Emissions by 2050 scenario estimate that by 2030 DACCS will have a capacity of 60Mt CO_2 captured per year. [29] Reaching this scale from the current deployment requires large investments and the imminent development of projects. In the following the scale of deployment and financing of the three leading direct air capture companies are listed.

Carbon Engineering launched a successful pilot plant in 2015 in Squamish, British Columbia. The pilot captures 365 tonnes of CO_2 per year and since 2017 converts some of the gas to synthetic fuel. The company’s first large scale commercial project is a plant capturing 0.5 – 1Mt CO_2 per year. Located in the Permian Basin (USA), it is predicted to start operations at the end of 2024. The plant would contribute to the deployment of the net-zero strategy of various firms. [30] Carbon Engineering is financially backed by Occidental Petroleum (Oxy), a large oil and gas firm, via their Oxy Low Carbon Ventures. Oxy will use the captured CO_2 for EOR+. [31] In the latest news Air Canada and Airbus partnered with Carbon Engineering to buy carbon dioxide removal (CDR) certificates and sustainable aviation fuels. Air Canada announced investing 5 million USD, Airbus did not disclose the invested sum. [32] [33]

Climeworks demonstrated multiple pilots and built the first ever commercial DAC plant in Hinwil, Switzerland in 2015. This plant captured 900t CO_2 per year until late 2022 after which it was decommissioned. In 2021 Climeworks started operations of the Orca plant in Iceland. Orca, the first large-scale commercial DACCS plant, has a yearly carbon capture capacity of 4'000t CO_2. The plant is located on the same site as the Hellisheidi geothermal power plant which supplies heat for the DAC process. [25] Climeworks' partner Carbfix, an Icelandic permanent CO_2 storage provider, operates the carbon sequestration side of the operations. In 2022 the company announced their second large-scale commercial DAC plant, Mammoth, with an annual capture capacity of 36'000t CO_2 and with operations expected to start at the end of 2024. [34] Climeworks is funded through equity financing and sells carbon dioxide removal (CDR) certificates to corporate and private customers. In April 2022 Climeworks closed an equity round led by GIC and Partners Group securing them 650 million USD, supporting the company in their ongoing and future projects. [35] [36]

Global Thermostat has a research collaboration with Georgia Tech and Stanford University. It operated an annual 1’000 – 10'000t CO_2 capture demo-plant at Menlo Park in 2013. In 2018 the company opened its first commercial plant in Huntsville, Alabama. The plant was said to capture 4’000t CO_2 per year, however concerns have been raised over the actual operation of the plant and it is now assumed to be decommissioned. [28] [38] Global Thermostat recently announced that they will supply the carbon capture equipment for HIF's Haru Oni plant in Chile. The Air-to-Fuels plant started operations towards the end of 2022, producing e-Fuels from CO_2, water, and wind energy. [38] Prior research projects seem to have been partially financed through agreements with large oil and gas company, ExxonMobil. Further detail on the type and amount of aid offered is not public. [39]

2. 2. 2 *Bioenergy with Carbon Capture and Storage*

2. 2. 2. 1 Technology and latest developments

Bioenergy with carbon capture and storage (BECCS) is a hybrid negative emission technology. It uses both nature’s capacity to capture CO_2 in plants via photosynthesis and man-made technology to capture CO_2 after the combustion process as shown in Figure 4. If more CO_2 is stored than is released during each of the steps in all associated supply chains and indirect impacts on ecosystems and natural sinks, then the total carbon footprint is net negative. BECCS is an interesting technology as it provides CO_2 capture on top of producing energy.

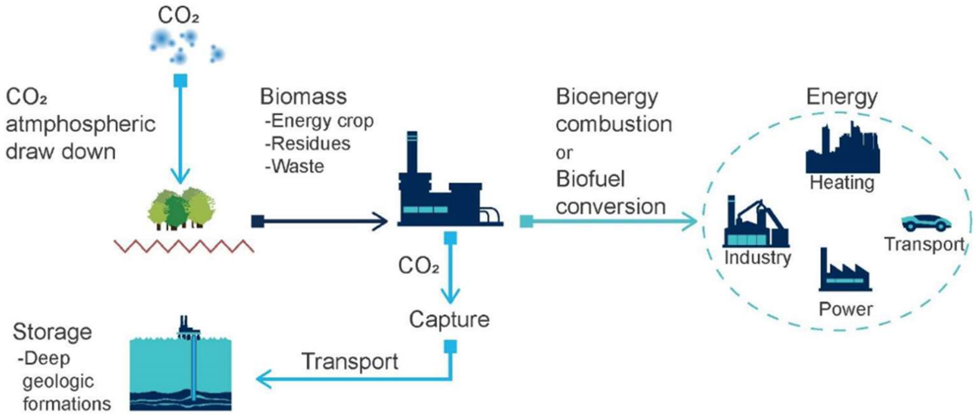


Figure 4: Bioenergy with carbon capture and storage process. [44]

In the following, different BECCS plant configurations including possible feedstocks and CO_2 capture processes are presented. Additionally, brownfield and greenfield plants as well as potential barriers to deployment are discussed.

Feedstocks such as wood pellets, municipal waste, agricultural and forestry residues, and dedicated crops can be used in a BECCS power plant. First, wood pellets can be provided from sustainably managed working forests or from residues of forest practices and related industries. In terms of process intensity, their production requires the milling of the material, compression into pellets and transport to the power plant site. [40] Their compact size allows for simple transport and storage and their high energy density makes pellets a good combustion fuel. [41] Second, solid municipal waste (SMW) is an interesting feedstock due to the increasing amount of waste produced worldwide. [42] This waste is currently, in most cases, burned to produce heat at SMW combustion plants leading to GHG emissions or left in landfills where it is at risk of decomposing and releasing GHG or contaminating soil and water. [43] Finally, short rotation crops (SRC) are bioenergy feedstocks with high energy density. Examples of SRC are poplar, willow trees and miscanthus. These crops are often mentioned in the literature due to their high yield even on marginal land (land not fit for agriculture) and less destructive impact on the ecosystem compared to other crops used for biofuels such as corn, wheat, sugar cane and sugar beet. [44] [45]

An essential part to the BECCS process is the integration of a **CO_2 capture unit** to the process. This is a decisive step to ensure that the energy produced leads to a negative carbon footprint. The CO_2 capture process step is slightly different for BECCS than for DACCS, due to the higher gas concentration in the flue gas. This leads to less energy intensive capture mechanisms. There exist three different industrial processes to capture CO_2 from flue gas: pre-combustion capture, post-combustion capture and oxy-combustion capture. The post-combustion capture rate is generally between 85% to 90% with the aim of reaching up to 99% and is further discussed below. [46]

Post-combustion CO_2 capture is performed either with solvent via absorption, sorbents via adsorption or membranes. These products generally include an amine rich molecule due to the good and reversible kinetics between amine and CO_2. Solvents absorption is discussed below.

Absorption involves solvents such as monoethanolamine (MEA) or piperazine (PZ) which are used in a process similar as depicted in Figure 5. As the flue gas passes through the packed-bed absorber the PZ-rich solution trickles down in an opposite flow direction. The CO_2 absorbs in the solution and goes into the packed bed desorber. There, steam desorbs CO_2 from the solution which is then cooled to separate the CO_2 from the water. Finally, the gas is compressed for transport and storage. [47]

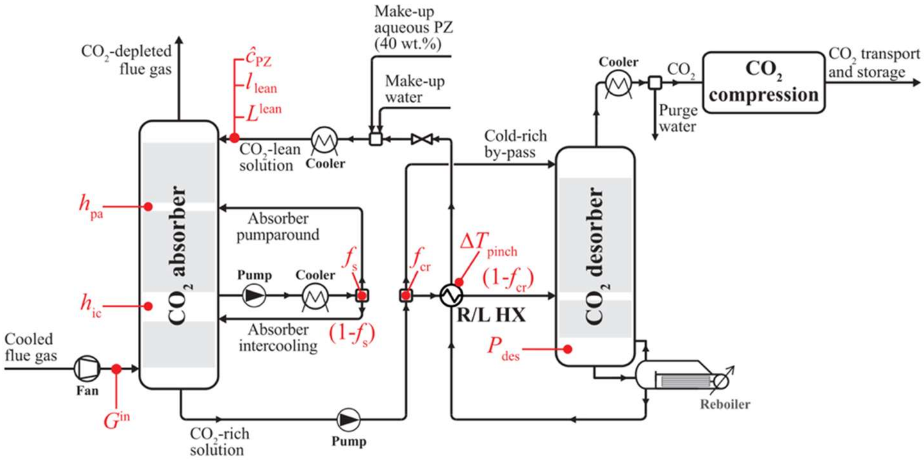


Figure 5: post-combustion absorption process using piperazine. Two packed-bed columns are used as the absorber and the desorber units. In the first, piperazine trickles down in the opposite direction from the flue. In the second the desorption is enabled with steam before the CO2 rich gas is cooled to separate CO_2 from water. [47]

There exists several barriers to the deployment of BECCS. Each BECCS plant is a one-of-a-kind project, involving a specific feedstock, supply chain, CO_2 capture process and downstream processes. Projects are either the retrofit of a plant (brownfield) or a new project (greenfield). These differ widely in their realisation, supply chain and costs. In case of a retrofit, the boilers must be changed to accommodate the new feedstock. Second, the plant's supply chain is influenced by pre-existing supply chains and the country's energy goals. Each feedstock requires accurate reporting on its origins, CO_2 emissions, land use, impact on ecosystem and transport emissions. This is crucial as it determines the overall carbon balance of the process. Finally, retrofitted plants use post-combustion capture processes to benefit from the add-on flexibility of the equipment, and new builds might consider any of the other capture processes. These factors shows the complexity and lack of standardization of BECCS projects. [48]

2. 2. 2. 2 Market Outlook

BECCS was first proposed as a negative emissions technology by Dr. Robert H. Williams, an American physicist and environmentalist. Following research showed that if the crops are grown sustainably and the CO_2 resulting from the combustion captured, the overall process would lead to net-negative emissions. [49]

There are currently 19 Bioenergy production facilities around the world either in operation, piloting or under construction. From the estimated 2Mt of CO_2 captured every year with bioenergy, a major part of it is converted to bioethanol applications. Notable facilities are the Decatur plant in the USA with an annual capture potential of 1Mt CO_2 for ethanol production and the Norcem plant in Norway storing CO_2 in cement material. [50] [51] In Europe two bioenergy projects with forthcoming durable geological storage have gained significant attention and are discussed below.

The Drax power plant in Selby, North Yorkshire is one of the major energy producers in the UK. It is responsible for 15TWh of power per year representing 6% of total UK electricity needs. [52] The site decommissioned from coal in 2021 after closing its last two coal units. Currently it uses sustainably sourced wood pellets to power four of the six boilers. [53] Drax announced in 2021 an innovative BECCS pilot project and states that the first fully operational BECCS unit could come online as soon as 2030. The first pilot started operations in 2019 and the second in 2020, together they capture 1.3t CO_2 per day[54] None of the CO2 captured at the pilots is currently stored although the intention for the full scale (8Mt/yr) plant is geological storage.

Stockholm Exergi AB, which is Stockholm's energy provider, inaugurated a research facility in 2019 aimed at retrofitting the Värtan combined heat and power (CHP) plant into a BECCS plant. Värtan is already one of the largest biomass-fired CHP plants in Europe with 280 MW of heat and 130 MW of boilerplate capacity produced annually. [55] Opened in 2016, the original CHP plant was a big step towards sustainable energy production due to the use of various wood residues as feedstock. The plant currently emits 126,000t of CO_2 emissions per year less than the equivalent fossil-fired unit and by integrating BECCS it aims at capturing about 800,000t of CO_2 per year. [56]

As prospective BECCS plants are developed by established power production companies, detailed financing information is not made public.

2. 3 Geological Storage and Monitoring

Whether for BECCS or DACCS technologies, the final and crucial step to make these processes carbon negative, is the stable and durable storage of CO_2. The most common approach to storing CO_2 underground is to compress it and inject the CO_2 into rocks at depths of 1 to 2 kilometers below the Earth's surface, which can then be securely trapped for many thousands of years in reservoirs, such as unmined coal seams, depleted oil and gas reservoirs or saline formations. [57] Another storage option is carbon mineralization of mafic and ultramafic rocks such as basaltic lavas.

Carbfix, an Icelandic company responsible to store the CO_2 captured from the Orca plant developed a method to speed up the mineral trapping of the gas. Their process involves injecting CO_2 at very high pressure with water, provoking the dissolution of the gas in the water as it is injected underground. It then reacts underground with basaltic rocks to form solid minerals. [58] The company is the official sequestration partner of Climeworks on their Orca and Mammoth plants. [57]

Geological storage sites which enable durable CO_2 storage are saline aquifers, unminable coal beds, and depleted oil and gas fields. European DACCS and BECCS projects aim to store CO_2 mainly in the North Sea, either through saline aquifers such as in the Norwegian Sleipner and Snohvit projects or in a combination of saline aquifers and depleted oil and gas fields such as in the UK CCS clusters. [59] [60]

In March 2023, Ineos and Wintershall Dea announced a project to capture up to 8 million tons of CO_2 per year in the Danish North Sea using a depleted oil and gas field. [61] In the USA the 1Mt CO_2 capture plant project from Carbon Engineering and Oxy will store CO_2 in oil and gas. [32]

Finally, the successful realisation for DACCS and BECCS projects relies on the safe and durable storage of CO_2. For this a strict monitoring of the subsurface is needed. Building on past experiences, CO_2 monitoring uses similar monitoring methods as in oil and gas fields. These include, for instance, seismic monitoring with dedicated trucks, micro-seismic monitoring using down-hole gauges, and satellite geodesy which can help detect changes to the surface of the earth. [59] Furthermore, gravimetric monitoring allows to monitor the dissolution of CO_2 in the brine. An example of a successful monitoring project is the Sleipner gas field where CO_2 injection has been ongoing since 1996. In the 20+ years of observation, no CO_2 leakage was recorded, ensuring containment. [62]

3. Aims and Research Questions

This research aims to provide model-builders and European policymakers with a better understanding of the uncertainty surrounding the costs and potential scale of DACCS and BECCS technologies. In the following, the contributions as well as scope and limitations of the research are presented.

3. 1 Research objective and hypotheses

Specifically, we aim to understand the current state of DACCS and BECCS technologies and how they may evolve in the future. Due to the lack of data on these technologies, we undertook expert elicitations to answer the following research questions:

1) How do the costs of DACCS and BECCS technology change over time? Does the uncertainty increase or decrease?
2) What is the potential scale of BECCS and DACCS that experts project will be deployed under the IEA STEPS and NZE policy scenarios? How does uncertainty evolve under the different policy scenarios?
3) According to experts, how do technological, economic, and political factors influence the deployment of DACCS and BECCS in Europe?

Prior to conducting the interviews, the following hypotheses were identified. These were tested and are discussed in the results.

(H1) Cost uncertainty increases over the years for both DACCS and BECCS technologies.

(H2) Total costs learning rate is higher for DACCS than BECCS.

(H3) Potential scale uncertainty under NZE is higher than under STEPS.

(H4) The NZE policy scenario leads to higher deployment scale for both DACCS and BECCS technologies.

(H5) BECCS technology remains cheaper than DACCS over time and is hence deployed at larger scale.

3.1 Contributions to the Literature

The expert elicitations we carried out provide valuable insights into the future of DACCS and BECCS technologies in Europe in the near term (2030), medium term (2040) and longer term (2050). Experts were able to provide uncertainty estimates surrounding the costs and deployment scale of these technologies. Additionally, the qualitative aspects gathered during the interviews provide a better understanding of the political and technological challenges Europe might be faced with when rolling out these technologies.

Ultimately, the goal of this research is to inform the economic models that are being developed within the NEGEM project framework. These models (such as MONET and TIMES-VTT) analyze potential pathways for negative emission solutions in future NEGEM decarbonization scenarios (see Deliverables 7.2, 7.3, and 8.6 for more information on these models). Directly feeding into them are the uncertainty ranges of costs and potential capture scale of DACCS and BECCS technologies in Europe elicited in this work.

Compared to other works, this research is developed along three axes, which together contribute to the novelty of this work. First, it presents a direct comparison of DACCS and BECCS technologies. Second, it provides uncertainty knowledge on both costs and potential scale estimates. Third, through the gathering of qualitative insights it inspects which factors can influence the costs and deployment of the technologies. These three axes have been tackled individually in prior work but never together.

To summarize, apart from its novelty, our research can assist in improving the models used to project and analyse future decarbonization scenarios. This study will be followed by a publication that summarizes the key insights from the surveys. Finally, both the models and the report aim to assist European policymakers in developing future climate policies.

3. 2 Scope and Limitations

The scope of this study covers the evolution of uncertainty of DACCS and BECCS processes in Europe. Through the expert elicitation protocol, experts are asked to speculate on future costs, potential scale of the technologies, and the technological and political factors which influence these variables. In total 34 experts were interviewed. A number of n_D=21 experts were fully or partially interviewed on DACCS technology and n_B=13 experts were fully or partially interviewed on BECCS technology (the difference in numbers between the two technologies is due to expert availabilities and time constraints). The experts come in majority from the academic or research sector and are based in Europe. Live interviews rather than online questionnaires were used to capture important qualitative insights next to the quantitative data gathered. This method of elicitation allows to discuss the obtained answers on the spot and gain a true understanding of expert opinions, helping build a first database of current expert judgements in DACCS and BECCS technologies. Finally, the protocol was developed in such a way that this study can be replicated. Additional experts can be interviewed on DACCS and BECCS and add to the current database, or interviews on different negative emission technologies or nature-based solutions can be performed.

The relatively small scale of the elicitation means strict system boundaries had to be set around DACCS and BECCS technologies so expert's answers could be compared. This in turn means that findings cannot be extrapolated to outside of the set technological boundaries. Next to the two set technologies, only systems with a permanent underground carbon sequestration were considered. Any other type of storage such as in cement, chemical products or e-fuels falls outside of the scope of the research.

The obtained results are directly tied to the background, expertise field and location of experts meaning that the obtained insights cannot be generalized. In this research most, but not all interviewees come from an academic background in engineering or natural sciences and are located around Europe. To best set context around the figures and overcome limitations relating to context specific contingencies, the obtained results are discussed using the qualitative insights provided by the experts.

Finally, expert elicitations are not free of biases. Biases can arise from protocol methodologies, poorly briefed experts, or unprepared interviewers. [65] [66] In this study the most common biases were avoided by ensuring a coherent protocol methodology which was tested during pilot elicitations. All experts were briefed on the interview and the technological systems prior to answering the questions. Despite this, cognitive biases such as anchoring, or overconfidence are common in social sciences and cannot be fully suppressed. An anchoring bias leads to experts giving too much importance to a piece of information they receive, such as the 2020 cost breakdown, and overconfidence arises when experts have an inflated or overly optimistic view of their own knowledge or judgments. [67] [68] To limit these mental shortcuts, or heuristics, experts were encouraged to build simple models to predict future costs and scale and they were allowed to consult literature during the interview.

4. Methods

4. 1 Expert Elicitation

DACCS and BECCS are technologies which have been tested and are in the process of being deployed at larger scale. Despite this, the amount of public information on active projects is limited. There exists an array of qualitative forecasting methods which allow to create knowledge on a subject where little real-life data is available. [69] For this research we decided to undertake expert elicitations, a method that supports the systematic gathering of quantitative and qualitative expert opinions. Due to the limited timeframe available to carry out this research no more than 34 interviews could be undertaken in the months of October 2022 – January 2023. Despite the relatively small number of experts interviewed, significant volumes of both quantitative and qualitative data was obtained. The in-person aspect ensures that experts provide quality answers, while giving them the freedom to provide context to the quantitative figures.

Historically, expert elicitations stem from probabilistic risk assessments of technological systems such as nuclear power plants or chemical process facilities. Interviewing a variety of experts using a formal protocol is one of the few ways to generate knowledge and quantitative data to characterize the risk or frequency of certain hazardous events. In the past decades, expert elicitations gained attention in the field of climate science, particularly for integrated assessment models (IAM) or climate change modelling. [66] Expert elicitations have also been conducted in the field of negative emission technologies, but none using a holistic elicitation method and directly comparing DACCS and BECCS technology costs and potential scale under two policy scenarios. [70] [71] [72] In a field where there is so much uncertainty and where future trajectories starkly depend on current political decisions it is imperative to use a structured method. Expert elicitations typically constrain expert answers to a particular system or framework. Although this prevents the generalization of answers to a wide range of technologies, it allows for a coherent and systematic modelling of uncertainty for a set of given technologies. [73] [74]

Results of an expert elicitation targeting DACCS technology specifically was published in 2021. [70] Comparable to the presented research, this study used expert elicitation to gather expert judgement on future cost estimates, capacity estimates, energy requirements and downstream use of CO_2 from solid and liquid sorbent DAC technology. Eighteen experts from industry and academia participated in this study. [70] An article released in 2016 used expert elicitations to assess if BECCS technology pathways developed at that time were on track with the IPCC scenarios to stay below 2°C of warming. Using the results gathered from 18 experts, this study concluded that IAMs had unrealistic assumptions concerning BECCS and supporting infrastructure deployment. [71] Finally, a study on technological and non-technological decarbonization solutions was published in 2023 and obtained 260 responses. This study assessed how experts perceived the impact of different innovations on achieving Net Zero. [72] These elicitations either focus on one technology or use questionnaires to obtain data. The work presented here wants to emphasise the differences of DACCS and BECCS technologies while using a method that allows for deep understanding of expert opinions. For these reasons, the used methodologies or system assumptions of the above studies are not directly comparable to the ones employed in this work and their results will not be further discussed.

Research on technologies, such as post-combustion CO_2 scrubbing, or floating offshore wind farms can be used to gain first insights on possible cost behaviours of DACCS and BECCS and their uncertainty implications. In a study which investigated post-combustion CO_2 capture from flue gas, it is shown that the main cost drivers are capital (capex) and operating costs (opex), which includes, among others, labour costs and the energy required to regenerate the amine solvent. [75] This research showed that in a first deployment stage, the use of more expensive materials lead to increasing capital costs and that the use of more efficient sorbents leads to decreasing energy costs. Despite the initial increasing total costs, capex and opex are expected to decrease over time. This is an example of non-linear cost behaviours due to material and process changes. The study also highlights that social and political factors can also influence costs and the rate of diffusion of the technology. Finally, it concludes that an initial cost increase for a technology leads to increased uncertainty which can affect energy-economic models. [75]

A second study on the cost evolution of fixed-bottom wind farms in the UK and the EU also shows an increase in capital expenditures during the first five years before the capex decreases. Factors such as financing, technology improvements and decreasing technology costs were highlighted as causes for a steep cost reduction in the technology in recent years. [76] Finally, a study on future deployment of floating offshore wind farms in the UK shows that cost reductions for this technology are mainly achieved through deployment and that long-term cost gains can be obtained from innovation. [77] These studies provide examples of non-linear cost behaviours which can have a significant impact on uncertainty and model outputs. They also highlight the importance of undertaking a cost analysis that is mindful of the time scale. Aggregating all results in a single learning rate can lead to overlooking important cost behaviours. Finally, they present a variety of factors that can influence the cost of a developing technology over time. Based on these learning, an analysis looking at different time periods and influencing factors is undertaken.

The following sections describe the developed methodology used to conduct the expert elicitations. The different steps to performing this research in a structured manner are the identification of the studied variables, the selection of experts, the preparation and testing of the protocol, and finally the conduction of the interviews. As a post-elicitation step is the aggregation and documentation of the outputs.

4. 2 Expert Selection

The experts for this elicitation were selected based on prior work undertaken by the team. We draw from our list of experts, developed with the aid and support of NEGEM partners, in the field of nature-based and technological CCS such as BECCS, DACCS, afforestation, reforestation, biochar, and ocean alkalinization. With more than 500 entries, these experts were reviewed taking account of their level of expertise and subjective capacity to answer the questions under consideration. 112 DACCS experts and 88 BECCS experts were contacted by email. Mailchimp was used to reach out to most of the experts. [78] In total, 21 experts for DACCS and 13 for BECCS answered positively and participated in the elicitation (equivalent to response rates of 19% and 15% for DACCS and BECCS respectively).

Two pilot elicitations were performed for both DACCS and BECCS at the beginning using experts in the NEGEM consortium. The goal of these interviews was to ensure proper understanding of the system assumptions and questions. Despite changes being made on the system assumptions following the pilots, these four experts' answers are considered in the following research as they provided interesting insights on the technologies.

Table 1 lists the experts who participated in the expert elicitation, including their primary affiliation. The experts are listed in alphabetical order, this order does not correspond to the numbers displayed in the results. Dr. Nixon Sunny and Dr. Selene Cobo-Guttierrez were the DACCS pilot experts, and Constanze Werner and Dr. Fabian Levihn were the BECCS pilot experts.

Table 1: Interviewed experts on DACCS and BECCS technologies and their principal affiliation.

DACCS Experts	*BECCS Experts*
Alauddin Ahmed – University of Michigan	Astley Hastings – University of Aberdeen
Eadbhard Pernot – Clean Air Taskforce	Caspar Donnison – University of California, Davis
Gaurav Sant – University of California, Los Angeles	Catriona Reynolds – DRAX
Greg Mutch – Newcastle University	Clair Gough – University of Manchester
Howard Herzog – Massachusetts Institute of Technology	Constanze Werner – Potsdam Institute for Climate Impact Research
Jennifer Wilcox – US Department of Energy	Eric Larson – Princeton University
Mai Bui – Imperial College London	Fabian Levihn – Stockholm Exergi
Maria Erans – King Juan Carlos University	Ilkka Hannula – International Energy Agency
Matteo Gazzani – Utrecht University	James Palmer – University of Bristol
MennatAllah Labib – University of Edinburgh	Mathias Fridahl – Linköping University
Nixon Sunny – Imperial College London	Mathilde Fajardy – International Energy Agency
Noah McQueen – Heirloom	Stefan Grönkvist – KTH Royal Institute of Technology
Peter Kelemen – Columbia University	Stephen Smith – University of Oxford
Petri Laakso – Soletair Power	
Selene Cobo-Guttierrez – Swiss Federal Institute of Technology (ETH) Zurich	
Shareq Mohd Nazir – KTH Royal Institute of Technology	
Stefano Brandani – University of Edinburgh	
Stuart Haszeldine – University of Edinburgh	
Volker Sick – University of Michigan	
Webin Zhang – Nottingham Trent University	
Zeynep Clulow – University of Cambridge	

Due to the pluri-disciplinary scope of the research, a mix of experts from academia, industry, policy, and technology fields was sought after. Figure 6 shows the breakdown of experts in terms of sector (distinguishing between industry, academia, research institutes, and policy experts).

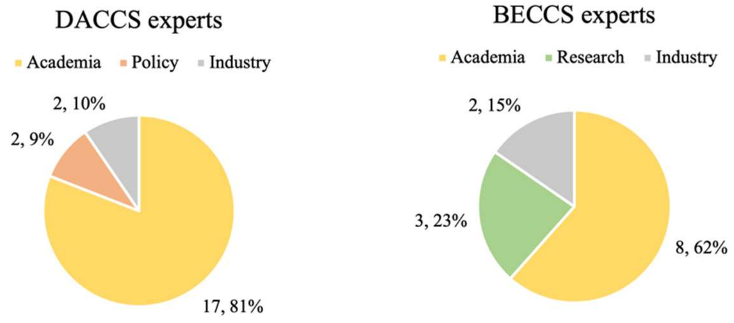


Figure 6: Sector breakdown of experts interviewed for DACCS and BECCS technologies. First figure is the number of experts in a field and the second figure is the percentage of experts from that field.

Academia represents the largest portion of experts with 62% and 81% of experts stemming from this sector for DACCS and BECCS respectively.

4. 3 Supporting Material

4. 3. 1 Two-Pagers

Along the meeting invitation, experts were sent a two-pager prior to the elicitation. The goal of this document is to inform experts on the NEGEM project and technological and policy assumptions used for the elicitation. It also contains a summary of typical learning curves of related technologies for the past decades. The system boundaries and cost models shown below are based on an extensive literature review and the help of Dr. Nixon Sunny and Dr. Solène Chiquier from Imperial College London.

4. 3. 1. 1 DACCS System Assumptions

The DACCS system is based on the low-temperature Climeworks process. The adsorption process is the same temperature-vacuum swing process as described in Section 2. 2. 1 . The units are assumed to be near the injection site to minimize transport. Six Climeworks collectors form a collector container, which is referred to here as a “unit” or a “collector unit”. Current capture capacity of one unit is assumed to be ~ 500t CO_2 per year. [21]

Table 2 shows the cost breakdown assumed for a first of a kind (FOAK), 1 Mt CO_2 capture capacity plant located in Europe with a solid sorbent adsorption system. Total costs calculation can be found in the Appendix.

Table 2: Key assumptions of a DAC system based on Climeworks’ technology. A transportation cost of $\$16_{2021}/tCO_2$ *was assumed. The reported figures were adjusted from* USD_{2020} *to* EUR_{2021} *and from* EUR_{2021} *to* EUR_{2020} *respectively. [79] [80] [81]*

Cost Type	EUR_{2020}/tCO_2
CAPEX	179
OPEX	202
Energy costs	181
CO_2 transport, storage & monitoring	18
Total costs	*581*

4. 3. 1. 2 BECCS System Assumptions

For BECCS, a 500MW thermal power plant for heat and power production located in Europe with an amine-based post-combustion carbon capture was studied. The plant has the capacity to capture up to

909.5kt of CO_2 per year. The plant was said to be based on the DRAX or Stockholm Exergi plants depending on the location of the expert, and the plant with which they might be the most familiar with.

At first, the following two assumptions were assumed – The feedstock was miscanthus and a $100km^2$ area was set around the plant for feedstock sourcing and transport. These assumptions were later dropped as pilot experts found them too stringent. Following this, experts were asked which feedstock they see fit for the plant. This change did not influence the 2020 cost breakdown. Table 3 shows the cost breakdown for BECCS technology in 2020. The total costs are based on a conference announcement from DRAX placing current costs at GBP_{2022} 150/tCO_2. [82]

Table 3: Total costs of a BECCS system based on the DRAX power plant with 2020 costs equivalents. Cost breakdown and assumptions are based on the MONET simulation provided by Solène Chiquier and adapted. Both a conversion rate from GBP_{2022} to GBP_{2020} and from GBP_{2020} to EUR_{2020} is used. [83] [82]

Cost Type	*EUR_{2020}/tCO_2*
CAPEX	164
OPEX	30
Feedstock costs	105
Energy revenues	-165
CO_2 transport, storage & monitoring	38
Total costs	*172*

4. 3. 1. 3 Policy Scenarios

To compare experts' beliefs on how policies influence the scalability potential of the technologies in Europe, they were asked to estimate the development for two policy scenarios. The two selected scenarios are the IEA's Stated Policies Scenario (STEPS) and Net Zero Emissions by 2050 Scenario (NZE).

STEPS is defined by the World Energy Outlook as a scenario where governments meet their existing commitments as envisioned in their NDCs but would not meet their 1.5°C pledges. Considered in this scenario are the various sectors' energy-related pledges that have been put in place or that have been mentioned as being put in place soon but with no specific climate objective being achieved. By contrast, NZE is defined by the IEA as a 'normative' scenario which shows the pathway to global net zero emissions for the energy sector by 2050. This scenario is useful in discussing the volume of negative emissions required to achieve this narrow target. [84]

Figure 7 shows the projected global CO_2 emissions under the STEPS, announced pledges (APS) and the NZE scenarios. STEPS projects global CO_2 emissions of 35Gt by 2030 and 34Gt by 2050. This scenario does not specify any carbon price or need for negative emissions. NZE projects 21Gt of global CO_2 emissions by 2030 and 0Gt by 2050. [84] This scenario assumes that additional methods are needed to reduce CO_2 emissions and remove excess CO_2 from the atmosphere. NZE relies on BECCS to annually remove 227Mt of CO_2 by 2030. BECCS power production would reach 28GW by 2030 and up to 152GW in 2050. [85] In terms of carbon price levels, this scenario stipulates the need for a carbon price of USD 250/tCO_2 in advanced economies and USD 200/tCO_2 in other economies. [86] These scenarios represent different policy contexts in which NETPs could be deployed. Therefore, experts can make different projections about the potential scalability of BECCS or DACCS under each scenario.

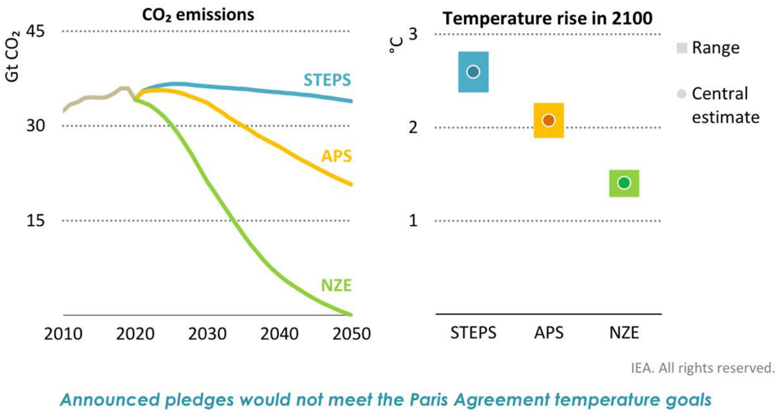


Figure 7: Global CO_2 emissions under different policy scenarios and associated temperature increases. Adapted from the World Energy Outlook 2021. [84]

4. 3. 2 Elicitation Protocols

To support the interview process, an excel-based protocol was prepared for both technologies. The goal of this protocol is to allow the experts to visualize their answers as they go through the elicitation. The protocols contain the following sheets:

1. DACCS
    - Sheet 1: Expert information
    - Sheet 2: DACCS system assumptions
    - Sheet 3: Costs, energy usage
    - Sheet 4: Capacity of a DACCS unit
    - Sheet 5: Scalability under two policy scenarios
    - Sheet 6: Limiting factors and enabling policies.

2. BECCS
    - Sheet 1: Expert information
    - Sheet 2: BECCS system assumptions
    - Sheet 3: Costs, feedstock type, land usage
    - Sheet 4: Scalability under two policy scenarios
    - Sheet 5: Limiting factors and enabling policies.

Sheet 1 collects expert's name, job title, affiliation, and email address. Sheet 2 is used as a reminder for experts to base their answers to the cost, energy, and land questions on the proposed system. This step is important to ensure all experts are answering the quantitative questions within the same system boundaries, allowing for statistical analysis of the answers.

All quantitative questions are asked for the years 2030, 2040 and 2050. For each variable a minimum, maximum and best estimate figure is asked. The min-max range is asked first to reduce expert's anchoring around one figure. This range represents the 90% confidence interval of the expert's expectation. The minimum level is the level under which events happen with a probability < 5% and the maximum the level is level above which events happen with a probability < 5%. This range represents the uncertainty level of each individual expert in the different decades. Following this, experts were asked to provide the best estimate for the variables. The best estimate must lie within the min-max range and represents the most likely level of a given variable in a year.

The quantitative questions for DACCS include the cost breakdown and total costs, and energy requirements. The DACCS protocol also contains an additional sheet with the capacity of one DACCS unit over the next decades. This was added to understand the variation in technology that experts expect. For this question experts are free to deviate from the system assumptions. The quantitative questions for BECCS include the cost breakdown of the technology and total costs in the coming decades, which feedstock will be used, and how much land will be needed to grow this feedstock.

In the scalability sheet experts must extrapolate on the potential capture scale of the technologies under two policy scenarios. For these questions, experts were reminded that they can assume any type of technology as there is little certainty on what the market will look like in 30 years.

All quantitative estimations are backed by percentage changes. For costs, 2030 levels were compared to the initial 2020 levels. Percentage changes are then calculated for the respective 10-year period. Additionally, a summary of the answers in form of table and graph was made available. This supporting information was used to allow experts to review their answers and amend any figure if needed. It must be noted that not all experts made equal use of the supporting information.

Finally, experts rank limiting factors and enabling policies. Experts were free to add new factors or policies to the lists. These new factors or policies were then kept for later interviews. In this part of the interview, experts are free to additionally discuss any theme they deem important.

4. 4 Expert Interviews

Experts that agreed to participate in the study were interviewed in 90 minutes slots through zoom. Prior to the meeting they were sent the two pager and were asked to review it. At the start of the interview, a short introduction of the interviewer and the NEGEM project was given. Then, the expert elicitation was introduced, and experts were reminded that they must speculate on costs and potential scale of the technology in the coming decades. Finally, it was emphasized that they must base their answers on their own beliefs and not on the guidelines dictated by the institutions they are affiliated with. However, it is important to note that they were encouraged to base their answers on research performed by themselves or colleagues within their organization.

Figure 8 shows the response frequency to each question. The disparity between ‘Total Costs’ and ‘Cost Breakdown’ is due to experts not feeling comfortable giving a detailed cost breakdown and only answering the total costs question. As not all questions are answered with the same frequency, this report focusses on the costs and scalability results.

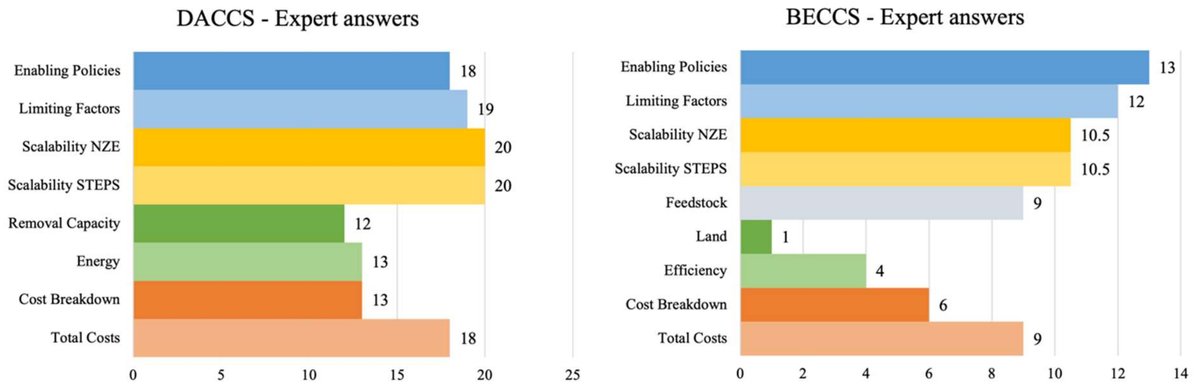


Figure 8: Response frequency to DACCS and BECCS technology questions. A full answer is recorded with 1 and a partial answer is recorded with 0.5.

To conclude, the post-elicitation steps include creating a copy of the original protocol to preserve the original answers. Then the protocol is reviewed, and notes and calculations are cleaned-up. The latter can involve finalizing the cost and scalability models following the instructions given by the expert. The final protocol is then sent back via email for expert review and safekeeping.

4. 5 Quantitative and Qualitative Methods

This section contains the methods used to handle the quantitative and qualitative insights gathered during the elicitations.

4. 5. 1 Quantitative Methods

The quantitative answers are aggregated in comma-separated values (csv) files. There, data is anonymized as expert names are omitted. As mentioned before, only questions concerning costs and scalability undergo a more detailed analysis using quantitative methods. In total, four different sets of data were examined for DACCS and BECCS technologies: future total costs, future breakdown costs, and scalability under the STEPS and the NZE policy scenarios, as these scenarios are expected to substantially affect the scalability. For data analysis and graphical representation, the open-source program ‘R’ was used. This program, as well as the necessary packages to perform enhanced analytics can be downloaded from the web. [87] R-scripts are documents in which the code that performs the data analytics is written and stored. For this research four R-scripts were created to analyse DACCS costs, DACCS scalability, BECCS costs and BECCS scalability. The source codes are joined to the folder with which this work is shared.

DACCS and BECCS data are handled in the same way. Costs and scalability are both analysed along two axes, namely uncertainty and best estimates. Uncertainty is analysed using the min-max intervals. Within experts, between the years and average range width evolution is discussed. Best estimates are analysed to understand the costs and potential scale expected by experts throughout the years. Although the uncertainty results are presented in detail, no summary frequentist statistical parameter measuring uncertainty can be built due to the small and non-random nature of the sample – any such measure would not have been able to properly represent the data.

4. 5. 1. 1 Costs Results Analysis

Costs are described along three dimensions. The first is the cost type: total cost, capex, opex, heat and fuel, feedstock, revenue, and CO_2 transport, storage and monitoring. The second is the year: 2030, 2040, or 2050. The third is the estimate type: minimum, maximum, or best estimate (BE).

First, the trajectories of all obtained min-max ranges are analysed using a scatterplot. For this, only the total costs and breakdown total costs are discussed. When necessary, specific cost items are mentioned in the discussion and the corresponding graph in the Appendix is referenced. To portray the spread of the answers, five experts are selected, and their results are presented in detail. These experts are selected according to their 2030 cost best estimate. The smallest, second smallest, median, penultimate, and largest best estimates are chosen. The second smallest and penultimate expert responses were included to prevent according too much importance to possible outliers. The trajectories of these experts represent the span of the obtained answers and are discussed in detail using qualitative insights from the respective experts.

An uncertainty metric is obtained by calculating the average width of the min-max intervals for the total costs and the breakdown costs over the years. This metric indicates how experts agree on their min-max ranges. The narrower the range, the higher the agreement of experts on the min-max range and the more certain they are. Additionally, the percentage change of the widths over the 10-year periods is calculated. A positive percentage change shows an increase in uncertainty and a negative percentage change shows a decrease in uncertainty.

Finally, the cost best estimates of the two technologies are compared using scatterplots and average best estimates over the years. The percentage change in the 10-year periods is calculated to show the evolution of the costs.

4. 5. 1. 2 Potential Scale Results Analysis

The scalability answers are characterized along three dimensions. The first is scalability: whether STEPS or NZE scenario. The second is the variable type: minimum, maximum, or best estimate. The third is the year: 2030, 2040 or 2050. It is important to note that in the scalability graphs use logarithmic axes to display all obtained ranges throughout the years and policy scenarios using the same axis length. Logarithmic plots do not allow to show 0 values. Hence, all 0 Mt scalability answers were manually changed to 10^{-6}Mt CO_2 captured per year. This arbitrary small value was chosen so the full min-max ranges are displayed in the logarithmic plots and because it is small enough to not influence the data analysis.

Like for the costs, the uncertainty of the scalability results is analysed through the evolution of the min-max ranges throughout the years and within the experts. For this, the trajectories of all potential scale results under the two policy scenarios in 2030, 2040 and 2050 are discussed. To gain a better understanding of the span of these results, five representative expert answers are selected. Since scalability depends on the policy scenarios, two sets of experts were chosen for each technology. The first batch of experts is selected based on the potential scale best estimate under STEPS in 2030. The second batch of experts is based on the potential scale best estimate under NZE in 2030. For both these sets the smallest, second smallest, median, penultimate, and largest potential scales are selected, and the best estimate and min-max trajectories are analysed.

Both under STEPS and NZE, up to three experts had the same scalability as the median result of BECCS scalability in 2030. Due to the already low number of respondents, showing all these experts in the trajectories analysis would have been counterproductive. For this reason, the median result of the expert interviewed last was selected.

Uncertainty is additionally analysed using the average widths of the min-max ranges. As explained previously, a narrow width indicates that experts agree on the min-max range and are more confident in their predictions in a certain year. The percentage changes are also indicated to portray an increase or decrease in uncertainty within a 10-year period.

Finally, the potential scale best estimates of the technologies under both policy scenarios are compared to understand the effect of policies on future scalability. Qualitative insights gathered during the interviews are used to discuss the results.

4. 5. 2 Qualitative Data

During the interview, qualitative insights such as expert views and comments were recorded. Important or recurring insights were collected in a separate sheet and classified according to different themes. This data is used to explain the obtained results. An anonymized copy of this file can be found in the Appendix.

The final part of the interview focused on limiting factors and enabling policies. These were classified by experts from most limiting to least limiting and most enabling to least enabling using a scale from 1 – 10. To analyse these results the frequency of occurrence is calculated. An average classification using both the importance ranking and the occurrence is calculated. It is important to note that additional factors and policies were added in later interviews. This leads to a skewed occurrence and average classification. For this reason, the discussion focusses on factors and policies chosen by most experts

5. Results and Discussion

In this chapter, the results from the expert elicitations are discussed. These are presented in three parts: uncertainty, best estimates, and finally a discussion on limiting factors and enabling policies. This order of presentation is motivated by the elicitation methodology where uncertainty ranges were probed first before the best estimates. As mentioned previously, the numbers used in this section do not correspond to the order of the expert list and all expert answers were anonymised.

5. 1 Cost Results

5. 1. 1 Cost Uncertainty

The following sections investigate trajectory and uncertainty evolution of DACCS and BECCS technology costs in 2030, 2040 and 2050 using. The elicitations for both the total costs and the cost breakdowns are analysed.

5. 1. 1. 1 DACCS Costs Uncertainty

For DACCS total costs trajectories, Figure 9 shows all expert ranges in €/tCO_2 over the years. Similar graphs for the cost breakdown items can be found in the Appendix. Of the 21 DACCS experts 18 provided total costs and 13 of those also gave a cost breakdown.

There is a clear disparity with some experts using very narrow ranges and others spanning over two orders of magnitude. Starting in 2030, there is a tendency for experts that gravitate towards higher costs to also provide wider min-max ranges while those gravitating towards smaller costs provide narrower ranges. This can indicate that the higher the cost, the larger the uncertainty of the experts or that experts which are confident in their belief of attaining low costs will provide narrower intervals.

Experts 10, 12, 13, 14 and 15 did not provide a breakdown of the costs. Comparing the total costs and total costs obtained from the cost item breakdown (from here on called ‘breakdown cost’), it is apparent that experts that gave a breakdown of the costs tend to provide cost ranges that span higher than the five experts which only provided total costs. The cause for this could be that by separating the costs in different items, a buffer for uncertainty is added to each item which would lead to higher overall costs.

Looking at the 2020 reference point, it is apparent that no expert assumes this reference costs to be the 2030 costs, although some may have used it as a starting point and then assumed some learning over the intervening seven years. Quite strikingly, some experts do not even include that point within the min-max ranges for 2030. When asked if they agreed with the 2020 starting costs, most DACCS experts answered positively. However, experts 15 and 19 likely believe that the technology is more expensive than what the current literature states and that the minimum possible costs in 2030 costs will be higher than EUR 581/tCO_2. Additionally, experts 2, 10, 14 and 21 show maximum costs which lie at or below EUR 305/tCO_2. That half of the experts' ranges lie outside of the reference point can be an indication that experts are able to answer the questions according to their own knowledge and are not strongly anchored by the reference costs. The cost breakdown graphs can be found in the Appendix. The biggest disagreement is over the future of energy costs - Heat and fuel (H&F) cost ranges do not overlap as much as other cost items as seen in Figure 30 in the Appendix. All expert ranges decrease throughout the decades, except for expert 11. This expert provided a very wide range that does not change throughout the years, skewing the average min-max range over the years. In the interviews, experts consistently commented that extrapolating on future energy costs was difficult. Reasons for this are the volatility of the energy market spearheaded by the war in Ukraine, the increasing energy prices throughout Europe, and the uncertainty surrounding the rate of adoption of renewable energy in the European grid. Hopes for energy prices to settle back to pre-war levels can explain the decrease of the energy cost min-max ranges over time.

Due to the limited pool of experts interviewed, the obtained data cannot undergo traditional inferential statistical analysis. As shown in Table 4, the smallest, second smallest, median, penultimate, and largest, best estimates were selected from the pool of 2030 cost best estimates to represent the obtained data. Figure 10, and Table 5 show the trajectories of the min-max ranges of these selected experts over the years. Experts 11* and 18* are indicated with an asterisk as they provided a cost breakdown.

Of the five selected experts, experts 11*, 15 and 18* believe in a general reduction of costs. Expert 18* uses the 2020 starting costs as a maximum point for 2030 and 2040 costs. Expert 15 starts with the highest costs and ends in a similar range as the median cost in 2050. This could point again to the behaviour that experts starting with large costs tend to decrease these more over time than experts starting with smaller costs. Finally, despite a decrease in costs over time, Expert 11* provides high costs and has a 2050 best estimate that is higher than the 2020 starting costs. To conclude, of these selected experts, it is apparent that those providing a cost breakdown believe in higher minimum and maximum costs. This could indicate that experts that are able to provide a cost breakdown account more for future uncertainty and are more reluctant to reduce their costs as fast as experts that only provide the total costs.

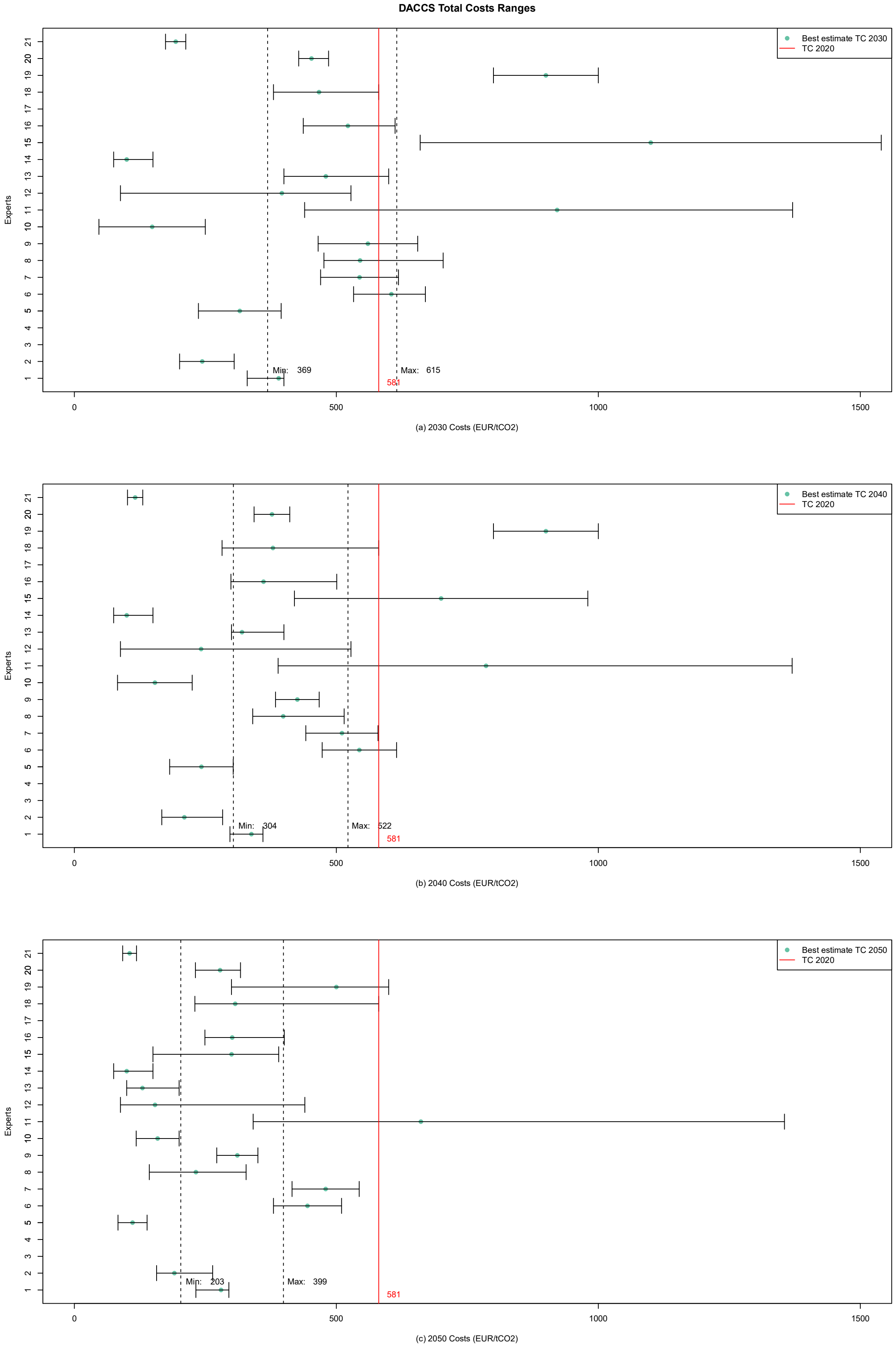


Figure 9: DACCS total costs estimates with minimum, maximum, and best estimate of each expert in €/tCO$_2$. Figures are given for 2030, 2040 and 2050. Best estimates are the blue dots, and the 2020 total cost is shown by the red line. Dashed lines show the average min and max ranges.

Table 4: DACCS total cost best estimates of selected experts for 2030, 2040 and 2050. A star indicates experts that provided a breakdown of the costs.

DACCS Total Costs BE (€/tCO_2)	***Min*** *(Expert 14)*	***Min + 1*** *(Expert 10)*	***Median*** *(Expert 18*)*	***Max -1*** *(Expert 11*)*	***Max*** *(Expert 15)*
2030	100	149	467	921	1100
2040	100	154	379	786	700
2050	100	159	307	661	300

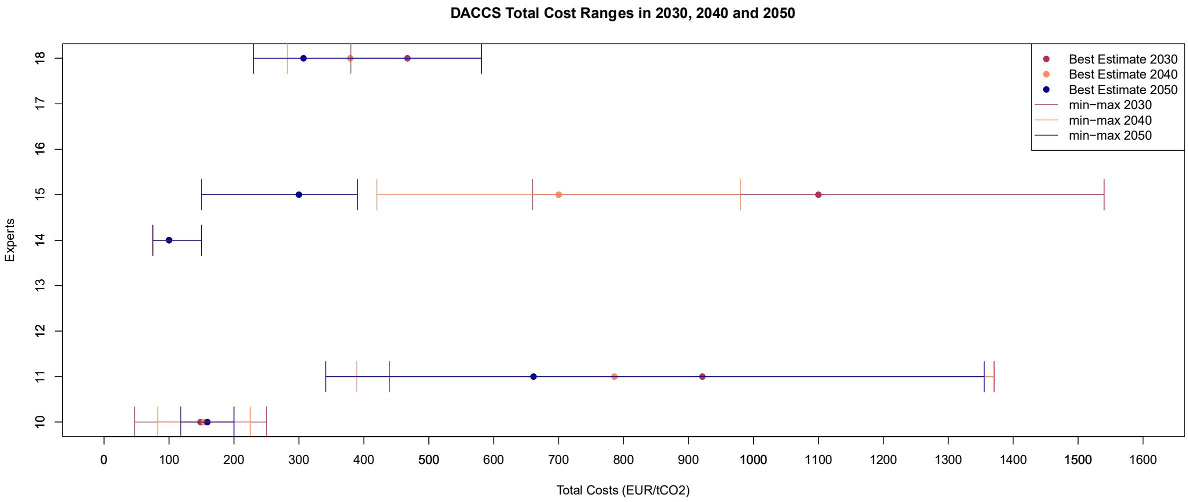


Figure 10: DACCS total cost range and best estimate evolution of 5 selected experts in 2030, 2040 and 2050.

Expert 14 has a constant min-max range and best estimate over the three decades. This expert's reasoning is that by 2030, only processes which are currently deployed in the industry will be used with significantly lower costs but that these will remain constant over the years. Finally, expert 10 shows a min-max range and best estimates which shift right. As highlighted previously, increasing costs in the first years of deployment of a technology is not uncommon (Section 4. 1). Here, the increase in minimum costs is due to the belief that despite capex and opex going down, H&F and transport, storage and monitoring (TSM) costs will remain high. However, the min-max range, or the uncertainty range of this expert narrows over the years. This again could indicate that experts which believe that low costs can be attained in 2030 are confident in this prediction and provide narrower intervals.

Table 5: DACCS costs min-max range of selected experts for 2030, 2040 and 2050. A star indicates experts that provided a breakdown of the costs.

DACCS Total Costs Min-Max Range (€/tCO_2)	***Min*** *(Expert 14)*	***Min + 1*** *(Expert 10)*	***Median*** *(Expert 18*)*	***Max -1*** *(Expert 11*)*	***Max*** *(Expert 15)*
2030	75 – 150	47 – 250	380 – 581	440 – 1370	660 – 1540
2040	75 – 150	83 – 225	282 – 581	389 – 1370	420 – 980
2050	75 – 150	118 – 200	230 – 580	341 – 1355	150 – 390

To conclude, many experts assumed that the introduction of more renewables into the energy grid will reduce energy costs, and that by 2050 novel and more efficient sorbents will reduce capex and opex costs. Additionally, experts also mentioned that minimum costs can be capped by technological or thermodynamical feasibility. This would constrain the minimum to certain ranges below which the costs cannot feasibly go.

Looking at the uncertainty within experts, Table 6 shows the average width of the min-max ranges of the costs throughout the decades and its relative percentage changes. It is important to note that these figures are not actual costs but the average difference between the minimum and maximum. A wider width indicates less expert agreement on the costs and a positive percentage change indicates increasing uncertainty for that cost item. These show that on average the five experts which only answered the total cost question provide wider ranges than those that also answered the cost breakdown questions. This indicates that there is less agreement within this set of experts when answering a one-parameter cost question.

Looking at the uncertainty evolution over the years, the percentage changes of the total costs decrease, compared to the breakdown costs. The increase in uncertainty when experts provide a cost breakdown of the technology can be caused by two factors. First, it could stem from a difference in opinion. The five experts that did not provide a cost breakdown could be cost optimists and be certain of a strong reduction in costs. Second, providing a breakdown of the costs could lead to an overhead or a 'safety-range' that is added on all cost items, leading to an average increase of the range width over the years. To conclude, these results could suggest that experts providing a cost breakdown agree more on their answers and know that they cannot predict the far future as well as the near future.

Table 6: DACCS min-max range width average across experts in €/tCO_2. The percentage change for each decade is provided in parenthesis.

DACCS min-max average width (€/ton CO_2)	*Total Costs (18 experts)*	*Breakdown Costs (13 experts)*	*Capex*	*Opex*	*H&F*	*TSM*
2030	246.46	202.92	45.68	43.60	106.11	7.53
2040	218.58 (-11%)	201.28 (-0.8%)	45.45 (-0.5%)	45.45 (+4.2%)	102.48 (-3.4%)	7.90 (+4.9%)
2050	195.81 (-10%)	205.79 (+2.2%)	45.67 (+0.5%)	48.10 (+5.8%)	103.40 (+0.9%)	8.62 (+9.1%)

To summarize, the trajectories and uncertainty in DACCS costs point to the following results. First, higher costs in 2030 seem to lead to an increase in expert uncertainty while experts with lower starting costs seem to be more confident. Second, experts which provide a cost breakdown seem to agree more on the min-max interval (smaller ranges) and are less certain of future costs (increasing percentage change).

5. 1. 1. 2 BECCS Costs Uncertainty

For BECCS, 13 experts were interviewed in total, nine experts provided total costs and six of those were able to also break the costs down in different items. Figure 11 shows the trajectory of expert total costs min-max ranges and best estimates in 2030, 2040 and 2050. Expert 1 did not answer the cost questions and is not included in the graphs and expert 4 has a min-max range that is the same as the best estimate in 2030 and 2040. The cost breakdown items graphs can be found in the Appendix.

There is a lot of agreement over the min-max ranges of the total costs as seen by the overlapping of the intervals. This is particularly evident in 2030 and 2050 with less overlap in 2040. Compared to DACCS, it cannot be stated that the higher the costs, the larger the min-max interval, due to the small sample size.

Expert 2 shows an interesting behaviour. For this response, themin-max range is narrow in 2030 before spanning wider in 2040 and 2050. Discussion with the expert reveal that this is based on a belief that BECCS will first be implemented in the most cost-effective locations and that later plants will be further from CO_2 transport and storage infrastructure and feedstock supply chains, making them possibly more costly.

Looking into possible anchoring based on the 2020 reference costs, expert 8 offers the 2020 total cost as their 2030 value, and the assessment of expert 2 sits just below that value. These responses indicate that the two experts could have been influenced by the 2020 reference point.

For BECCS it also seems that some experts disagree with the starting costs. Experts 4, 10, 11 and 13 have 2030 costs that sit above the reference value. In the case of BECCS, extensive conversations were had with experts on the system assumptions and costs. The complexity of BECCS lies not in the technology itself but in the case-by-case deployment thereof. Each expert has a specific feedstock, supply chain, plant location, furnace type and energy production that they are accustomed with. Imposing a reference plant configuration on experts was in many cases prohibitive. For this reason, not only were the feedstock assumptions dropped, but also as most experts were based in Europe, they were told to answer the questions with either the DRAX or Stockholm Exergi plant in mind. That way, experts could choose the plant configuration they are the most familiar with to answer the questions. Due to this disparity, the obtained cost ranges could contain varying underlying system assumptions, leading to some unavoidable differences.

The cost breakdown graphs can be found in the Appendix. There, the feedstock costs show interesting results (Appendix Figure 34). All experts assumed forest residues to be the main feedstock of BECCS technologies in the coming decades. Some also mentioned municipal waste, however as one expert indicated, the supply chain from municipal waste must be closely studied as this feedstock could not count towards making BECCS net negative. Interestingly experts 2 and 11 stem from the same geographical region and provide starting feedstock costs that are diametrically different. However, the trend for both experts is that the costs increase over time. One expert explains the cost increase by saying that forest residues are in abundance but that supplying to the different BECCS plants will become more costly over time. The other assumes that any feedstock whether forest residues or municipal waste will be in high demand in the coming decades and therefore their price will go up.

Finally, looking at the revenues (Appendix Figure 35), the ranges tend to overlap and increase in width over the decades. Energy revenues for BECCS has the same uncertainty as the energy prices in DACCS. The volatile energy market means that future prices are highly uncertain. Additionally, as mentioned by expert 13 BECCS revenues will depend on the type of technology, the where and the how. Compared to DACCS the additional uncertainty is well translated in the increasing revenue ranges.

As for DACCS, five BECCS experts were selected based on their best estimate and their trajectories is analysed in detail. For BECCS, experts 6, 7*, 8, 11* and 10 were selected as the smallest, second smallest, median, second largest, and largest best estimates respectively. An asterisk indicates that experts 7* and 11* also provided a breakdown of the costs. Table 7 shows the best estimates and Figure 12 and Table 8 show the evolution of the ranges over time. Interestingly all best estimates decrease over time, but for expert 11*. The reasoning behind this is that capex and opex do not decrease and feedstock costs increase over the years due to higher competition for waste material.

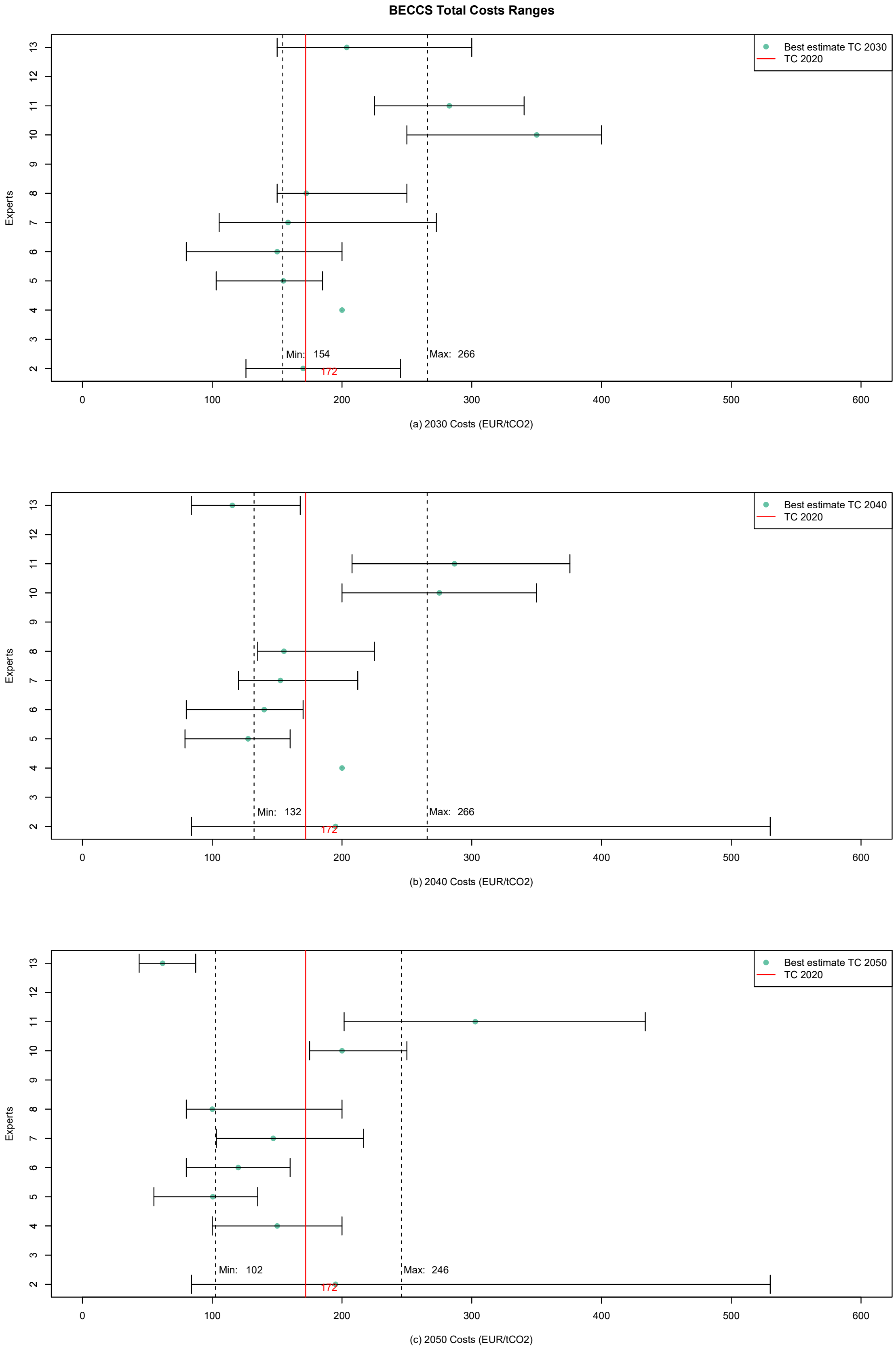


Figure 11: BECCS total costs estimates with minimum, maximum, and best estimate of each expert in €/tCO₂. Figures are given for 2030, 2040 and 2050. Best estimates are the blue dots, and the 2020 total cost is shown by the red line. Dashed lines show the average min and max ranges.

Table 7: BECCS total cost best estimates of selected experts for 2030, 2040 and 2050. A star indicates experts that provided a breakdown of the costs.

BECCS Total Costs BE (€/tCO_2)	***Min*** *(Expert 6)*	***Min + 1*** *(Expert 7*)*	***Median*** *(Expert 8)*	***Max -1*** *(Expert 11*)*	***Max*** *(Expert 10)*
2030	150	158	172	283	350
2040	140	152	155	287	275
2050	120	147	100	303	200

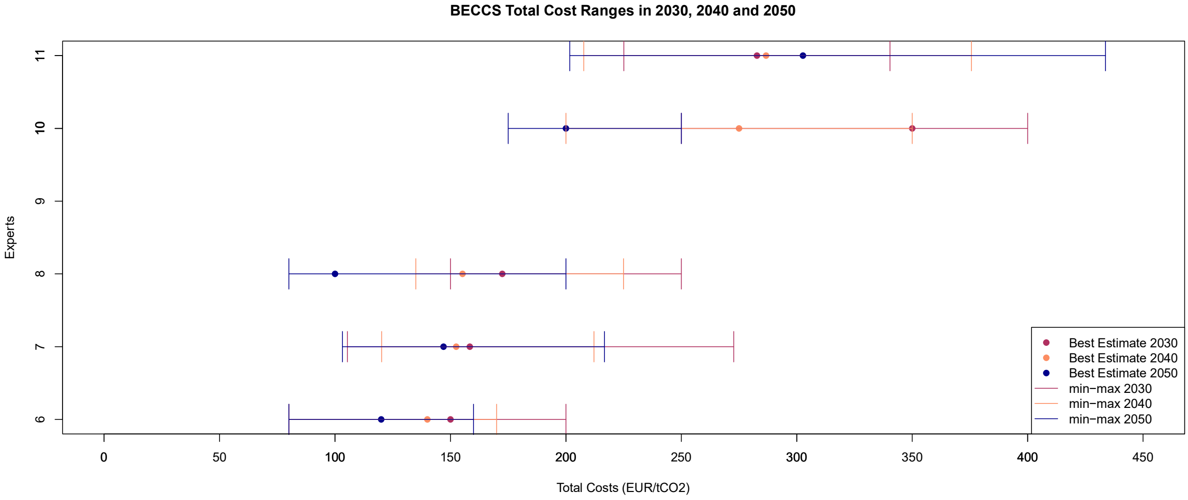


Figure 12: BECCS total cost range and best estimate evolution of 5 selected experts in 2030, 2040 and 2050.

For four of the five experts, the cost ranges shift towards lower costs over the years. Expert 6 believes that the minimum achievable costs stay constant over the years. This expert stated that the pulp and paper industry would use BECCS in the first portion of the deployment and that the energy sector would integrate them only later. The costs would be higher in the beginning due to the smaller scale of the plants but this expert trusts that larger plants will drive the costs down. Expert 7* sees first an increase in the minimum costs and later a decrease. The initial increase in minimum costs is due to an increase of capex between 2030 and 2040. As mentioned previously, an increase in costs is not unlikely for a new technology. The increase in maximum costs between 2040 and 2050 is caused by a reduction in energy revenues that is higher than the combined decrease of capex and TSM costs for the same period. Expert 8 sees a constant decrease in BECCS costs despite the forecasted increase in feedstock costs which are linked to needing both forestry and adapted crops. Expert 10 doesn’t believe there will be much deployment between now and 2030. According to this expert, most of the cost reductions will be in the capex and to a lesser extend in the feedstock costs. Additionally, it is interesting that both experts 6 and 10 which have the smallest and largest ranges, show increasing confidence over time. This behaviour is at odd with the common assumption that future values are more uncertain.

Finally, expert 11* shows a min-max range that shifts towards higher costs, and which becomes wider over the years. As mentioned before, this increase in costs is largely due to increasing feedstock costs which despite increasing energy revenues and decreasing TSM costs, leads to an overall increase of the costs. The expert stated that these dynamics happen simultaneously, which causes the min-max range and uncertainty to increase over time.

Table 8: BECCS costs min-max ranges of selected experts for 2030, 2040 and 2050. A star indicates experts that provided a breakdown of the costs.

BECCS Total Costs Min-Max Range (€/tCO_2)	**Min** (Expert 6)	**Min + 1** (Expert 7*)	**Median** (Expert 8)	**Max -1** (Expert 11*)	**Max** (Expert 10)
2030	80 – 200	105 – 273	150 – 250	225 – 340	250 – 400
2040	80 – 170	120 – 212	135 – 225	208 – 375	200 – 350
2050	80 – 160	103 – 217	80 – 200	202 – 434	175 – 250

Table 9 portrays the uncertainty evolution of BECCS costs by showing the average min-max ranges for the total costs and the cost breakdown items. Again, a wider span indicates less expert agreement on the costs and a positive percentage change indicates increasing uncertainty for that cost item.

Table 9: BECCS min-max range width average across experts in €/tCO2. The percentage change for each decade is provided in parenthesis.

BECCS min-max average width (€/ton CO_2)	*Total Costs (9 experts)*	*Breakdown Costs (6 experts)*	*Capex*	*Opex*	*Feedstock*	*Revenues*	*TSM*
2030	111.52	96.27	65.16	13.59	41.04	-56.03	32.51
2040	133.42 (+20%)	134.10 (+39%)	73.42 (+12%)	17.54 (+29%)	57.04 (+39%)	-66.16 (+18%)	52.26 (+60%)
2050	143.35 (+7.4%)	154.31 (+15%)	85.42 (+16%)	19.43 (+11%)	82.22 (+44%)	-89.28 (+35%)	56.52 (+8.2%)

For BECCS, the total cost intervals are on average larger than the ones from those who offered the breakdown costs. This shows again, a higher agreement for experts providing a costs breakdown. Contrary to DACCS, the percentage changes of both total costs for BECCS are positive. This indicates that most BECCS experts experience less confidence than DACCS experts in the total costs. The increasing ranges for the total cost of breakdown show that on average experts get less confident of their answers over the decades. This increasing uncertainty reflects what one expects in general from technology estimates but in the case of BECCS could also reflect the case-by-case deployment of the technology, and hence the high intrinsic uncertainty.

There is not only a clear increase in uncertainty for TSM costs but also a significant difference between these costs for DACCS and BECCS respondents. These differences may reflect the fact that DACCS plants are newbuilds which can be located right next to a storage site, reducing the transport distance and total infrastructure investment needed whereas BECCS plants are less modular and must be fully integrated within the existing energy system. This could lead to longer transport routes to the storage sites and higher costs. Most experts stated that this supporting infrastructure is crucial, and its development will greatly depend on government and consortium's willingness to invest. Experts also believe that a large part of this investment will happen between 2030 and 2040. Any differences between BECCS and DACCS TSM costs may also reflect the composition of the experts recruited for each technology nd the small sample size for BECCS.

To summarize BECCS costs uncertainty, experts tend to be less confident than for DACCS. They believe that future costs depend on many different parameters and that overall, the uncertainty of BECCS costs should grow in the future. Finally, the cost breakdown leads to more optimistic cost ranges than the total costs. In some extreme minimum cases, experts place the cost of BECCS below EUR 100/tCO_2.

5. 1. 1. 3 Costs Uncertainty Discussion

In the previous section the uncertainty surrounding DACCS and BECCS costs was discussed. Notable learnings are that for DACCS, high costs lead to higher uncertainty and a higher rate of change over time. For BECCS it was seen that those offering a cost breakdown provide more optimistic ranges than those who only offered total cost estimates. Then, the two technologies show that on average those providing a cost breakdown also offer narrower ranges.

Finally, the total costs for DACCS might indicate a degree of overconfidence bias with ranges getting narrower over time while this effect disappears in the cost breakdown. For BECCS, there is no clear overconfidence bias. This can be explained by the difference in complexity of the two technologies. DACCS technology is still undergoing significant development and various novel processes are under consideration and could emerge over time. The form the technology might have in 10 years could differ widely from current practices. For this reason, grasping the full complexity of the technology in just the total cost metric can prove to be difficult. To conclude Hypothesis (H1) is partly disproved as uncertainty increases for both BECCS costs metrics and for the DACCS breakdown costs but not the DACCS total costs.

5. 1. 2 Cost Best Estimates

In the following section, the best estimates for DACCS and BECCS total costs in 2030, 2040 and 2050 are presented. Figure 13 shows the best estimate of all experts for DACCS and BECCS in 2030, 2040 and 2050. It is apparent that DACCS shows a far higher variation of costs between experts compared to BECCS. DACCS spans over two orders of magnitude while BECCS stays within the same order of magnitude.

DACCS expert 10 is the only expert for either technology stating that costs will slightly increase. As mentioned before this expert's reason behind this is the belief that the technology cannot achieve any lower minimum costs. For BECCS, results for experts 2 and 11 show interesting cost behaviours. They believe that the costs will increase between 2030 and 2040 and stay constant or respectively increase by 2050. The reason for this is the existing gap between first cost-effective projects and the later more expensive projects.

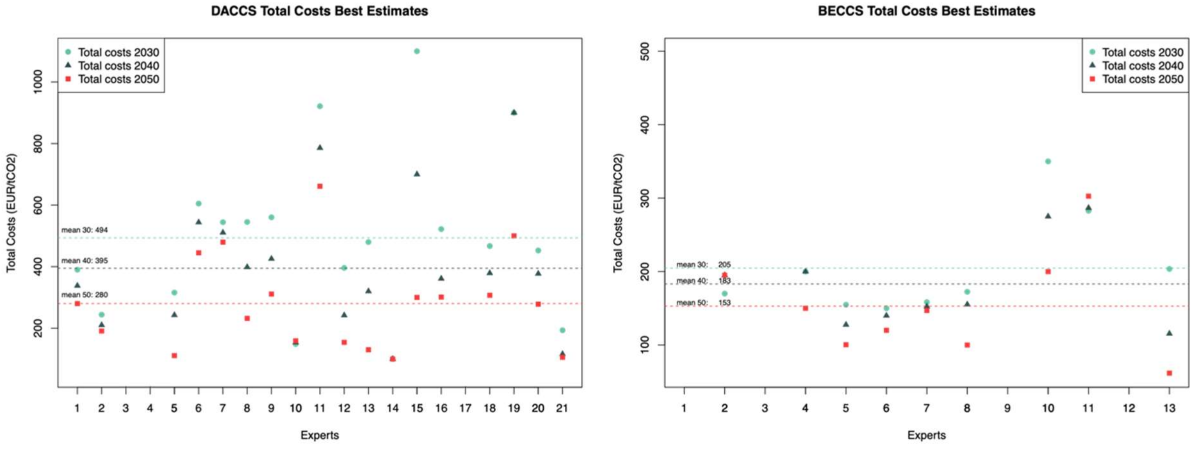


Figure 13: DACCS and BECCS total cost estimates by experts in 2030, 2040 and 2050.

The cost breakdown graphs for DACCS and BECCS can be found in the Appendix. It is apparent that the revenue obtained from the sale of power makes BECCS technology has a large impact on BECCS costs. The breakdown also shows that even without the revenue streams BECCS technology would still be cheaper than DACCS.

It is notable that BECCS has significantly lower opex costs than DACCS because of the energy consumption of DACCS (versus the energy production of BECCS).

Table 10 shows the average of the best estimates. BECCS results show that, on average, experts expect a higher starting cost in 2030 than the 2020 reference cost and a gradual cost reduction thereafter in the following decades. DACCS results show, on average, a steeper decrease in costs in the coming decades than BECCS. Despite the narrowing between the two costs, in 2050, the cost of DACCS is 83% higher than the cost of BECCS.

Table 10: Average DACCS and BECCS total costs and the decadal learning rate.

Total Costs (€/tCO_2)	*DACCS*	*Learning Rate*	*BECCS*	*Learning Rate*
2020 (ref)	581		172	
2030	494	-15%	205	+19%
2040	395	-22%	183	-11%
2050	280	-27% (-52% from 2020)	153	-16% (-11% from 2020)

Summarizing the DACCS findings, experts believe that costs will come down for several reasons. First, economies of scale, process optimization, including the development of more efficient and less costly sorbents, will bring fabrication costs down. Finally, the ability to use renewable energy, where costs are also falling, could significantly reduce the energy costs of the technology.

Summarizing the BECCS findings, the costs do come down, but not as steeply as for DACCS. Some experts firmly believe that costs of BECCS will increase in the coming decades due to increasing running costs of up- and down-stream operations. BECCS is currently the far cheaper technology of the two, but deployment at large scale will require significant investments and international coordination in the down-stream transport, storage, and monitoring infrastructure as well as for upstream sourcing and transport of biomass and additional investments to distribute any biomass energy that is generated. While the former costs would also be incurred for DACCS at scale, the potential for location-independent sourcing of CO2 means that capture facilities can be located near renewable energy sources, thereby avoiding costly infrastructural and regulatory challenges that are associated with transporting biomass for powering BECCS.

5. 1. 2. 1 Costs Best Estimates Discussion

To summarize, the nominal difference between DACCS and BECCS costs can be explained by differences in both technology and perceptions. DACCS is a more novel technology which can still undergo significant improvements. This is especially visible in the decreasing operational costs. Experts believe in the potential for sorbent improvements and novel materials. BECCS, on the other hand, uses common industrial processes, with lower current costs but also limited room for improvement. These results confirm hypothesis (H2) as the learning rate between 2020 and 2050 is higher for DACCS than for BECCS.

Interestingly, both technologies are highly dependent on the energy markets. For DACCS, energy represents about a third of its total costs and experts hope that an expanding role for renewables into the energy grid will lower costs. For BECCS, as an energy producer, the market price of feedstocks and energy influences more broadly the revenue levels of the plant. BECCS power production, however, could be a strategic advantage for the technology in the future. By providing base load power, BECCS can help stabilize a volatile green energy grid.

To conclude on total costs, it is interesting to benchmark NETs costs against other costs. For example, it can be compared to the price of a barrel of crude oil, standing at EUR 97 in October 2022. [88] For BECCS, three of twelve experts believe that BECCS costs will be at or below EUR 100 by 2050. For DACCS, seven out of eighteen experts believe that the costs of DACCS will be below EUR 200 in 2050 and only one of them places the costs at EUR 100. This again shows that DACCS is expected to remain a relatively costly technology. Improving the current processes or subsidizing the technology will require heavy investments, large subsidies, or technological breakthroughs.

5. 2 Potential Scale Results

5. 2. 1 Potential Scale Uncertainty

In this section, the potential for scaling up DACCS and BECCS technologies under two policy scenarios is discussed. The IEA's Stated Policies Scenario (STEPS) is a scenario where only existing or proposed policies are in place, while the NZE describes the scenario whereby the global energy sector reaches net-zero emissions by 2050. For this part of the elicitation, we describe stylized versions of these two scenarios and experts were asked what role DACCS and BECCS could play in those scenarios. They were also free to assume technologies other than those specified in the previous stage of the elicitation.

5. 2. 1. 1 DACCS Potential Scale Uncertainty

Figure 14 shows the obtained DACCS potential scale trajectories of all experts for 2030, 2040 and 2050. The graphs on the left show the responses under the STEPS policy scenario and the ones on the right show those under the NZE policy scenario. Of the 21 interviewed DACCS experts, experts 4 and 13 provided only partial answers on potential scale. Expert 4 gave a potential scale of 0 under STEPS in all years and did not provide a scale under NZE. Expert 13 only provided a min-max range for STEPS in 2030 but no other estimates. Further, the min-max range of expert 5 is very narrow, and the logarithmic scale makes it disappear.

Looking at the ranges provided by the experts it is apparent that the two scenarios lead to different behaviours. In STEPS 2030, four experts believe that the minimum scale is zero, two of those experts still believe this is the case in 2040 and 2050. Under NZE 2030, two of the same experts believe the minimum scale is 0 and only one of them believes that for 2040 and 2050. Overall, there is a clear increase in the potential scale under NZE, as the ranges shift to the right. Looking at STEPS and NZE range evolution over time, there is clear majority of experts increasing their ranges. In STEPS expert 2 decreased its range and experts 14 and 15 kept it unchanged. In NZE all experts increased their ranges over time. On average the ranges are narrower for STEPS than for NZE. This could indicate that experts tend to agree more on potential scale under STEPS than NZE. This could be due to most experts agreeing that under STEPS only voluntary market forces are at play, limiting the possible scale attained. Additionally, the NZE scenario is less familiar as it requires more stringent measures than the STEPS scenario.

Within experts there is a lot of agreement that future deployment in STEPS depends on early plants and on how long consumers can pressure companies to compensate for their emissions as is currently the trend. Experts explained that the success of 2030 plants under STEPS will directly influence the influx of capital from investors for the realization of large-scale projects in 2040 and 2050. Additionally, experts believe that until 2030 companies will be willing to invest large sums in the technology as it supports their decarbonization strategies. However, beyond that point market forces alone will not allow the deployment of technology at large scale unless governments impose or help subsidize the technologies. Finally, under NZE the potential deployment scale heavily depends on the types of policies deployed and their rightful implementation, but experts expressed doubts around the plausibility of reaching the scale needed for NZE.

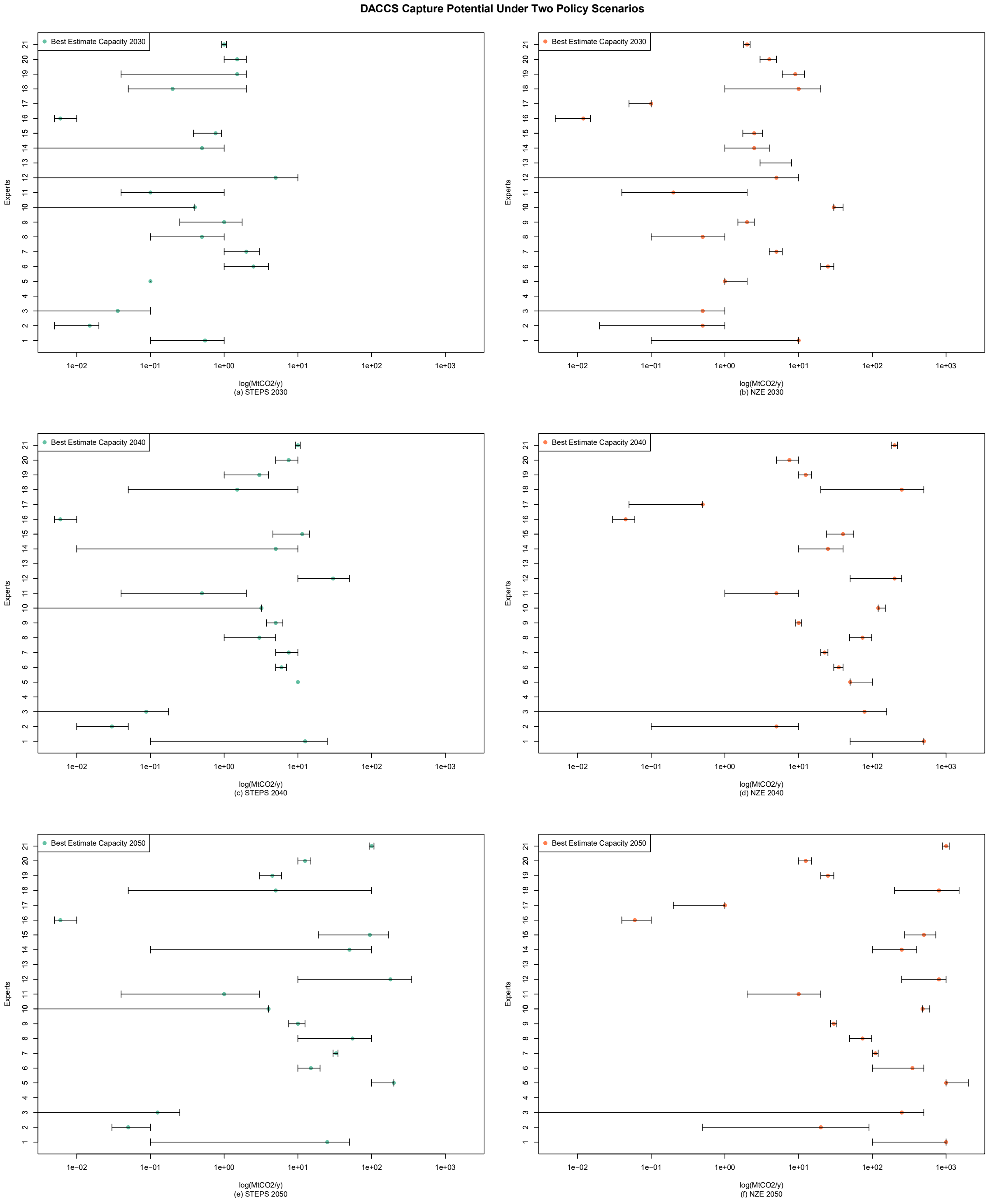


Figure 14: DACCS potential scale under two policy scenarios in 2030, 2040 and 2050. Estimates with minimum, maximum, and best estimate of each expert in log(MtCO$_2$) captured per year. Left graphs are the STEPS scenario, right graphs are the NZE scenario.

As for the costs, the trajectories of selected experts are followed over time. As two different policy scenarios were used during the elicitations, five experts were selected once based on of their STEPS

2030 best estimates (v1) and a second time based on their NZE 2030 best estimates (v2). Table 11 shows the obtained best estimates that span across the STEPS 2030 results and Figure 15 shows the trajectories of the best estimates and min-max ranges.

Table 11: DACCS potential scale best estimates of selected experts (v1) under STEPS and NZE policy scenarios in 2030, 2040 and 2050. The experts were selected based on their STEPS 2030 best estimate (bold).

DACCS Best Estimate	*Expert 4 (Min)*		*Expert 17 (Min + 1)*		*Expert 14 (Median)*		*Expert 6 (Max – 1)*		*Expert 12 (Max)*	
MtCO$_2$/year	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**
2030	**0**	NA	**0**	0.1	**0.5**	2.5	**2.5**	25	**5**	5
2040	0	NA	0	0.5	5	25	6	35	30	200
2050	0	NA	0	1	50	250	15	350	180	800

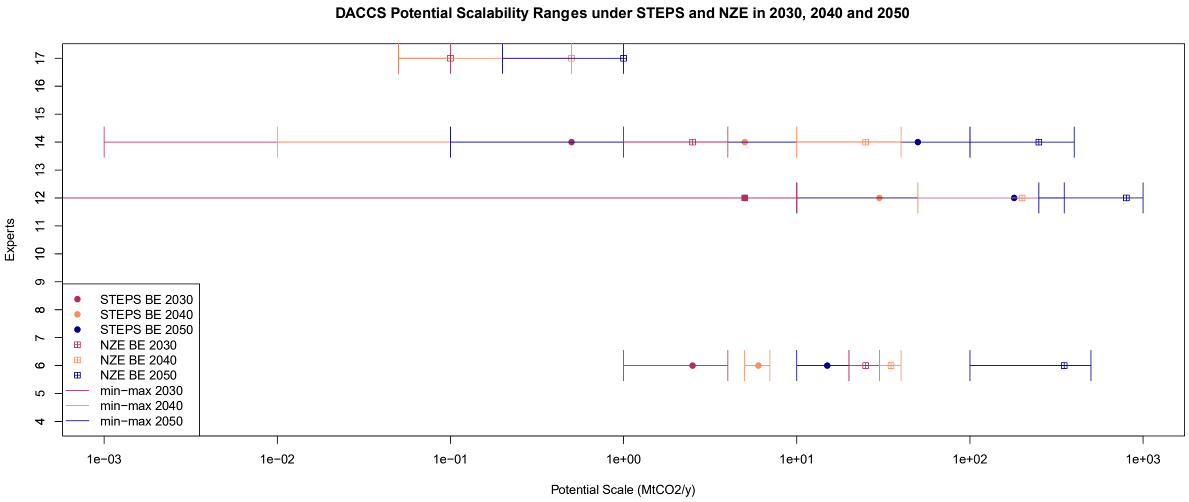


Figure 15: DACCS potential scale trajectories of selected experts (v1) using the scale best estimate under STEPS in 2030.

Table 12 shows the trajectories of the selected experts. The experts giving the smallest values are experts 4 and 17. These experts believe that the maximum scale obtained under STEPS is 0 Mt CO$_2$ captured per year. This shows that there is a non-negligible probability for the development of DACCS to not go past the pilot scale. Expert 17 stated that under STEPS there would be no market unless the CO$_2$ is used downstream and that for under NZE leads to some deployment because it is completely policy driven.

Table 12: DACCS potential scale trajectories of selected experts (v1) under STEPS and NZE policy scenarios in 2030, 2040 and 2050.

DACCS Min-Max Range	*Expert 4 (Min)*		*Expert 17 (Min + 1)*		*Expert 14 (Median)*		*Expert 6 (Max – 1)*		*Expert 12 (Max)*	
MtCO$_2$/year	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**
2030	0–0	NA	0–0	0.05–0.1	0.001–1	1–4	1–4	20–30	0–10	0–10
2040	0–0	NA	0–0	0.05–0.5	0.01–10	10–40	5–7	30–40	10–50	50-250
2050	0–0	NA	0–0	0.2–1	0.1–100	100–400	10–20	100–500	10–350	250-1000

There is a clear trend in the expert trajectories that NZE leads to a larger deployment scale. Experts 6 and 17 have no overlap between their STEPS and NZE scale, while experts 12 and 14 have NZE ranges that overlap with STEPS ranges. These experts mentioned that the deployment in 2040 depends greatly on the success of the plants in 2030 and that CO_2 capture should be scaled like municipal waste management.

Finally, looking at the most optimistic experts, expert 12 believes that STEPS leads to less than 0.5 Gt of CO_2 removed annually at best. According to this expert, NZE would at best lead to a 1 Gt scale. Similarly, all other experts but expert 4 show a clear increase in scale between STEPS and NZE in 2050. This shows the impact that these experts believe policies can have on the later deployment of DACCS in Europe.

Table 13 shows the selected experts which span the obtained results under NZE in 2030. Figure 16 and Table 14 show the trajectories of these experts over time under STEPS and NZE policy scenarios.

Table 13: DACCS potential scale best estimates of selected experts (v2) under STEPS and NZE policy scenarios in 2030, 2040 and 2050. The experts were selected based on their NZE 2030 best estimate (bold).

DACCS Best Estimate	*Expert 16 (Min)*		*Expert 11 (Min + 1)*		*Expert 14 (Median)*		*Expert 6 (Max – 1)*		*Expert 10 (Max)*	
MtCO_2/year	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**
2030	0.006	**0.012**	0.1	**0.2**	0.5	**2.5**	2.5	**25**	0.4	**30**
2040	0.006	0.045	0.5	5	5	25	6	35	3.2	120
2050	0.006	0.06	1	10	50	250	15	350	4	480

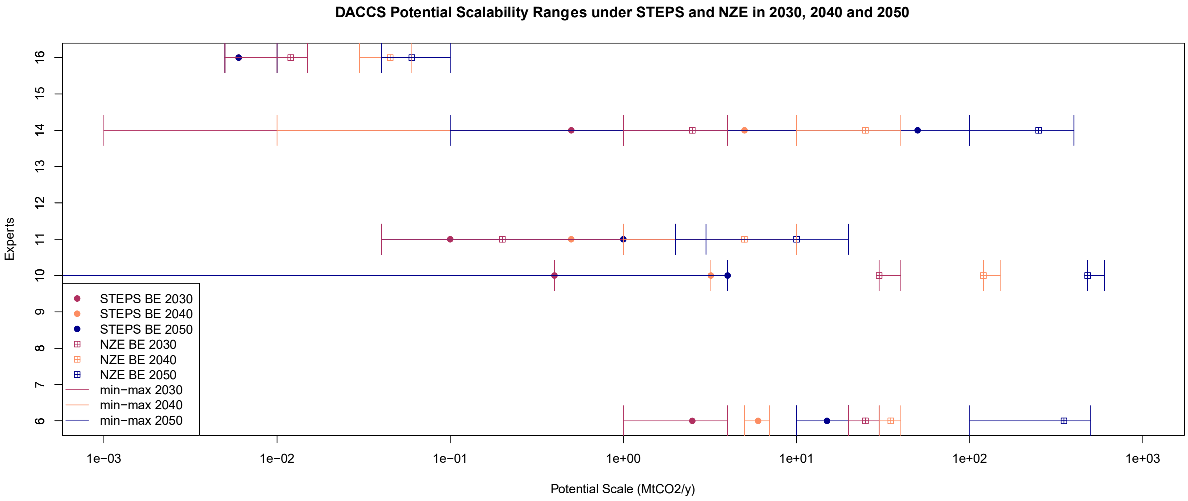


Figure 16: DACCS potential scale trajectories of selected experts (v2) using the scale best estimate under NZE in 2030.

Using the NZE 2030 best estimates leads to a different set of experts spanning the scalability results. Experts 16 and 11 both have the smallest NZE 2030 best estimates. These two experts however show a different range behaviour. Expert 16 has a constant STEPS range and under NZE leads to a maximum deployment scale of 0.1Mt CO_2 captured per year. Expert 11 on the other hand leads to up to 20Mt CO_2 captured per year under NZE in 2050.

The most optimistic expert is expert 10. One can observe that using the expert that provides the largest 2030 estimate under NZE leads to a smaller maximum deployment scale under NZE in 2050 than using the expert which provided the largest STEPS estimate in 2030. Additionally, there is a 400 Mt difference between expert 10 and 12 which is non-negligible. This shows that expert 12 which believes in some deployment under STEPS also believes in deployment close to the gigaton scale under NZE in 2050. This is again aligned with the statement that later development depends greatly on the early plants.

The second most optimistic expert is expert 6 in the first and second expert selection. For this expert the maximum deployed scale under NZE is half a gigaton of CO_2 captured per year. This expert states that deployment under STEPS depends on how much companies are willing to voluntarily invest in green technologies and that NZE requires standardized carbon accounting practices. Finally, this expert explains that the increase between 2040 and 2050 under NZE is due to lessons learned and the existence of surrounding infrastructure.

Experts 6, 10 and 17 have minimally overlapping ranges between STEPS and NZE while experts 11, 14 and 16 have strong ranges overlaps. It also appears that the largest gaps between STEPS and NZE of a given year happen towards the middle of the century. It can be seen in the table that there is often a one to three orders of magnitude jump in 2050 between the two scenarios. This can be explained by expert's belief that by that time DACCS is proven at large scale and that better and more efficient materials are utilized which leads to larger scale-up opportunities.

Table 14: DACCS potential scale trajectories of selected experts (v2) under STEPS and NZE policy scenarios in 2030, 2040 and 2050.

Expert 16 (Min)	*Expert 11 (Min + 1)*		*Expert 14 (Median)*		*Expert 6 (Max – 1)*		*Expert 10 (Max)*
NZE	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**NZE**
0.005–0.015	0.040–1	0.04–2	0.001–1	1–4	1–4	20–30	30–40
0.03–0.06	0.04–2	1–10	0.01–10	10–40	5–7	30–40	120-150

0.04–0.1	0.04–3	2–20	0.1–100	100–400	10–20	100–500	480-600

To summarize the observations of the trajectories of both batches of experts spanning the STEPS and NZE 2030 best estimates, it is apparent that all experts agree that the NZE policies would lead to an increase of deployment. Additionally, of the selected experts, enabling policies seem to have the strongest increase in the deployment of DACCS between 2030 and 2040. Hence it could be said that policies are necessary to ensure the deployment of a base capacity in Europe between now and 2040.

Looking now into the uncertainty in the future potential scale of DACCS in Europe, Table 15 shows the average width of the min-max ranges under STEPS and NZE. The average STEPS range width is narrower than the NZE range width. STEPS ranges as seen previously, are narrower and overlap more within experts than NZE ranges. Finally, the increase of uncertainty is particularly observable with the high percentage change between 2030 and 2040 under NZE. This supports that expert's uncertainty increases between the STEPS and the NZE scenario. This behaviour could be explained by the fact that NZE is a scenario that is far more ambitious, hence its implications are less well understood.

Table 15: Average width of DACCS potential scale min-max intervals in 2030, 2040 and 2050 under STEPS and NZE scenarios. Figures are in MtCO$_2$ per year.

Average width of DACCS Min-Max Ranges (MtCO$_2$/y)	*STEPS*	*NZE*
2030	1.32	4.29
2040	6.15 (+366%)	82.31 (+1819%)
2050	49.06 (+698%)	322.02 (+291%)

To summarize, DACCS potential scale uncertainty results show the following trends. First, there is a clear indication of the perceived probability of failure of DACCS in Europe. Some minimum worst-case scenarios lead to a capture capacity of 0 Mt CO$_2$ per year. The development of DACCS plants seems to depend highly on the success of the early plants. Ensuring the correct deployment in the coming years could prove to be an enabling factor to create the necessary capture base, learning opportunities and secure the trust of investors. Second, policies supporting the deployment of negative emission technologies have a clear impact on the development of DACCS at scale. There is a sharp increase in the minimum and maximum scale obtained in NZE compared to STEPS. Finally, uncertainty clearly increases over time, especially under NZE scenario, as it is intrinsically less well understood than STEPS.

5. 2. 1. 2 BECCS Potential Scale Uncertainty

Figure 17 shows expert uncertainty ranges for BECCS deployment in Europe in 2030, 2040 and 2050. The graphs on the left show the ranges under the STEPS policy scenario and the ones on the right show the ranges under the NZE policy scenario. Of the 13 interviewed BECCS experts, experts 12 and 13 did not answer the potential scale questions and expert 3 only provided the best estimates.

Figure 17 shows that the NZE scenario leads to higher deployment scale in all three decades than the STEPS scenario. Compared to DACCS, BECCS ranges are narrower and overlapping, and there is no clear outlier in the results. All min-max ranges increase or stay constant for STEPS and NZE as shown in Figure 17 or with the increasing average widths in Table 20.

For STEPS, some experts stated that only the UK and Scandinavian countries would operate BECCS plants. One expert believes that only the currently developed projects of DRAX and Stockholm Exergi would be operational. Scandinavia is an ideal choice to develop the plants due to the large amount of waste that can be used from forest residues and the pulp and paper industry. Sweden is predicted to assume about one third of European BECCS as the country has existing policies encouraging the deployment of the technology (but this can also be influenced by the overrepresentation of Scandinavian experts in our sample). Finally, strong opinions were expressed on the uniqueness of each BECCS project. Experts stated that as BECCS is a case-by-case scenario there is no one-size-fits all deployment strategy. Because of this, experts assume that NZE targets will be missed. This shows the need for other negative emission technologies that can undergo a more coherent large-scale deployment.

The trajectories of two different expert batches are shown below. These trajectories help understand the specific evolution of expert ranges that span throughout the obtained result range. Table 16 shows the best estimates of the experts selected based on their span of the STEPS 2030 best estimates. Figure 18 shows the trajectories of these selected experts. Expert 3 provided only the best estimate and no min-max ranges.

Table 16: BECCS potential scale best estimates of selected experts (v1) under STEPS and NZE policy scenarios in 2030, 2040 and 2050. The experts were selected based on their STEPS 2030 best estimate (bold).

BECCS Best Estimate	*Expert 5 (Min)*		*Expert 9 (Min + 1)*		*Expert 7 (Median)*		*Expert 3 (Max – 1)*		*Expert 4 (Max)*	
MtCO$_2$/year	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**
2030	**0.1**	35	**0.8**	11	**2**	5	**8.8**	10	**33**	33
2040	0.3	93	0.8	40	10	75	8.8	155	66	66
2050	15	150	0.8	178	75	150	8.8	300	132	132

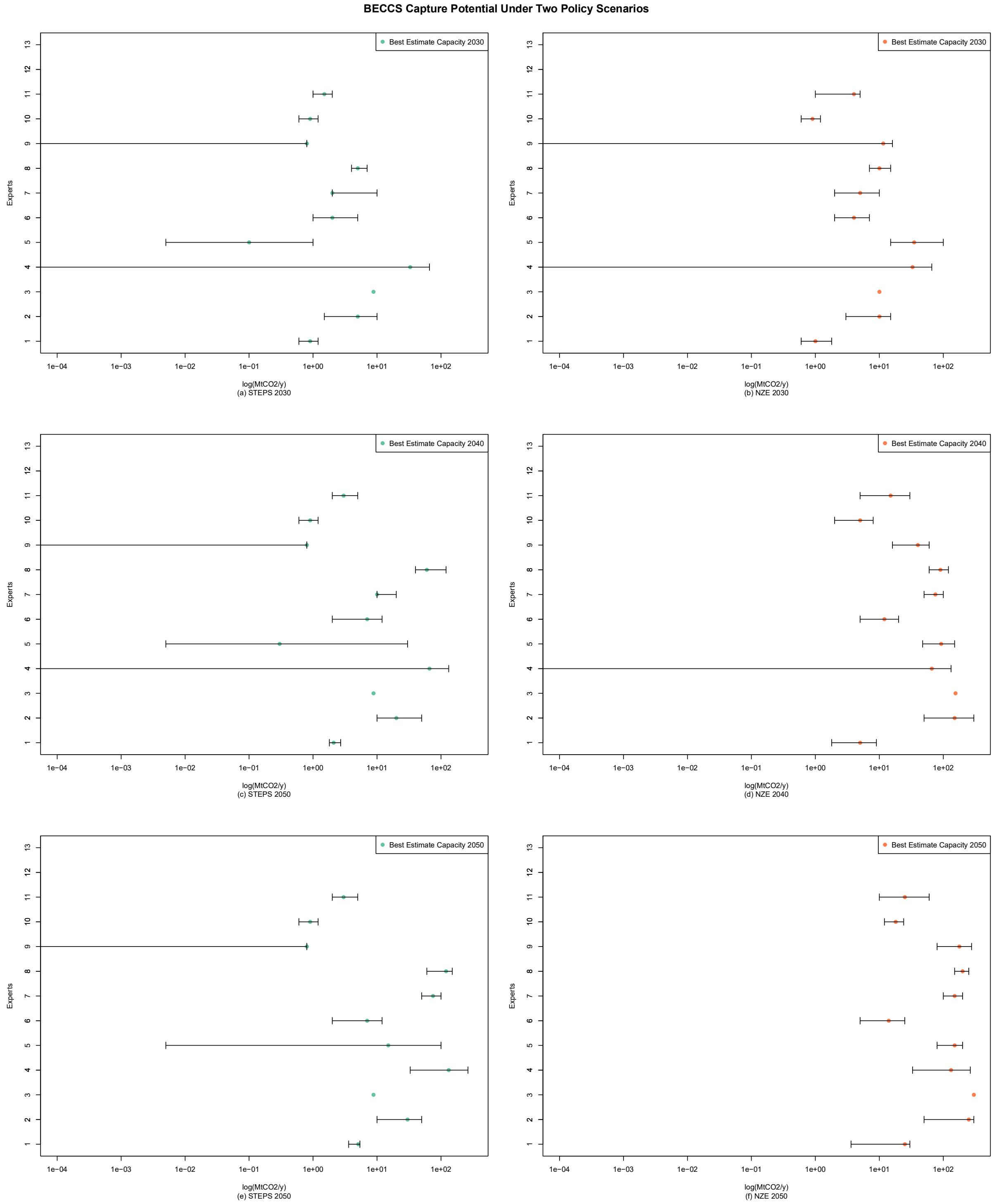


Figure 17: BECCS potential scale under two policy scenarios in 2030, 2040 and 2050. Estimates with minimum, maximum, and best estimate of each expert in log(MtCO$_2$) captured per year. Left graphs are the STEPS scenario, right graphs are the NZE scenario.

From the graph and Table 17 which shows the min-max ranges of the selected experts it is apparent that compared to DACCS the BECCS ranges vary less between experts. Experts 4 and 9 believe that in the worst-case the BECCS capture capacity in Europe will be 0. Both these experts provide very wide ranges under for 2030 and 2040 and show a high confidence in narrow min-max range for 2050 under both scenarios. We argue that the increase in confidence could be due to these experts' belief that BECCS is necessary to help decarbonize hard to abate industries such as steel and cement. Additionally, according to these experts the interest in BECCS is dependent on feedstock availability and the need for BECCS to provide base-load power as the share of renewables increases in the energy grid.

Table 17: BECCS potential scale trajectories of selected experts (v1) under STEPS and NZE policy scenarios in 2030, 2040 and 2050.

BECCS Min-Max Range	*Expert 5 (Min)*		*Expert 9 (Min + 1)*		*Expert 7 (Median)*		*Expert 3 (Max – 1)*		*Expert 4 (Max)*	
$MtCO_2$/year	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**
2030	0.005–1	15–100	0–0.8	0–16	2–10	2–10	NA	NA	0–66	0–66
2040	0.005–30	48–150	0–0.8	16–60	10–20	50–100	NA	NA	0–132	0–132
2050	0.005–100	80–200	0–0.8	80–276	50–100	100–200	NA	NA	33–264	33–264

Experts 5 and 7 show similar NZE ranges despite different STEPS starting points. Under STEPS expert 5 believes that infrastructure delays can greatly influence the deployment of the technology while the higher STEPS ranges from expert 7 stem from the belief that there will be two large functioning BECCS plants in Europe by 2030. Under NZE expert 7 believes that BECCS deployment is driven by the need to capture emissions from hard-to-abate industries.

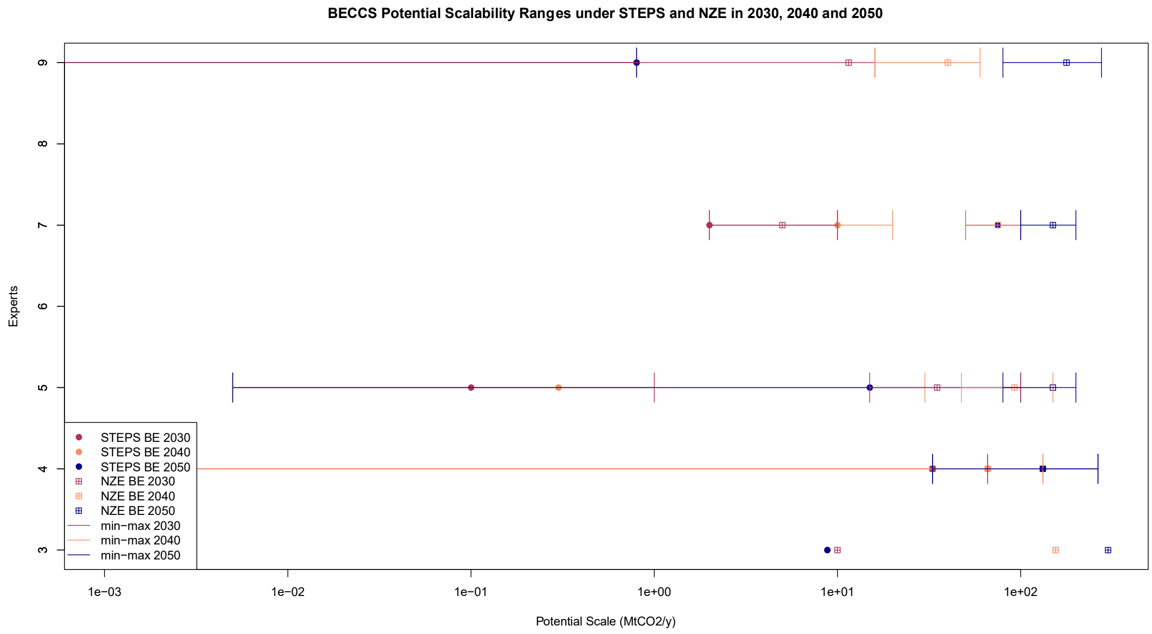


Figure 18: BECCS potential scale trajectories of selected experts (v1) using the scale best estimate under STEPS in 2030.

Like for DACCS potential scale, a second batch of experts is analysed. These are selected based on the 2030 best estimates under the NZE scenario. Table 18 shows these best estimates, and Figure 19 and Table 19 show the trajectory of the min-max ranges over the years.

From the second batch of experts, expert 10 and expert 5, despite spanning opposite sides of the range, agree that infrastructure and logistics are an important aspect to regard in NZE deployment. Expert 1 states that the NZE scenario is far from attainable in Europe and that as each individual BECCS plant is different, larger plants are favoured for cost reasons. Compared to the minimum and second minimum of the previous batch of experts, the deployment scale of expert 10 and 1 is much more limited, not going over the 30 Mt CO_2 captured in the best-case. This could indicate that infrastructure and the difficulty to scale the capacity by building a lot of smaller plants is limiting to BECCS deployment.

Table 18: BECCS potential scale best estimates of selected experts (v2) under STEPS and NZE policy scenarios in 2030, 2040 and 2050. The experts were selected based on their NZE 2030 best estimate (bold).

BECCS Best Estimate	*Expert 10 (Min)*		*Expert 1 (Min + 1)*		*Expert 8 (Median)*		*Expert 4 (Max – 1)*		*Expert 5 (Max)*	
MtCO₂/year	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**
2030	0.9	**0.9**	0.9	**1**	5	**10**	33	**33**	0.1	**35**
2040	0.9	5	2.1	5	60	90	66	66	0.3	92
2050	0.9	18	5.1	25	120	200	132	132	15	150

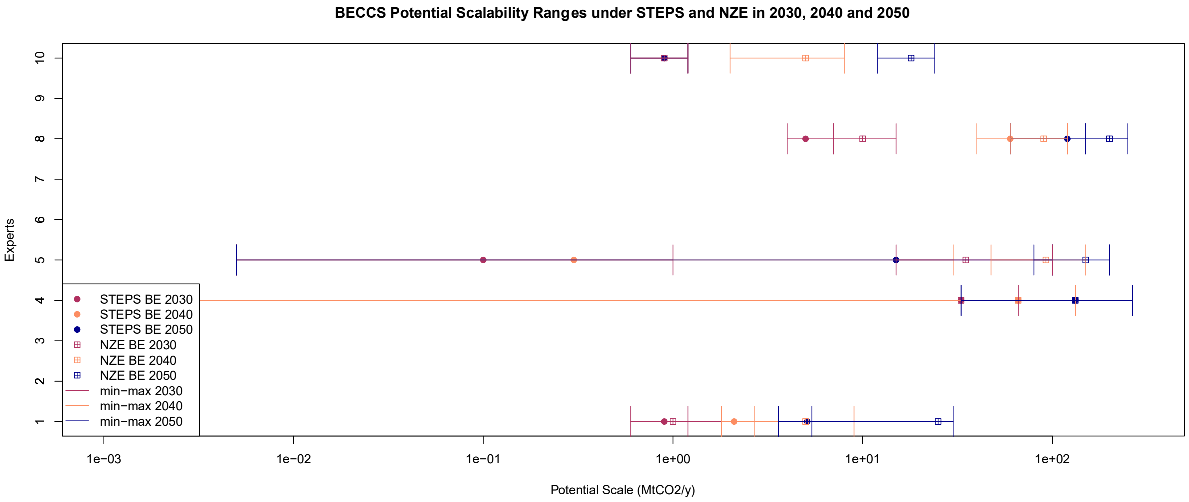


Figure 19: BECCS potential scale trajectories of selected experts (v2) using the scale best estimate under NZE in 2030.

Then, expert 8 believes that next to Scandinavia and the UK where 50% of the deployment will be made, Germany, Poland and Baltic countries could make interesting BECCS cases by retrofitting a lot of their hard-to-abate industries.

Table 19: BECCS potential scale trajectories of selected experts for IEA STEPS and NZE policy scenarios in 2030, 2040 and 2050.

BECCS Min-Max Range	*Expert 10 (Min)*		*Expert 1 (Min + 1)*		*Expert 8 (Median)*		*Expert 4 (Max – 1)*		*Expert 5 (Max)*	
MtCO₂/year	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**	**STEPS**	**NZE**
2030	0.6–1.2	0.6-1.2	0.6–1.2	0.6–1.8	4–7	7-15	0-66	0-66	0.005–1	15–100
2040	0.6–1.2	2-8	1.8–1.2	1.8–9	40–120	60-120	0–132	0-132	0.005–30	48–150
2050	0.6–1.2	12-24	3.6–1.2	3.6–30	60–150	150-250	33–264	33-264	0.005–100	80–200

Summarizing the insights from both batches of experts it is interesting that under STEPS the minimum scale can be 0 Mt CO_2 per year while often is larger than naught under NZE. BECCS is estimated to show maximum capture capacities of ~0.3Gt CO_2 annually under both STEPS and NZE and it is visible that the maximum scale stagnates from 2040 to 2050. This shows that despite the NZE scenario enabling faster and larger BECCS deployment, the impact of policies is expected to be much more limited for BECCS than it is for DACCS.

Looking into uncertainty, Table 20 shows the average widths of the min-max intervals under STEPS and NZE for BECCS deployment. The ranges clearly increase between the years and from STEPS to NZE. This could indicate that experts are not subject to overconfidence bias and that NZE is intrinsically less certain than STEPS. To conclude, experts also mentioned that there is a need for a coherent transport and storage infrastructure being developed around BECCS plants. This can further increase the expected variability in future BECCS capture scale.

Table 20: Average width of BECCS potential scale min-max intervals in 2030, 2040 and 2050 under STEPS and NZE scenarios. Figures are in $MtCO_2/y$.

Average width of BECCS Min-Max Ranges ($MtCO_2/y$)	*STEPS*	*NZE*
2030	9.36	20.59
2040	30.74 (+228%)	69.18 (+236%)
2050	52.74 (+71%)	110.56 (+60%)

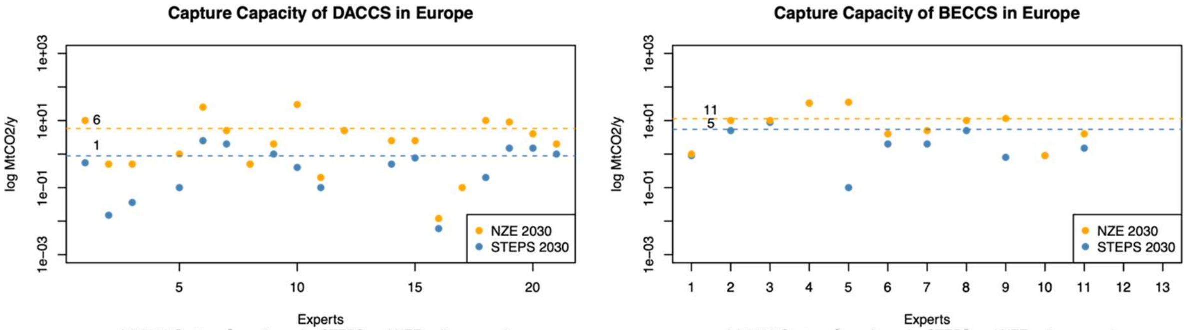
5. 2. 1. 3 Potential Scale Uncertainty Discussion

The previous sections showed the uncertainty for potential scale of DACCS and BECCS technologies in Europe under two policy scenarios. First, expert answers appear to be free of overconfidence bias both for DACCS and BECCS technologies. DACCS average widths under STEPS are clearly narrower than BECCS average widths under STEPS. This spread of possible BECCS scale could be caused by current projects still being in the pilot phase, making experts feel less certain of the potential scale. Additionally, there is a clear trend for experts to increase their uncertainty in the NZE scenario, supporting hypothesis (H3). This can be explained by the fact that this scenario includes numerous policies that are not yet deployed.

The influence of policies is positive for both technologies, confirming hypothesis (H4). BECCS shows a higher chance to develop in the minimum cases under STEPS compared to DACCS. However, the estimated maximum potential deployment scale of BECCS remains limited to around 0.3 Gt CO_2 captured per year, both under STEPS and NZE. This may be caused by BECCS being currently only piloted in Europe and the existing uncertainty surrounding the development of a coherent transport and storage infrastructure. While similar infrastructural considerations are also relevant for DACCS, the potential for location-independent sourcing of CO_2 for DACCS suggests the latter might be able to avoid some of the important upstream transport hurdles that will need to be addressed for BECCS. Additionally, the apparent preference to build one-of-a-kind large BECCS plants could also limit the scale of BECCS in the long run. Compared to DACCS the results show that BECCS may have a more limited potential scale, which reinforces the view expressed by several experts that NZE goals cannot be reached with a single technology alone. This calls for the deployment of an array of negative emission technologies that can undergo large-scale deployment.

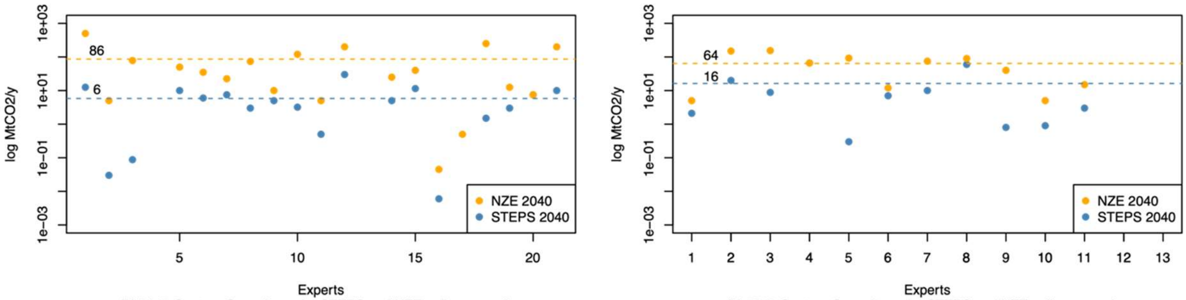
5. 2. 2 Potential Scale Best Estimates

In this section, the obtained best estimates for the potential deployment of DACCS and BECCS technologies are discussed. Figure 20 shows that under STEPS, DACCS leads to less agreement than BECCS. For all years DACCS best estimates for STEPS are more widely spread than those of BECCS. Additionally, in 2030 BECCS deployment is expected to be on average larger than DACCS deployment. This trend is reversed in 2040 under NZE and for both scenarios in 2050. The early 2030 results for BECCS stem from the base scale provided from the assumed completion of the DRAX and Stockholm Exergi projects. DACCS technology is still under development, and it will take time before a dominant design emerges. However, predictions are that when DACCS technology is fully mature, its rollout will be rapid.



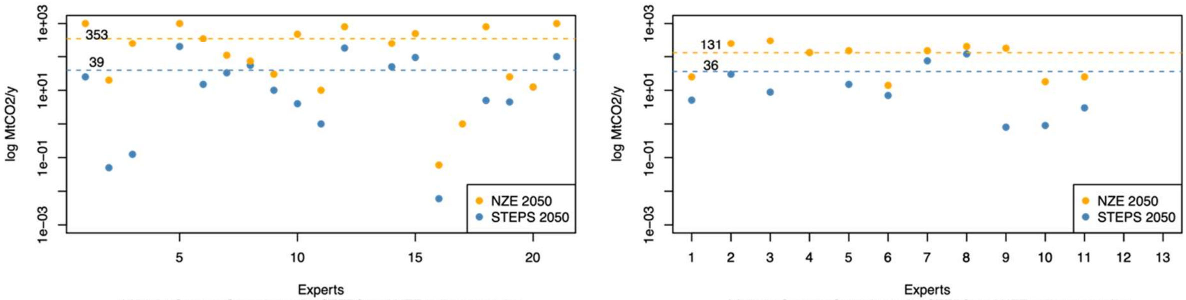
(a) 2030 Capture Capacity under STEPS and NZE policy scenarios

(a) 2030 Capture Capacity under STEPS and NZE policy scenarios



(b) 2040 Capture Capacity under STEPS and NZE policy scenarios

(b) 2040 Capture Capacity under STEPS and NZE policy scenarios



(c) 2050 Capture Capacity under STEPS and NZE policy scenarios

(c) 2050 Capture Capacity under STEPS and NZE policy scenarios

Figure 20: Potential scale best estimates for DACCS and BECCS technologies in 2030, 2040 and 2050. STEPS and NZE policy scenarios are represented. Figures are in MtCO$_2$ captured per year.

Table 21 shows the average of the best estimates for the potential scale of DACCS and BECCS in Europe under the STEPS and NZE scenarios for each year. For 2030, DACCS deploys more slowly than BECCS, before the trend reverses. For DACCS, the assumptions under STEPS scenario lead to a linear increase up to 39.5 MtCO$_2$ captured per year. The expected development under the NZE scenario however involves a very sharp increase in the 2040s, leading to up to 353Mt $_{CO2}$ captured per year. For BECCS, the NZE scenario leads to additional captu45apacitycity, but the change is not as drastic as for DACCS. Under NZE, the deployed scale the average volume of CO$_2$ capture per year is 131 Mt, not even half that of DACCS.

Table 21: Average of capacity best estimates for DACCS and BECCS technologies under STEPS and NZE in 2030, 2040 and 2050. Figures are in Mt CO$_2$ captured per year. The 10-year percentage change is given in parenthesis.

Average capacity (MtCO$_2$/y)	*DACCS*		*BECCS*	
	STEPS	*NZE*	*STEPS*	*NZE*
2030	0.88	5.78	5.46	11.31
2040	5.82 (+561%)	86.04 (+1389%)	16.27 (+198%)	64.14 (+467%)
2050	39.49 (+579%)	353.27 (+311%)	36.16 (+122%)	131.10 (+104%)

To summarize, the best estimates show that stringent climate policies are expected to lead to larger capacity deployment for both DACCS and BECCS. Enabling policies have a particularly strong effect on the deployment of DACCS, with a sharp increase in the years leading to 2040. With the ongoing research and investment in that field, experts expect that by 2040 a dominant design is adopted. This would reduce DACCS costs and combined with the modularity of the technology, would enable a quick scale-up of capacity. However, figures show that for this to happen, it is crucial to develop and implement the right policies.

5. 2. 2. 1 Potential Scale Best Estimates Discussion

The the International Energy Agency (IEA) NZE scenario assumes that 1.9 $GtCO_2$ are in annual carbon dioxide removals are needed by 2050, although . According to the IEA, by 2030, DACCS and BECCS are expected to remove 60 Mt and 227Mt CO_2 respectively. [89] By contrast, the scale of DACCS deployment estimated by experts in our elicitation for a stylized NZE scenario would not reach this capacity in 2030 but would exceed it in 2040. For BECCS, the average best estimate for 2050 across all experts represents roughly half of the IEA's 2030 capacity. This clearly shows that experts do not expect BECCS technology will be deployed at net-zero compliant scales consistent with the IEA analysis. The average expert best estimate of the combined capture capacity of DACCS and BECCS for the stylized NZE scenario leads to 484.37 Mt CO_2 being captured per year in 2050, which is only a quarter of the volume that the IEA expects and less than one fifth that used in the central case by Pozo et al [90].

For DACCS, experts strongly believe that deployment in the middle of the century depends on the success of the plants developed between now and 2030. Due to the high costs of DACCS, experts also often mentioned the need for special financing schemes. For example, it was suggested that DACCS should be treated similarly to municipal waste management and paid for by governments or tax schemes. Finally, energy usage was often discussed in the context of large-scale deployment of DACCS. Many experts believe that the bulk of DACCS development will happen towards the mid-century as the energy-grid gets decarbonized.

For BECCS many experts cited DRAX and Stockholm Exergi as the leading BECCS deployment projects in Europe. Without any further incentives, and despite the lower costs of BECCS compared to DACCS, experts do not believe that other large-scale projects could materialize in the coming years. These results negate hypothesis (H5) which supposed that low technological costs would lead to a high scalability. Under STEPS, a significant bottleneck for BECCS is the roll-out of an interconnected and efficient CO_2 transport and storage infrastructure with access to all plants, with experts believing that this policy scenario would not be conducive for the development of facilitating policies or harmonisation between developers and policymakers. Experts voiced doubts as to whether the NZE targets were achievable. However, they collectively agreed that under NZE, the correct policies and an alignment between developers and policymakers BECCS deployment can be enhanced.

To conclude, these results strongly indicate that more ambitious policy scenarios enable larger and more rapid deployment of capture capacity for both technologies, but that despite all efforts this will likely not be enough to meet the Net Zero targets. This stresses the need for a simultaneous effort coming from industries and policymakers to allow the concerted deployment of an array of negative emission technologies.

5. 3 Limiting Factors and Enabling Policies Results

In the final step of the elicitation experts were asked to rank limiting factors and enabling policies from most to least limiting and most to least enabling respectively. The scale used spans from 1-10 with 1 representing the most limiting factor and the most enabling policy. Experts were free to suggest additional factors or policies they deemed were not represented.

Figure 21 and Figure 22 show the obtained results for the limiting factors and enabling policies. Each graph shows the frequency of occurrence (i.e., the number of experts that chose to include the parameter) and the ranking (sum of attributed importance from 1-10 divided by occurrence). The lower the ranking the more limiting the factor and the more enabling the policy is perceived overall.

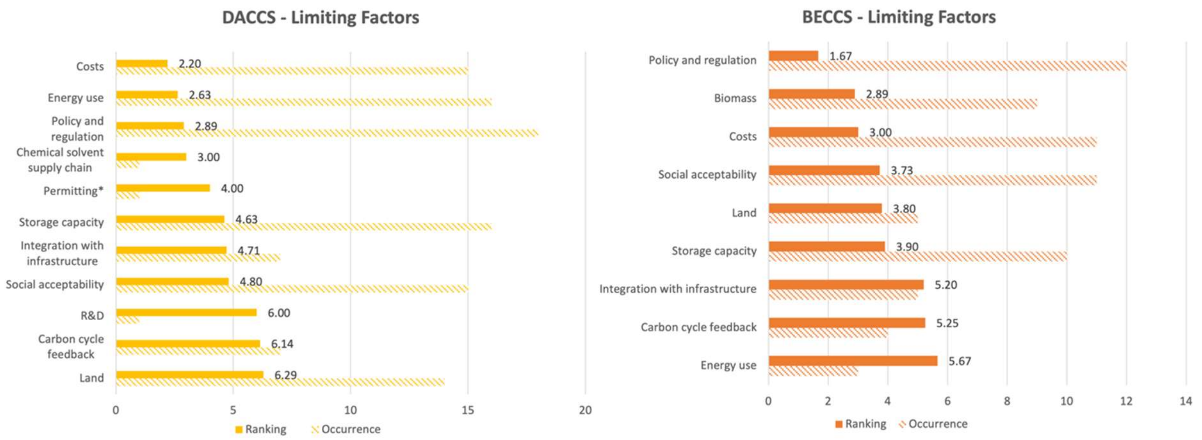


Figure 21: DACCS and BECCS limiting factors. Frequency of occurrence and ranking are given for each factor. Ranking figures indicate the most to least limiting factors from 1-10 with 1 representing the most limiting factor. An asterisk means the factor was added throughout the interviews.

For DACCS, the three most limiting factors are costs, energy use, and policy and regulations. These also correlate with the factors that were chosen the most amongst experts. Costs is a clear limiting factors as even in 2050 the technology is predicted to be on average around EUR 280/tCO_2. Then, DACCS is widely viewed as always being an energy intensive process. Thus, some experts mentioned that DACCS makes the most sense when running on a decarbonized energy grid. Finally, in third place are policies and regulations. Experts ranked them highly because improper policies and regulations or lack thereof can raise barriers for DACCS development. Chemical solvent supply chain and permitting were only cited by a few experts but those who did considered it to be a serious limiting factor.

For BECCS, the three most limiting factors are policy and regulations, biomass availability, and costs. These factors were also chosen by most respondents. Even more than for DACCS, improper policies and regulations or the lack thereof were cited as potentially leading to slower technology deployment. Biomass availability is a major concern for a lot of experts. Many assume that BECCS projects will mainly run on forest residues. However, the supply chain around this biomass feedstock is still quite uncertain and could prove to be limiting to BECCS deployment. Finally, costs, despite ‘only’ averaging EUR 153/tCO_2 in 2050, are also seen as limiting since though much lower than DACCS, many other technologies will also have made significant progress by 2050.

Additionally, storage capacity social acceptability and land were chosen by most of DACCS and BECCS experts. For DACCS, storage capacity and social acceptability are seen as moderately limiting factors and land was ranked as the least limiting factor. For BECCS social acceptability ranks higher and is followed by storage capacity and land.

For storage capacity, it was stated that there is available space to put CO_2 underground, but major developments must be undertaken and soon. Experts also mentioned that in Europe only offshore storage is possible as onshore storage is much more difficult and even forbidden in many countries. Social acceptability is ranked higher for BECCS than DACCS. Although difficult to interpret because these are different experts, one reason for this difference could be caused by BECCS plants being built near centres of energy demand whereas DACCS can be built in remote locations near access to CO_2 stores. Greater acceptance of BECCS could also be attributable to the familiarity (or tacit acceptability?) of biomass use for energy generation or a reflection that preferences for remote versus near energy demand are influenced more heavily by T&S cluster developments rather than demand and storage locations. Finally, land is seen by experts as a less limiting factor to DACCS than BECCS. Due to the ability to site DACCS anywhere (apart from the storage component) land is less of a constraint whereas BECCS plants will have land use concerns linked to feedstock production.

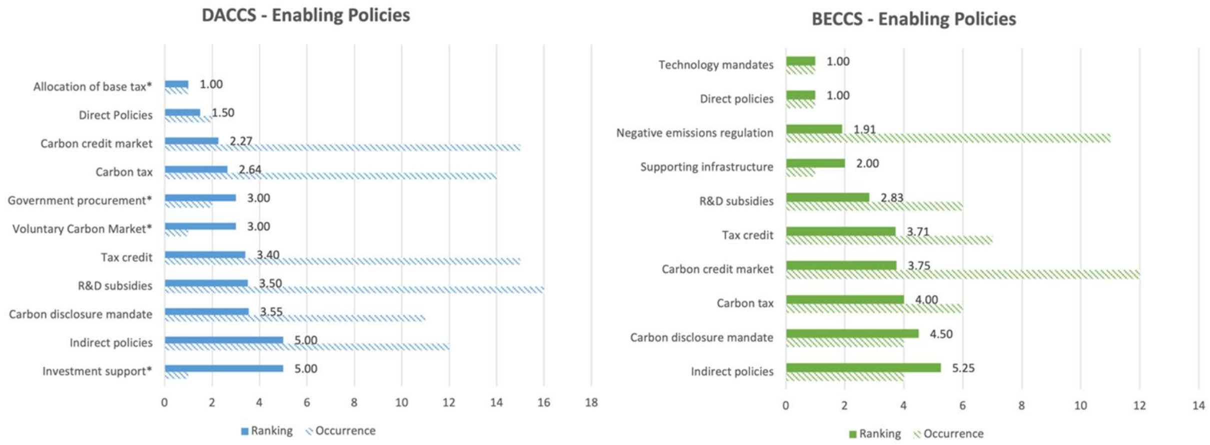


Figure 22: DACCS and BECCS enabling policies. Frequency of occurrence and ranking are given for each factor. Ranking figures indicate the most to least enabling policies from 1-10 with 1 representing the most enabling policy. An asterisk means the factor was added throughout the interviews.

Enabling policies presented in Figure 22 had the additional challenge that experts talk about similar policies under different names. Over the course of the interviews, experts added many new policies to the list. Where possible, similar policies were aggregated under the same name. As policies are an ever-changing tool, these can take different name and form depending on the geographical region or authority issuing them. For this reason, more weight is added to their frequency of occurrence rather than their ranking.

A majority of DACCS experts selected the carbon credit market and a carbon tax as very enabling policies. The carbon credit market is seen as important by experts as it will lay the foundation for a new negative emission market or will be the market where negative emissions will be traded in the future. Carbon taxes are what many experts called the “stick approach”. It abides by the polluter pays principle and its revenues can be used to subsidize NETs. Then, the allocation of base government tax to fund renewable technologies, and direct policies are ranked high but were only selected by one or two experts. In one expert’s view an allocation of base tax is necessary to the deployment of carbon capture capacity. This would allow a recurring revenue that can partly subsidize an expensive technology. In term of direct policies, these include any regulating paper that makes explicit mention of subsidizing or legally enforcing the deployment of DACCS.

Additionally, tax credits, and research and development (R&D) subsidies were chosen by a majority of DACCS experts, but their enabling impact is ranked lower. Tax credits are currently in place in the USA. Even though this is not currently considered in Europe, experts stated that it could help deploy the technology. R&D subsidies are important as DACCS technology still requires technological improvements.

For BECCS, the most voted policies are negative emissions regulation and the carbon credit market. Negative emissions regulations are seen as important for the deployment of the technology. The current state of European regulation is not clear for negative emissions and experts strongly feel that until carbon accounting rules are put in place, the technology is being developed without a concrete legal framework. Additionally, the carbon credit market was selected by many experts as for DACCS, but it does not rank as high. Reason for this could be that because BECCS revenues are both the sale of energy and the sale of CDR certificates, experts could think that the carbon credit market is relatively less important for BECCS than it is for DACCS.

Technology mandates, and direct policies, and supporting infrastructure were each chosen once but ranked high. Technology mandates are the obligation for large polluting industries to deploy NETs and was seen as necessary by one expert. The expert choosing direct policies for BECCS believes that, like a limiting factor, these are prohibitive if not properly implemented. Hence, this expert believes that for BECCS to be deployed, policies targeting BECCS specifically are a necessity. Finally, one expert believes that as the parallel development of supporting infrastructure is critical for BECCS technology, this should also be written into legislation.

5. 3. 1. 1 Limiting Factors and Enabling Policies Discussion

To summarize, the results from the limiting factors show that DACCS and BECCS share costs, and policy and regulations as most limiting factors. This reinforces the need for policy instruments taking on some of the cost burden and promoting the deployment of both technologies. Then, DACCS is most severely affected by its energy consumption, and BECCS by its biomass consumption. Technological limiting factors call for additional research fostering energy-saving processes and high energy density feedstocks.

To conclude on enabling policies, experts voice the need for European policies to fulfil two roles. The first is to fully integrate negative emissions to their structure. Without a concrete framework that defines how these negative emissions are accounted for, disposed of, and paid for, there is too much uncertainty for investors to provide the initial capital needed to deploy the technologies. The second is to truly enforce the ‘polluter pays’ principle. Experts stated the need for more policies penalizing carbon emissions. The dividends from these policies could then be used to subsidize currently expensive NETs technology before these technologies are adopted are large scale and other financial help as well as cost reductions are secured.

6. Conclusions

The results of our study imply the following conclusions about the core hypotheses:

(H1) Cost uncertainty increases over the years for both DACCS and BECCS technologies.

The results of this research suggest mixed conclusions about the validity of H1. While experts’ projected ranges of uncertainty increase for BECCS (breakdown and total) cost metrics and DACCS breakdown costs, DACCS total costs are expected to fall within a narrower range with time, suggesting an over-confidence in DACCS total costs.

(H2) Total costs learning rate is higher for DACCS than BECCS.

In accordance with H2, the results indicate that experts expect operational costs for DACCS to diminish more sharply than BECCS costs, suggesting that the former is associated with higher rates of learning resulting from the novel status of the technology and potential for larger improvements.

(H3) Potential scale uncertainty under NZE is higher than under STEPS.

As expected, expert projections about potential deployment scales suggest a wider range of uncertainty under the NZE scenario compared to STEPS.

(H4) The NZE policy scenario leads to higher deployment scale for both DACCS and BECCS technologies.

In accordance with H4, the more ambitious policy context implied by the NZE scenario is associated with higher deployment scales for both BECCS and DACCS.

(H5) BECCS technology remains cheaper than DACCS over time and is hence deployed at larger scale.

Despite BECCS being the cheaper technology, experts did not generally expect other large-scale projects to materialise in the coming years. By contrast, under a conducive policy environment such as the NZE scenario, the maximum scale of DACCS deployment is estimated to be twice as high as BECCS, negating H4 that deployment scale is limited by technology cost.

In conclusion, this study provides valuable insights into the future of DACCS and BECCS technologies in Europe. The experts' quantitative inputs, supported by their judgement of the factors influencing the field, shed light on the cost and potential scale uncertainties of these technologies.

6. 1 Costs

To answer the NEGEM research questions, the results indicate that while DACCS total costs show decreasing uncertainty over time, the cost breakdown displays increasing uncertainty. Grasping the full complexity of the technology in one total cost metric can prove to be difficult especially as the form the technology might have in 10 years could differ widely from current practices. Additionally, DACCS involves an energy intensive process and hence depends on energy prices. The current geopolitical climate does not favour energy cost certainty and the experts which provided the cost breakdown found it hard to speculate on this cost item. DACCS experts were confident that in the future new and better materials as well as economies of scale will lower the costs of the technology but overall, the uncertainty of European energy prices remains a hurdle to the deployment of the technology.

BECCS costs show growing uncertainty over time due to the unique aspect of each plant development. BECCS plants are developed as a one-of-a-kind plant, with specific up- and down-stream supply chains, leading to high uncertainty. As for DACCS, the energy revenue of BECCS is linked to European energy prices and hence, uncertain. However, the revenues obtained through the sale of energy help make the technology financially attractive and BECCS is consistently cheaper than DACCS with some extreme minimum cases attaining costs below EUR 100/tCO_2.

Overall, the results shows that BECCS costs are expected to decrease in the coming decades but not as starkly as DACCS costs. On average, DACCS reaches costs of EUR 280/tCO_2 and BECCS costs of EUR 153/tCO_2. Despite being the cheaper technology, large-scale BECCS deployment will require both significant investments and international coordination for regulating relatively diverse plants, sourcing and transporting biomass upstream and distributing biomass energy downstream. By contrast, by facilitating location-independent sourcing of CO_2, DACCS avoids some of the transport and regulatory challenges that are encountered for powering BECCS at scale and regulating potential biomass energy generation. However, by providing base load power, BECCS could be positioned strategically to help stabilize a volatile green energy grid and, unlike DACCS, will actually be generating revenues from power generation rather than consuming vast amounts of electricity.

To conclude on the cost best estimates, the main cost reduction drivers are economies of scale, process optimization and energy cost reductions. With the costs of both technologies linked to European energy prices, policymakers must prioritize securing a stable green energy grid to reduce the uncertainty linked to energy prices of these technologies.

6. 2 Potential Scale

The potential scale uncertainty shows that DACCS has a non-zero probability of failure and that the deployment of DACCS plants highly depends on the success of their early deployment. Additionally, the years leading up to 2040 are essential to create the base capture capacity, learning opportunities and secure the trust of investors. Under NZE the potential scale is expected to significantly increase by one or two orders of magnitude in 2050. By contrast, BECCS was assessed by experts to have a lower potential scale over the longer term than DACCS with experts (though admittedly a different set of experts than for DACCS) indicating an increasing uncertainty over BECCS deployment.

For both technologies, enabling policies have a positive impact on the potential scale uncertainty. The uncertainty tends to sharply increase under the NZE scenario. This is due to this scenario being intrinsically less well understood than STEPS. Under NZE, DACCS estimates show maximum scales of up to 600 Mt CO_2 captured annually. BECCS on the other hand is expected to be limited to maximum capture capacities of 300 Mt CO_2 under both scenarios. Despite the limited additional development of BECCS under NZE, the impressive DACCS results show that it is imperative that policymakers shed light on the concrete implications of NZE-compatible policies and enable their rapid implementation. Assumptions under NZE policies show that in the best-case, important capture capacity could be developed with DACCS.

Looking at the best estimates under STEPS, the capture capacity of DACCS and BECCS in 2050 are expected to be similar with 39 Mt CO_2 captured by DACCS and 36 Mt CO_2 captured by BECCS. In contrast, the obtained potential scale in 2050 under NZE takes different proportions for both technologies. DACCS is predicted to capture an average of 353 Mt CO_2 annually and BECCS 131 Mt CO_2. The results show not only that there is a clear expected increase in potential deployment when the correct policies are put in place but also that there is a significant increase expected in capacity between 2030 and 2040.

Contrary to dominant expectations among energy modellers, who focus largely on BECCS and AR as the main CDR options in IAMs, and despite its lower costs, BECCS does not display a high capture capacity by 2050. The scale obtained shows a clear gap between the scale experts believe the technology will reach in Europe and what current emission scenarios call for. For BECCS, the current best estimate for 2050 represents roughly half of the needed 227Mt CO_2 2030 capacity under NZE.

Finally, the combined average capture capacity of DACCS and BECCS emerging from the expert elicitations under the stylized NZE scenario leads to an estimate of 484.4 Mt CO_2 captured per year in 2050. This value would cover just one quarter of the required annual capture capacity of 1,9 Gt CO_2 that the IEA believes is needed to meet global net zero targets by 2050. Despite the increase in potential scale under NZE, these mitigation solutions are perceived to lack the needed deployment scale, highlighting the urgent need to prioritize impactful decarbonization strategies. Additionally, this calls for simultaneous effort coming from industries and policymakers to allow the concerted deployment of a diversified portfolio of negative emission technologies to ensure that. DACCS and BECCS are crucial technologies to help narrow the emissions gap to reach net zero emissions, but they cannot achieve this alone. It is crucial that industries and policymakers invest in developing a diversified portfolio of negative emission technologies and prioritize the development of a robust supporting infrastructure to ensure a sustainable future.

6. 3 Policy Implications and Recommendations

DACCS and BECCS experts unanimously view policy and regulations as a limiting factor to the deployment of the technologies. This highlights the importance of the role that policies have in the future development of these technologies.

The insights obtained from the enabling policies show that these can be separated in three groups. The first group encompasses policies which enable and support R&D and piloting of small-scale experiments. The second group of policies penalizes polluters and increases the visibility and need for negative emission technologies. Finally, the third group are policies which subsidize costly technologies or give a market for CDR certificates to be traded on, securing revenue stream, and increasing investor confidence.

For DACCS, a majority of experts believe in the two last groups of policy and believe the carbon credit market and carbon tax are enabling policies for the deployment of the technology. The first calls for policymakers to define the framework by which negative emissions are introduced within or next to the current ETS market. The second shows that experts believe in stricter policies, such as increasing the burden on polluters. Additionally, allocating a part of base government tax for practices aimed at reducing CO_2 levels would secure recurring revenues, partly subsidizing these expensive technologies. Finally, this set of pre-dominantly European experts believe that tax credits, as seen in the USA, can subsidize the technology but these are likely not the most impactful way forward in Europe.

For BECCS, experts ask for negative emissions regulations and the integration of CDR credits in the carbon credit market. Experts believe that until carbon accounting rules are put in place the technology is being developed without a concrete legal framework supporting it.

To conclude, these results show that to ensure a concrete and impactful deployment of the technologies between now and 2050, European policies must start including a suite of negative emission technologies and become intransigent on emissions. Without a concrete framework that defines how negative emissions are accounted for, disposed of, and paid for, there is too much uncertainty for investors to provide the initial capital needed to deploy the technologies. Ensuring this is particularly difficult as these technologies require large downstream infrastructure investments. It is imperative that Europe as a whole dedicates efforts and resources in developing the necessary CCS hubs and transport routes for the captured CO_2. Then, enforcing stricter sets of rules and policies on pollution are needed. Experts stress the need for more policies penalizing carbon emissions. The cost incurred by the polluter would not only encourage them to find better and greener solutions but can also be used to subsidize costly emission technologies before these are deployed at large scale and their financial viability is secured.

These results suggest that the following recommendations could assist policymakers adopt effective enabling policies for upscaling DACCS and BECCS in Europe and, potentially, beyond:

- *Incorporate DACCS and BECCS into the ETS:* There is a strong consensus among experts on the need for an effective European-wide framework for governing DACCS and BECCS, with some speculating that this could pave the way for the inclusion of other NETPs that are more difficult to quantify [91]. In its current form, the ETS does not cover negative emissions specifically and the European Climate Law explicitly calls for the separation of the accounting of removals from emissions reductions, over the longer term, ETS does provide a comprehensive framework for regulating CO2 flows and climate policy. Indeed, there are already European regulations in place for dealing with physical leakage from geological storage of CO2 captured at plants covered by the ETS - the current rule being that physical leakages detected at storage sites must be compensated for by surrendering a corresponding amount of ETS allowances [92]. Furthermore, various member states have expressed support for including BECCS and DACCS in the ETS. For example, there is an emerging coalition of national governments including Denmark, Sweden, Norway and the Netherlands to develop EU policy incentives for these technologies [93]. European industrial actors also seem supportive, several of which have signed memorandums of understanding to collaborate on developing solutions for CO_2 delivery, transport and storage [94].

In its present form, the ETS provides weak incentive for CCS beyond avoiding the need to surrender CO_2 allowances [95]. Since this is unlikely to provide sufficient impetus for upscaling, some fundamental changes will be needed, although what these changes should be is less obvious. While the use of quantity constraints such as minimum targets for emissions reductions or maximum targets for DACCS or BECCS is politically appealing because of its potential to alleviate concerns that CDR could deter conventional emissions reduction, analysts warn that this would likely result in efficiency losses in comparison with a situation of no quantity targets [96]. A better way forward appears to be allowing DACCS and BECCS to generate emissions allowances, which would be market based and incentive cost reductions in NETs by following the polluter pays principle. Yet this would require an effective governance framework to ensure that centrally auctioned certificates were reduced based on negative emissions achieved by NETs to prevent over supply. Such assurances would remove an important source of uncertainty for potential investors, who would benefit from clearer expectations about the nature and magnitude of incentives for DACCS and BECCS.

- *Key infrastructural investment:* The expert elicitations suggest that changes to the ETS would likely need to be complemented by significant investment in key infrastructures that are important sources of cost uncertainty for stakeholders. For example, investing in CO_2 transport would increase the competitiveness of both CCS based technologies. Similarly, the carbon negative electricity supplied by BECCS and large energy needs of DACCS create strong links between these technologies and the power system, making it imperative that energy infrastructure is significantly developed to allow for effective integration [97]. While almost all countries would need to make considerable infrastructural investments in order to be able to deploy significant scales of CCS-based technologies, the level of investment required is likely to vary widely between Member States. Political and socio-ethical obstacles regarding the funding source of such investments, particularly if they need to be made in the most (geophysically) optimally suited countries, which may also be poorest, are likely to be easier to overcome if they are included in EC frameworks for regulating NETs.

- *Effective and comprehensive governance:* The uneven distribution of domestic capacities (e.g. biomass resources, storage sites and renewable resources) to deploy DACCS and BECCS means that an effective transboundary framework is imperative to coordinate the various stages, resource-inputs and processes that are involved in the deployment of these technologies and ensure that upscaling results in optimal outcomes for Europe (and beyond) [98]. On the surface, the governance of DACCS and BECCS appears to raise technocratic problems that can be managed through economic and legal regulation. Yet it is unlikely that laissez-faire market outcomes would be politically and socially acceptable. For example, an optimal division of labour assumes that countries that consume the most electricity have the largest potential for NETs and should host the bulk of BECCS plants. However, supplying large volumes of energy to power BECCS and/or DACCS and integrating biomass electricity produced via BECCS into existing energy systems is a formidable task even for industrialised economies. In relation to BECCS, countries that have the highest biomass production capacity would experience the largest impacts on land use, which is likely to encounter opposition from agriculture and publics, as demonstrated by past biofuel booms [99]. Therefore, the feasibility of policies for upscaling CCS-based technologies is likely to depend on their ability to address important political and social obstacles alongside questions about (geophysical and economic) optimality. One option is for the European Directive to include some kind of socio-politically and ethically acceptable compensation or incentivisation mechanism for Member States that are expected to host optimal DACCS/ BECCS facilities. This sort of balancing act between optimality and socio-economic and political concerns is likely to become even more challenging as European policymakers begin to develop more ambitious transboundary NETPs initiatives involving non-European countries, particularly from the global south, where optimal deployments might encounter more precarious conflicts with countries' rights to development and equity. The policies that Europe designs to navigate these challenges, at first, within the Union, and later, outside, will provide critical lessons for other countries and continents.

6. 4 Future Research

The results and insights gathered in this work present a first assessment of the uncertainty of future costs and potential scale of DACCS and BECCS technologies. The study focusses on the wider Europe in the years 2030, 2040 and 2050. It helps gain a first understanding of selected expert views on parameters which influence future emission scenarios and European wide policies.

The scope of this work was limited by the time allocated to the research. The following points present additional angles for future research.

1) It is imperative to collect more expert judgements. Increasing the pool of experts would greatly contribute to the results. This would allow to perform inferential statistics, by which the current limited pool of expert was not well represented. Additionally, ensuring that more industry experts are represented is crucial in building an accurate view of the challenges developers face.
2) As presented in the literature research, there exists a wide array of negative emission technologies which can undergo expert elicitations. Nature-based solutions such as afforestation, reforestation, ocean alkalinization and biochar are integral to the fight against climate change and gathering expert knowledge on them would increase the understanding on the uncertainty surrounding their deployment.
3) Finally, this research could be extended along two axes.
    a. First, this research could be extended to other regions of the globe such as North America, where important carbon capture clusters and supporting policies are being developed.

b. Second, the scope of the research could be extended to include research on uncertainty surrounding the supporting infrastructure. Players in this field are the infrastructure companies which develop the transport routes from the carbon capture site to the carbon storage sites and the carbon storage companies. These are oil and gas companies or companies specializing in carbon storage. Building understanding on the challenges and uncertainties that these companies face is crucial to the development of a robust carbon capture supply chain.

6.5 Relevance for the NEGEM project

This study highlights the need to understand the nature and sources of uncertainty surrounding key emerging climate technologies for reaching realistic assessments about the potential of CDR to achieve climate neutrality. The results of this study show that expectations about cost margins and deployment scales vary widely and tend to expand with rising time horizons. Therefore, better understandings about the uncertainty surrounding deployment scales and costs, particularly in relation to the distant future, would significantly improve projections about the relative role and scale of different NETPs and other technologies/ activities within the wider portfolio of climate policy options. Better projections would ultimately assist policymakers design effective legislation for meeting decarbonization and net zero targets. Relatedly, this study suggests that more ambitious policy contexts (such as the NZE) are associated with higher deployment projections for both DACCS and BECCS as well as much wider scales of uncertainty. Therefore, under NZE-compliant scenarios, it is particularly important that member states send clear signals about their commitment to decarbonization (e.g. incorporating negative emissions into the ETS and creating initiatives for co-funding CCS-based NETPs).

Fundamentally, projected deployment scales and costs reflect expectations about future socio-economic and political conditions that will shape the scalability of BECCS, DACCS and other NETPs in practice. Incorporating these sources and scales of uncertainty into IAMs would enable modelers, policymakers and industry stakeholders reach more realistic assessments about the role of different NETPs and other climate policies for meeting net zero.

For preparing this report, the following deliverable/s have been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
2.1	Quantitative survey of commercialisation mechanisms	UOXF	R	Public	18
3.1	Upgraded LPJmL5 version	PIK	R	Public	12
7.2	Extended MONET-EU	ICL	R	Public	17
7.3	Link MONET-EU and JEDI	ICL	R	Public	24
8.6					

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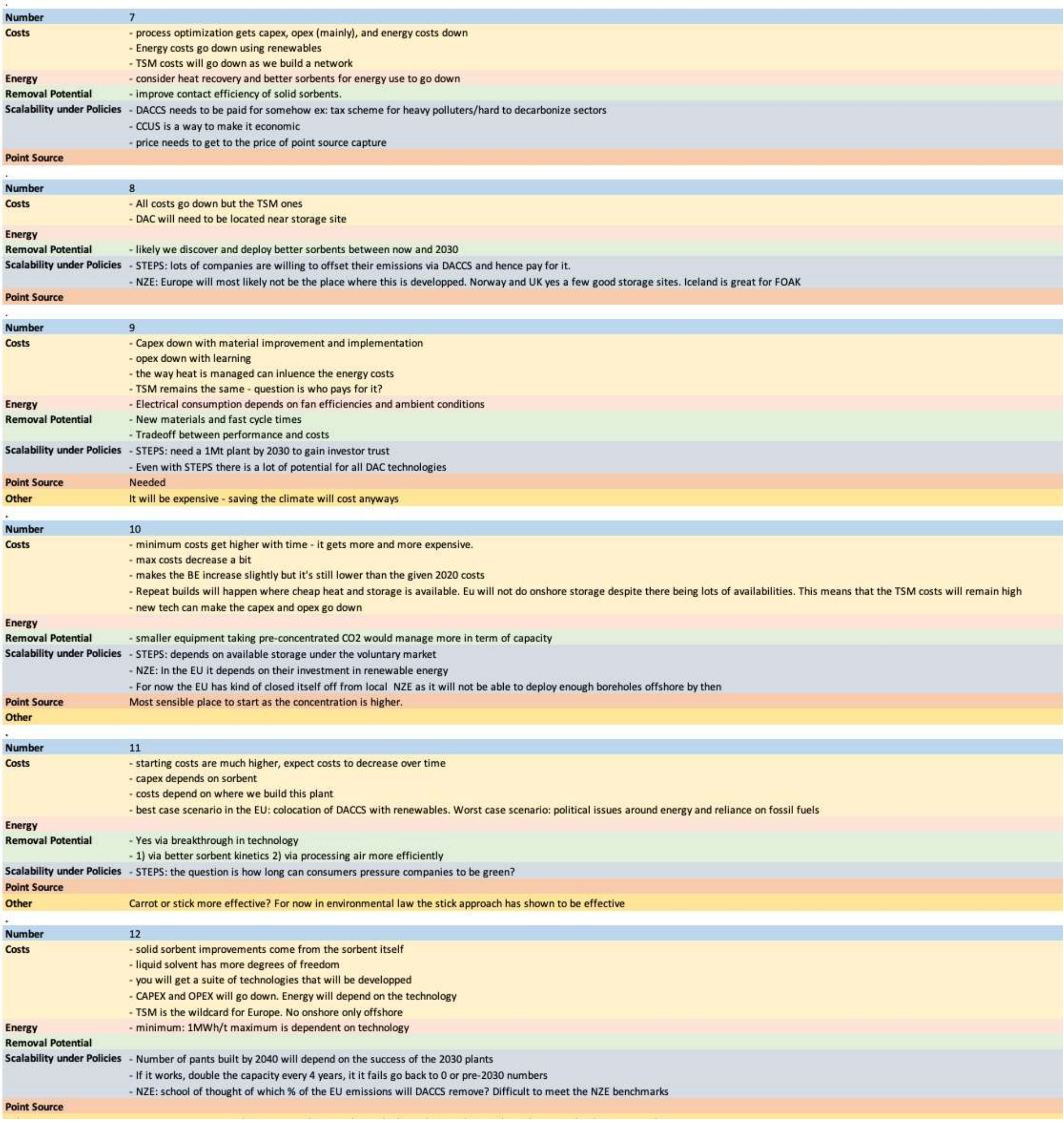
8. Appendix

8. 1 Anonymized Extract of Qualitative Insights

Items	Comments
Number	1
Costs	- If only small scale, capex will go up - Energy will be a cost reduction driver
Energy	- Post combustion CC would use much less energy
Removal Potential	- Hinges on adsorbent technology
Scalability under Policies	- Deployment under NZE assumes a green decabonized grid by 2040, this is where the bulk of DACCS gets deployed.
Number	2
Costs	- Energy prices go up on average in the decades - higher LR between 30-40 than 40-50
Energy	- Main restriction to build a DACCS plant in Europe is the availability of green electricity.
Removal Potential	
Scalability under Policies	- STEPS: if nothing changes then growth in next decade (voluntary) but then on nothing much more - NZE: Policies put in place to reach NZ but we realistically will not
Number	3
Costs	- tradeoff between your capex and energy. The more energy you have the lower your capex. Minimal energy would require infinite capital - fabrication costs might go down but labour and commodities will still cost - increase the unit size for costs to go down - cost of carbon free energy will go up
Energy	
Removal Potential	- different sorbent with better kinetics (+ superstructure) - increase throughput via more efficient fans
Scalability under Policies	- NZE by 2050 is not realistic - Plants being built now will determine how people see DACCS in a decade - as it is uneconomical all we will see will be a function of policy
Number	4
Costs	- Who pays for it?
Energy	- Use the right materials to improve the air flow
Removal Potential	- improving the recovery (minimize the air flow) via better materials (material productivity) - Energy use is a major issue as it puts pressure on the grid
Scalability under Policies	
Point Source	- Opinion is that doing Point Source capture makes the most sense compared to DACCS
Number	5
Costs	- capex & O&M must come down radically - energy costs will come down due to renewables (heat storage would be a way to use heat when it is free) - TSM will not go down
Energy	- will go down under assumption of new and better sorbents
Removal Potential	- With new sorbent and CW tech you can capture more but you will need to push more air through - however more you scale the capture capacity you scale the air flow accordingly
Scalability under Policies	
Point Source	PS doesn't get you to net zero - it only limits your emissions
Number	6
Costs	- capex and opex will go down - energy costs come down with a more diverse energy production - Who pays for it?
Energy	
Removal Potential	- better sorbents and optimized operations can push the unit to capture more - liquid sorbents allow for more optimization parameters
Scalability under Policies	- STEPS: voluntary market would be developed a bit - greenwashing from companies - uncertainty in the future - NZE: need for standardized carbon accounting practices. Large step in 2040-50 due to lesson learned and developed infrastructure
Point Source	

Figure 23: DACCS qualitative insights 1.



Number	7
Costs	- process optimization gets capex, opex (mainly), and energy costs down - Energy costs go down using renewables - TSM costs will go down as we build a network
Energy	- consider heat recovery and better sorbents for energy use to go down
Removal Potential	- improve contact efficiency of solid sorbents.
Scalability under Policies	- DACCS needs to be paid for somehow ex: tax scheme for heavy polluters/hard to decarbonize sectors - CCUS is a way to make it economic - price needs to get to the price of point source capture
Point Source	

Number	8
Costs	- All costs go down but the TSM ones - DAC will need to be located near storage site
Energy	
Removal Potential	- likely we discover and deploy better sorbents between now and 2030
Scalability under Policies	- STEPS: lots of companies are willing to offset their emissions via DACCS and hence pay for it. - NZE: Europe will most likely not be the place where this is developped. Norway and UK yes a few good storage sites. Iceland is great for FOAK
Point Source	

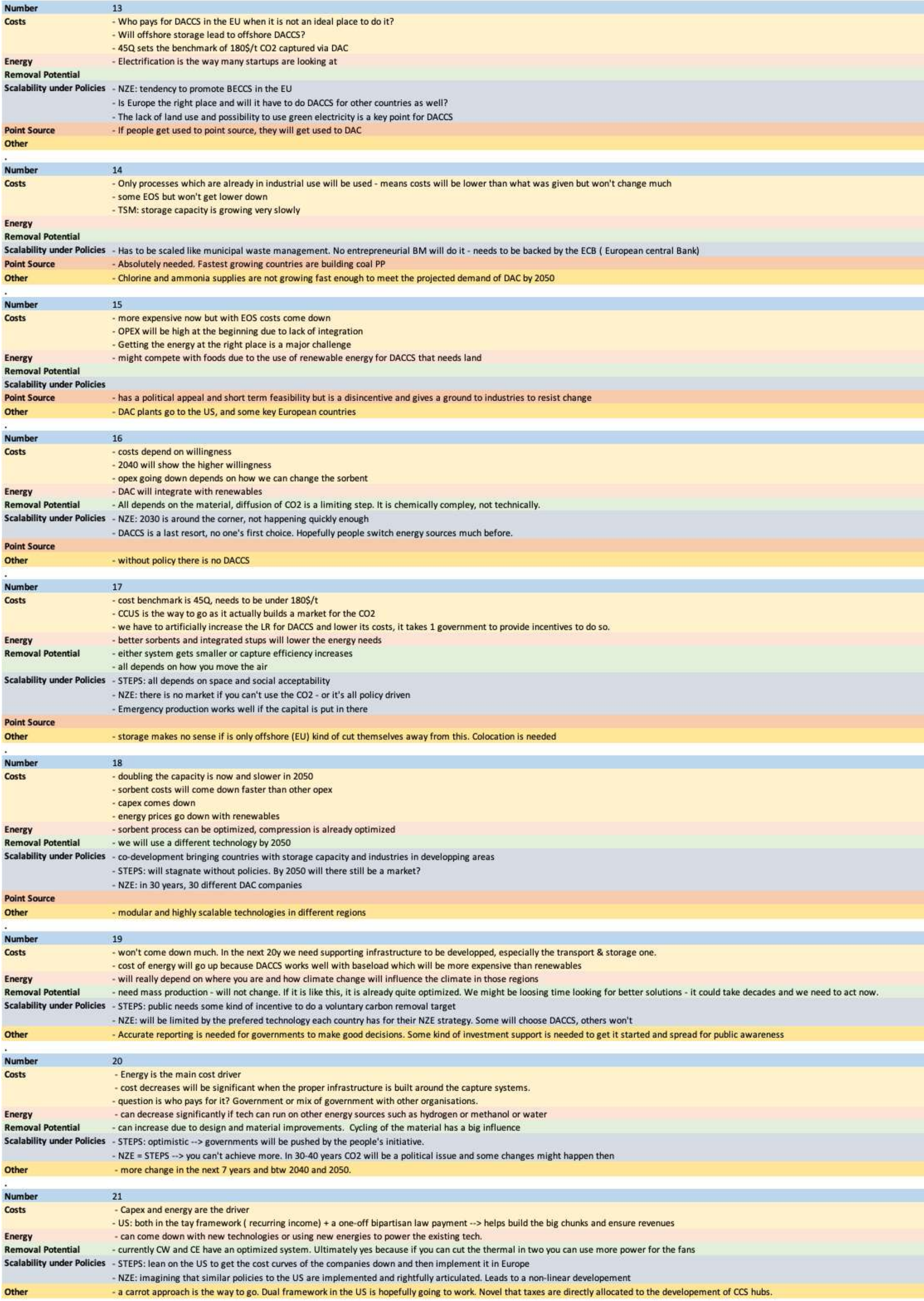
Number	9
Costs	- Capex down with material improvement and implementation - opex down with learning - the way heat is managed can inluence the energy costs - TSM remains the same - question is who pays for it?
Energy	- Electrical consumption depends on fan efficiencies and ambient conditions
Removal Potential	- New materials and fast cycle times - Tradeoff between performance and costs
Scalability under Policies	- STEPS: need a 1Mt plant by 2030 to gain investor trust - Even with STEPS there is a lot of potential for all DAC technologies
Point Source	Needed
Other	It will be expensive - saving the climate will cost anyways

Number	10
Costs	- minimum costs get higher with time - it gets more and more expensive. - max costs decrease a bit - makes the BE increase slightly but it's still lower than the given 2020 costs - Repeat builds will happen where cheap heat and storage is available. Eu will not do onshore storage despite there being lots of availabilities. This means that the TSM costs will remain high - new tech can make the capex and opex go down
Energy	
Removal Potential	- smaller equipment taking pre-concentrated CO2 would manage more in term of capacity
Scalability under Policies	- STEPS: depends on available storage under the voluntary market - NZE: In the EU it depends on their investment in renewable energy - For now the EU has kind of closed itself off from local NZE as it will not be able to deploy enough boreholes offshore by then
Point Source	Most sensible place to start as the concentration is higher.
Other	

Number	11
Costs	- starting costs are much higher, expect costs to decrease over time - capex depends on sorbent - costs depend on where we build this plant - best case scenario in the EU: colocation of DACCS with renewables. Worst case scenario: political issues around energy and reliance on fossil fuels
Energy	
Removal Potential	- Yes via breakthrough in technology - 1) via better sorbent kinetics 2) via processing air more efficiently
Scalability under Policies	- STEPS: the question is how long can consumers pressure companies to be green?
Point Source	
Other	Carrot or stick more effective? For now in environmental law the stick approach has shown to be effective

Number	12
Costs	- solid sorbent improvements come from the sorbent itself - liquid solvent has more degrees of freedom - you will get a suite of technologies that will be developped - CAPEX and OPEX will go down. Energy will depend on the technology - TSM is the wildcard for Europe. No onshore only offshore
Energy	- minimum: 1MWh/t maximum is dependent on technology
Removal Potential	
Scalability under Policies	- Number of pants built by 2040 will depend on the success of the 2030 plants - If it works, double the capacity every 4 years, it it fails go back to 0 or pre-2030 numbers - NZE: school of thought of which % of the EU emissions will DACCS remove? Difficult to meet the NZE benchmarks
Point Source	

Figure 24: DACCS qualitative insights 2.



Number	13
Costs	- Who pays for DACCS in the EU when it is not an ideal place to do it? - Will offshore storage lead to offshore DACCS? - 45Q sets the benchmark of 180$/t CO2 captured via DAC
Energy	- Electrification is the way many startups are looking at
Removal Potential	
Scalability under Policies	- NZE: tendency to promote BECCS in the EU - Is Europe the right place and will it have to do DACCS for other countries as well? - The lack of land use and possibility to use green electricity is a key point for DACCS
Point Source	- If people get used to point source, they will get used to DAC
Other	

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Number	14
Costs	- Only processes which are already in industrial use will be used - means costs will be lower than what was given but won't change much - some EOS but won't get lower down - TSM: storage capacity is growing very slowly
Energy	
Removal Potential	
Scalability under Policies	- Has to be scaled like municipal waste management. No entrepreneurial BM will do it - needs to be backed by the ECB (European central Bank)
Point Source	- Absolutely needed. Fastest growing countries are building coal PP
Other	- Chlorine and ammonia supplies are not growing fast enough to meet the projected demand of DAC by 2050

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Number	15
Costs	- more expensive now but with EOS costs come down - OPEX will be high at the beginning due to lack of integration - Getting the energy at the right place is a major challenge
Energy	- might compete with foods due to the use of renewable energy for DACCS that needs land
Removal Potential	
Scalability under Policies	
Point Source	- has a political appeal and short term feasibility but is a disincentive and gives a ground to industries to resist change
Other	- DAC plants go to the US, and some key European countries

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Number	16
Costs	- costs depend on willingness - 2040 will show the higher willingness - opex going down depends on how we can change the sorbent
Energy	- DAC will integrate with renewables
Removal Potential	- All depends on the material, diffusion of CO2 is a limiting step. It is chemically compley, not technically.
Scalability under Policies	- NZE: 2030 is around the corner, not happening quickly enough - DACCS is a last resort, no one's first choice. Hopefully people switch energy sources much before.
Point Source	
Other	- without policy there is no DACCS

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Number	17
Costs	- cost benchmark is 45Q, needs to be under 180$/t - CCUS is the way to go as it actually builds a market for the CO2 - we have to artificially increase the LR for DACCS and lower its costs, it takes 1 government to provide incentives to do so.
Energy	- better sorbents and integrated stups will lower the energy needs
Removal Potential	- either system gets smaller or capture efficiency increases - all depends on how you move the air
Scalability under Policies	- STEPS: all depends on space and social acceptability - NZE: there is no market if you can't use the CO2 - or it's all policy driven - Emergency production works well if the capital is put in there
Point Source	
Other	- storage makes no sense if is only offshore (EU) kind of cut themselves away from this. Colocation is needed

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Number	18
Costs	- doubling the capacity is now and slower in 2050 - sorbent costs will come down faster than other opex - capex comes down - energy prices go down with renewables
Energy	- sorbent process can be optimized, compression is already optimized
Removal Potential	- we will use a different technology by 2050
Scalability under Policies	- co-development bringing countries with storage capacity and industries in developping areas - STEPS: will stagnate without policies. By 2050 will there still be a market? - NZE: in 30 years, 30 different DAC companies
Point Source	
Other	- modular and highly scalable technologies in different regions

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Number	19
Costs	- won't come down much. In the next 20y we need supporting infrastructure to be developped, especially the transport & storage one. - cost of energy will go up because DACCS works well with baseload which will be more expensive than renewables
Energy	- will really depend on where you are and how climate change will influence the climate in those regions
Removal Potential	- need mass production - will not change. If it is like this, it is already quite optimized. We might be loosing time looking for better solutions - it could take decades and we need to act now.
Scalability under Policies	- STEPS: public needs some kind of incentive to do a voluntary carbon removal target - NZE: will be limited by the prefered technology each country has for their NZE strategy. Some will choose DACCS, others won't
Other	- Accurate reporting is needed for governments to make good decisions. Some kind of investment support is needed to get it started and spread for public awareness

.

Number	20
Costs	- Energy is the main cost driver - cost decreases will be significant when the proper infrastructure is built around the capture systems. - question is who pays for it? Government or mix of government with other organisations.
Energy	- can decrease significantly if tech can run on other energy sources such as hydrogen or methanol or water
Removal Potential	- can increase due to design and material improvements. Cycling of the material has a big influence
Scalability under Policies	- STEPS: optimistic --> governments will be pushed by the people's initiative. - NZE = STEPS --> you can't achieve more. In 30-40 years CO2 will be a political issue and some changes might happen then
Other	- more change in the next 7 years and btw 2040 and 2050.

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Number	21
Costs	- Capex and energy are the driver - US: both in the tay framework (recurring income) + a one-off bipartisan law payment --> helps build the big chunks and ensure revenues
Energy	- can come down with new technologies or using new energies to power the existing tech.
Removal Potential	- currently CW and CE have an optimized system. Ultimately yes because if you can cut the thermal in two you can use more power for the fans
Scalability under Policies	- STEPS: lean on the US to get the cost curves of the companies down and then implement it in Europe - NZE: imagining that similar policies to the US are implemented and rightfully articulated. Leads to a non-linear developement
Other	- a carrot approach is the way to go. Dual framework in the US is hopefully going to work. Novel that taxes are directly allocated to the developement of CCS hubs.

Figure 25: DACCS qualitative insights 3.

Items	Comments
Number	1
Land	Forestry and materials from industry don't take up land. However closing all streams is complicated
Feedstock	
Scalability under Policies	- STEPS: DRAX with assuming 300'000t CO2 captured per year - maybe a few more of these as people are eager to produce negative emissions. But it takes time to develop it. - NZE: the EU is not capable of producing this much CDR by 2050. All CCS will be improved and deployed. - Bigger plant development is pushed as it costs a lot to plan for each individual plant --> each is a special case
Other	
.	
Number	2
Costs	- will tend to increase. We will start by doing the optimal plants first and then we'll go to more secluded and smaller plants which will cost more.
Energy	Technology improvements won't change much, close to Carnot efficiency. Flue gas condensation allows for >100% Mwh_out/MWh_in. Locked in in term of Technology by each contract for 40y (lifetime of plant)
Land	In Sweden won't need any extra land
Feedstock	
Scalability under Policies	- STEPS: Sweden will take a good chunk of EU BECCS as they have some current policies (about 1/3) - NZE: no chnage by 2030 as it takes 7y from ideation to operation
Other	Currently in Sweden there is 30Mt of potential to do BECCS. 1/3 in CHP the rest in pulp&paper industry. 1/6 of current forest residues are used --> space to use much more without more land use. Policies: 2Mt of BECCS by 2030 are financed in Sweden. 10Mt of BECCS by 2045 is financed.
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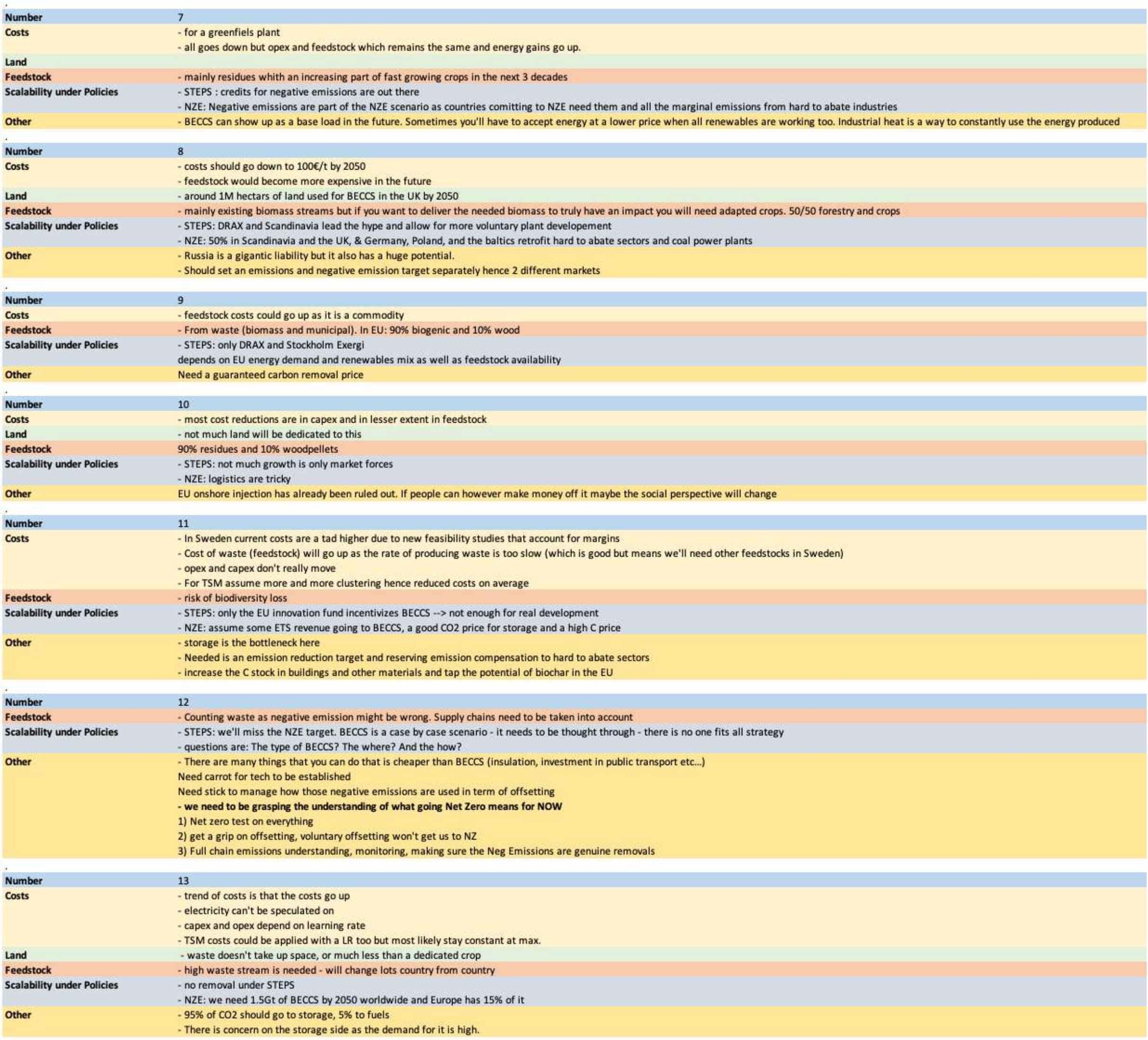
Number	3
Costs	- 2030-2040 costs would go up due to rising infrastructure and energy costs. - 2040-2050 costs would go downdue to learning
Energy	turbine designs could improve a bit
Land	- DRAX: Uses wood from the USA and south america
Feedstock	- Trend moves to less transport. Co-location of BECCS and Feedstock - Feedstock innovation such as fast growing crops is needed to ensure stability of supply in the EU - No constraint around the feedstock availability. Only arounf the logistics around it.
Scalability under Policies	- STEPS: nothing values negative emissions. You need a contract for difference - NZE: as BECCS co-produces power with CDRs. The more renewables you have the higher the need to base load power will be --> interest for BECCS
Other	- Are developers aligned with policy makers? This will have an influence on the supply, transport and pipelines etc... - Nothern lights is already overbooked - UK is trying to do a more holistic approach to the entire CCS supply chain. Building clusters via governmental help to incentivize all developers
.	
Number	4
Costs	- Opex and capex will go down but feedstock cost will not go down as much because you need to pay the farmer for it a certain (good) price
Land	Taking away from forests residues reduces the soil carbon.
Feedstock	- Where you have agreable land you will do miscanthus, in countries with forestry you will do willow. - In the far north and boreal parts of the earth you'll use forestry
Scalability under Policies	- Assumption here is that you will not go faster in STEPS as in NZE - BECCS will help decarbonize hard to abate industries such as steel, cement etc...
Other	
.	
Number	5
Costs	- Capex goes down. Opex stays the same (known tech) - Feedstock costs will depend on efficiency to grow them - TSM requires urgent massive investments
Land	
Feedstock	- only is there is a push for BECCS will developers ask for more biomass which could then start the production of fast growing crops. Until then we'll use woodpellets int he UK - important these would be more resistant to extreme weathers
Scalability under Policies	- STEPS: there might be delays in infrastructure to store CO2 - NZE: you need policies to accompany the entire infrastructure around BECCS.
Other	
.	
Number	6
Costs	- costs go down - the price for the CO2 needs to be artificially set by a policy - in 10-15y the capex and opex part should be roughly the same
Energy	- By adding CCS on a plant you loose energy
Land	- no extra land use
Feedstock	- Sweden will first use the pulp and paper industry and do CCS there. No energy for now - use the feedstock from today, don't produce it. The marginal difference of extra biomass you use with CCS is 5-10%
Scalability under Policies	- STEPS: rational would be to put CCS on all plants that emit. Ex: coal plants in Poland - NZE: would double the numbers. 2030-2040 not much hapenning as there is first a large need for infrastructure.
Other	- you should see CCS as a product not as a BECCS plant. But CCS added onto a plant Climate change is a **political problem,** not a technical one. + It is partly a financial problem Needed is: longer guarantees for the projects + CCS clusters of different actors

Figure 26: BECCS qualitative insights 1.



Number	7
Costs	- for a greenfiels plant - all goes down but opex and feedstock which remains the same and energy gains go up.
Land	
Feedstock	- mainly residues whith an increasing part of fast growing crops in the next 3 decades
Scalability under Policies	- STEPS : credits for negative emissions are out there - NZE: Negative emissions are part of the NZE scenario as countries comitting to NZE need them and all the marginal emissions from hard to abate industries
Other	- BECCS can show up as a base load in the future. Sometimes you'll have to accept energy at a lower price when all renewables are working too. Industrial heat is a way to constantly use the energy produced

Number	8
Costs	- costs should go down to 100€/t by 2050 - feedstock would become more expensive in the future
Land	- around 1M hectars of land used for BECCS in the UK by 2050
Feedstock	- mainly existing biomass streams but if you want to deliver the needed biomass to truly have an impact you will need adapted crops. 50/50 forestry and crops
Scalability under Policies	- STEPS: DRAX and Scandinavia lead the hype and allow for more voluntary plant developement - NZE: 50% in Scandinavia and the UK, & Germany, Poland, and the baltics retrofit hard to abate sectors and coal power plants
Other	- Russia is a gigantic liability but it also has a huge potential. - Should set an emissions and negative emission target separately hence 2 different markets

Number	9
Costs	- feedstock costs could go up as it is a commodity
Feedstock	- From waste (biomass and municipal). In EU: 90% biogenic and 10% wood
Scalability under Policies	- STEPS: only DRAX and Stockholm Exergi depends on EU energy demand and renewables mix as well as feedstock availability
Other	Need a guaranteed carbon removal price

Number	10
Costs	- most cost reductions are in capex and in lesser extent in feedstock
Land	- not much land will be dedicated to this
Feedstock	90% residues and 10% woodpellets
Scalability under Policies	- STEPS: not much growth is only market forces - NZE: logistics are tricky
Other	EU onshore injection has already been ruled out. If people can however make money off it maybe the social perspective will change

Number	11
Costs	- In Sweden current costs are a tad higher due to new feasibility studies that account for margins - Cost of waste (feedstock) will go up as the rate of producing waste is too slow (which is good but means we'll need other feedstocks in Sweden) - opex and capex don't really move - For TSM assume more and more clustering hence reduced costs on average
Feedstock	- risk of biodiversity loss
Scalability under Policies	- STEPS: only the EU innovation fund incentivizes BECCS --> not enough for real development - NZE: assume some ETS revenue going to BECCS, a good CO2 price for storage and a high C price
Other	- storage is the bottleneck here - Needed is an emission reduction target and reserving emission compensation to hard to abate sectors - increase the C stock in buildings and other materials and tap the potential of biochar in the EU

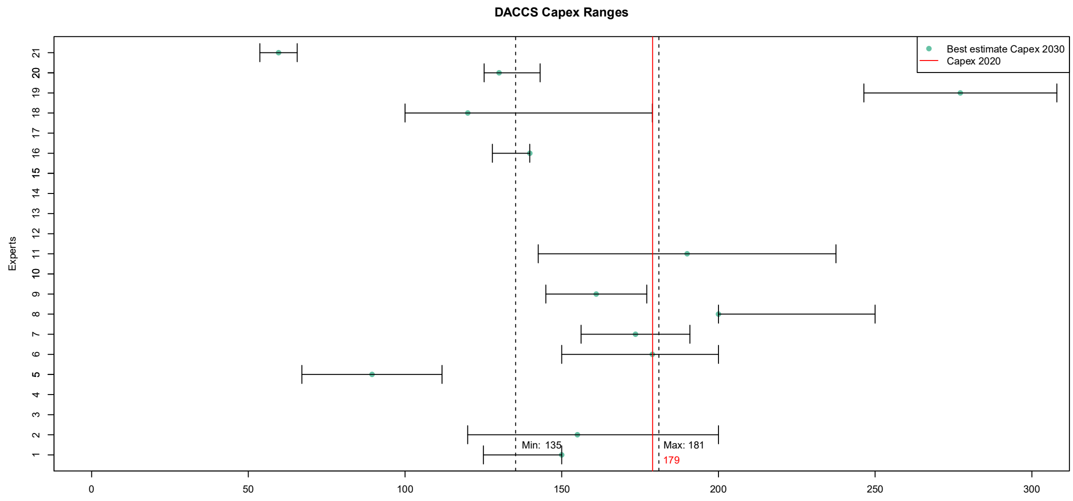
Number	12
Feedstock	- Counting waste as negative emission might be wrong. Supply chains need to be taken into account
Scalability under Policies	- STEPS: we'll miss the NZE target. BECCS is a case by case scenario - it needs to be thought through - there is no one fits all strategy - questions are: The type of BECCS? The where? And the how?
Other	- There are many things that you can do that is cheaper than BECCS (insulation, investment in public transport etc...) Need carrot for tech to be established Need stick to manage how those negative emissions are used in term of offsetting **- we need to be grasping the understanding of what going Net Zero means for NOW** 1) Net zero test on everything 2) get a grip on offsetting, voluntary offsetting won't get us to NZ 3) Full chain emissions understanding, monitoring, making sure the Neg Emissions are genuine removals

Number	13
Costs	- trend of costs is that the costs go up - electricity can't be speculated on - capex and opex depend on learning rate - TSM costs could be applied with a LR too but most likely stay constant at max.
Land	- waste doesn't take up space, or much less than a dedicated crop
Feedstock	- high waste stream is needed - will change lots country from country
Scalability under Policies	- no removal under STEPS - NZE: we need 1.5Gt of BECCS by 2050 worldwide and Europe has 15% of it
Other	- 95% of CO2 should go to storage, 5% to fuels - There is concern on the storage side as the demand for it is high.

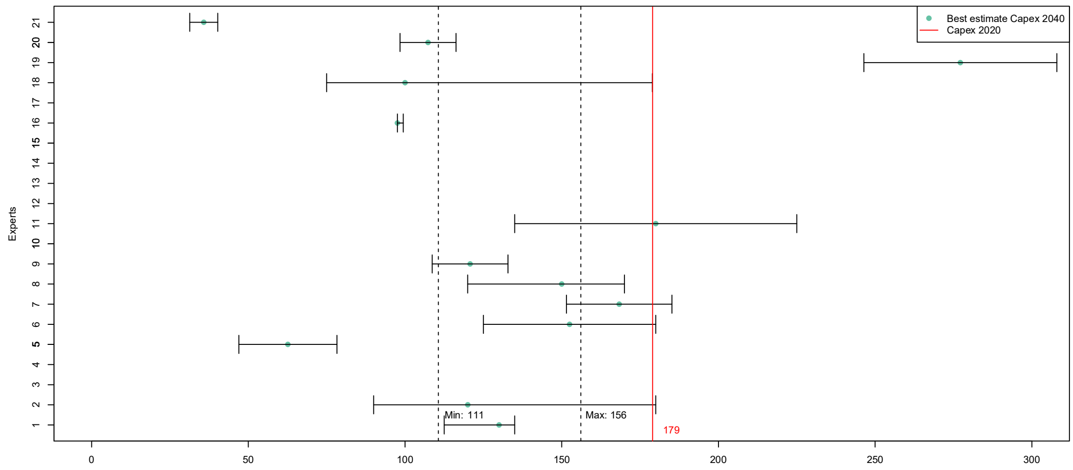
Figure 27: BECCS qualitative insights 2.

8. 2 Supporting Graphs

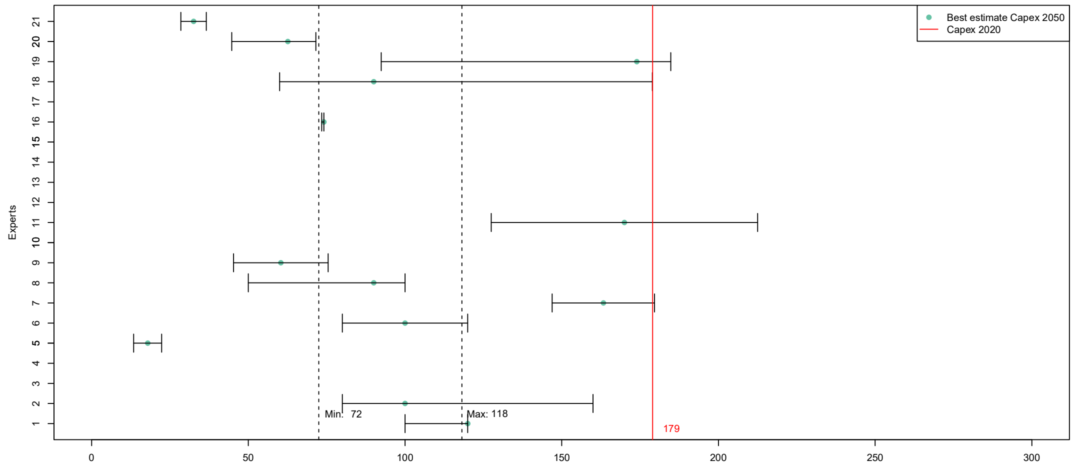
DACCS Cost Item Ranges



(a) 2030 Costs (EUR/tCO2)



(b) 2040 Costs (EUR/tCO2)



(c) 2050 Costs (EUR/tCO2)

Figure 28: DACCS Capex estimates with minimum, maximum and best estimate of each expert for 2030, 2040 and 2050.

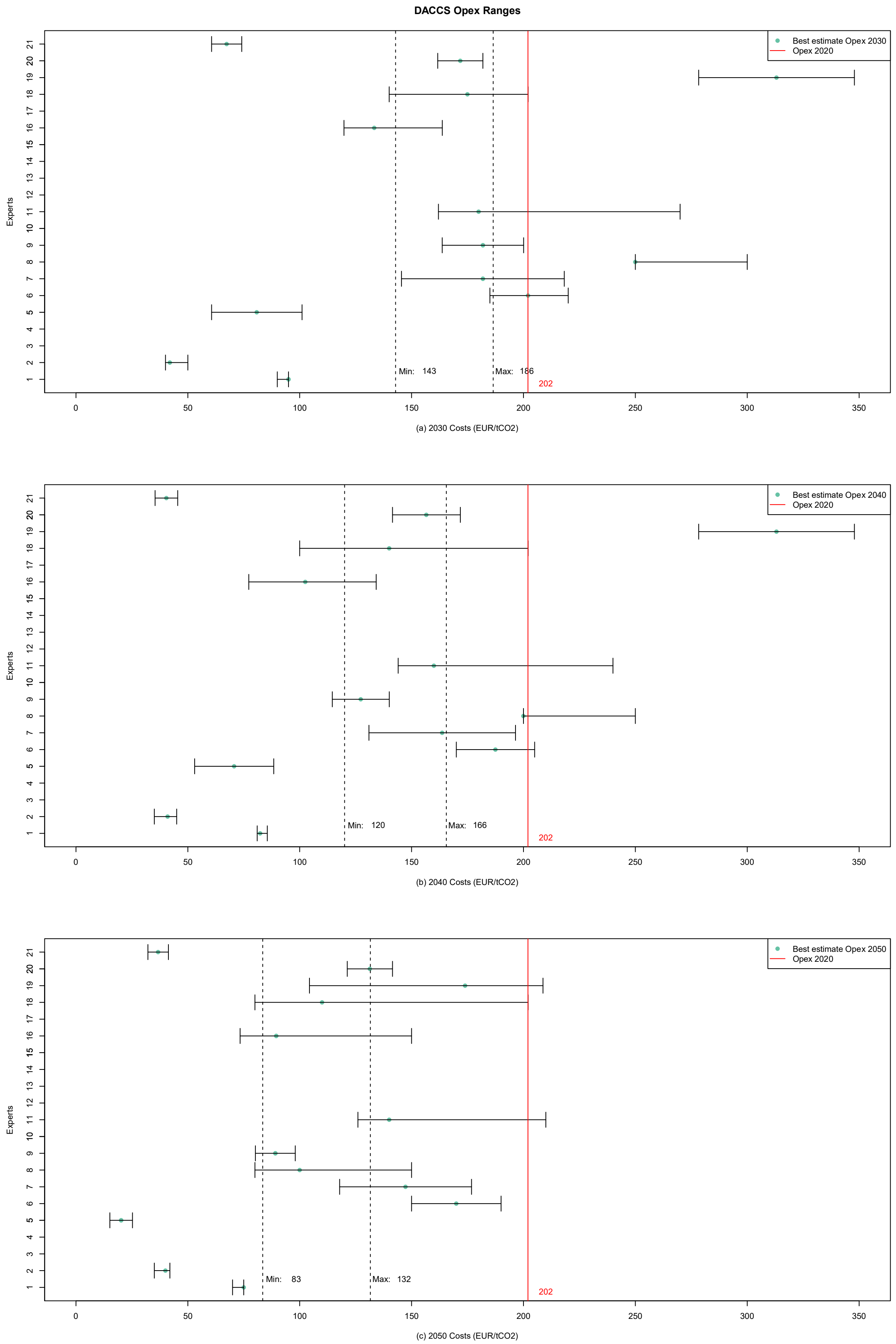
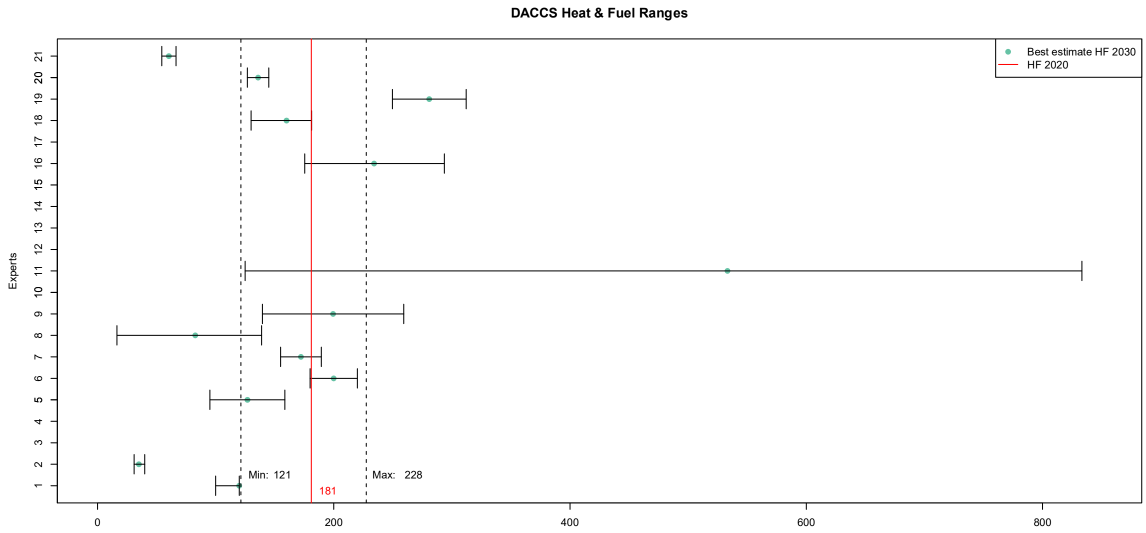
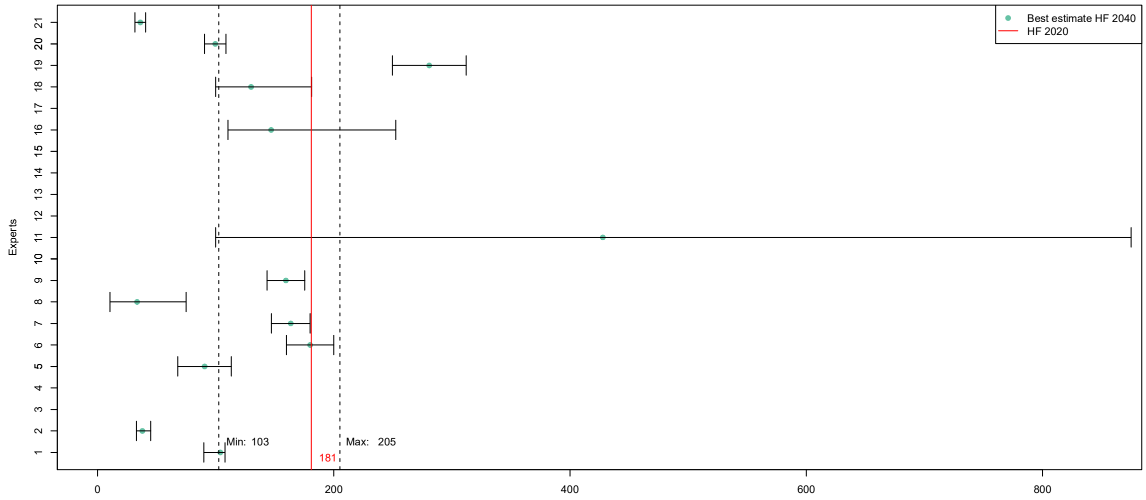


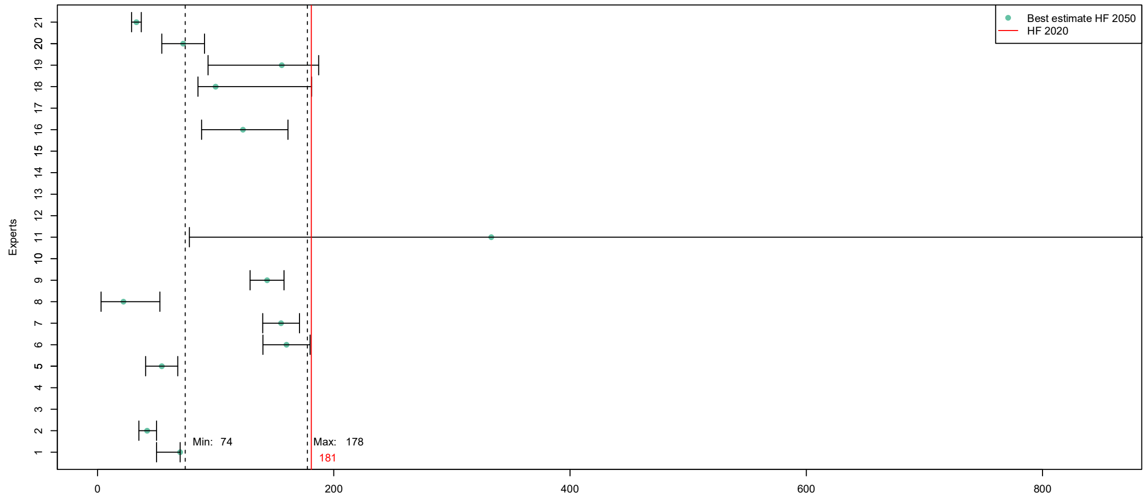
Figure 29:DACCS Opex estimates with minimum, maximum and best estimate of each expert for 2030, 2040 and 2050.



(a) 2030 Costs (EUR/tCO2)



(b) 2040 Costs (EUR/tCO2)



(c) 2050 Costs (EUR/tCO2)

Figure 30:DACCS Heat & Fuel estimates with minimum, maximum and best estimate of each expert for 2030, 2040 and 2050.

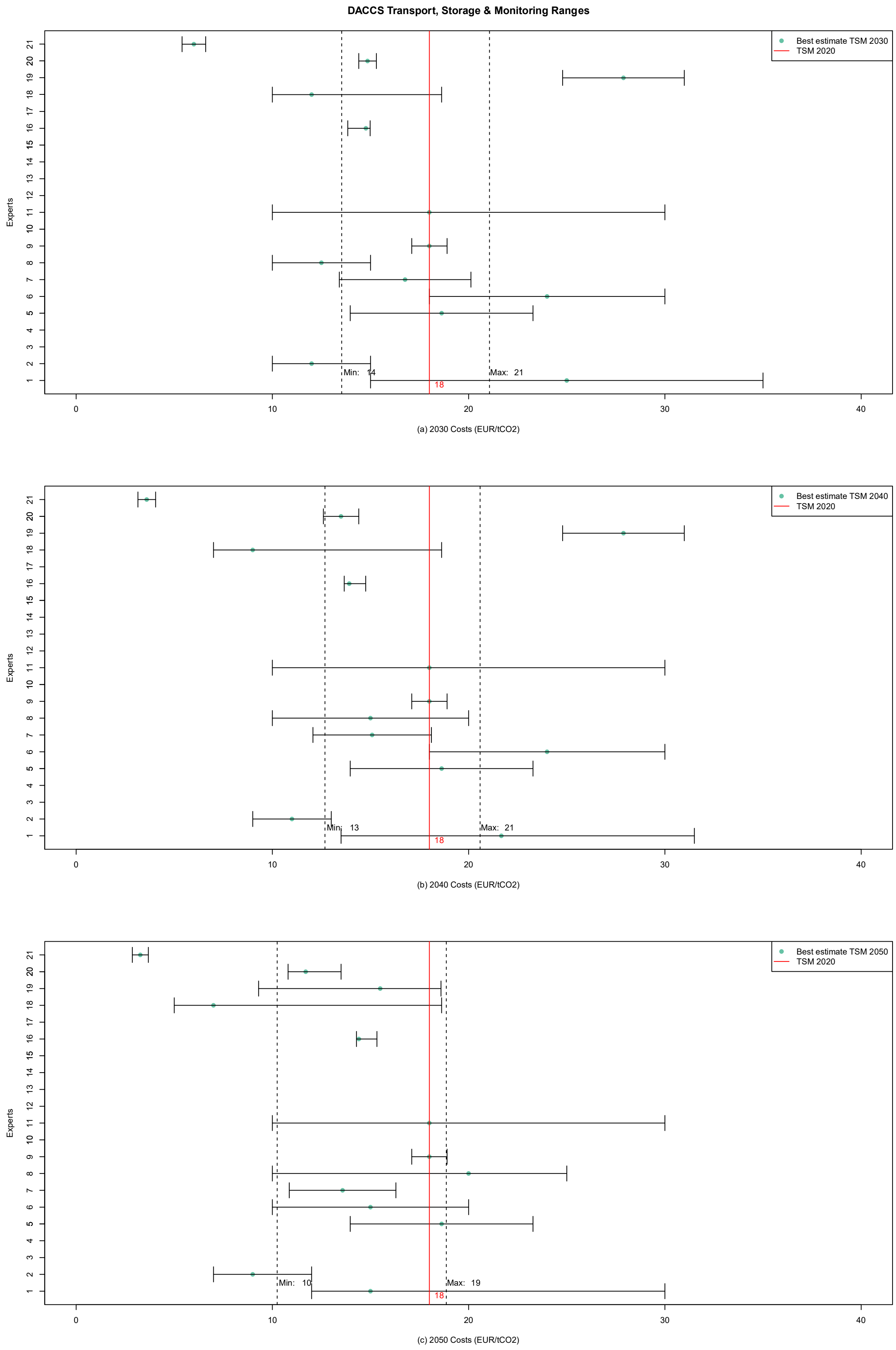
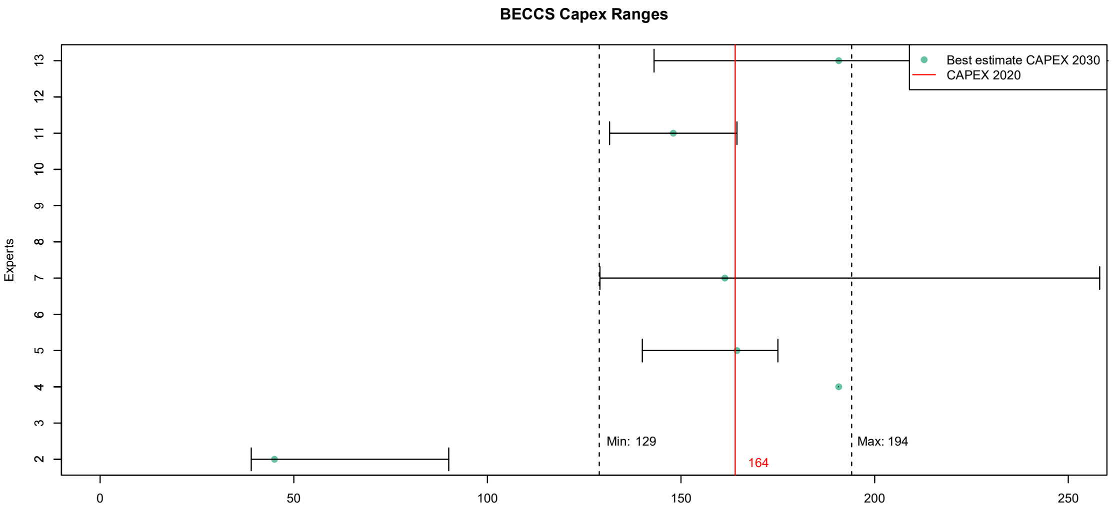
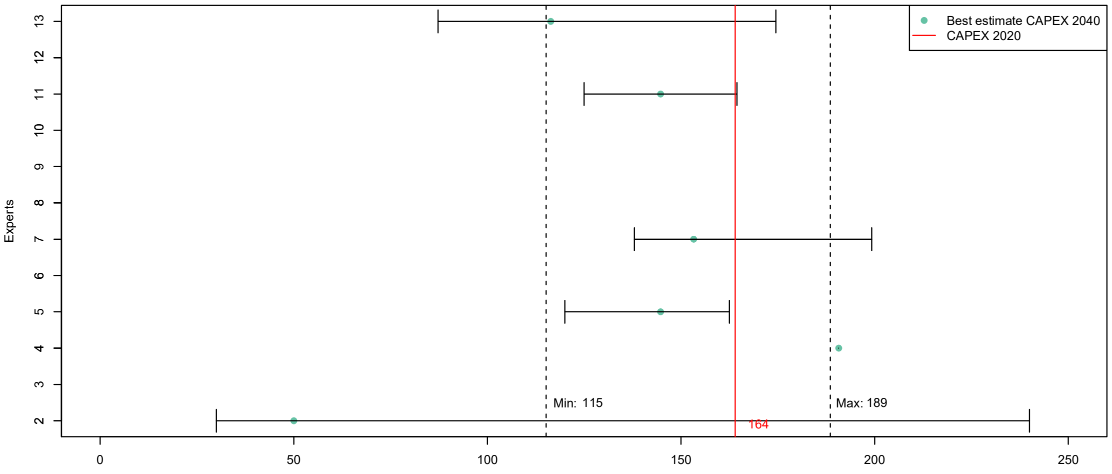


Figure 31:DACCS TSM estimates with minimum, maximum and best estimate of each expert for 2030, 2040 and 2050.

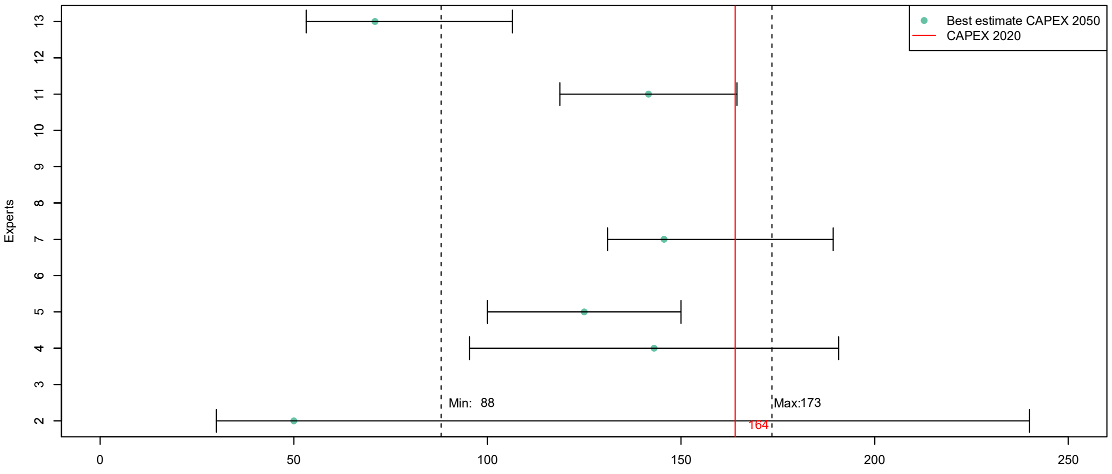
BECCS Cost Item Ranges



(a) 2030 Costs (EUR/tCO2)



(b) 2040 Costs (EUR/tCO2)



(c) 2050 Costs (EUR/tCO2)

Figure 32: BECCS Capex estimates with minimum, maximum and best estimate of each expert for 2030, 2040 and 2050.

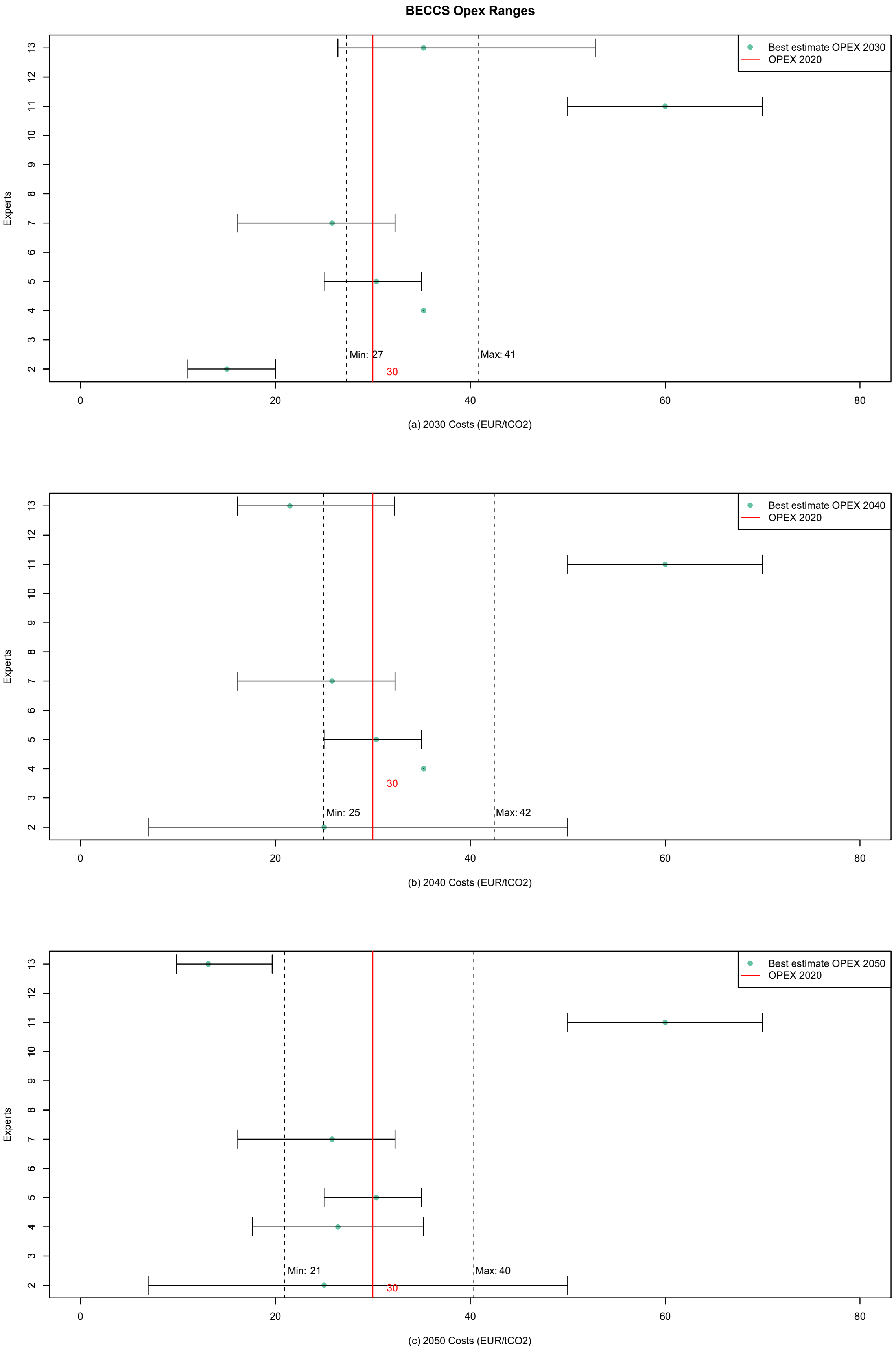


Figure 33: BECCS Opex estimates with minimum, maximum and best estimate of each expert for 2030, 2040 and 2050.

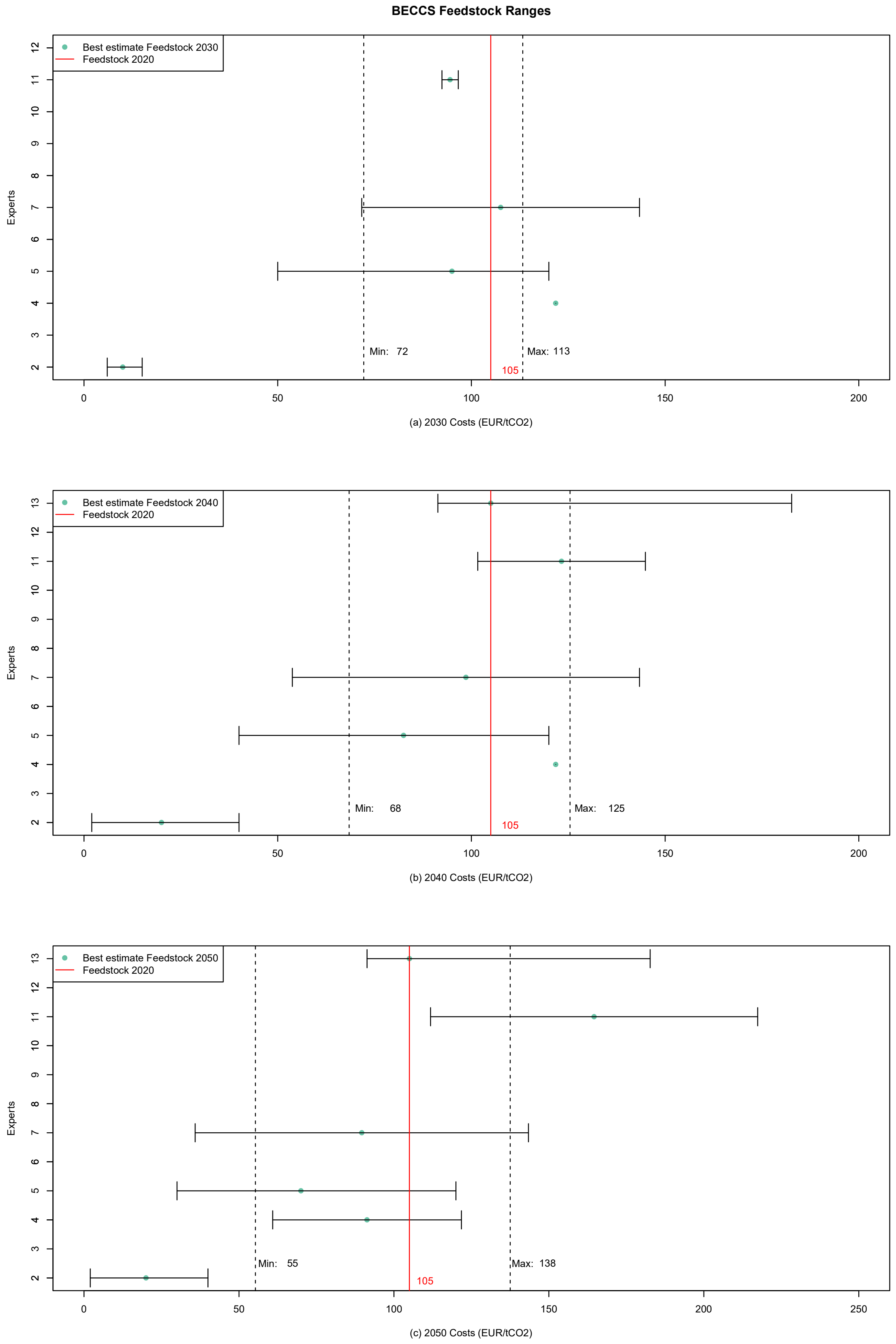


Figure 34: BECCS Feedstock estimates with minimum, maximum and best estimate of each expert for 2030, 2040 and 2050.

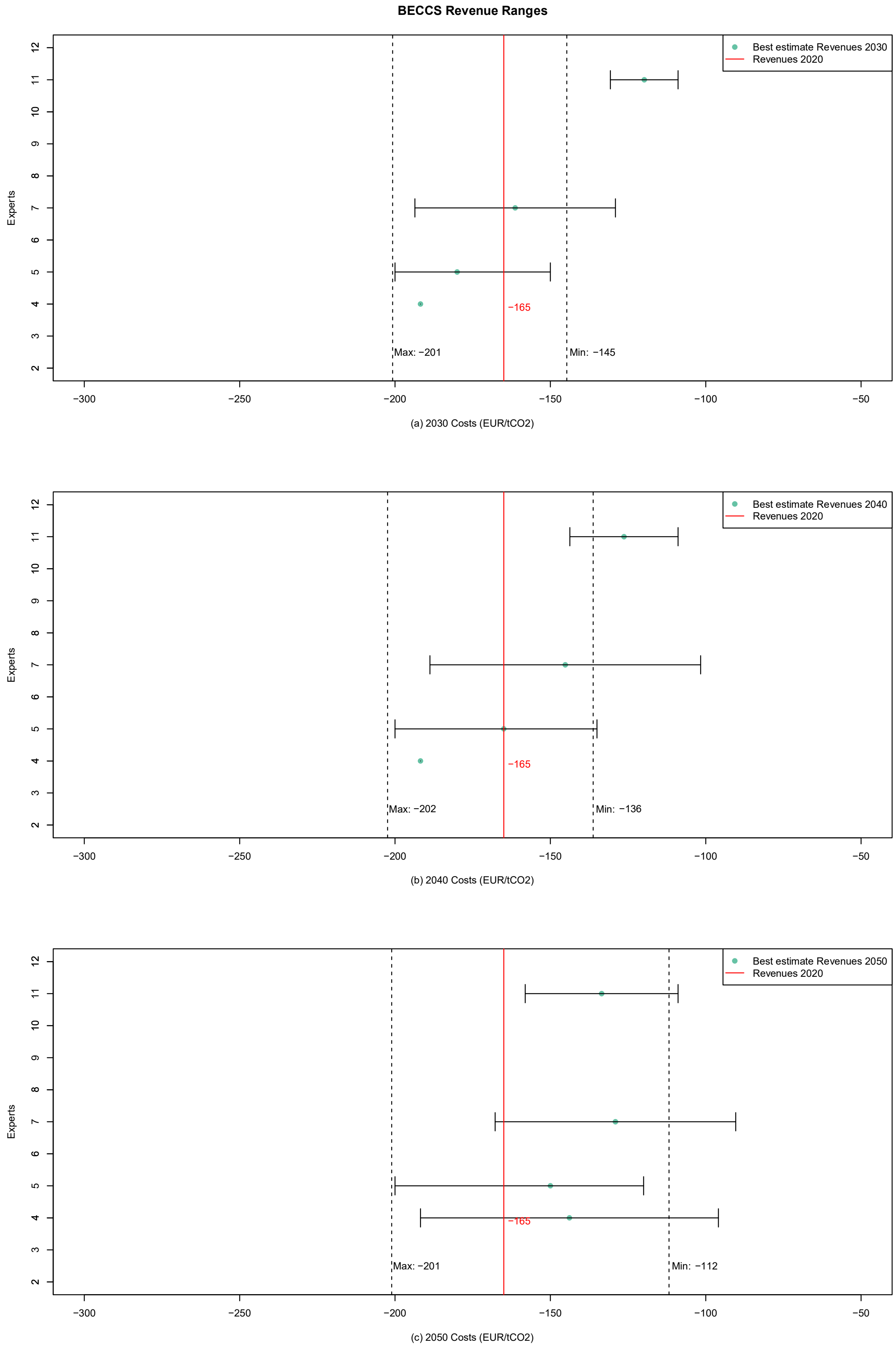
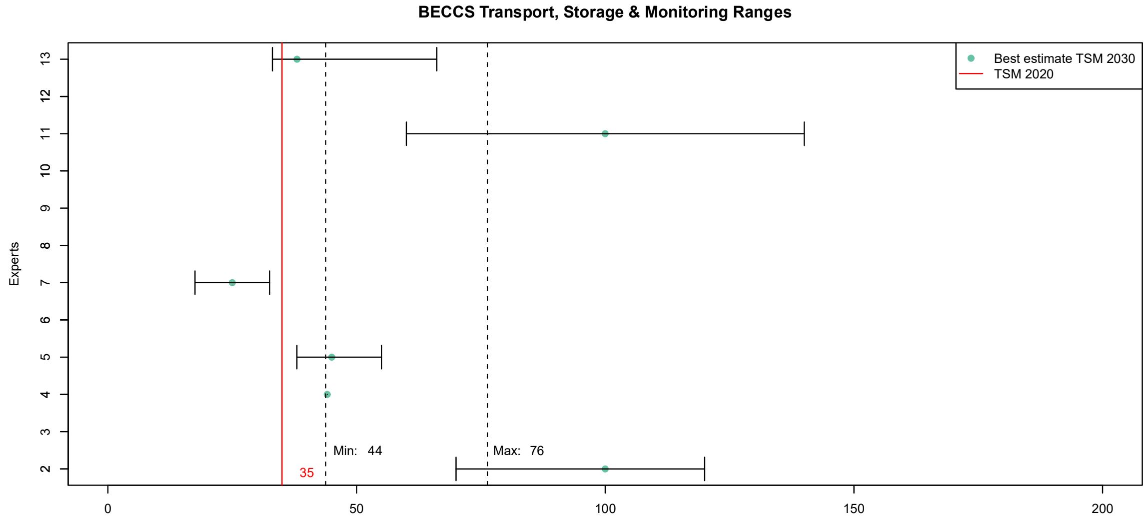
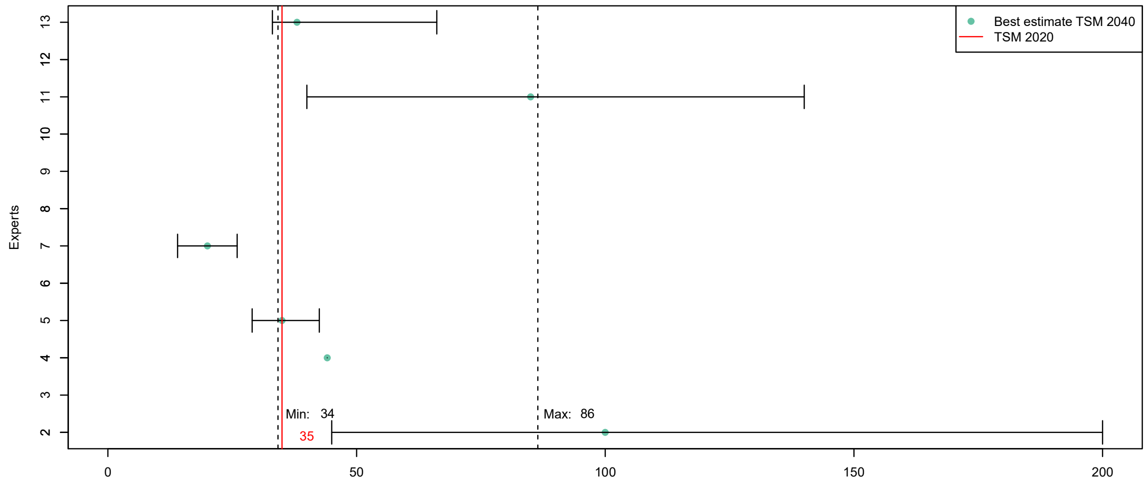


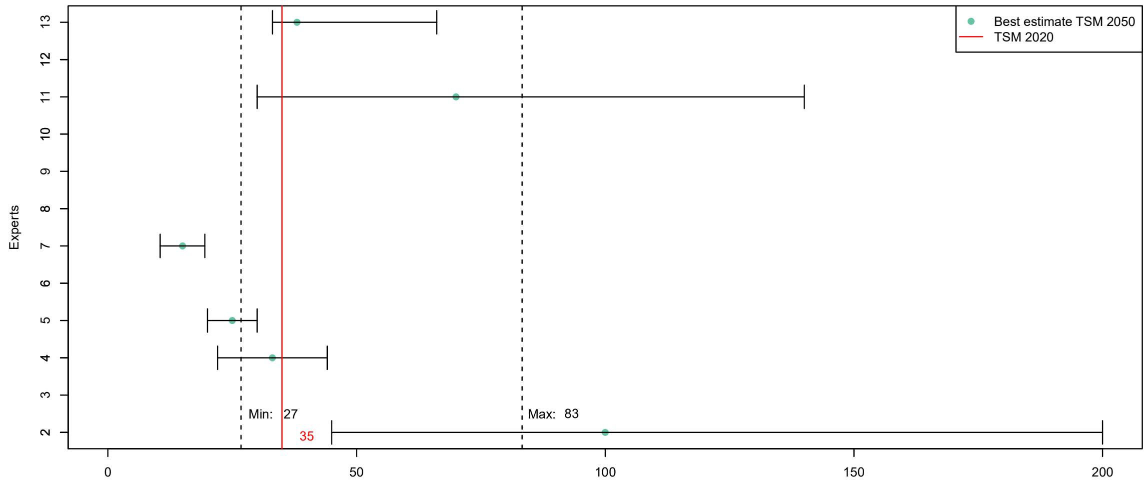
Figure 35: BECCS Revenues estimates with minimum, maximum and best estimate of each expert for 2030, 2040 and 2050.



(a) 2030 Costs (EUR/tCO2)



(b) 2040 Costs (EUR/tCO2)



(c) 2050 Costs (EUR/tCO2)

Figure 36: BECCS TSM estimates with minimum, maximum and best estimate of each expert for 2030, 2040 and 2050.

Costs Best Estimates

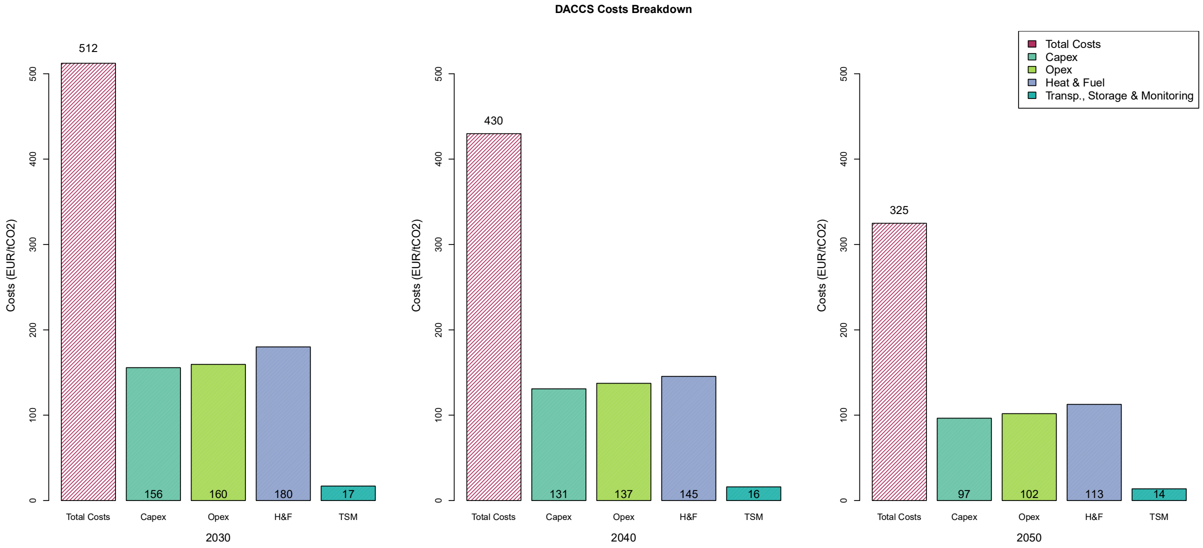


Figure 37: DACCS cost breakdown in 2030, 2040 and 2050. Costs are in €/tCO₂ captured per year.

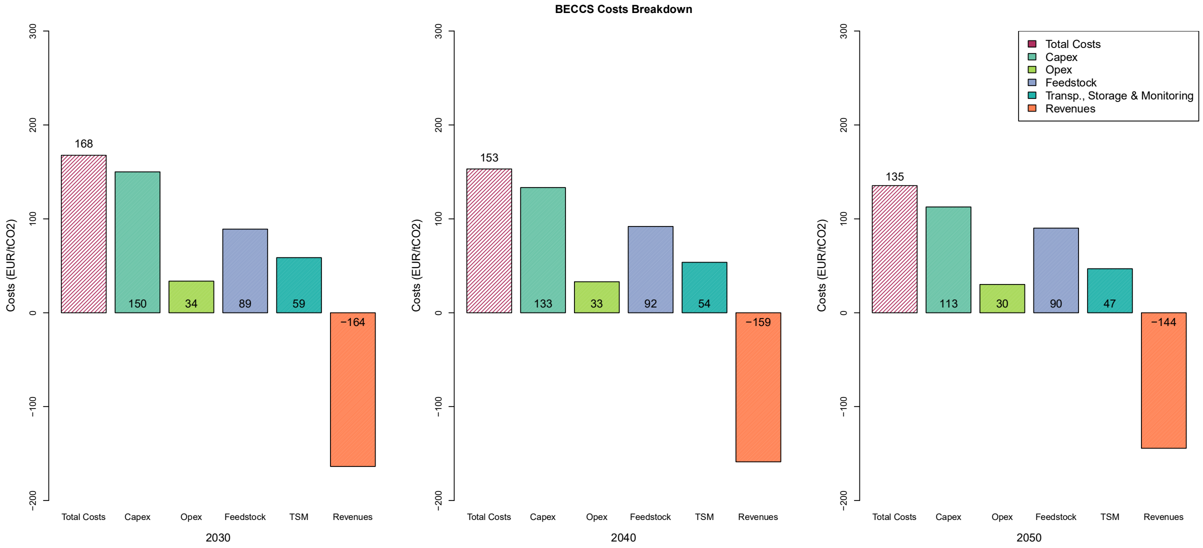


Figure 38: BECCS cost breakdown in 2030, 2040 and 2050. Costs are in €/tCO₂ captured per year.