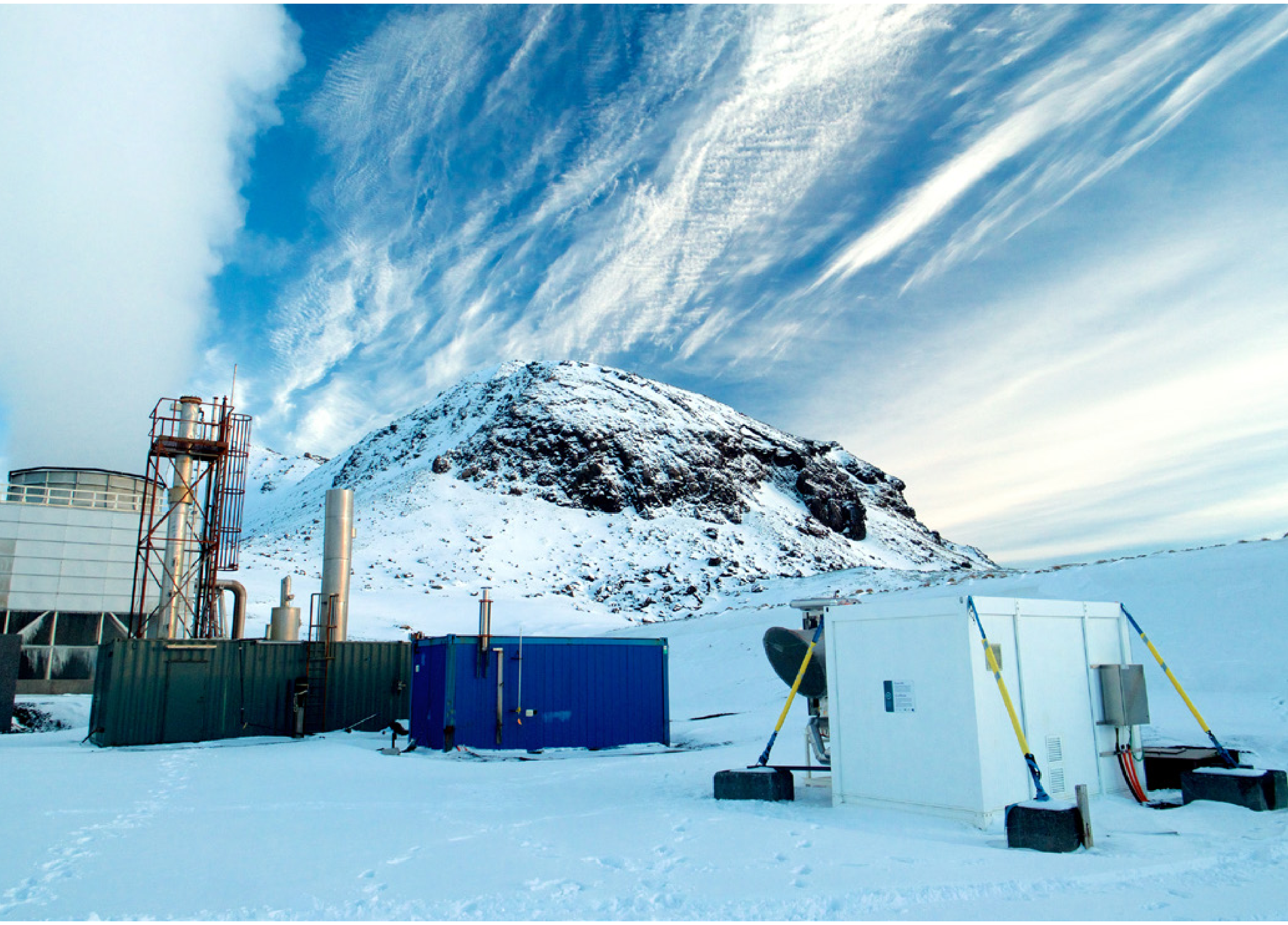
2022 THOUGHT LEADERSHIP

THE ECONOMICS OF DIRECT AIR CARBON CAPTURE AND STORAGE

GLOBAL CCS INSTITUTE

ERIC WILLIAMS
Principal Consultant – Economics

CONTENTS



EXECUTIVE SUMMARY

Carbon capture and storage (CCS) is a set of technologies that capture CO_2 from large emission sources or from the atmosphere and safely stores it underground or permanently in products. CCS is a versatile technology that enables both emissions mitigation from industry, power generation and hydrogen production as well as carbon dioxide removal (CDR) through direct air capture with CCS (DACCS) and bioenergy with CCS (BECCS). CCS is an essential part of the solution to climate change, a perspective supported through analysis of potential pathways to net-zero from organisations including the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) which have highlighted a clear role for point source capture CCS as well as engineered CDR technologies such as DACCS and BECCS.

As the scale and urgency of climate action has become clearer in recent years and governments and companies have done the necessary work to map their own pathways to climate neutrality, CDR technologies - DACCS in particular - have become a focal point in climate mitigation. DACCS is a class of technologies designed to take carbon out of the atmosphere. Typically, this is done by using large arrays of fans to pass air through carbon capture equipment, using a chemical that absorbs CO_2 and then storing it permanently underground.

This paper explores the economics of DACCS. The intent is a thought experiment to show how DACCS deployment (based on different cost assumptions) might affect the global energy system through 2065 while maintaining a net-zero CO_2 pathway consistent with a 1.5°C global average temperature increase.

This paper is focused on change in a single variable: the cost of DACCS. The analysis relies on the economic model described in the methodology, in which the actors within the energy system are free to pursue least-cost options in meeting the net-zero CO_2 pathway (page 8). The study is not a forecast and does not take into account a broader array of cost scenarios, including varying cost reductions in mitigation pathways such as point source CCS, renewables or hydrogen. Further, we do not apply any additional policy assumptions like the phasing out of coal or oil.

We find that low-cost DACCS, should it become available, would reduce the total cost of decarbonisation and meeting global climate goals. DACCS plays a unique role among technological options in meeting net-zero as it can function as a backstop technology. Further, DACCS can be deployed anywhere with good zero-carbon energy and carbon storage nearby.

When DACCS deployment is limited due to high costs, the main decarbonisation pathway for industry and transport (except light duty vehicles, which are electrified) is hydrogen. Electricity generation, buildings, and light vehicles are largely unaffected by the deployment of DACCS and decarbonise through increased efficiency and renewable energy pathways. If breakthroughs materialise in technologies to decarbonise hard-to-abate sectors at low cost, then the relative cost-effectiveness of DACCS and the need to deploy it declines. However, if hard-to-abate applications remain technically difficult and costly to decarbonise, and hydrogen infrastructure at scale proves more difficult than expected, then DACCS may play a more important role in achieving climate goals.

Whilst the amount of fossil fuels used varies considerably between the low cost DACCS and the high cost DACCS scenarios, all scenarios follow the same net-zero trajectory and deliver the same 1.5° Celsius climate outcome. Under all DACCS cost scenarios, direct emissions decrease significantly along the same pathway to the mid-2040s. In the mid-2040s DACCS at very low cost, were it to be realised, has the potential to lead to a rebound in direct emissions as low-cost fossil fuels become economic, leading to less hydrogen and synthetic fuels in the energy system. However, this modelled pathway assumes DACCS would offset any increase in direct emissions and does not take any additional policies that may limit fossil fuel use into account.

DACCS can play an important role as a safety net for achieving net zero, potentially avoiding a climate disaster if other low-cost pathways are not realised. The challenge inherent for governments is to implement policy and give incentives to immediately available mitigation pathways, while supporting the development and commercialisation of lower-cost DACCS. Additional focus should go to the necessary transport and storage infrastructure to support widescale DACCS deployment.

1.0 INTRODUCTION

This paper explores the economics of direct air carbon capture and storage (DACCS), a type of carbon dioxide removal (CDR) technology. The intent is a thought experiment to show how DACCS might affect the global energy system through 2065 while maintaining a net-zero CO_2 pathway consistent with a 1.5°C global average temperature increase. This study is not a forecast of what will happen, but an exploration of how the global energy system might evolve over a range of DACCS costs. We assume that the actors within the energy system are free to pursue least-cost options in meeting the net-zero CO_2 pathway – we do not apply any additional policy assumptions like phasing out coal or oil. Greater levels of DACCS deployment leave more room in the carbon budget for direct emissions that would be more costly to mitigate, whilst still achieving the same net-zero emissions trajectory consistent with a 1.5°C global average temperature increase.

We ground our cost and performance assumptions for DACCS in an assessment of current technologies, but how DACCS technologies evolve over time is uncertain. Therefore, we have designed the study to consider a range of DACCS costs that would likely encompass any potential DACCS technology development. Our scenarios range from a high cost of USD 412 per tCO_2 for DACCS, above which effectively zero DACCS would be deployed, to a low of USD 137 per tCO_2.[1] We assume that the cost of DACCS is essentially flat beginning in 2035 for each scenario. By examining a range of scenarios with incremental differences in DACCS costs, we can identify when DACCS would become economic at each of the assumed costs. The most recent IPCC report considers DACCS cost as likely falling in a range of USD 100 – 300 per tonne CO_2 (IPCC 2022).

Our results show that DACCS reduces the speed with which the existing system must be replaced with advanced fuel production and the infrastructure to transport and consume these advanced fuels, thereby not only lowering overall costs but enabling a more reliable path to net zero and increasing the likelihood of success. When DACCS is limited, the main decarbonization pathway for industry (in addition to direct CCS) and transport (except light duty vehicles) is via hydrogen. Electricity generation, buildings and light-duty vehicles are largely unaffected by the cost and deployment of DACCS and decarbonise independent of hydrogen pathways. DACCS offers an alternative to costly direct mitigation options in industry, heavy-duty vehicles, marine transport, and aviation. In addition to the cost of hydrogen production, deploying hydrogen at scale necessitates a vast new delivery infrastructure and a replacement of many end-use technologies[2], which is also expensive and takes time. Another option is to convert hydrogen to a synthetic fuel and continue using existing fuel transport, storage, and delivery infrastructure and existing end-use technology, but synthetic fuels are also expensive and require carbon neutral CO_2 derived from BECCS or DACCS for synthetic fuels to be carbon neutral.

We find that the technology pathways needed to reach net zero and their corresponding costs are sensitive to changes in the cost of DACCS. As we compare the high-cost DACCS scenario (USD 412 per tCO_2) to the lowest cost one (USD 137 per tCO_2) in our study, the cumulative global low-carbon energy supply (i.e. hydrogen, synthetic fuels and biofuels) through 2065 is lower by 2,034 EJ, while the cumulative global supply of fossil fuels is higher by 1,377 EJ. In the middle-cost DACCS scenario (USD 223 per tCO_2), the cumulative global low-carbon energy supply through 2065 is lower by 1,475 EJ, and cumulative global supply of fossil fuels is higher by 757 EJ compared to the high-cost scenario.

---

[1] For the sake of simplicity, these prices are global costs that are an output of the model because they take into account actual electricity costs for CO_2 compression by scenario; the inputs to the model are region-specific capital costs that reflect energy sector equipment cost differences between regions plus fixed and variable operating costs and relevant operating characteristics.

[2] For example, hydrogen cannot be used as a drop-in fuel replacement in a diesel truck; only trucks designed specifically for hydrogen can use hydrogen. Even if hydrogen were produced at scale to supply the world's truck fleet, the existing diesel fuel transport and storage would need to be replaced with hydrogen-capable transport, storage and refuelling stations.

> **DACCS CAN PLAY AN IMPORTANT ROLE AS A SAFETY NET FOR ACHIEVING NET ZERO, POTENTIALLY AVOIDING A CLIMATE DISASTER IF OTHER LOW-COST PATHWAYS ARE NOT REALISED.**

By delaying some high-cost low-carbon energy and maintaining some low-cost high-carbon energy, low-cost DACCS can lead to global energy system savings of as much as USD 3 trillion in net present value (NPV), while still following the same net CO_2 emissions pathway and achieving the same climate benefit. If breakthroughs materialize in technologies to decarbonise hard-to-abate applications at low cost or more generally in hydrogen production and use, then the relative cost-effectiveness of DACCS and the need to deploy it will decline. On the other hand, if hard-to-abate applications remain difficult and costly, and hydrogen infrastructure at scale proves more difficult than expected, then low-cost DACCS, were it to be realised, may play a critical role in achieving climate goals by providing a safety net.

2.0 CARBON DIOXIDE REMOVAL

CDR technologies, falling in three broad categories, remove carbon dioxide directly from the atmosphere. One category is bioenergy with carbon capture and storage (BECCS). BECCS is considered a carbon removal technology because bioenergy that is already very low carbon or carbon neutral on a lifecycle basis can be combined with carbon capture technology to make the overall process carbon negative. Another category of CDR is DACCS, which is a class of technologies designed for the exclusive purpose of taking carbon out of the atmosphere. A typical DACCS technology does this by using large arrays of fans to pass air through carbon capture equipment using a chemical that absorbs the CO_2, then uses heat to separate the CO_2 from the chemical into a concentrated stream that can be stored. Most of the CO_2 captured by BECCS and DACCS is expected to be stored geologically or through other means such as mineralization, but some CO_2 may be used to produce carbon-neutral synthetic fuels. The 3rd category of CDR is nature-based solutions in agriculture, forestry, and other land-uses (AFOLU), oceans and enhanced weathering in which these natural processes take in CO_2 from the atmosphere.

Energy models used for analysing CO_2 reductions have traditionally included a “backstop” technology, which was a generic undefined high-cost technology that was available if all other mitigation options were exhausted in the model. CDR, and in particular DACCS, is in many ways a real backstop technology, not just for energy models, but for meeting net zero targets. The IPCC finds that all scenarios that limit warming to no more than 1.5°C deploy carbon dioxide removal (CDR) technologies. Further, most models are unable to find pathways that limit warming to 1.5°C without CDR technologies (Schipper et al. 2022).

DACCS plays a unique role among technological options in meeting net zero. As will be shown in a later section, DACCS functions as a backstop technology that caps the overall price of CO_2 as long as that price would otherwise exceed the cost of DACCS. DACCS can be deployed anywhere with good zero-carbon energy and carbon storage nearby. At the global level in quantities that are likely to deploy on an economic basis, DACCS is likely to be more limited by cost and technological readiness than by capacity of carbon storage and availability of low-carbon energy, as there are many locations that have both.[3] Unlike energy production that is spread throughout the world because it must be cost-effectively delivered to demand, DACCS provides the same global benefit wherever it is located, so locations with good storage and low-carbon energy can be scaled up to serve global needs.

BECCS and nature-based solutions are important for CDR, but they are fundamentally different than DACCS. We find that, if available, BECCS is always preferred by the model because it provides both CDR and usable energy, thus lowering overall system costs compared to a combination of DACCS and another costly zero-carbon energy source. BECCS, though, is limited by the sustainable biomass available for energy, assumed to be about 131 EJ globally (Haberl et al. 2010). Exactly how many tonnes of CO_2 are removed through natural processes in AFOLU are less certain than DACCS and BECCS, as is the permanence of those sequestered tonnes of carbon compared to geologic storage. While nature-based solutions within AFOLU tend to be low cost, they also carry higher risks of reversal through processes such as fire, drought or disease impacting reforested areas.

---

[3] We assume that DACCS in this study is powered by solar, but it can also be powered by any low-carbon energy sources that can deliver electricity and heat, such as nuclear or a combination of PV/wind/hydro plus a fossil fuel with direct CCS.

3.0 METHODOLOGY

For the analysis presented in this paper, we use a global energy model based on the Open Source Energy MOdeling SYStem (OSEMOSYS) framework. Much of the data and assumptions that define this model were originally developed at the King Abdullah Petroleum Studies and Research Center (KAPSARC). We have updated the costs for the compression and transport of CO_2 as well as the compression and transport of hydrogen and added options for CCS retrofits for the electricity sector. We have also updated the costs for all electricity generation and hydrogen production technologies. The model consists of four groupings of countries.[4]

The model finds a global energy system with the lowest discounted system cost while meeting the demand for energy and services[5] and complying with a CO_2 reduction trajectory to reach net zero and beyond by 2054. The model can build and operate technologies that span the whole energy system from resource extraction to final end-use, including end-use energy efficiency investments. The time horizon of the model runs through 2065. Multiple technologies are available for the model to decarbonise energy systems. Details of the model methodology and description are available in a brief technical report available at *www.globalccsinstitute.com.*

Because DACCS is a pre-commercial technology, the cost is highly uncertain. The purpose of this study is to explore the energy system implications for a range of DACCS costs. What drives the analysis presented here is a series of scenarios in which the cost of DACCS varies. We assume that by 2035 the lowest DACCS cost is consistent with the range of costs for DACCS with low temperature heat requirements (90° – 100°C) in Fasihi, Efimova, and Breyer (2019) and that capital costs decline thereafter by 0.3% per year and that the energy needed to operate DACCS declines by 0.5% per year after 2035. Starting with this lowest DACCS capital cost (DACCS-01), we increase the capital cost incrementally for a total of 31 scenarios through DACCS-31. Capital cost for the DACCS technology is only part of the cost of DACCS.

The model endogenously builds the required energy source for DACCS, based on a hybrid solar panel and solar thermal technology that produces electricity and heat in a ratio of 3.5 GJ of heat (at 90°C) to 1 GJ of electricity (Raygen 2018).[6] We scale up this solar technology to meet the heat load of DACCS and also adjust the capacity factor for DACCS to that of the solar technology. The model also provides grid electricity with endogenously determined prices and resource mix to operate CO_2 compression and pumps for pipeline transport and injection. The hybrid PV technology, when scaled to best match the heat demand for DACCS, produces more electricity than the DACCS technology requires directly. This additional electricity generation is assumed to offset a portion of the electricity needed for CO_2 compression. The cost of pipelines and storage is also accounted for endogenously within the model.

The full cost of CO_2 captured by DACCS, transported and stored is therefore a model output rather than a model input, and the total cost can only be found after the model runs and in years in which the model has deployed DACCS. The global cost of CO_2 captured by DACCS, transported and stored is USD 137 per tCO_2 for the DACCS-01 scenario and USD 412 per tCO_2 for the DACCS-31 scenario.[7] For context, the latest IPCC report cites a cost range of DACCS between USD 100 – 300 per tCO_2 (IPCC 2022).

---

[4] The grouping of countries (Advanced Economies, "Brazil, China, Russia and South Africa", the Middle East, and Rest of World) is a holdover from the original work at KAPSARC. We only have regions or groupings in the model for this study as a way to add some heterogeneity to the global results. We do not draw any conclusions about regional/grouping level results.

[5] Energy and service demands are defined and met for buildings, industry, and transport sectors (passenger vehicles, heavy-duty vehicles, marine freight, and air travel). These demands are met through chains of technologies and fuels from resource extraction through primary (e.g. direct fossil fuel consumption), secondary (e.g. electricity generation or refined transportation fuels or hydrogen from natural gas), tertiary (hydrogen via electricity) and even quaternary (e.g. synthetic fuel via hydrogen from electricity) conversion and transport of energy.

[6] While we base the energy supplied for DACCS on PV Ultra, we have not done an engineering assessment of this hybrid system. DACCS is first deployed in the model at low-cost assumptions in 2043. We assume that by this date that an integrated renewable DACCS technology will be available that falls within the cost and performance assumptions modelled.

[7] The model assumes a simple 5% real discount rate for all capital investments, including DACCS. The resulting DACCS costs per tonne may appear low compared to published DACCS cost values because those studies typically use a weighted average cost of capital that would result in annualized capital costs that are 50% to 100% higher than using a simple 5% real discount rate, depending on the debt-to-equity ratio and the assumed return on equity.

The resulting full cost of DACCS for each scenario is shown in Figure 1 with the high-, mid- and low-cost DACCS scenarios highlighted. A given scenario can vary from year to year as the model operates DACCS at maximum capacity in some years but at less than maximum capacity in other years. When DACCS cost is high, total DACCS deployment is low, and new DACCS capacity coming online in a different region of the model with a slightly different cost can shift the global average cost shown in the figure, accounting for the uptick for some of the cost lines at the top of the figure.

The CO_2 reduction trajectory for this analysis is based on the IPCC SSP1-1.9 scenario, which reaches net zero in 2054 and net negative CO_2 emissions beyond (Figure 2) (Masson-Delmotte et al. 2021). All scenarios presented here follow this same CO_2 trajectory. In fact, all scenarios are identical except for the changes in DACCS costs discussed above, so all changes in results stem from those varied DACCS cost assumptions.

Figure 1: Global average DACCS cost in years deployed by scenario

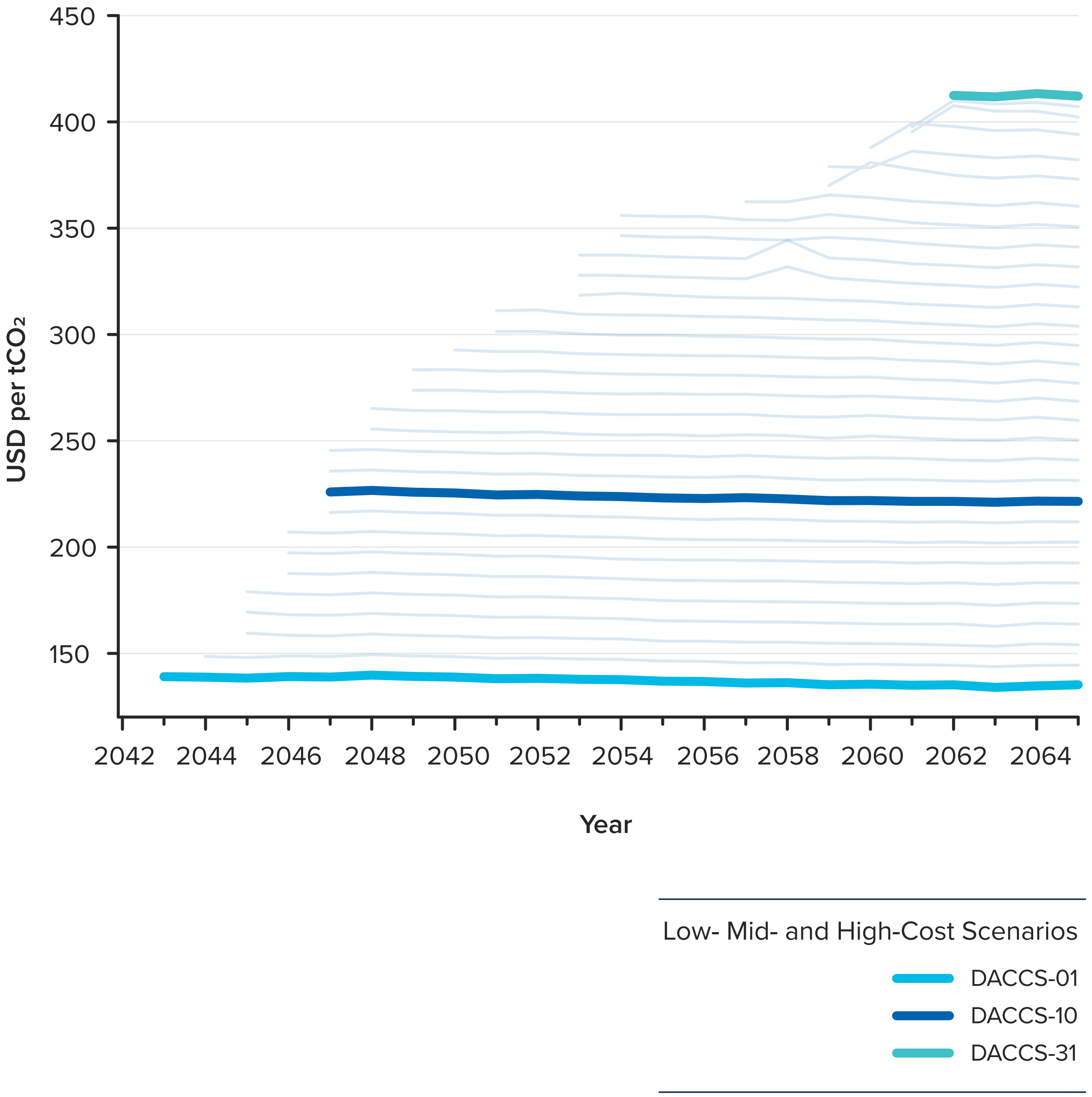
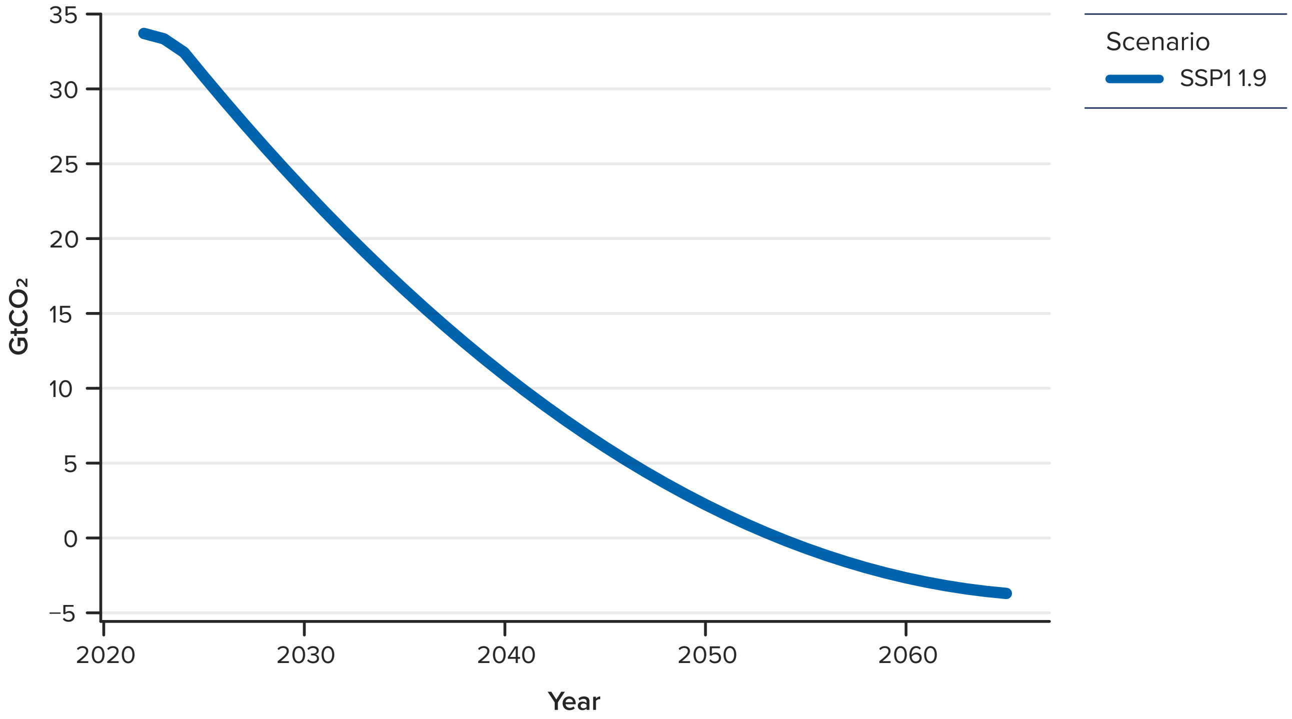


Figure 2: Net zero emissions trajectory used in study



4.0 RESULTS

4.1 Emissions

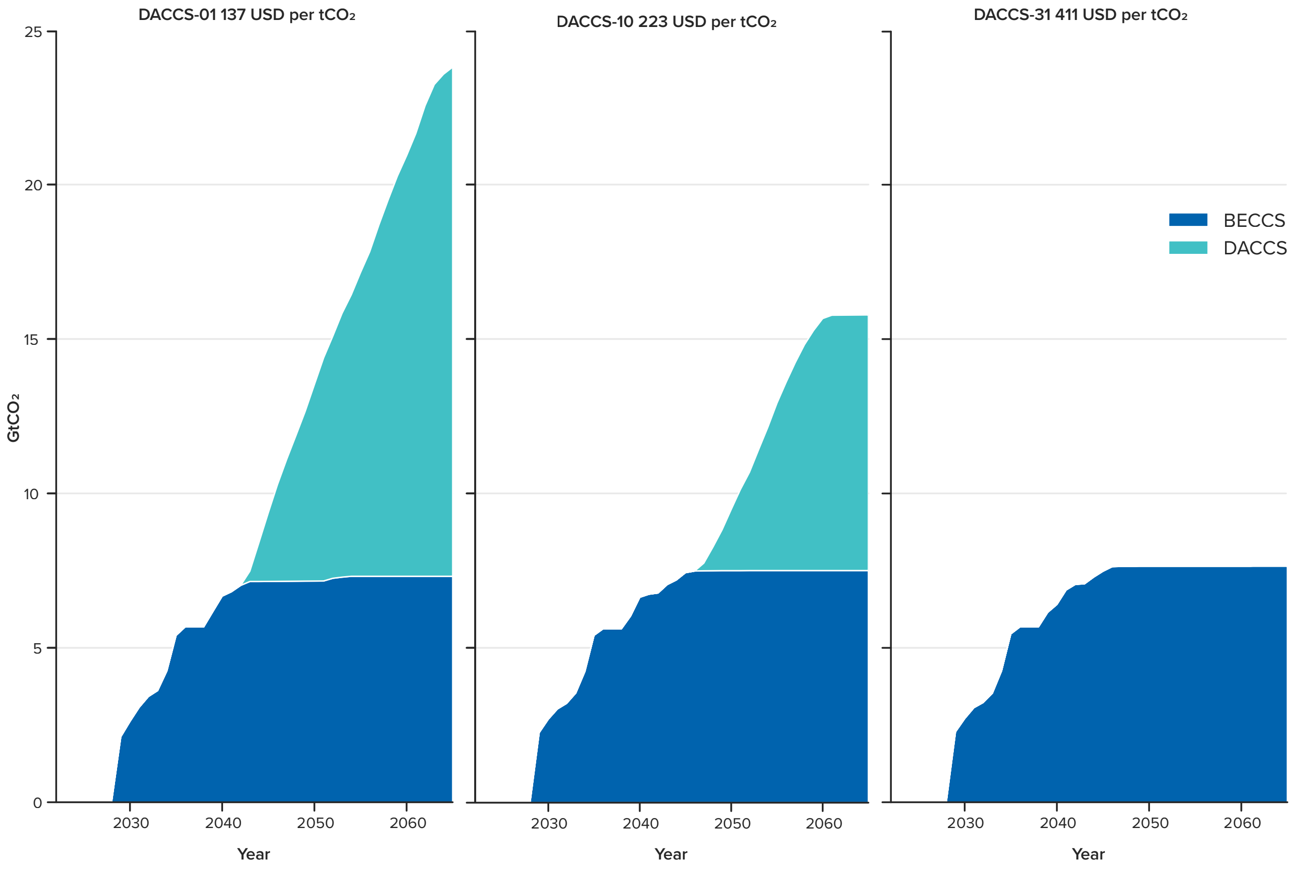
The quantities of CDR that result from the scenarios analysed in this paper fall within the range in the scientific literature, except for the upper end of DACCS with the lowest cost scenarios. In its recently released report on mitigation, the IPCC reviewed the literature on mitigation pathways, and the range of CDR with high temperature overshoot is shown in Table 1 along with the results of this study (IPCC 2022).[8,9]

Table 1: Cumulative CDR through 2100

	BECCS ($GtCO_2$)	DACCS ($GtCO_2$)	Total CDR ($GtCO_2$)
IPCC	226 – 842	109 – 539	333 – 1221
Our results	491 – 510	1.2 – 786	511 – 1277

Figure 3 shows CO_2 emission results for low (DACCS-01), middle (DACCS-10) and high (DACCS-31) cost scenarios. All three scenarios result in nearly the same number of tonnes of CO_2 removed by BECCS, but they differ significantly in the tonnes of CO_2 removed by DACCS. In 2065, the high-cost DACCS scenario results in only 0.03 $GtCO_2$, the middle cost DACCS scenario results in 8.3 $GtCO_2$, and the low-cost DACCS scenario results in 16.4 $GtCO_2$.

Figure 3: CDR at low-, middle- and high-cost DACCS



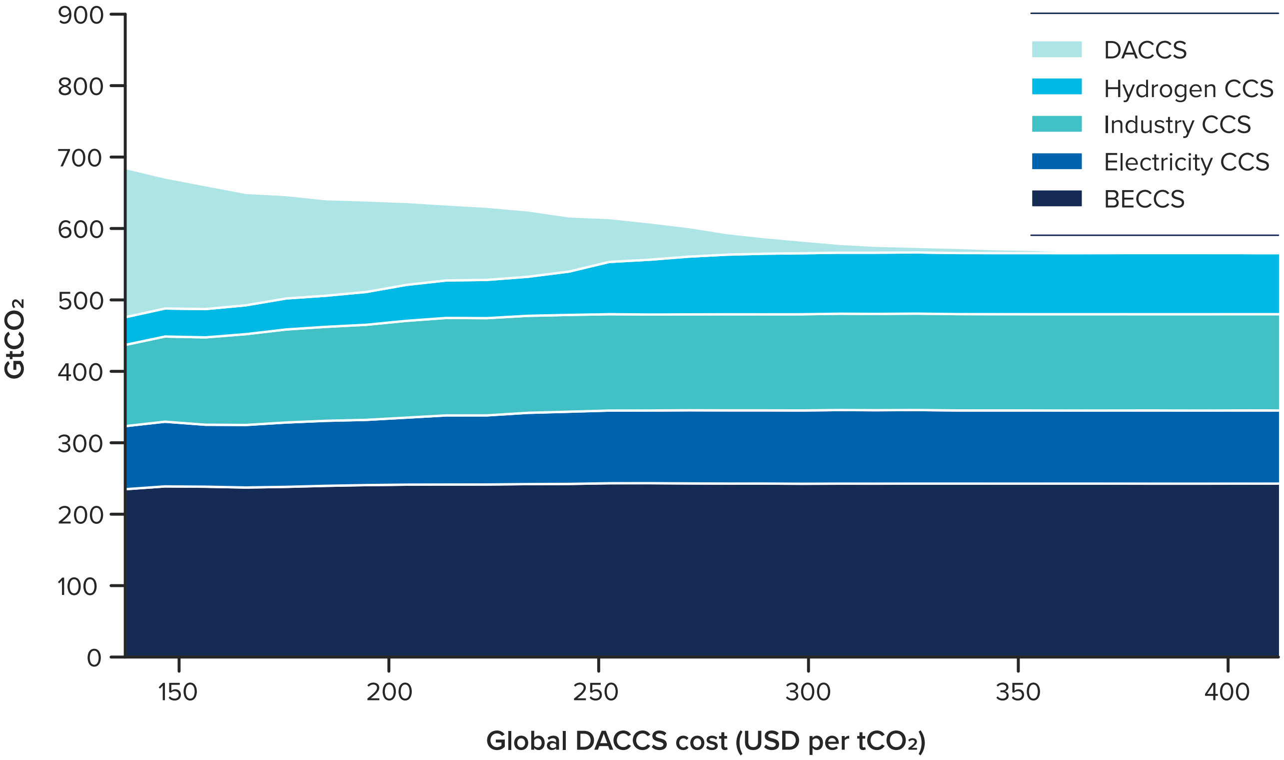
---

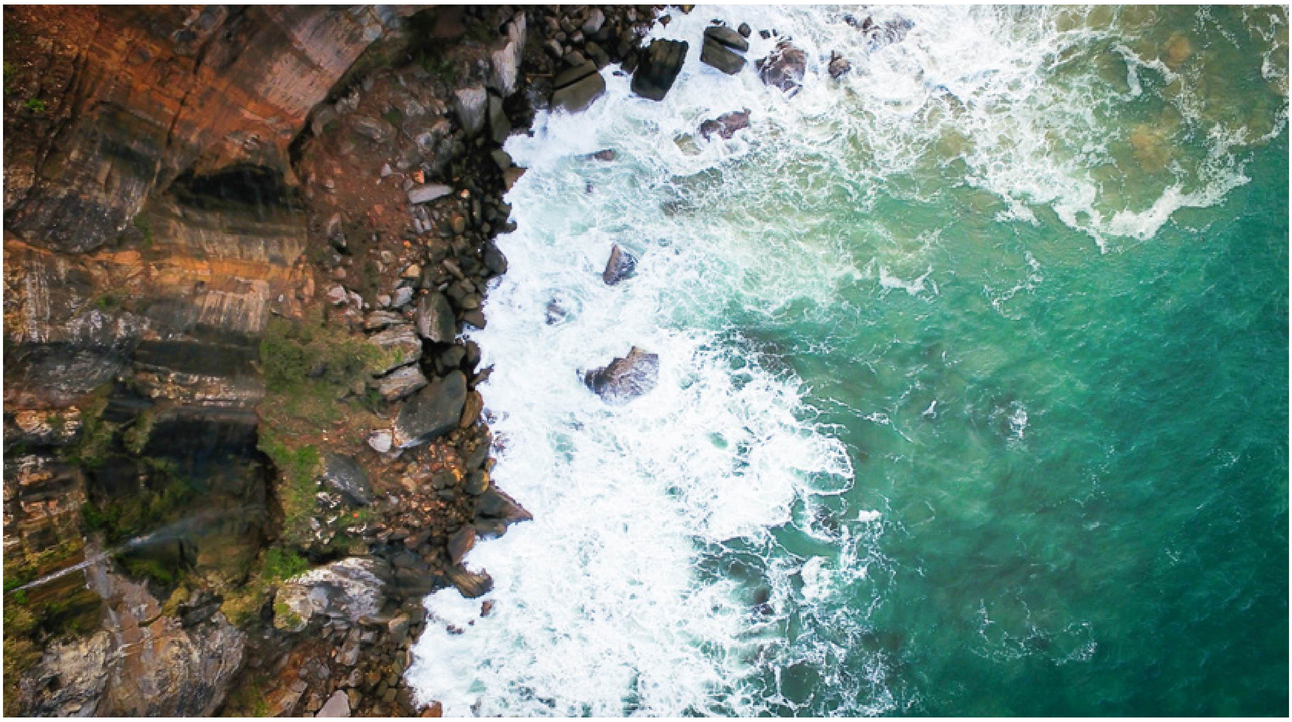
[8] The IPCC reports that afforestation and reforestation can contribute 20 – 400 $GtCO_2$. The model used in this analysis does not model agriculture, forestry and other land use (AFOLU).

[9] The model for the analysis presented in this paper runs through 2065. The CDR results for the year 2065 were assumed to repeat for years 2061 – 2100 to arrive at an approximate value for the 21st century for comparison to the IPCC results.

Figure 4 shows cumulative CO_2 stored from 2022 through 2065 by type of CCS, showing results for all scenarios from lowest DACCS cost to highest DACCS cost. This figure reveals that DACCS and hydrogen CCS are partial substitutes; as the cost of DACCS declines, DACCS expands and replaces some hydrogen CCS. As the cost of DACCS approaches USD 400 per tCO_2, DACCS deployment goes to near zero. The model contains higher cost mitigation options than USD 400 per ton, but BECCS is sufficient to offset the emissions from these very high-cost applications. A view of the CO_2 results as presented in Figure 4 belies the significant changes in the energy system and its overall cost.

Figure 4: Cumulative CO_2 stored from 2022 to 2065 by CCS type as the cost of DACCS changes





4.2 Economics

The model optimizes the global energy system to find the lowest cost configuration that satisfies all constraints, based on the input assumptions provided. The model does not account for any macroeconomic feedback from the changes in direct costs. By varying the capital cost of DACCS for DACCS-01 (resulting in USD137/t CO_2) through DACCS-31 (resulting in USD412/t CO_2) scenarios, the model finds the lowest total discounted cost of the global energy system for each scenario. Figure 5 plots the NPV savings in the global energy system at different DACCS costs. For example, at a DACCS cost of USD 137 per tCO_2, the global energy system saves NPV USD 3 trillion compared to a DACCS cost of USD 412 per tCO_2 and above. A DACCS cost of USD 223 per tCO_2 saves 787 billion compared to a DACCS cost of USD 412 per tCO_2. At DACCS cost of USD 307 per tCO_2, savings drops to USD 58 billion.

Figure 5: NPV global energy system savings as the cost of DACCS changes

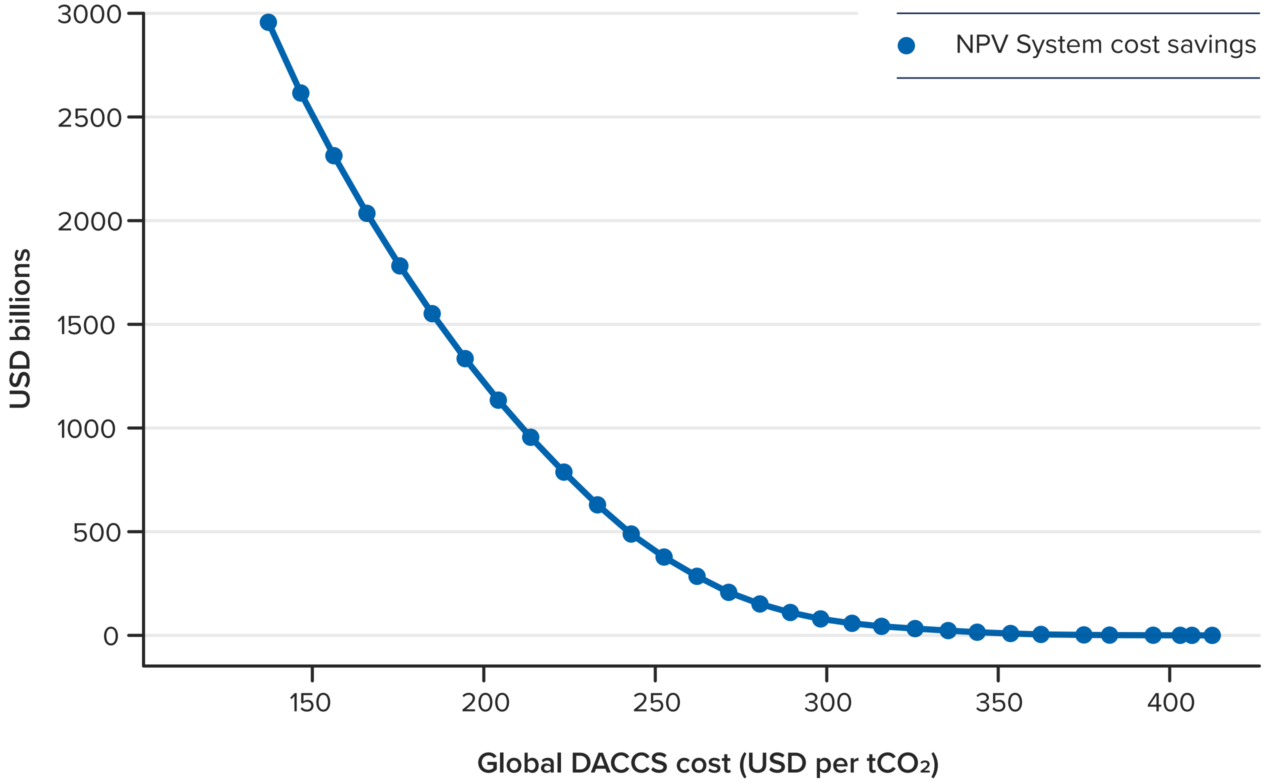


Figure 6 shows the global CO_2 price and DACCS cost for selected scenarios. The length of the line representing DACCS costs also reflects the years in which DACCS is deployed and operated. Low DACCS costs result in earlier DACCS deployment and lower CO_2 prices. As DACCS costs increase, the resulting CO_2 prices increase, and DACCS deployment is delayed until CO_2 prices reach the cost of DACCS. DACCS is clearly functioning as the marginal CO_2 mitigation option in the model and is capping CO_2 prices.

The CO_2 price goes up and down in the early years because the overall constraint on net CO_2 emissions starts immediately, but the model has some reasonable constraints on how quickly options like CCS, hydrogen production, synfuels, biomethane, etc. can ramp up. The implicit demand in the model for carbon mitigation drives up the CO_2 price in the early years because of these constraints. By 2028/29, most of these capital-intensive CO_2 mitigation options have begun to deploy and drive down the price of CO_2.

Many models allow CO_2 banking that can smooth out some of this bumpiness. In effect, banking finds a CO_2 price at the outset that smoothly grows at a rate equal to the discount rate while providing a price signal that results in CO_2 emissions that equal the net CO_2 target. While smooth CO_2 price curves that banking enables are attractive, they are difficult to compare with the cost of DACCS, as banking masks the actual marginal cost/price of CO_2 in any given year. Because we want to compare the real marginal cost of CO_2 at a system level with the cost of CO_2 captured and stored for DACCS, we run the model without CO_2 banking.

Figure 6: Global CO_2 prices and DACCS cost per tCO_2 by scenario

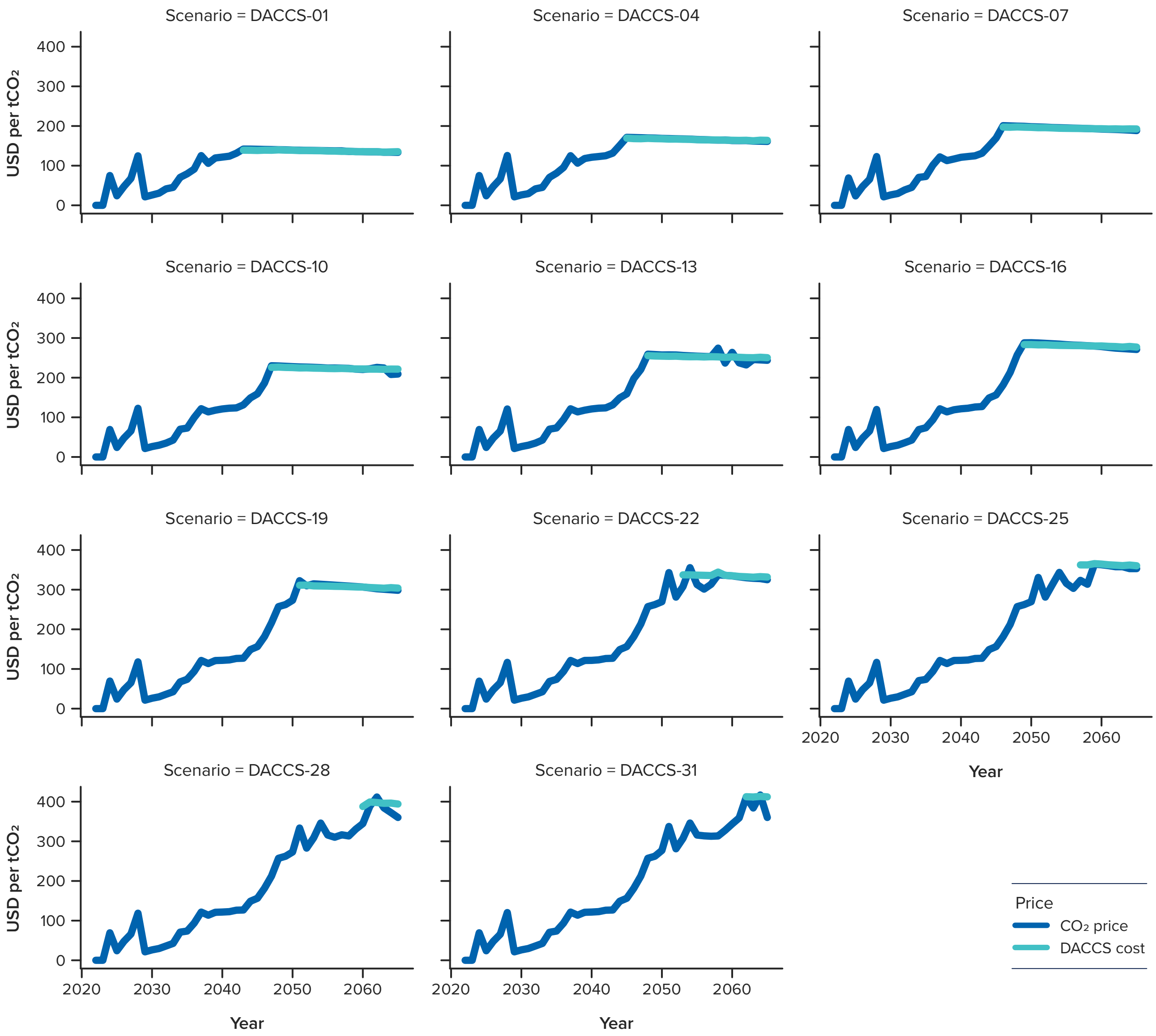


Figure 7 shows when DACCS becomes economic to deploy commercially at what cost per tCO_2. The higher the cost of DACCS, the later DACCS is economically deployed in the model. The lower the cost of DACCS, the earlier it becomes economic. This threshold between uneconomic and economic does not imply that once DACCS crosses that threshold that investment suddenly grows at any DACCS cost.

Figure 8 shows the extent to which DACCS is deployed at what cost and when. At DACCS costs above around USD 350 per tCO_2, the quantity of tonnes stored is low. Below around USD 250 per tCO_2, the quantity of tonnes stored becomes significant.

Figure 7. Breakeven costs for DACCS over time (assumes no DACCS-specific incentives)

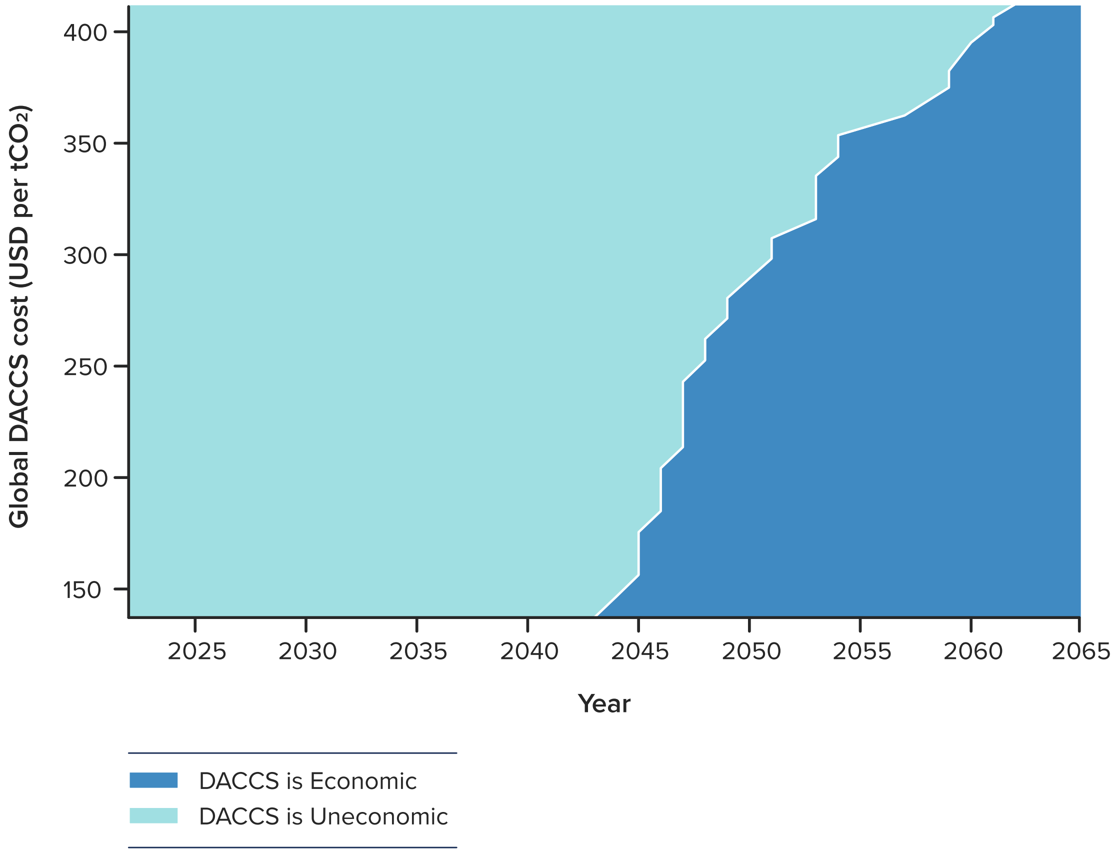


Figure 8. Quantities of CO_2 stored from DACCS at different costs over time

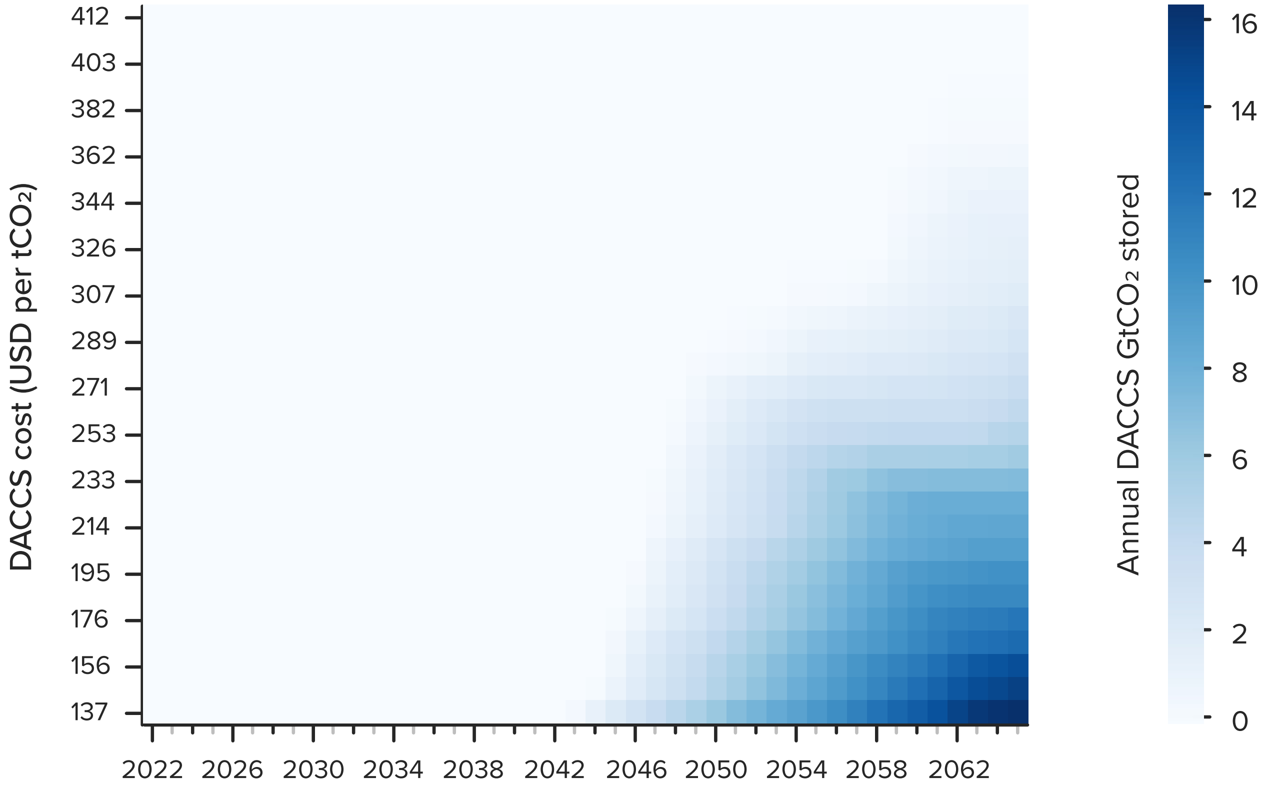
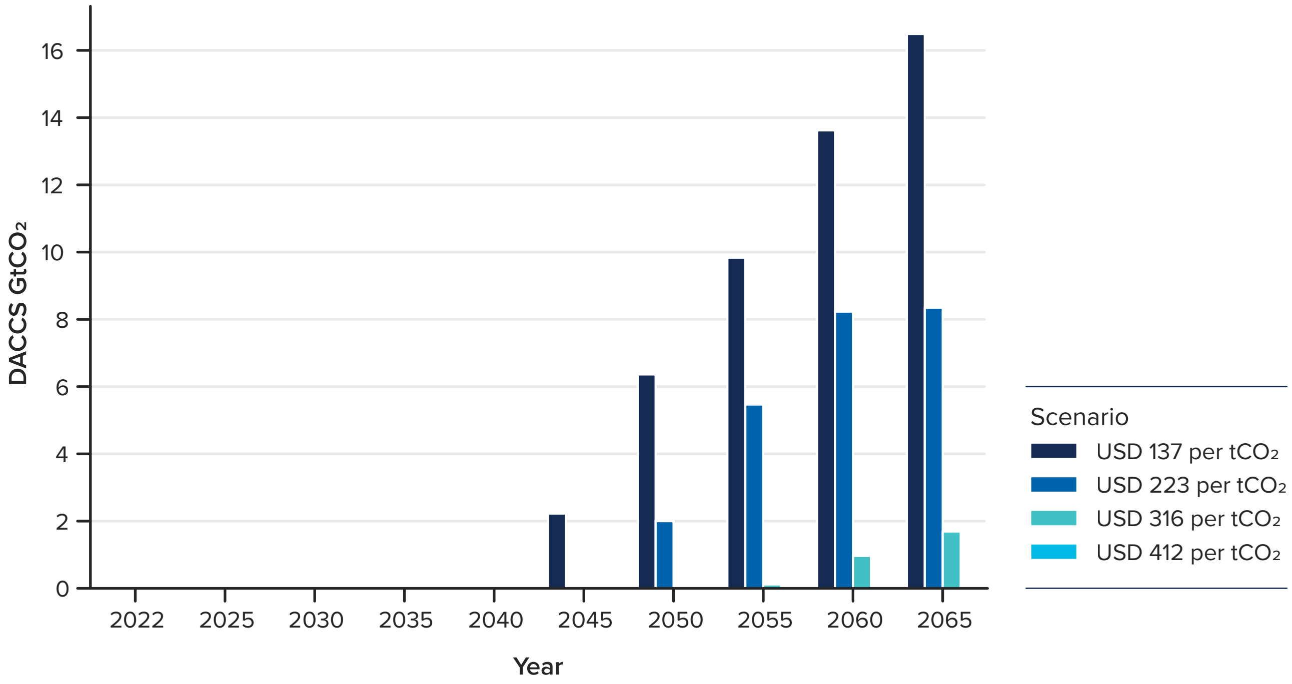


Figure 9 highlights several DACCS cost scenarios and the $GtCO_2$ stored in each. The amount of DACCS that can be deployed expands with time as the cost of CO_2 in the system goes up, enabling more and more cost-effective DACCS. The lower the cost of DACCS, the earlier and more rapid the growth in DACCS; the higher the cost of DACCS, the later and slower the growth in DACCS.

Figure 9: Annual CO_2 captured and stored from DACCS by year at varying costs of DACCS

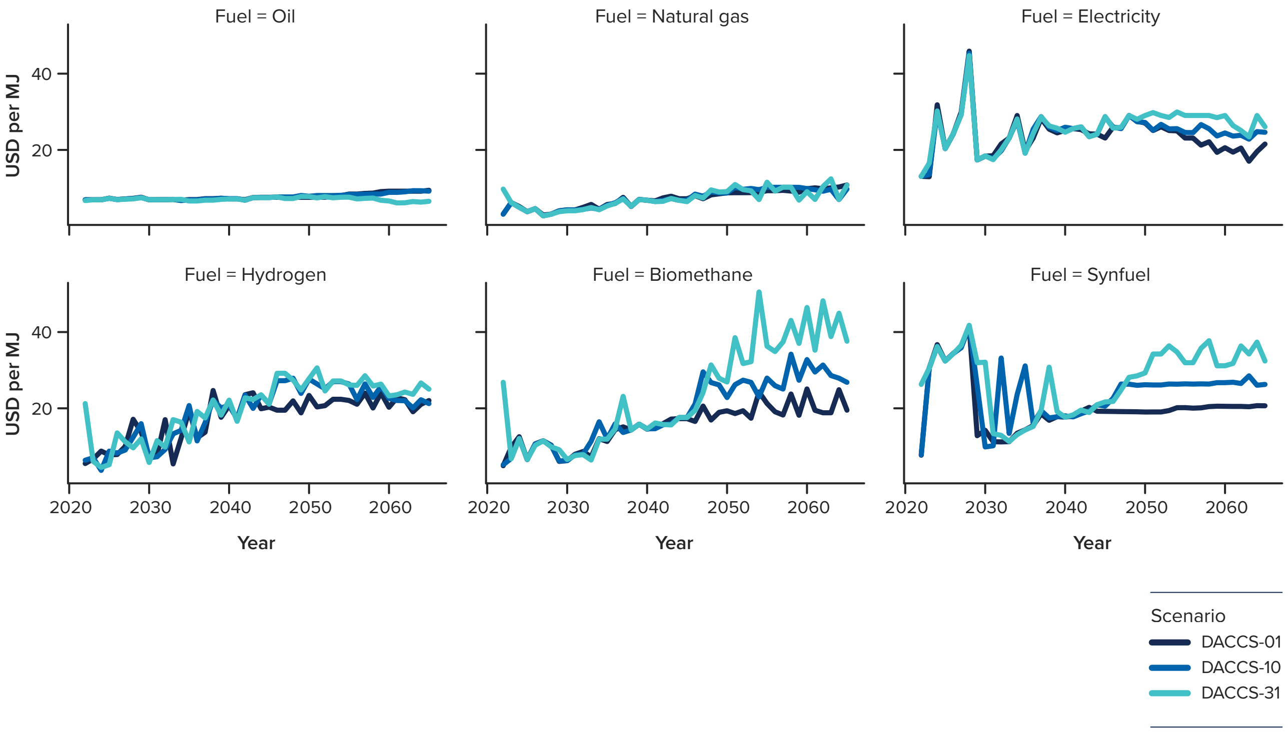


In a net zero world, every tonne of CO_2 must either be avoided or directly captured or removed from the atmosphere. Once BECCS and nature-based offsets have been exhausted, DACCS becomes the option on the margin to remove CO_2 from the atmosphere and to stay on a net zero and beyond trajectory. In the absence of DACCS or in cases where DACCS is expensive, more costly mitigation options must be deployed.

Changes in system cost are a reflection of how DACCS drives changes in the energy system itself. Decarbonization pathways often involve tertiary and even quaternary conversions that lose energy and require major capital investments at each step in the chain. An example of a tertiary conversion is solar to electricity to hydrogen, and an example of a quaternary conversion is to then convert hydrogen to a synthetic fuel. The resulting prices for advanced fuels that require multiple conversions from solar, wind or biomass are not only far higher than the prices for the fossil fuels they replace, as shown in Figure 10, but are higher as the cost of DACCS increases. Higher cost of DACCS means greater deployment of advanced fuels like hydrogen (both blue and green), biomethane and synfuel to achieve the same net-zero trajectory. This in turn means higher prices for these fuels because, as with any commodity, increased demand leads to higher prices, but also the cost of the inputs increases (e.g. the cost of natural gas goes up as the demand for hydrogen made from natural gas goes up; the quality of solar and wind resource declines as the ideal locations are already taken to produce electricity and hydrogen; as more biomass is used for biomethane, cost goes up; as the cost of electricity and biomass goes up, so does the cost of synfuels). For example, by 2050, the price of synfuel in scenarios with high-cost DACCS is about 4 times the price of oil, yet for low-cost DACCS, synfuel is about twice the price of oil.

The prices of electricity, hydrogen and synfuel spike in early years. The reason for these spikes is that the model places realistic constraints based on lead times for the construction of certain capital-intensive technologies like power plants with CCS, hydrogen from natural gas with CCS, nuclear, etc. The carbon trajectory toward net zero drives the demand for low-carbon electricity and other fuels, but the opportunities to meet these demands are limited in the early years, driving prices up.

Figure 10: Real fuel prices for DACCS-01, DACCS-10, and DACCS-31 scenarios



4.3 Energy system

Total primary energy production by 2065 is 186 EJ per year lower for the lowest-cost DACCS scenario and 126 EJ lower for the middle-cost DACCS scenario than the highest-cost DACCS scenario (Figure 11) because the greater reliance on hydrogen (both blue and green) and other advanced fuels in the high-cost DACCS scenario ultimately requires more primary energy.[10]

Fossil fuels, both with and without CCS, represent 34% of primary energy in the lowest-cost DACCS scenario in 2065, 30% in the middle-cost DACCS scenario and 22% in the highest-cost DACCS scenario. Fossil with CCS represents 13% of primary energy for low-cost DACCS, 14% for middle-cost DACCS, and 16% for high-cost DACCS.

BECCS, Nuclear and hydro are essentially the same regardless of the cost of DACCS. Despite the considerable use of solar to operate DACCS in the low-cost scenario, solar by 2065 comprises only 16% of primary energy for low-cost DACCS compared to 20% for middle-cost DACCS and 29% for high-cost DACCS. Similarly, wind is 19% of primary energy for low-cost DACCS, 30% for middle-cost DACCS and 31% for high-cost DACCS.

Most of the additional solar and wind in the high-cost DACCS scenario is used for hydrogen production. Hydrogen production and consumption pathways are primarily how scenarios with limited DACCS can meet the CO_2 trajectory by decarbonizing hard-to-abate sectors and applications that are not good candidates for direct CCS or electrification powered by low-carbon generation.

Even with high-cost DACCS, fossil fuels continue to play a role in the global energy system. Natural gas is used primarily in conjunction with CCS in electricity and industry. The cost of coal is low enough that in the low-cost DACCS scenario, some continued coal use is economic and coal without CCS rebounds in later years in the absence of any further policy interventions. At middle-cost DACCS, overall coal consumption drops significantly, and a substantial portion of remaining coal is used in conjunction with CCS, despite a small portion of coal without CCS rebounding in later years. High-cost DACCS results in coal use only with CCS by around 2045.

Oil continues at nearly the same level when the cost of DACCS is low or moderate, despite the passenger transport sector shifting entirely to electricity by 2050. Low-carbon options for aviation but also marine transport and heavy-duty vehicles are expensive. Low-cost and even middle-cost DACCS offers an alternative to the most expensive mitigation options in transport. When the cost of DACCS is high and virtually no DACCS is deployed, oil production declines in 2065 to about 30% of current production.

Whilst the amount of fossil fuels used varies considerably between the low cost DACCS and the high cost DACCS scenarios, all scenarios follow the same net-zero trajectory and deliver the same 1.5° Celsius climate outcome.

---

[10] Primary energy for fossil fuels is a straightforward measure of the energy value of the fuels produced. Defining primary energy for renewables is less straightforward. Several approaches are used. One approach is to count the energy value of the output of the first conversion, typically electricity, which results in the lowest accounting of renewable primary energy. Another approach, used in this study, counts how much fossil energy would be needed to produce the same amount of renewable electricity assuming an average 33.3% efficiency; this method results in a middle value of renewable primary energy. The third approach is to estimate the energy value of the renewable resource needed to produce the initial energy conversion, which results in the highest value for primary renewable energy.

Figure 11: Primary energy production for low-, middle- and high-cost DACCS scenarios

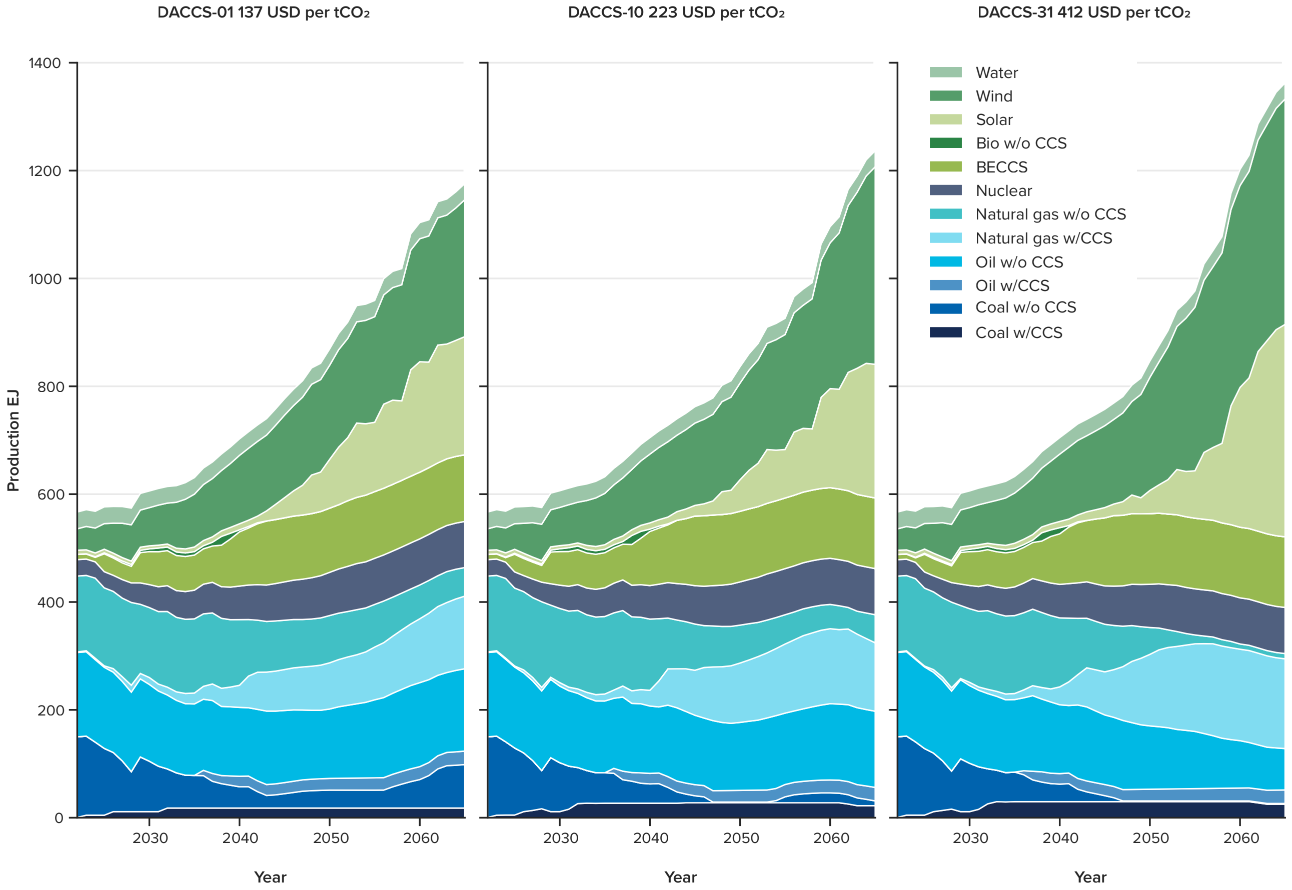


Figure 12 shows secondary traditional and advanced fuels production. For low-, middle- and high-cost DACCS scenarios, gasoline production declines to zero around 2050 as gasoline is replaced by electricity for passenger vehicles. Diesel fuel for heavy-duty vehicles and marine transport declines until around 2040, then grows again to approximately 2022 levels by 2065 in the low-cost DACCS scenario, but continues to drop until 2055 with a slight uptick in the middle-cost DACCS scenario. Diesel continues to decline over the whole period in the high-cost DACCS scenario. All three DACCS scenarios are substituting hydrogen and some synfuel for diesel, but the high-cost DACCS scenario substitutes more, the middle-cost DACCS scenario less, and the low-cost DACCS scenario even less. Much more hydrogen is produced in the high-cost DACCS scenario than the low- and middle-cost scenarios because 1) hydrogen is used in transportation to a much greater degree, 2) hydrogen displaces some coal, oil and natural gas consumption in industry and buildings, and 3) hydrogen is used to make more synfuel. The prices of advanced fuels (Figure 10) remain much higher than the prices of fossil fuels they replace and explain much of the increase in total system cost as the cost of DACCS increases.

Grid-based electricity generation plus distributed renewables and efficiency – everything in Figure 13 except solar and wind for hydrogen and solar for DACCS – is largely the same no matter the cost of DACCS. An exception is that the low-cost DACCS scenario deploys more natural gas with CCS because more natural gas is available than in the middle-cost and high-cost DACCS scenarios, which need more natural gas for hydrogen production. As a result of less natural gas with CCS for electricity generation, the middle-cost and high-cost scenarios also deploys some CCS retrofits on existing coal generation, along with more hydrogen fuel cells to make up the difference in firm power capacity.

Figure 12: Secondary: traditional and advanced fuel production for low-, middle- and high-cost DACCS scenarios

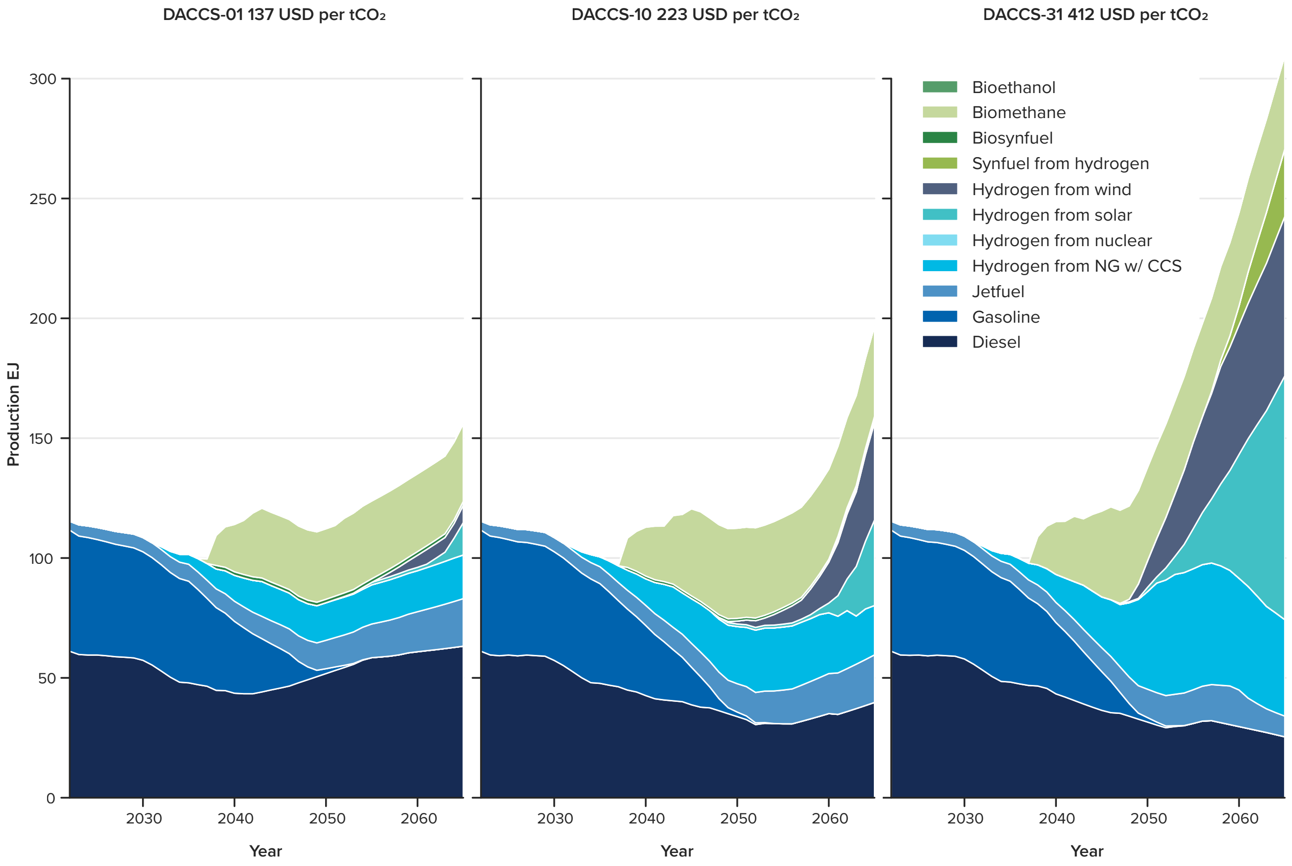
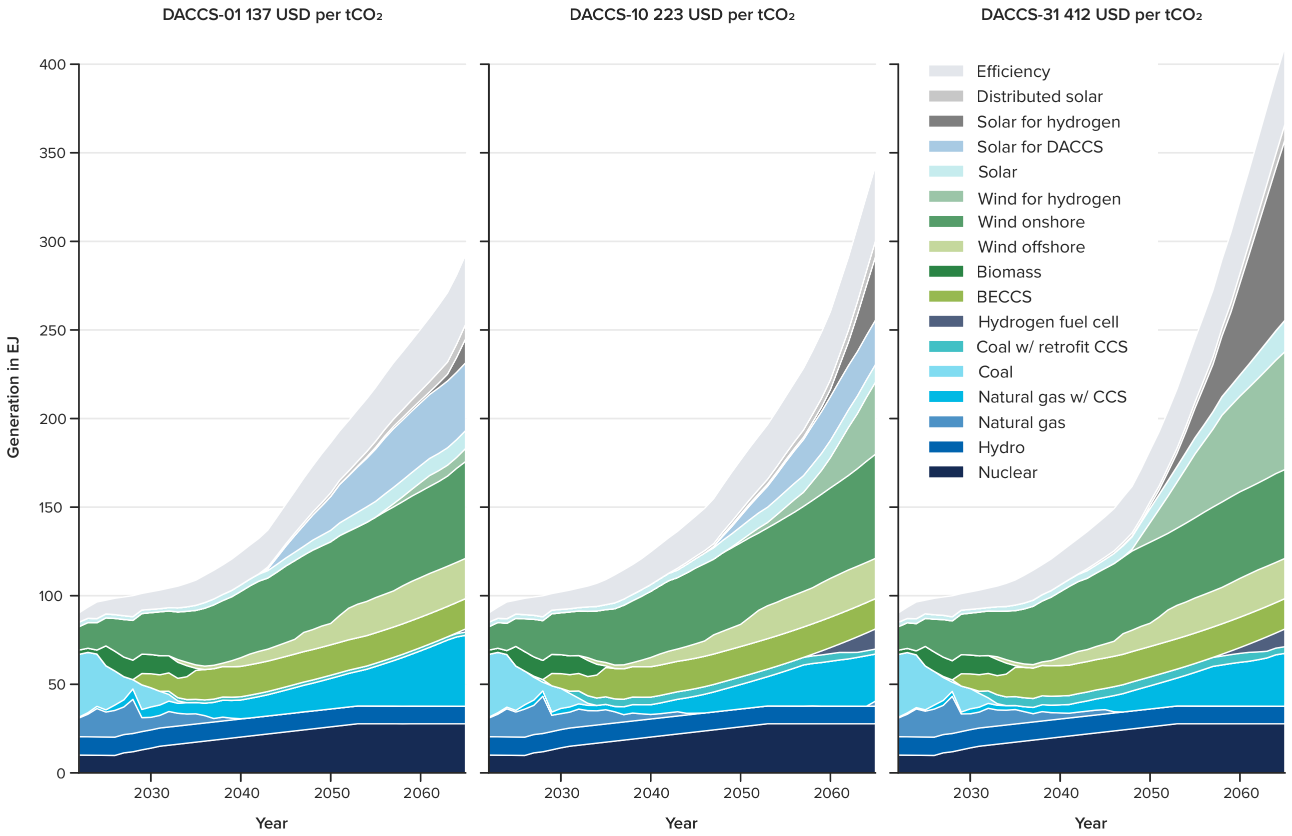


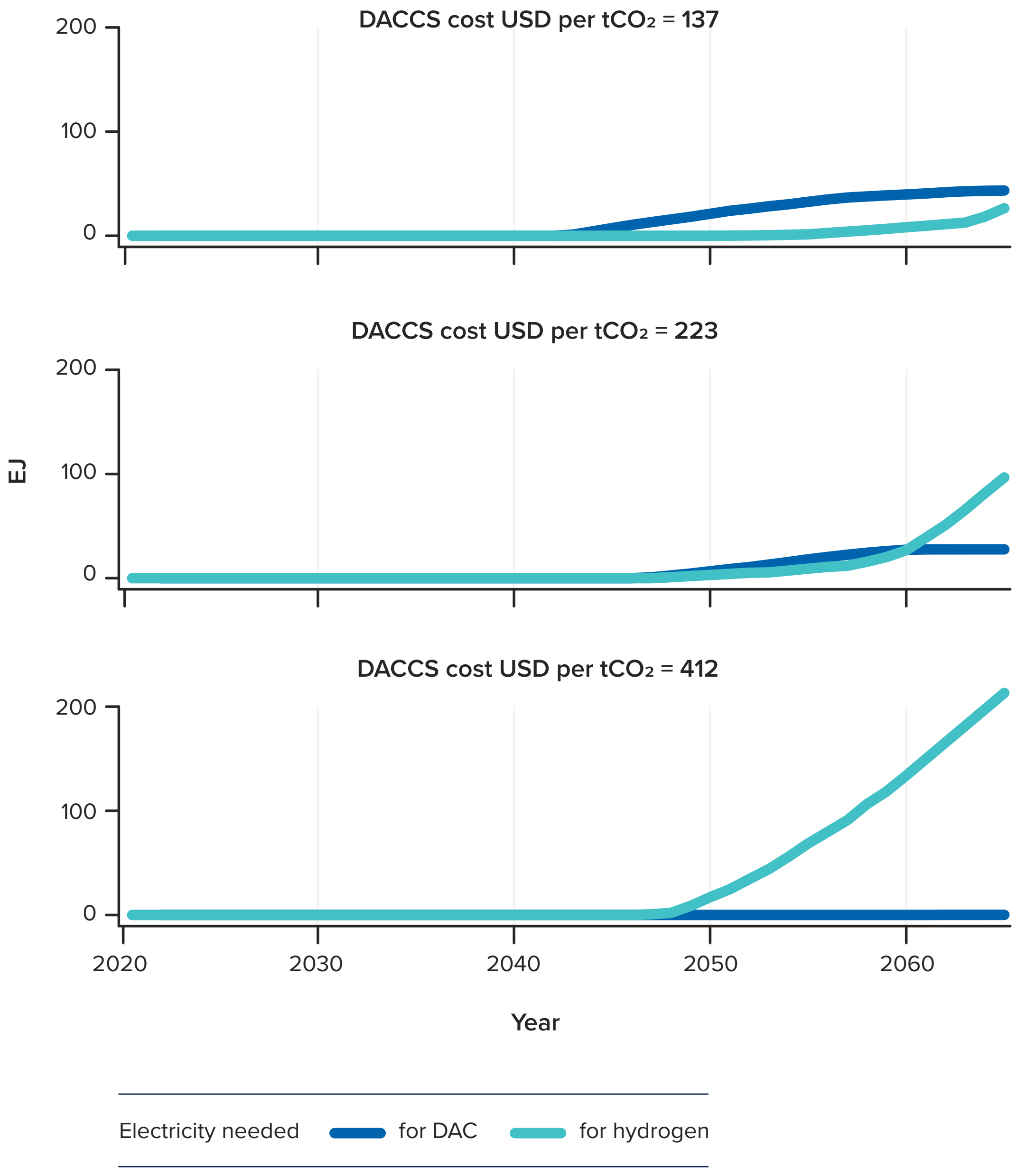
Figure 13: Electricity generation for low-, middle- and high-cost DACCS scenarios



Regardless of the cost of DACCS, the electricity sector dedicated to grid generation broadly decarbonises by 1) avoiding generation by investing in end-use energy efficiency, 2) retiring fossil fuel generation without CCS, 3) and expanding nuclear, BECCS, solar, and wind. Wind and solar for hydrogen increase dramatically from 21 EJ to 168 EJ in 2065 as the cost of DACCS increases from low to high, while solar for DACCS declines from 38.2 EJ to 0.09 EJ in 2065.

Figure 14 shows the total electricity needed for DACCS and hydrogen production for the low-, mid-, and high-cost DACCS scenarios and underscores the extent to which the need for electricity to produce hydrogen grows dramatically when the cost of DACCS is high.

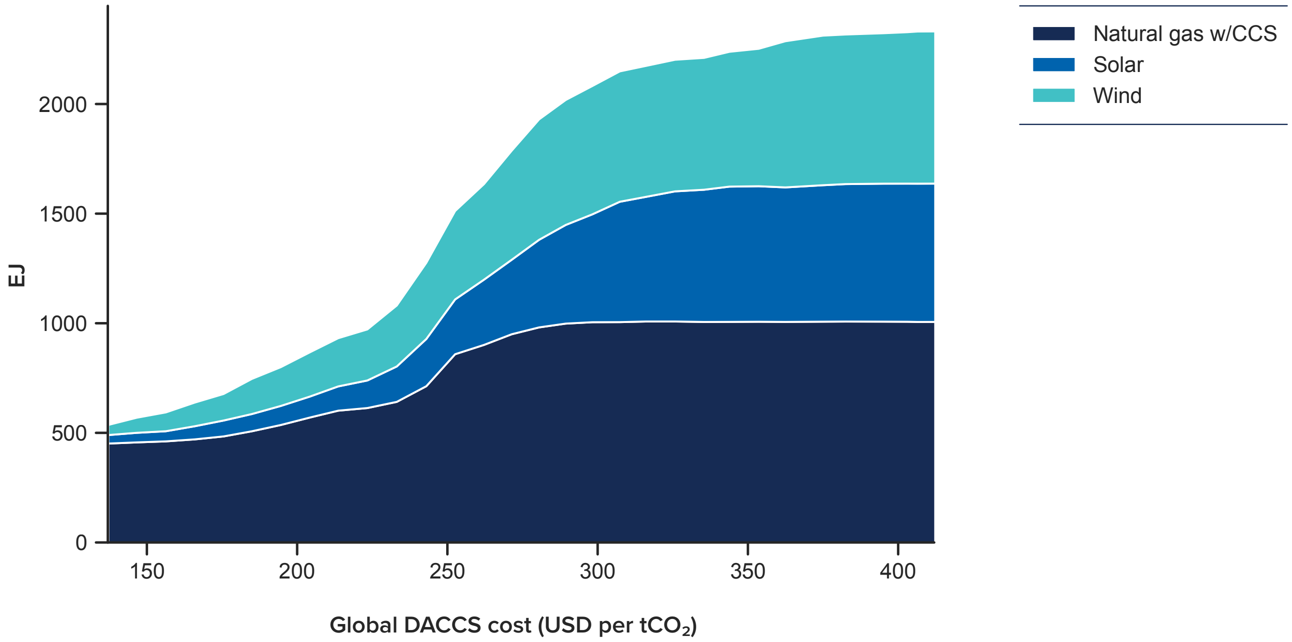
Figure 14. Electricity needed for DACCS and hydrogen in low-, mid- and high-cost DACCS scenarios



To put the requirements for solar capacity for all uses – electricity, hydrogen and DACCS – by 2065 into perspective, the low-cost DACCS scenario needs the equivalent of 32 million soccer/football fields covered in solar panels to produce 73 EJ of solar at the system level, the middle-cost DACCS scenario needs the equivalent of 35 million fields to produce 80 EJ of solar, and the high-cost DACCS scenario needs 58 million fields to produce 131 EJ of solar.[11] As population also expands and competition for land becomes greater, siting land-intensive solar PV will become more challenging.[12] The low-cost DACCS scenario's land requirement is 45% lower than the high-cost DACCS scenario.

More and more applications must make direct CO_2 reductions as the cost of DACCS increases, and one of the primary ways to reduce emissions in industry and heavy-duty vehicles is to switch from fossil fuels to hydrogen. Aviation and maritime shipping tend to shift toward synfuels produced via hydrogen or biomass pathways rather than use hydrogen directly. Hydrogen plays a key role in the energy system regardless of the cost of DACCS, but in a higher-DACCS costs scenario the growth in hydrogen increases substantially (Figure 15). As DACCS costs increase, not only does renewable (green) hydrogen production increase, so does hydrogen from natural gas with CCS (blue hydrogen), which is one of the main reasons that point-source CCS increases in a higher-cost DACCS scenario.

Figure 15: Cumulative hydrogen production by fuel source with changes in DACCS cost



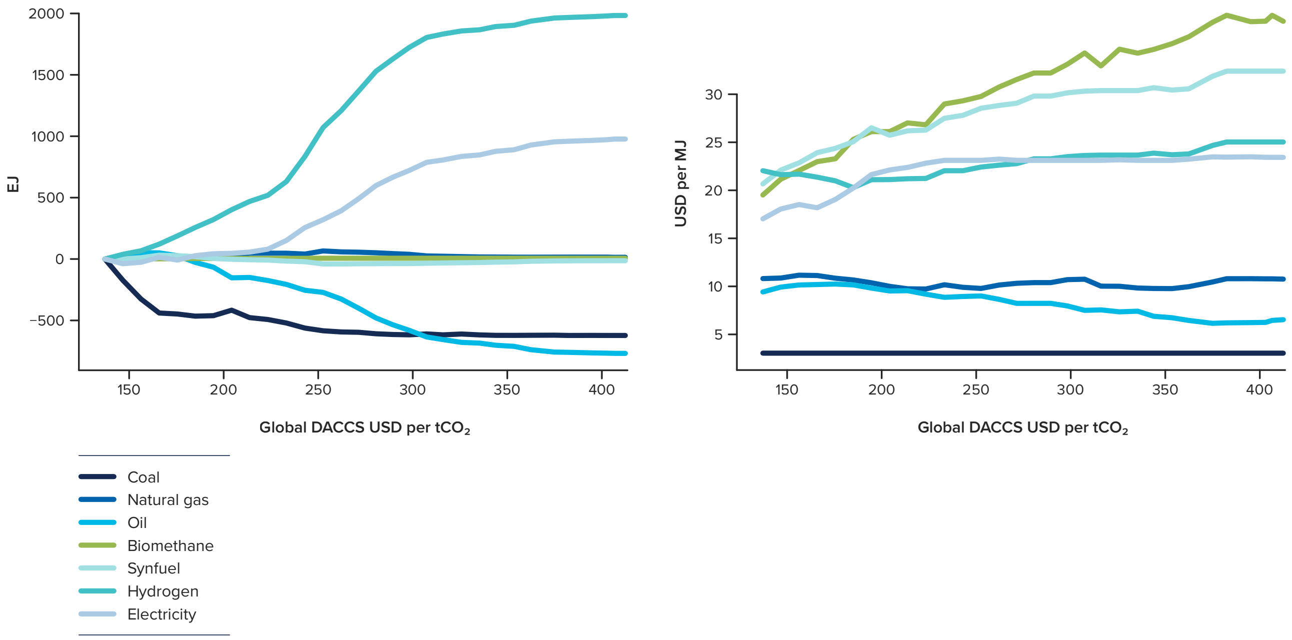
---

[11] Based on an NREL estimate of 2.8 acres per GWh of solar or 11,331 sq m per GWh or 3.148 billion sq m per EJ. A soccer field is 7,140 sq m, so 1 EJ requires 440,827 soccer fields. In 2065, DACCS-01 solar is 73 EJ, DACCS-10 solar is 80 EJ, and DACCS-31 solar is 131 EJ.

[12] Growing biofuels will also become more challenging as population grows, as more and more arable land will be needed for agriculture.

Taken altogether, Figure 16 shows changes in cumulative fuel production relative to the lowest cost DACCS scenario, as well as fuel prices for 2065 with changes in the cost of DACCS. Even though hydrogen made with natural gas increases as the cost of DACCS increases, the overall consumption of natural gas remains mostly constant because hydrogen directly displaces many traditional uses of natural gas. Biomethane also stays mostly constant as the cost of DACCS changes, yet the price of biomethane increases significantly as the cost of DACCS increases. In high-cost DACCS scenarios, the demand for biomethane to use with CCS increases to create slightly more carbon removal given the low DACCS deployment, which in turn drives up the price of biomethane. Another implication of the shift toward as much BECCS as possible with high-cost DACCS is that biosynfuel declines and hydrogen-based synfuel increases, yet total synfuel stays relatively constant.[13] As the cost of DACCS increases and less DACCS is deployed, a substantial amount of oil is replaced by hydrogen and synfuels, resulting in an increase in the price of hydrogen. The decline in oil consumption leads to a decline in oil prices as the cost of DACCS increases. Electricity consumption also increases with the cost of DACCS, largely because electricity is one of the primary pathways to make hydrogen; electricity prices also rise as the cost of DACCS rises. Similarly, the use of coal decreases as the cost of DACCS increases, though the use of coal with CCS increases slightly.

Figure 16: Change in cumulative fuel production with changes in DACCS cost and change in fuel prices (in 2065) with changes in DACCS cost



---

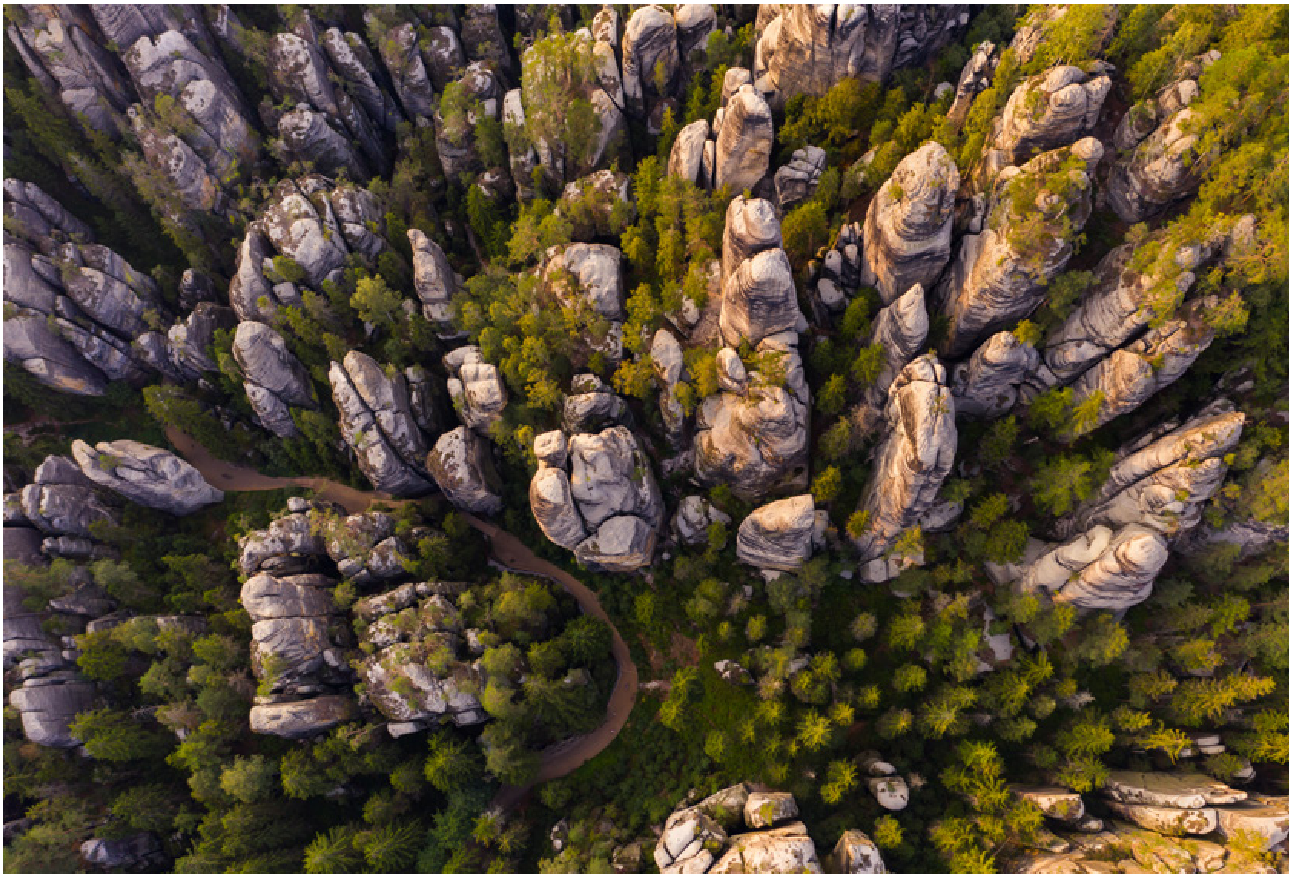
[13] Growing biofuels will also become more challenging as population grows, as more and more arable land will be needed for agriculture.

5.0 POLICY IMPLICATIONS

How much DACCS will cost in the future depends largely on the success of R&D and commercialization efforts, both of which can be aided by government policy. With the potential savings – as much as NPV USD 3 trillion – and the greater certainty in meeting climate goals, much is at stake with DACCS technology development. Policy intervention can help ensure the development of viable, low-cost DACCS technologies.

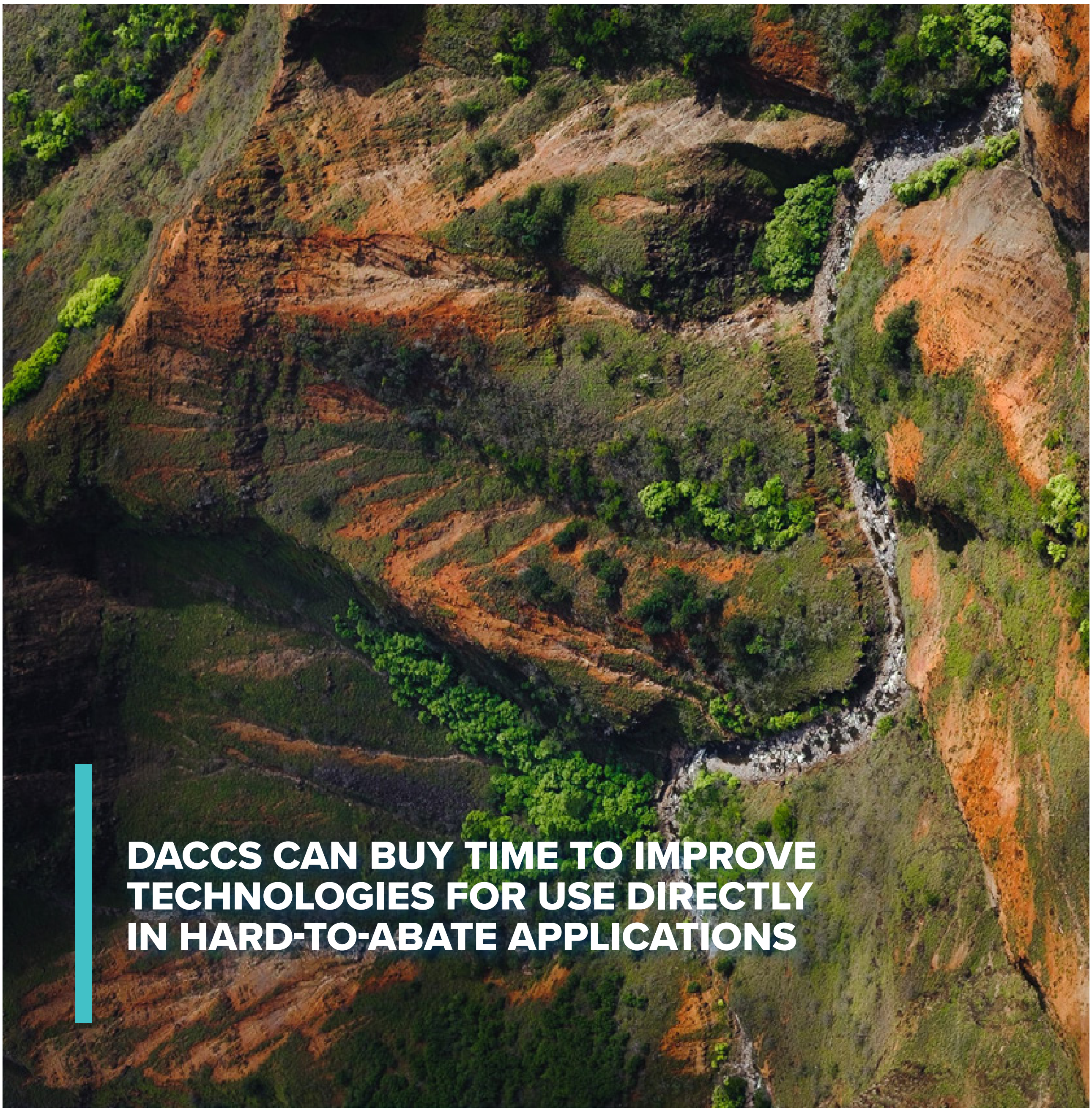
This policy discussion focuses exclusively on DACCS and is not intended as a comprehensive discussion of policies needed for net zero or CCS deployment in general. Possible policy interventions for DACCS could include 1) public-private partnerships to support R&D into novel approaches to direct air capture, 2) tax incentives akin to 45Q in the USA but targeted specifically for DACCS deployment, 3) direct payments for each tonne of CO_2 removed from the atmosphere and stored, 4) subsidies on the capital investment of DACCS equipment, such as the recently announced investment tax credit of 60% for direct air capture equipment in Canada through 2030 and 30% through 2040 (Government of Canada 2022), 5) a mandate on fossil fuel producers to fund DACCS, 6) a public utility model in which an entity is given the directive to build and operate DACCS and is funded through an adder to fuel bills or through general taxes.

An individual country is unlikely to invest in DACCS at a level needed for global benefits. Therefore, cooperation among countries is critical to ensure that DACCS can reach levels that benefit all. This cooperation would fall within Article 6 of the Paris Agreement and the UNFCCC process. KAPSARC has put forward one idea for cooperation on CCS in general that can be applied directly to DACCS: a group of likeminded countries can form a club and pool money to invest in DACCS projects to "jumpstart" the market and drive commercialization (Zakkour and Heidug 2019).



6.0 CONCLUSIONS

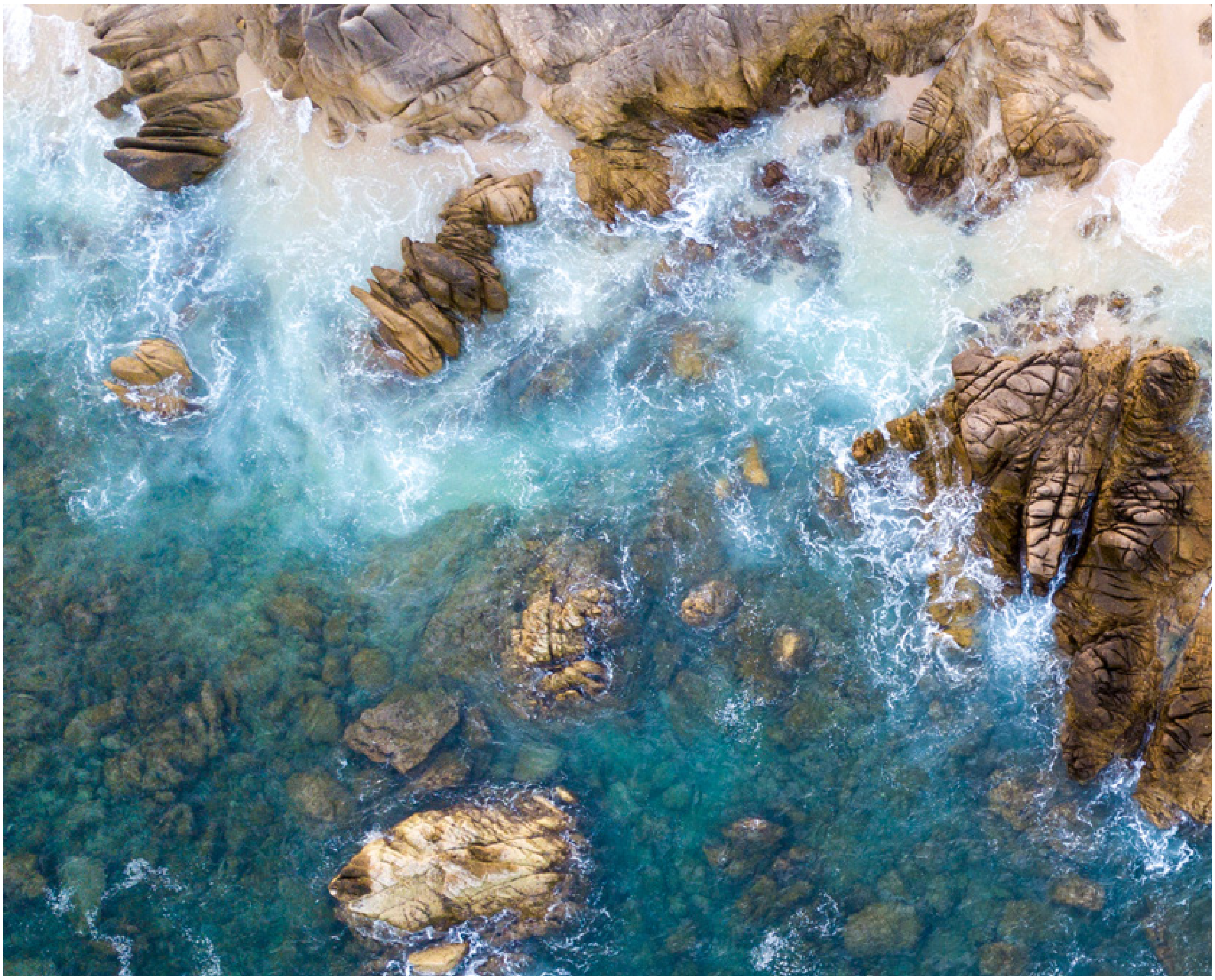
The cost of DACCS is uncertain, but if policy can be tailored to drive down that cost and then assist in the deployment of DACCS, then not only would the world potentially save a significant amount of money reaching net zero, the probability of success would be higher. The scale of the energy transition to net zero is staggering. Even with low-cost DACCS, advanced fuels and their infrastructure will be developed, the electricity sector will decarbonise, industry and transport will be transformed, but the rate of that transformation for the hardest-to-abate, highest cost applications will be slowed enough to make it more manageable, while buying more time to improve technologies for use directly in hard-to-abate applications. Even if the full transition of the energy system to net zero without CDR can occur more quickly and at lower cost than expected, thereby reducing the need for DACCS, the cost of developing and commercializing DACCS technology can be thought of as insurance.



DACCS CAN BUY TIME TO IMPROVE TECHNOLOGIES FOR USE DIRECTLY IN HARD-TO-ABATE APPLICATIONS

7.0 REFERENCES

1. Fasihi, Mahdi, Olga Efimova, and Christian Breyer. 2019. "Techno-Economic Assessment of CO_2 Direct Air Capture Plants." Journal of Cleaner Production 224 (July): 957–80. https://doi.org/10.1016/j.jclepro.2019.03.086.
2. Government of Canada. 2022. "2022 Budget: A Plan to Grow Our Economy and Make Our Life More Affordable." 2022.
3. Haberl, Helmut, Tim Beringer, Sribas C. Bhattacharya, Karl Heinz Erb, and Monique Hoogwijk. 2010. "The Global Technical Potential of Bio-Energy in 2050 Considering Sustainability Constraints." Current Opinion in Environmental Sustainability. https://doi.org/10.1016/j.cosust.2010.10.007.
4. IPCC. 2022. "Mitigation of Climate Change Climate Change 2022 Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.
5. Masson-Delmotte, Valérie, Panmao Zhai, Yang Chen, Leah Goldfarb, Melissa I Gomis, J B Robin Matthews, Sophie Berger, et al. 2021. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. www.ipcc.ch.
6. Raygen. 2018. "RayGen PV Ultra Knowledge Sharing." https://www.raygen.com/raygen-technology/.
7. Schipper, E.L.F., A. Revi, B.L. Preston, E.R. Carr, S.H. Eriksen, L.R. Fernandez-Carrill, B. Glavovic, et al. 2022. "Climate Resilient Development Pathways: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change."
8. Zakkour, Paul, and Wolfgang Heidug. 2019. "A Mechanism for CCS in the Post-Paris Era." Riyadh, Saudi Arabia. https://doi.org/10.30573/KS--2019-DP52.



GET IN TOUCH

To find out more about the Global CCS Institute including Membership and our Consultancy services, visit globalccsinstitute.com or contact us.

AMERICAS

Washington DC, United States

americasoffice@globalccsinstitute.com

AUSTRALIA

Melbourne, Australia

info@globalccsinstitute.com

CHINA

Beijing, China

chinaoffice@globalccsinstitute.com

EUROPE

Brussels, Belgium

europeoffice@globalccsinstitute.com

MIDDLE EAST AND NORTH AFRICA

Abu Dhabi, United Arab Emirates

menaregion@globalccsinstitute.com

UNITED KINGDOM

London, United Kingdom

ukoffice@globalccsinstitute.com

JAPAN

Tokyo, Japan

japanoffice@globalccsinstitute.com

The Global CCS Institute and the author believe that this document represents a fair representation of the current state of law in the key areas and jurisdictions considered, however its content should not be construed as, or substituted for, professional legal advice. The Global CCS Institute has tried to make information in this publication as accurate as possible. However, it does not guarantee that the information in this publication is totally reliable, accurate or complete. Therefore, the information in this publication should not be relied upon when making investment or commercial decisions or provided to any third party without the written permission of the Global CCS Institute. The Global CCS Institute has no responsibility for the persistence or accuracy of URLs to any external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate. To the maximum extent permitted, the Global CCS Institute, its employees and advisers accept no liability (including for negligence) for any use or reliance on the information in this publication, including any commercial or investment decisions made on the basis of information provided in this publication.