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NET-ZERO AND GEOSPHERIC RETURN: ACTIONS TODAY FOR 2030 AND BEYOND

BY S. JULIO FRIEDMANN, ALEX ZAPANTIS, BRAD PAGE, CHRIS CONSOLI, ZHIYUAN FAN, IAN HAVERCROFT, HARRY LIU, EMEKA OCHU, NABEELA RAJI, DOMINIC RASSOOL, HADIA SHEERAZI, AND ALEX TOWNSEND

SEPTEMBER 2020

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With expertise in climate change, energy systems, and in the oil and gas industry, Chris is also an experienced geomodeller and sedimentologist, with a background in palaeontology.

Chris has been part of a variety of advisory boards and lectures at universities in Melbourne and around the world and is always keen to promote, discuss and share his experience and knowledge. Chris received his PhD from Monash University in Melbourne, Australia.

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Prior to joining the Institute, Alex worked in the UK Government for nine years as part of the Government Economic Service. During this time, he worked on a range of energy and climate change topics, including household energy efficiency, wholesale gas and electricity markets, climate change adaptation, and the rollout of smart electricity and gas meters. He also worked on trade policy and the assessment of applications for grant funding for large industrial projects during the early stages of his career in the UK Government.

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EXECUTIVE SUMMARY

The case for rapid and profound decarbonization has never been more obvious or more urgent, and immediate action must match growing global ambition and need. An important new component of this discussion is the necessity of achieving net-zero global greenhouse gas emissions for any climate stabilization target. Until net-zero emissions are achieved, greenhouse gas will accumulate in the atmosphere and oceans, and concentrations will grow, even with deep and profound emissions reduction, mitigation, and adaptation measures. This places a severe constraint on human enterprise: any carbon removed from the earth must be returned to the earth.

To manage this aspect of the global carbon budget, carbon capture and storage (CCS) must play a central role. In particular, CCS will be important in two major roles:

- To manage emissions from existing, long-lived capital stock. This is especially true for rapid emissions reduction from three kinds of facilities: heavy industrial sector (i.e., cement, steel, and chemicals); production of near–zero-C hydrogen in abundance; and recently built power plants, in particular coal and gas facilities in Asia.
- To enable large-scale rapid carbon dioxide (CO_2) removal through engineered systems. This will include approaches like direct-air capture with storage (DACS), bioenergy with CCS (BECCS), and carbon mineralization.

Due to the intense urgency of the climate crisis, global emissions must drop 50 percent by 2030 and reduce a further 50 percent from that level by 2040 to achieve net-zero by midcentury—this is the science-based target of the Intergovernmental Panel on Climate Change (IPCC) 1.5°C report and the "well below 2°C" scenario ratified in the Paris Accord. Thus, reducing global emissions rapidly and profoundly, plus gigatonne-scale CO_2 removal, are the only ways to achieve these climate goals. The demands of 2030 place additional urgency on laying the foundations for growing deployment of CCS to achieve net-zero global emissions at lowest cost and greatest speed. A set of actions are essential:

Infrastructure

CO_2 transportation and storage networks today help illustrate the scale of what is required. Estimates suggest that the 8,000 kilometers (5,000 mi) of existing CO_2 pipelines in North America must be expanded by an additional 35,000 kilometers (21,000 mi) to maximize emissions reduction. Similarly, industrial hubs and clusters, now under development in Europe, China, and the Middle East, can accelerate the deployment of CCS at reduced cost. More storage sites must be assessed and approved, and options like CO_2 shipping must be explored for costs, opportunities, and technology requirements.

Projects

Large capital projects like CCS projects and related infrastructure require 6–10 years from conception to commissioning. Currently, there are 19 large-scale industrial and two large-scale CCS power facilities operating, with combined capacity of about 40 million tonnes of CO_2 per annum, and an additional 20 projects under development. The International Energy Agency (IEA), IPCC, and many other groups estimate CCS projects must mitigate 1.5 Gigatonnes per annum (Gtpa) by 2030 to stay on a 1.5°C increase climate trajectory—an increase by a factor of 35 from today. This places urgency on commencing construction and completing infrastructure to serve the volume of CCS projects needed, and it is likely that additional human capital is needed to serve this essential market.

Market-Alignment Through Policy

Durable policies that align market dynamics and attract private capital will be essential—most importantly, policies that enable project finance. These can include tax credits, feed-in tariffs, rate recovery, construction or procurement mandates, grants, projects of common interest, carbon pricing, contracts for differences, regulatory emissions caps, or combinations of these policies. Some additional modest policy measures (e.g., modification of the London Protocol; innovation policy and Research, Development, and Deployment, or RD&D, support; clarification of long-term liability requirements) could play important roles in facilitating market adoption.

By focusing on 2030 targets as a stepping-stone to midcentury net-zero targets, governments can select what actions, investments, and policies can best serve domestic and global needs. Similarly, investments and policies made over the next decade will lay the foundation for continued decarbonization to achieve global net-zero emissions by midcentury.

INTRODUCTION

The case for rapid and profound decarbonization has never been more obvious or more urgent. The consequences of unrestricted greenhouse gas emissions continue to manifest. As the atmospheric concentration of CO_2 exceeds 415 parts per million (ppm) and the atmospheric load of CO_2 approaches 1 trillion tonnes, the hottest decade on record is closing with the second-hottest year on record. Other chronic concerns, including wildfires, hurricanes, flooding, and extreme heat, are leading to widespread ecosystem damage and economic loss. Scientists predicted much of this over 30 years ago with surprising accuracy. The devastating wildfires in Australia, the bleaching of coral reefs, and the flooding associated with major storms and continued sea-level rise offer the starkest representation of what is at stake.

Against this backdrop, it is increasingly clear how profoundly the world has failed to meet this challenge. Carbon emissions continue to rise, despite enormous progress on efficiency and clean energy generation, especially in wind and solar. The global climate agreement made in Paris and signed in Marrakesh is far from sufficient, placing the world on a trajectory well above 3°C of warming (UNEP, 2019). While it was meant to be a first step leading to more ambitious targets, most countries are failing to meet their Nationally Determined Contributions (NDCs), and it is unclear how they will achieve even these modest initial goals (FEU-US, 2019). While some nations, notably in Europe, find that politics supports higher ambition, the same politics can run counter to achieving environmental goals, as evidenced by the EU's recent climate deal with Poland (Strupczewski and Baczynska, 2019), retrenchment in Brazil with President Jair Bolsonaro (Diaz, 2019), continued investment in coal in India (Rathi, 2019; Bordoff, 2020), and other examples. Since the consequences of climate change are tied to the cumulative emissions in the atmosphere, every year of delay adds to our problem, making time the scarcest resource of all.

The IPCC 1.5°C report has highlighted the risks of further failure and made clear that we must achieve two specific, arithmetically binding targets to avoid the worst outcomes of climate change:

- Global net-zero emissions by midcentury, and
- Global net CO_2 removal afterwards at the multi-gigaton scale.

The framework embodied by both of these targets is relatively new but now widely accepted. It also helps clarify a fundamental axiom of a successful energy transition and climate counterstrike: **managing carbon emissions requires actually managing carbon emissions**.

Above all, one thesis remains central to both CO_2 reduction and climate restoration: **withdrawals from the geosphere must be balanced by returns to the geosphere**. Carbon stocks removed from Earth (the geosphere), past, present, and future, must be returned to the earth to balance the carbon and climate books for good. Said differently, the 2 trillion tonnes of CO_2 pulled from underground will not fit into the biosphere, which was in balance before the Industrial Revolution.

With this straightforward point in mind, the technologies and tools of carbon management have special relevance. Carbon capture and storage, deployed in many sectors, is a tool for CO_2 reduction. Approaches like direct-air capture, CO_2 mineralization, and bioenergy with CCS (BECCS)—technologies and approaches described in this report— are tools for CO_2 removal.

Despite decades of economic and technical findings underscoring the importance of these approaches, they remain misunderstood and are often misrepresented as "experimental."

- ***The core technology is mature***: Industrial-scale CO_2 capture has operated successfully since 1938, and geological storage of CO_2 since 1972.
- ***The technology works on existing stock and new facilities***: Carbon capture has already retrofitted steel, power, hydrogen, and other large facilities. This can accelerate decarbonization without premature retirement delay and takes advantage of existing capital stock. It also can serve to accelerate deployment of low-carbon hydrogen, low-carbon biofuels, and CO_2 removal technologies.
- ***Some supply chains are ready, while others require more support***: Industrial-scale CO_2 capture units are commercially available from multiple vendors. Commercial geological storage expertise and systems operate around the globe. However, scaling up these systems will involve deployment of infrastructure, cultivation of human capital, and expanding operating systems through investment.
- ***Policy support is required***: In some parts of the globe, regulatory systems operate well. Other parts of the globe require improved regulation. However, policies that align markets and help finance projects are inadequate for the task of global deployment.

The arithmetic requirements and technical opportunities of a net-zero global energy system are clearest when considering the road to a midcentury goal. In this, 2030 stands out as a specific milestone on that journey, in part due to the framework of the Paris Accord and the opportunities and limits to managing new and existing capital stocks. Ten years is sufficient time to create and modify policy, plan large-scale capital investments, and build infrastructure necessary to achieve midcentury decarbonization. This next decade will be central to any successful climate strategy, and respecting the primacy of carbon management is essential for success.

THE ARITHMETIC OF NET-ZERO

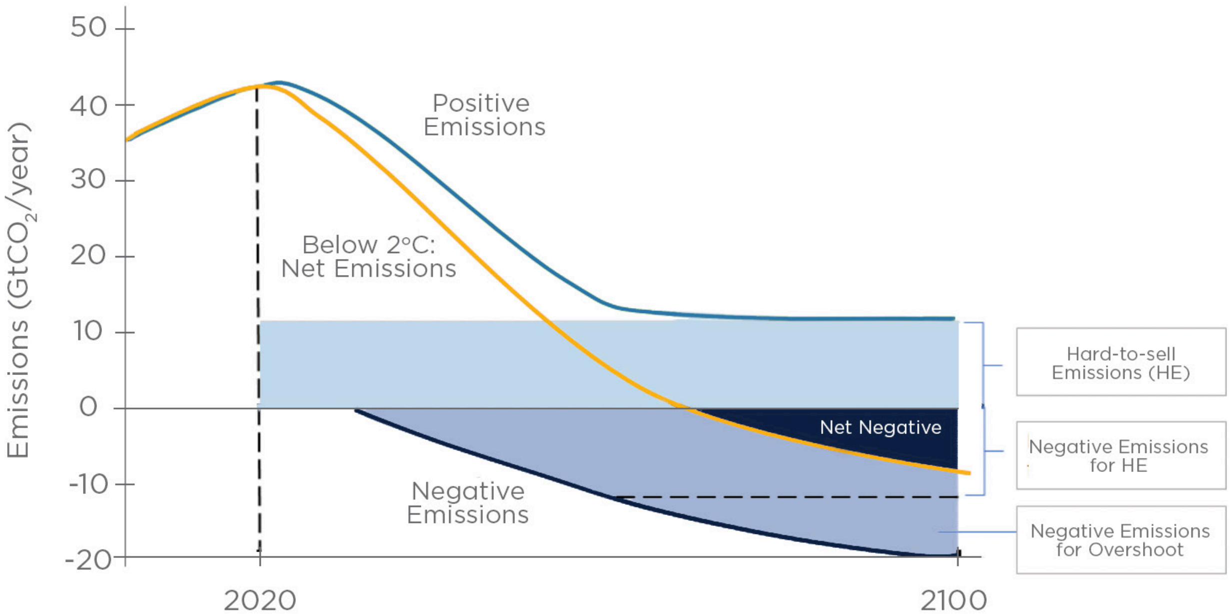
First and foremost, atmospheric concentrations of CO_2 will continue to grow and global warming will increase until the world achieves net-zero emissions. By definition, achieving net-zero emissions requires that any emissions that are not *reduced* must be *removed*. Emissions reduction and removal are distinct in nature and are different from emissions avoided:

- *Avoided emissions* are those that might have occurred but do not (for example, by not building a steel mill due to overcapacity or by building a solar PV power station instead of a natural gas power plant).
- *Reduced emissions* are existing emissions that no longer occur. Emissions may be reduced by many means, including conservation, efficiency, CCS, or shutting down or displacing existing emissions sources.
- *Removed emissions* are those that were emitted and are retrieved from the air and oceans. These can be from natural processes (e.g., mineral weathering), managed ecosystems (e.g., afforestation) or engineered systems (e.g., BECCS).

To achieve net-zero emissions, all emissions trajectories must decrease (Figure 1). However, if there are any residual emissions that are not reduced or mitigated, net-zero requires an equal mass of CO_2 removal. In many scenarios and descriptions, residual emissions are considered "hard-to-abate," meaning either the cost is extremely high (e.g., for aviation) or the technology does not exist (e.g., application of fertilizer). This is the core arithmetic of a net-zero emissions plan: ***any residual CO_2 emissions must be balanced by an equal amount of CO_2 removal***.

$$CO_2\text{emissions} - CO_2\text{removals} = 0$$

Figure 1: Representative pathway to net-zero and net-negative emissions. Orange line represents the emissions trajectory as the sum of the green and blue trajectories.



Source: J. Wilcox et al. 2020.

However, most analysis finds that it is not possible to achieve zero emissions soon enough to stabilize global average temperature below 2°C through reduction alone (e.g., Rogelj, 2018). In particular, the IPCC found that to achieve emissions consistent with a 2°C limit to human-caused warming, would likely require 85 percent emissions reduction by 2050 and annual removal of gigatonnes CO_2 before 2100 (IPCC, 2014a). Another important scenario is to aim at limiting human-caused warming to 1.5°C, and this requires that 100 percent emissions reduction and annual removal of 5–10 gigatonnes of CO_2 must occur around midcentury (IPCC, 2018).

By 2050: CO_2emissions(residual) - CO_2removal < 0

After 2050: CO_2emissions(residual) - CO_2removal = (-5 to -10 Gt/a)

The Scale of the Problem

When it comes to climate change arithmetic, the numbers are staggering and hard to understand or internalize. To help understand the numbers, it is useful to understand the nature of a gigatonne (Gt).

- **All the people on Earth combined weight roughly 1/2 a gigatonne.**
- **The global annual production of plastic is about 1 gigatonne.**
- **Global consumption of meat is approximately 1/3 a gigatonne.**

Unsurprisingly, managing many gigatonnes of emissions is extremely daunting. For example, the global oil market is roughly 5 Gt of material. Removing 5 Gt of CO_2 from the air and oceans requires an industry the size of the oil and gas industry operating in reverse.

This core arithmetic produces difficult corollaries. For example, the hard-to-abate sectors commonly are expressed as an irreducible annual sum of 8–10 Gt CO_2 equivalence (IPCC, 2014; ETC, 2018). The persistence of residual emissions is founded on the lack of alternatives, especially for land-use emissions, shipping, and aviation. Although some analysis has laid the foundation for innovation and progress in these arenas (ETC, 2018), the lack of realistic plans for deployment means that these emissions persist stubbornly across almost all analyses. Other difficult corollaries include:

- Achieving an 85 percent reduction in greenhouse gas emissions by midcentury requires a 50 percent emissions reduction each decade between now and 2050 (e.g., Rogelj et al., 2018). Given the long capital lives of existing infrastructure and facility stock, it is not clear how this might be achieved.
- A 1.5°C trajectory requires 5–10 Gt removal of CO_2 by 2050 and greater volumes thereafter. The National Academies (NASEM, 2018) find that this is not possible through reforestation alone given the limits of land and current technology.
- Any failure to reduce emissions must be balanced by CO_2 removal. For example, a failure to scale-up renewables, efficiency improvements, or electric vehicles will lead to a larger removal burden (FEU-US, 2019).

The core arithmetic produces an uncomfortable finding: existing capital stocks will overwhelm a 1.5°C or 2°C carbon budget. The IEA (2018) analyzed the global energy infrastructure either built or under construction. Assuming a natural capital life for facilities, just the existing capital stocks would emit 95 percent of the CO_2 emissions allowable under their sustainable development scenario, which is roughly 2°C of warming, and a 1.5°C budget was not possible without 100–1,000 Gt of CO_2 removal by 2100.

This leads to a straightforward arithmetic truth: achieving climate goals requires (a) premature retirement of existing facilities at an enormous scale, (b) many gigatonnes of annual abatement using CCS, or (c) both.

It is important to note that this is not a new or recent finding. On the contrary, the simple arithmetic of climate change makes CCS a central plank of abatement, like efficiency or renewables. In 2004, two very different sources reached this conclusion, both in Science. Socolow and Pacala (2004) argued that climate change impacts could be avoided through deployment of many "wedges" of technology. In their analysis, CCS featured prominently as a key pathway. The same year, then-US Secretary of Energy Spencer Abraham wrote that the costs of achieving climate targets were very sensitive to the presence or absence of CCS in analysis and that the costs of achieving the same goals without CCS were enormous. The IPCC reached the same finding in 2014, indicating that without CCS, the costs of achieving 2o C stabilization would be roughly 140 percent higher than without. The IEA reached the same conclusion in 2016 and 2018.

CENTRALITY OF CARBON CAPTURE

Given net-zero arithmetic and the urgency of climate change, two central roles emerge for CCS: CO_2 reduction and CO_2 removal. Reduction is a climate mitigation measure and involves preventing emissions from entering the atmosphere associated with existing systems. Removal is an additional set of measures that withdraws CO_2 from the air and oceans directly as a way to balance residual emissions and ultimately to un-emit legacy carbon in the air and oceans and restore climate. The versatility of carbon capture and the functionally limitless carbon storage capacity of the geosphere allows CCS to play these key roles immediately, growing toward the 2030 timeframe.

CO_2 Reduction and Mitigation

Heavy Industry—heat and process emissions

Reducing emissions in industry is one of the greatest challenges of reaching net-zero emissions. Industry is the basis of our modern society and is an essential source of economic growth, bringing financial benefits and job opportunities to communities around the world. While creating this wealth, industry produces nearly one-third of global greenhouse gases. The cement, iron and steel, and chemical sectors are the largest sources of industrial emissions. These industries provide a range of products that are vital to everyday life. Demand for the goods produced by industry is expected to grow in the future, driven by a growing population, increased living standards and economic growth.

Around one-quarter of industry CO_2 emissions are process emissions that are inherent to production processes. For example, in cement production, 65 percent of emissions come from the calcination of limestone, a chemical process underlying cement production (ICEF, 2019). In addition, one-third of industry energy demand is for high-temperature heat, for which there are few mature alternatives to the direct use of fossil fuels (Friedmann et al., 2019).

Many regions of the world are planning to grow their industrial sectors, which will likely contribute to a rise in industry emissions without additional policy action. For example, the Indian government has set an ambition in its National Steel Policy 2017 to increase steel production from 122 million tonnes in 2015–16, to 300 million tonnes in 2030–31. The steel sector is central to economic development in India, contributing 2 percent to India's GDP, and employing 0.5 million people directly and two million indirectly through supply chains. In Qatar, plans are in place to increase LNG production capacity from 77 million tonnes per annum today to 126 million tonnes per annum by 2027. The construction of coal-fired power plants continues, mostly in Asia, with nearly 600GW new capacity expected to be added by 2030 (Cui et al., 2019). The IEA estimates industry CO_2 emissions will rise by 11 percent, to 6.7 gigatonnes of CO_2 per year, without further climate mitigation policies (IEA, 2019).

CCS provides one of the most mature and cost-effective options for reducing emissions from industrial processes and high-temperature heat. Several reports, including from the Energy Transition Commission and the IEA, have concluded that achieving net-zero emissions in hard-to-abate industry without CCS may be impossible and at best is much more expensive.

CCS in the Power Sector

Achieving net-zero emissions by midcentury would not be possible without decarbonizing the power sector, which accounts for one-third of global CO_2 emissions (IEA, 2019). The rapid deployment of renewable energy, associated with strong policies (like renewable portfolio standards and construction mandates in China and India) and dramatic cost reductions are positive contributors to success in reducing electricity emissions. That progress is grossly insufficient to achieve net zero by 2050, and existing coal and gas power systems continue to be built and are expected to operate through 2050 and beyond. Analysis shows that CCS provides both the fastest and cheapest pathway to deep decarbonization for these plants (IEA, 2020b). In many deep decarbonization scenarios, coal use reduces rapidly (Table 1).

Table 1: Coal utilization reductions assumed in IPCC Illustrative Pathways

IPCC Illustrative Pathway to 1.5°C	Pathway 1	Pathway 2	Pathway 3	Pathway 4
Reduction in primary energy from coal in 2030 compared to 2010	-78%	-61%	-75%	-59%
Reduction in primary energy from coal in 2050 compared to 2010	-97%	-77%	-73%	-97%

Source: IPCC, 2018.

Actual trends are very different from those required by these scenarios. Although investment in fossil fuel power generation has fallen over the past decade, it received USD $120 billion in 2018 (IEA WEI, 2019) and the global coal and gas fleets continue to grow, **more rapidly since the COVID-19 pandemic began** (IEA, 2020a). These facilities have economic lives of decades and a large global fleet of coal- and gas-fired power stations are expected to remain in operation well past the middle of this century (IEA, 2020b). Most gas power plants operate for about 30 years, while coal-fired generation plants operate for 40–50 years, and this newly installed capacity will remain in operation through to 2060 without premature closure—CO_2 emissions from the global coal fleet are expected to approach 10GtCO_2 in 2030 and exceed 7GtCO_2 in 2050 (Cui et al., 2019). If they operate, around 90 percent of those emissions must be captured and stored in 2030, and effectively all emissions must be captured and stored in 2050 to achieve net-zero. If power production from the global coal fleet is only half what has been assumed in this simple illustrative analysis, approximately 85Gt of CO_2 must be captured and stored from coal-fired power generation alone between 2030 and 2050 to be consistent with a 1.5°C climate outcome.

Clean Hydrogen

Hydrogen, as a fuel and feedstock, can play a significant role in the decarbonization of hard-to-abate sectors, provided production is clean and with a low-carbon footprint. Hydrogen can be burned in turbines or be used in fuel cells to generate electricity and can fuel both light and heavy-duty vehicles. Hydrogen can provide a source of domestic and industrial heat and is a feedstock for industrial processes and synthetic fuels (like ammonia). The virtue of hydrogen is that it produces zero carbon emissions at point of use.

A clean hydrogen network of the future is quite different from today's system in volume, emissions, and use. In 2018, around 70 Mt per annum of pure hydrogen was used, almost entirely for refining (38 Mt) and the production of ammonia (31 Mt). Less than 0.01 Mt of pure hydrogen was used in fuel cell electric vehicles.

- Currently, 97 percent of global hydrogen production is from unabated fossil fuels, around three-quarters from reforming natural gas and the rest from gasification of coal (IEA, 2019; GCCSI, 2020). This is sometimes called "gray" hydrogen, which currently emits 830 Mtpa.
- When fossil fuel emissions from hydrogen production are abated through CCS, there are either reduced or zero associated greenhouse gas (GHG) emissions. This is sometimes called "blue" hydrogen.
- The remaining 2 percent of hydrogen is produced using water with electrolysis (IEA, 2019). When the electricity supply comes from zero-emissions power sources (e.g., hydro, solar, wind, or nuclear) it is sometimes called "green" hydrogen.

According to the IEA (2019), less than 0.7 percent of hydrogen production today is from fossil plants equipped with CCS (blue hydrogen) or renewable energy via electrolysis (green hydrogen).

For net-zero progress by 2030 and net-zero targets by 2030, rapid scale-up of clean hydrogen production will prove critical. ***The "Mission Possible" report (ETC, 2018) stated that global hydrogen production needs to grow by between 80 to 95 percent per annum by 2050 to reach net-zero emissions.*** The Hydrogen Council identified near-zero hydrogen could deliver around 6 Gt of annual abatement in 2050. (Hydrogen Council, 2017). In this respect, scaling up production of clean hydrogen from fossil fuels with CCS is simple and cost advantaged. Low-carbon hydrogen has been produced at commercial scale through gas reforming or coal gasification with CCS since 1982 (Table 2). Five large-scale "blue" hydrogen facilities with CCS produce low-carbon hydrogen today and three are under construction, with a total annual capacity of 1.5 Mtpa hydrogen, capturing over 7 Mtpa CO_2 (GCCSI, 2020).

Table 2: Hydrogen production facilities with CCS

Facility	H_2 Production Capacity (tonnes/day)	H_2 Production Process	Operational Commencement
Enid Fertilizer	200 (in syngas)	Methane reformation	1982
Great Plains Synfuel	1,300 (in syngas)	Coal gasification	2000
Air Products	500	Methane reformation	2013
Coffeyville	200	Petroleum coke gasification	2013
Quest	900	Methane reformation	2015
Alberta Carbon Trunk Line - Sturgeon	240	Asphaltene residue gasification	2020
Alberta Carbon Trunk Line - Agrium	800	Methane reformation	2020
Sinopec Qilu	100 (estimated)	Coal/Coke gasification	2021 (planned)

In comparison, the largest operating renewable powered electrolyzer in Fukushima Japan can produce ~2.4 tons/day of clean hydrogen.[1] The largest announced "green" hydrogen project to date, the Air Products-NEOM project in Saudi Arabia, would produce 650 tonnes of clean hydrogen using a combination of solar and wind (Air products, 2020) and shows both the promise and limits of "green" hydrogen production. The $7 billion project would supply 0.9 percent of global demand today. Meeting potential future global clean hydrogen demand of 530 million tonnes per year using electrolysis would require more than 26,000 TWh[2] of electricity—approximately equal to the total global combined electricity demand from all sectors in 2018 (IEA, 2019).

In this context, CCS-enabled blue hydrogen adds speed and saves money. For the price of the Air Products-NEOM project, roughly 300 Mt CO_2 could be captured and stored every year. Low-carbon hydrogen from fossil fuel with CCS is distinctly cost advantaged. Hydrogen made from fossil with CCS cost USD $1.50 –2.40/kg, compared to USD $4.00–7.45 for "green" hydrogen (IEA, 2019). Finally, when combined with biomass conversion, hydrogen production with CCS can remove CO_2 from the atmosphere.

CO_2 removal

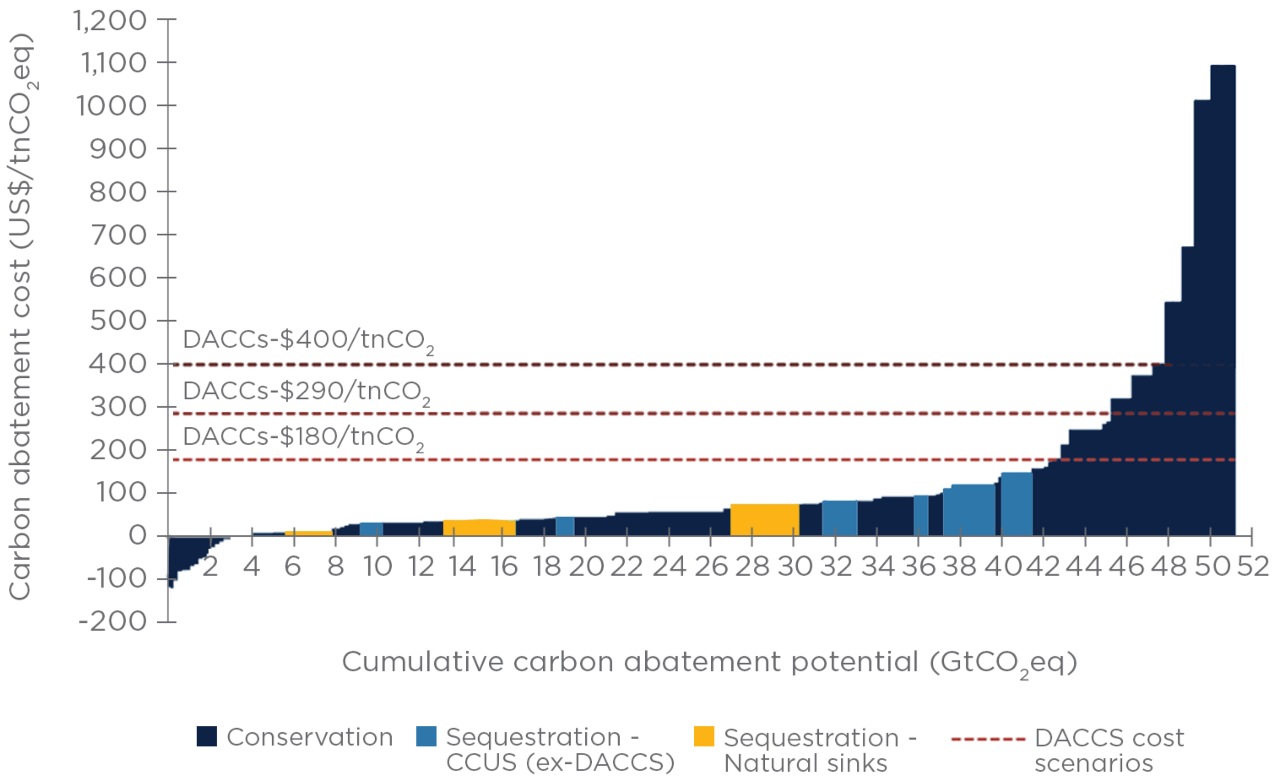
As discussed, arithmetic demands that to achieve net-zero any residual annual emissions must be matched by an equal volume of CO_2 removal. There are many approaches to CO_2 removal, each of which has challenges (UNEP 2017, ICEF 2018). Three of those approaches require geological storage and return of CO_2 to the geosphere: DACS, bioenergy with CCS (BECCS), and carbon mineralization (CMin). The National Academies (2018) estimate that ~75 percent of CO_2 removal demanded of the carbon budgets requires these three approaches. Similarly, a recent report by Lawrence Livermore National Lab (2020) indicates that 80 percent of the residual emissions identified by the state of California require geospheric return paired with CO_2 removal (BECCS and DACS).

Direct-Air Capture with storage (DACS)

Although many consider DACS technology to be new, the core technology is not. Devices that scrub CO_2 from air have operated since world-war II in submarines and since the 1960's in spacecraft—as dramatized in the iconic scene from Apollo 13 (ICEF, 2018). Capturing CO_2 from the air has become a climate mitigation strategy only recently, in part driven by increased urgency and prior failure to reduce emissions. Today, several companies operate DAC facilities and more provide options for CO_2 removal services.

Deployment of DACS requires the process itself to have near-zero emissions. However, if these conditions are met, then large-scale DACS can avoid enormous costs associated with our climate targets and provide a pathway to climate restoration (Figure 2; Goldman Sachs, 2020). NOTE: Arithmetic demands that failure in *any other mitigation pathway*, including efficiency, renewables, CCS, or reforestation, requires more DACS to balance the carbon budget. On this basis, and because DACS appears to have few technical, resource, or geographic limits, it can be considered a "backstop" technology to achieve climate goals.

Figure 2: Global marginal abatement cost curve for all greenhouse-gas emissions Dark-blue bars (conservation) represent substitution of emitting sources with non-emitting sources or efficiency measures. Pale-blue represents CCS on point sources. Green represent CO_2 uptake from managed ecosystems.



Source: Goldman Sachs, 2020.

A critical limitation of DAC is that the low concentration of CO_2 in air (~410 ppm) requires both lots of energy and large contacting systems, which today result in high costs. It is clear that these costs can come down (NASEM 2018) and are likely to drop dramatically over the next 30 years given appropriate policy support for deployment and innovation (EFI, 2019; Rhodium Group, 2019) with many experts agreeing on a total system cost of <$150/t sometime beyond 2030.

Biomass Energy with Carbon Capture and Storage (BECCS)

Biomass is the oldest energy supply used by humankind. The fundamental premise of BECCS is to combine CCS with bioenergy, in which biomass systems gather CO_2 from the air and oceans, people harvest the energy through conversion, and the carbon is permanently returned to the geosphere. The core technology options, such as biomass gasification, are available today and used widely (e.g., wood-based biomass gasification under the German

Energiewende). One large BECCS facility, the ADM corn-ethanol project in Decatur, Illinois, currently removes ~1 Mt/year through fermentation and geological storage. The "Getting to Neutral" report on California's emissions reduction strategy (LLNL, 2020) finds that ~100 Mt/y of BECCS is the cost-preferred pathway for CO_2 removal to achieve their state goals, representing ~70 percent of the state's needs.[3]

The core limitations to BECCS deployment today are cost and scale. Most biofuels and biomass-based power systems enter markets well above commercially competitive prices, even without the additional cost and energy requirements of CCS. In addition, the land required to grow large volumes of bioenergy crops places limits on what can be realistically considered for the upper limits of deployment (Reid et al., 2019), and also place additional costs on future deployment. Finally, BECCS will necessarily compete with agriculture for land, water, and energy, which presents challenges of governance and balancing policy needs.

An intrinsic concern regarding BECCS deployment is overall sustainability. Land-use changes (LUC) associated with biomass have led locally to severe environmental damage, affecting biodiversity, water quality, and environmental justice for indigenous peoples. Moreover, risks of carbon leakage and ecosystem carbon release from LUC can completely void the carbon and climate benefits of BECCS if executed using poor life-cycle pathways or systems with substantial LUC emissions. Conversely, with the appropriate focus on sustainable forestry and agriculture, including issues of equity and governance, BECCS could be scaled up quickly to good effect (Reid et al., 2019).

Mineralization

Over very long timescales, CO_2 reacts with silicate minerals at Earth's surface to make carbonate minerals. This is how nature removes large volumes of CO_2 over geologic time and is one of the processes that leads to ice-ages (Chamberlain, 1900). Recently, it has become clear that humans can accelerate this process, either by adding heat and energy or by combining air with the most reactive mineral fractions (IPCC, 2005; Keleman et al., 2020). This binds CO_2 in mineral form, making a highly stable pathway for geospheric return.

The enormous volumes of reactive minerals at Earth's surface and near subsurface make the volume potential for carbon mineralization effectively limitless (NASEM 2018), although the practical limits are a function of mineral kinetics, reactive surface area, and the quality of the mineral resource. As with any other mineral resource, the geographic distribution of high-quality carbon-mineralization resources are uneven. However, recent work has identified locations where mineral resources, low-carbon energy, and existing infrastructure are available to support carbon-mineralization projects. It would be generous to say this pathway and approach has received very little scientific and policy attention (EFI, 2019).

CO_2 utilization (CO_2U)

For good reasons, many see the value in turning CO_2 into goods for scale—that will be essential at some point for a circular carbon economy (CCE). The main types of valuable products made from CO_2 in a CCE are cement and aggregate, fuels and chemicals, and durable carbon. (ICEF, 2018) The products (and mid-products) of CO_2-to-fuels conversion include: CO, syngas (H_2 and CO mixture), methanol (CH_3OH), and eventually to long-chain hydrocarbons—which are more challenging but also of greater value (Hu et al., 2013).

- CO_2-based cement and aggregates are thermodynamically favored, and many companies exist today that sell these products.
- CO_2-derived fuels can be carbon neutral or even carbon negative and can be used as alternative drop-in fuels, especially for hard-to-abate sectors (e.g., aviation and shipping). They require substantial input energy to synthesize.
- Durable CO_2-based-products, including carbon fiber/tubes, plastics, and composites, etc., can last longer and keep carbon away from the atmosphere.

Unfortunately, even the largest applications are unlikely to use more than 1–2 Gtpa. Even that will require enormous energy requirements. The largest market, cement and aggregates, is unlikely to exceed more than 1–2 Gt (ICEF 2018). All other CO_2 utilization pathways identified, especially fuels and chemicals, are expensive and require more energy input than originally produced in combustion. For other durable carbon products (e.g., carbon fiber and carbon nanotubes), the value is high but the total market value is very small and cannot absorb large CO_2 volumes. For example, the global carbon fiber market is of the order of 100,000 tons. (Das et al., ORNL, 2016). Similarly, plastics cannot provide a large-enough market either (e.g., Epoxide, DOE's testing plant products, has ~20 Mt/y production and can take 40 percent CO_2 by weight [DOE, 2013; Rebstadt and Meyer, 2001]). Finally, if CO_2 utilization consumes energy or feedstocks with substantial carbon footprints, the life-cycle emissions could be very high. **For these and other reasons, geospheric return of CO_2 is essential to balance the climate books, even with a lot of CO_2U.**

THE ROLE OF THE GEOSPHERE IN ESTABLISHING CARBON BALANCE

Before the Industrial Revolution, the carbon cycle was effectively in balance. Since 1800, humans have perturbed that balance by adding 2 trillion tonnes of CO_2 to the air, much of which was taken up by the ocean and the rest into soils and forests (IPCC, 2014a). The rates at which soils and forests gained and lost carbon were fixed by evolution and the natural carrying capacity of ecosystems and further reduced by other human activities (e.g., deforestation). Today, the global economy (energy and land use) emits roughly 40 gigatonnes of CO_2 and other non-CO_2 greenhouse gases equal to 13–16 gigatonnes more CO_2.

Almost all of this CO_2 is taken from the geosphere in the form of coal, oil, and natural gas. Earth's crust effectively held this material in solid, liquid, and gaseous forms for many hundreds of millions of years. This demonstrates an important opportunity in net-zero accounting: Earth's crust is well-configured to hold carbon indefinitely (IPCC, 2005). In fact, natural occurrences of CO_2, produced today for enhanced oil recovery, had accumulated and remained in Earth's crust for as long as 280 million years.

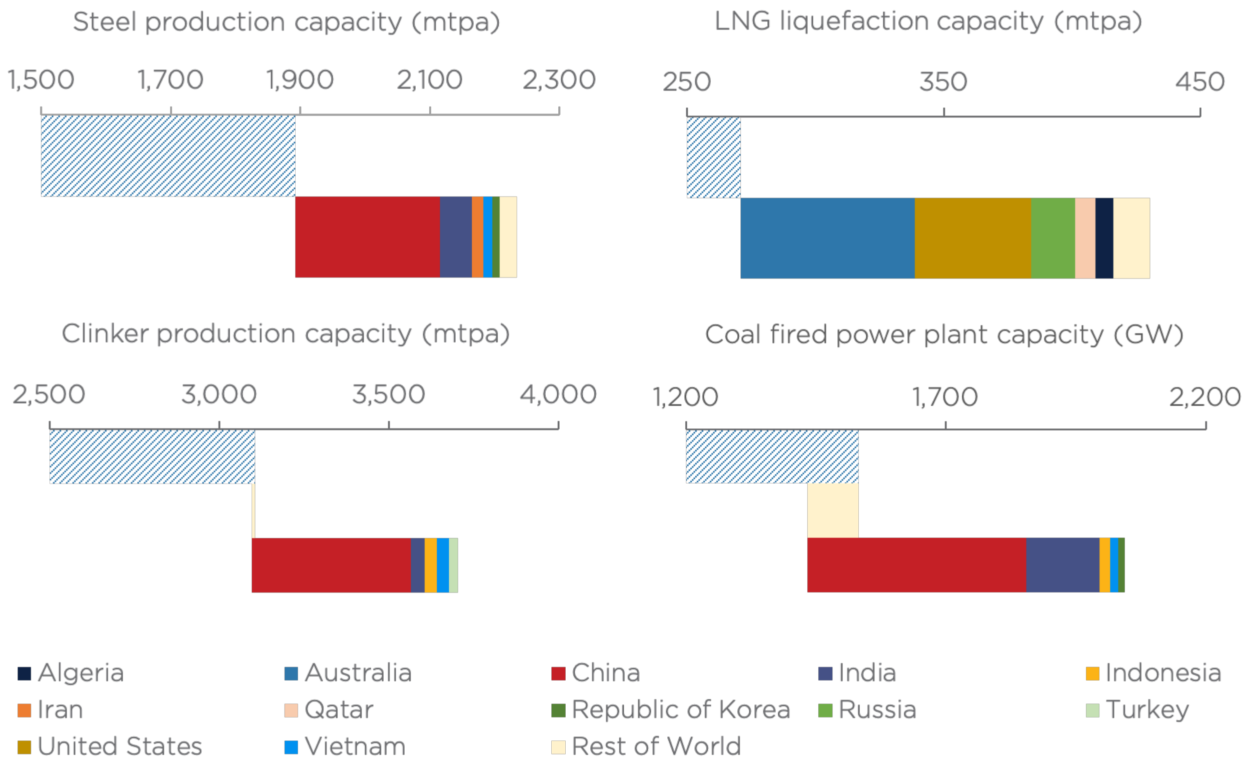
The capacity of Earth's crust to store CO_2 is effectively limitless (NASEM, 2018). Conventional geological storage systems like saline formations have an estimated storage volume of 10–20 trillion tonnes—far more than either annual emissions or our historic emissions. Unconventional systems, such as basalts and ultramafic rocks, are many orders of magnitude larger still. This capacity can serve in the coming decades to deeply curtail today's existing facilities as a strategy to halve today's emissions by 2030 and assist deep decarbonization by 2050. This capacity also can serve to balance any residual emissions and beyond that serve as the permanent repository of human legacy emissions. ***In a net-zero framework, the withdrawal of carbon from the geosphere can be balanced by return to the geosphere***—safe and permanent, both more durable and less risky than temporary carbon banking in the biosphere (e.g., Anderegg et al., 2020).

2030 Goal, Arithmetic and Requirements

Achieving net zero by midcentury will require a 45 percent reduction in CO_2 emissions worldwide by 2030 relative to 2010 levels—to get on track, CO_2 emissions would need to fall at a rate of roughly 5 percent per year between now and 2030 (e.g., Rogelj et al., 2018). In contrast, global CO_2 emissions have continued to rise since 2010.

A significant proportion of emissions are already locked into the system, making the transition ever-more challenging (IEA, 2019; Tong et al., 2019). Industrial and power plants have long lifetimes, typically around 30 to 50 years. Over the past decade there has been a significant increase in capacity of emissions-intensive infrastructure that under conventional assumptions will remain in place in 2050. For example, steel, clinker, and coal-fired power plant capacities have increased by between 18 and 34 percent since 2010, primarily driven by expansion in China and India (Figure 3). Plans are in place to increase unabated capacity further in many of these markets, accentuating the challenge of transitioning to a net-zero emissions economy.

Figure 3: Net capacity additions for three industrial sectors (steel, LNG, and cement) and coal-fired power in the world's five highest growth markets and the rest of the world.



Source: IEA WEI 2019.

Most models indicate CO_2 emissions will need to peak globally in the next few years (e.g., IPCC 2014; 2018; IEA 2019). Even in 1.5°C-consistent scenarios that initially overshoot temperature rises of 1.5°C, emissions peak by or shortly after 2030 (e.g., Fuss et al., 2018; Rogelj et al., 2018). Achieving this peak in emissions will require widespread climate mitigation action in a range of sectors. Across the 90 1.5°C-consistent scenarios in the *IPCC Special Report on Global Warming of 1.5°C*, CO_2 sequestration reaches 1.5 gigatonnes per annum on average by 2030, 35 times higher than the mass of CO_2 captured today. Other common themes include the continued growth in the deployment of solar and wind, the rapid phase-out of coal and the growth in low-carbon hydrogen as an energy carrier.

CCS has a critical role to play in achieving cheaper, easier, and rapid deep decarbonization of the hard-to-abate sectors, such as the power and industrial sector (mostly from cement, steel, and chemical subsectors). The IEA Clean Technology Scenario (2020) confirms that CCS is expected to contribute almost one-fifth of the emissions reductions needed across the industry sector (38 percent in the chemical subsector and 15 percent in both cement and iron and steel) to achieve the midcentury climate goals. One-third of industrial sector energy demand is for high-temperature steam heat, which has only few renewable alternative sources. Further, process emissions inherent in some industrial production as a result of chemical reactions account for one-quarter of industrial emissions and cannot be easily avoided by switching to alternative fuels.

Thus, it is unrealistic to expect the achievement of net-zero emissions by 2050 without CCS. Even if all economically viable energy efficiency pathways are pursued, energy intensity will only be able to improve by 3.6 percent year-on-year from 2018 to 2040, without CCS (IEA, 2019).

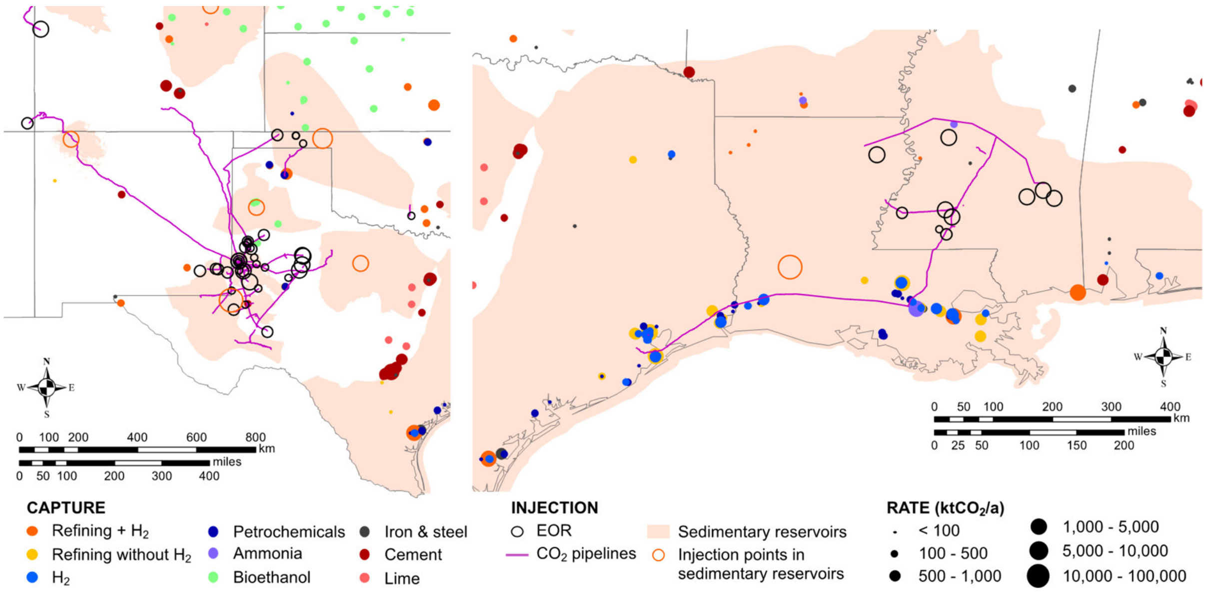
Time to Build

The life cycle of any large industrial project includes several feasibility and engineering studies prior to the investment decision followed by more detailed engineering design and finally, construction. This life cycle takes between 6–10 years, depending on logistical constraints and speed of approval (GCCSI, 2019b). Construction alone takes an average of 3–4 years. For example, the 1 Mtpa Boundary Dam project (Saskatchewan) and the 1.2 Mtpa Quest project (Alberta) took four years to progress from being identified to entering construction, and PetraNova (Texas) took three years. The Alberta Carbon Trunk Line project took eight years from inception to commissioning. Considering that CCS projects, like all infrastructure take time to develop, installing sufficient capacity to deliver 2.8 Gtpa CO_2 capture required to achieve the 2050 emissions target requires actions now.

Industrial CCS hubs offer significant cost and risk reductions compared to single sink-source CCS projects. Each segment of the CCS value chain requires investment in infrastructure such as CO_2 capture equipment, pipelines, and injection wells. These investments can only be made if they provide an appropriate risk-weighted return, so reducing cost and risk is key to rapid deployment of CCS. Hubs significantly reduce the unit cost of CO_2 transport and storage through economies of scale and provide multiple sources of CO_2 with access to shared infrastructure (see the later discussion of infrastructure). Hubs also reduce market risk by creating multiple customers and service providers for each actor in a CCS value chain. They have already become the dominant setting for CCS investments. For example, in the US the 10 large-scale CCS facilities, capturing 24.9 Mtpa of CO_2, utilize approximately 2,000 kilometers (1,182 mi) of shared pipeline connection to transport captured CO_2 (GCCSI, 2019a; NPC, 2019). In Canada, the Alberta Carbon Trunk Line brought two CCS projects online simultaneously, with more projects planned.

The US offers many additional opportunities for CCS hubs. A recent National Petroleum Council's report (2019) that examined the central United States identified 115 sites, with total annual emissions of 477 million tonnes, would be suitable for CCS retrofit based on their location, size, age, fuel efficiency, criteria pollutant emissions, and competitive status in local power markets. Many of these potential sites could be served by proximal storage sites, including along the Gulf of Mexico and in the Permian Basin of Texas (Figure 4).

Figure 4: Demonstrated "carbon hub" potential with CO_2 capture and neighboring sink opportunities surrounding existing CO_2 pipelines in the Permian Basin (left) and Gulf Coast (right) regions.



Source: Pilorgé et al., 2020.

In Europe, a majority of all proposed CCS projects are similarly part of an industrial cluster. Examples of some planned CCS hub development in industrial regions include:

- Port of Rotterdam and Port of Amsterdam, Netherlands
- Port of Antwerp, Belgium
- Humber and Teesside, United Kingdom
- Northern Lights, Norway
- Ravenna Hub, Italy
- The Acorn Hydrogen and CCUS project in Scotland, United Kingdom

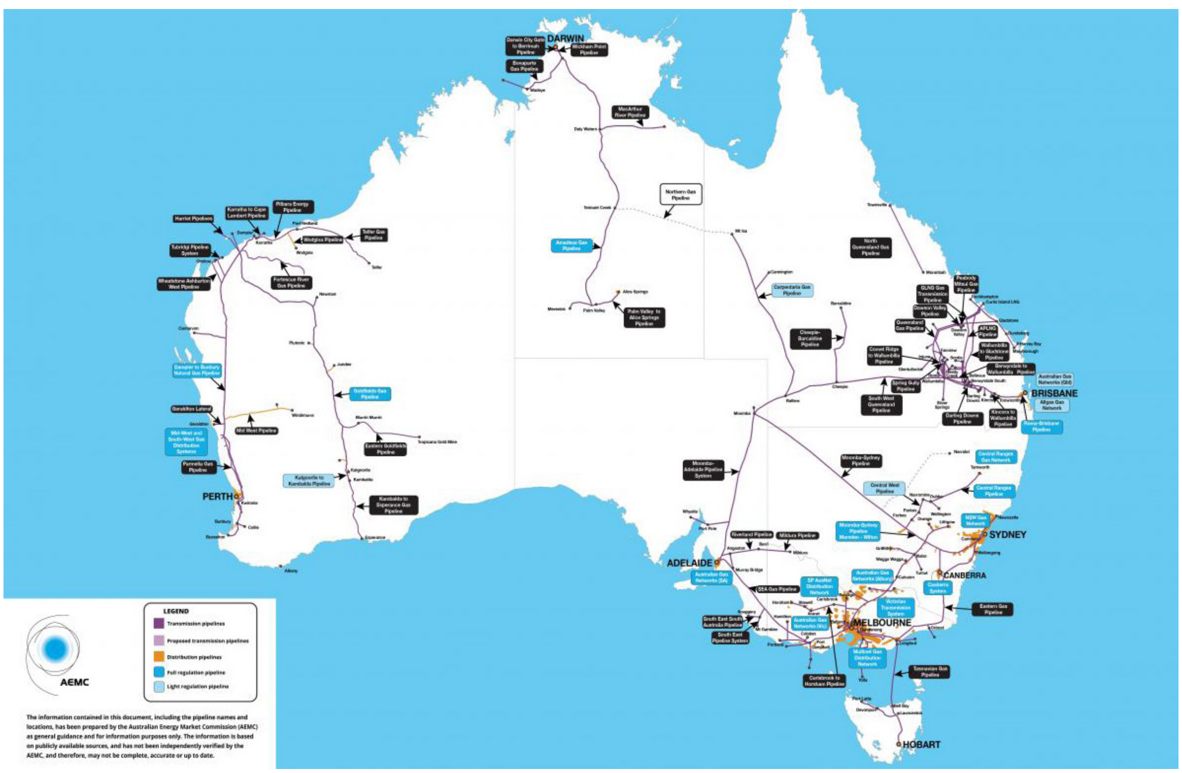
Interestingly, five countries are required to access funding for projects of common interest under the European Commission (EC) rules. As the number of EU countries considering hubs has reached five, this could be material and provide a policy window for infrastructure development and support. The UK government plans to develop the first net-zero carbon cluster by 2040, and the heavy industry of the Ruhr Valley in Germany could take advantage of emerging hubs in the Netherlands. The government of Denmark is also considering CCS infrastructure. Such hubs in the EU and US can serve as a policy and development model for other industrialized regions (e.g., Tianjin/Hubei/Dalian in China or Cambay/Ahmedabad in India).

The development of individual hubs requires significant capital investment, including hundreds of kilometers of pipelines and proven storage infrastructure and requiring many billions of dollars. This is well within the range of typical industrial development. In 2019, there were more than 8,000 kilometers (5,000 mi) of CO_2 pipelines transporting more than 70 Mtpa of CO_2 from both natural and anthropogenic sources. Wallace, et al., (2015) and GPI (2020) independently estimate that roughly 28,000–35,000 kilometers (17,000–21,000 mi) of new pipeline would be needed to connect nearly 500 Mtpa of plant emissions to storage sites—roughly four times longer than today's network size and substantially smaller than the 4 million kilometers (2.5 million mi) of existing natural gas and oil pipeline networks. GPI (2020) also argues that this network could serve future CO_2 removal through direct-air capture.

Infrastructure Development Model: Australian LNG

Development of the Australian LNG industry demonstrates how similar infrastructure can be rapidly developed where there is a business case. In 2018, Australia was able to scale its export capacity to overtake Qatar's capacity, in part as a result of the infrastructure support of the Gorgon CO_2 storage project (required for operation of and export from the LNG facility there). Even more companies are investing in infrastructure throughout the region, turning Western Australia into a global LNG hub. Australia has more than 39,000 kilometers (24,000 mi) of natural gas transmission pipelines that efficiently transport gas under high pressure from where it is produced to the outskirts of cities both large and small. Transmission pipelines in the Northern Territory take gas from fields near Alice Springs in the center of the country to Darwin for use and LNG export. It is likely that the CO_2 storage infrastructure for the Australian continent will be substantially smaller and cheaper than the natural gas and LNG infrastructure.

Figure 5: Existing and Proposed Gas Transmission and Distribution Pipelines in Australia



Source: Australian Energy Market Commission 2020

Storage Resource Development

A worldwide portfolio of strategic, viable geological storage sites is essential to enable the planning and the development of CCS for net-zero. To reach 2030 and 2050 targets, a global stock-take of known storage capacity is critical, especially in key countries.

For decades, experts have known the global storage resources are more than enough to reach these climate targets (IPCC, 2005; Dooley et al., 2009; USGS, 2013; NETL, 2015). Their conclusion is based on a fundamental understanding—***rocks suitable for storing CO_2 are common and abundant around the world***. All global estimates greatly exceed 5 trillion tons of capacity (Table 3) and can accept CO_2 at a rate much larger than most nations' total emissions (e.g., Crippa et al., 2019).

Table 3: Global CO_2 capacity estimates

Geography	Low estimate (P10) in Gt	High estimate (P90) in Gt	Source
Global	8,000	53,000	Kearns et al., 2017
Global	6,000	40,000	Consoli and Wingust, 2017
North America	2,400	22,000	NETL, 2015; USGS 2013
China	1,100	3,600	Li et al., 2009; Consoli and Wingust, 2017

This high level of confidence in those storage resources is based in part on the natural occurrence of CO_2 storage systems, some holding CO_2 for over 250 million years (IPCC, 2005; IEAGHG, 2006). Mostly, this confidence rests on the well-understood physics, chemistry, and operational experience of oil and gas fields and the detailed characterization of rocks above, below, and adjacent to them. Although global gas and oil fields have substantial CO_2 storage potential (the US alone hosts between 185–230 billion tonnes of storage capacity in oil and gas fields) (NETL, 2015), they make up only a small percentage of the total resource available for CO_2. However, experience gained from hydrogeology and the oil and gas industry provides high confidence in an overabundance of CO_2 storage capacity.

A significant gap remains in key jurisdictions between available resources and known, commercially viable storage capacity (similar to the distinction between resource and proven reserves in oil and gas). The CO_2 Storage Resource Catalogue reviewed about 500 sites around the world (OGCI, 2020). The Catalogue reviewed over 12,000 $GtCO_2$ of storage resources using the industry-adopted classification system for CO_2 storage, the *Storage Resource Management System* (SPE, 2017). Only 400 $GtCO_2$ is "Discovered"; that is, having sufficient data that confirms the storage resource. Only 0.001 percent (100 $MtCO_2$) is considered qualified today and commercially ready.

Today, the majority of those well-assessed storage resources are in nations with advanced CCS enterprises, including Norway, UK, US, Canada, and Australia. By 2030, a global portfolio of storage capacities in additional nations (especially China, India, Gulf Coast nations, and those in Southeast Asia) must match the required CCS capture rate. Such sites must commercially de-risked, technically feasible, environmentally sustainable, and locally accepted.

As a climate policy objective, injection and storage rate of individual storage sites must be confirmed and prepared, a process known as characterization and appraisal. Characterization and appraisal are time consuming and labor intensive, but well understood. A number of standards and best practice manuals exist, including the NETL best practice manual and DNV GL Recommended Practice (DNV GL, 2012). The International Standards Organization is also developing standards on site selection and appraisal. Characterization and appraisal of specific sites carry significant risk and uncertainty. Given the time it takes to develop storage sites and manage uncertainties, a focus should be on key sites (e.g., near industrial clusters) in key nations. Additional characterization work would help prepare potential sites for CO_2 removal projects, which today may be too far from emissions sources for conventional CCS projects.

Role of Law and Regulation

Transparent and predictable law and regulation are essential prerequisites for CCS investment. National governments and intergovernmental organizations emphasize the need to clarify CCS's position within international and domestic law and develop frameworks to support its deployment (e.g., Faure, 2016). Uncertainty surrounding existing law and regulation is frequently highlighted as major concern by investors, industry, and the wider public alike. Key uncertainties include:

- Access to and ownership of pore-space, especially in the US
- Operational requirements, including monitoring, reporting, and verification (MRV)
- Liability issues, including long-term liability requirements and transfer of liability to the state.

For several early-mover governments, addressing the issue was a priority when formalizing early policy commitments to the technology's deployment. In the past decade, the removal of legal barriers and the development of regulatory pathways within national regimes has become a defining aspect of national CCS activity.

Emergence of CCS-Specific Legislation

Although core elements of the CCS process have been practiced for many years as part of wider oil and gas industry operations, its role as a climate mitigation technology has challenged policymakers and regulators to adopt new approaches to its regulation. The result has been the development of new legal and regulatory frameworks aimed at regulating the entirety or discrete aspects of the CCS process. The past 10 years have seen amendments to international and regional agreements that explicitly include CCS activities within their scope, as well as the development of CCS-specific legislation in jurisdictions across Europe, North America, Asia, and Australia.

In all but one instance, one of two approaches has been adopted by policymakers and regulators: either enhance existing regulatory frameworks with CCS-specific provisions or enact standalone CCS-specific legal frameworks. The exception has been the development of "project-specific" legislation that regulates the operations of a single project; an example of which is the Barrow Island Act, which regulates Western Australia's Gorgon CO_2 injection project (Government of Western Australia, 2003).

The European Union's Directive 2009/31/EC offers an early example of a CCS-specific legal framework that deals with all aspects of the technology, throughout the project life cycle and within the context of climate change (European Parliament, 2009). The directive removes several potential legal barriers to CCS and clarifies the status of the technology under wider EU directives and regulations, including waste and water legislation. The European Commission chose to focus the directive upon the storage aspect of the CCS process and utilized several pre-existing legal instruments to manage some of the risks associated with the capture and transport aspects of the process. The resulting directive is a comprehensive CCS-specific regime, which includes requirements for the permitting of exploration and storage activities, monitoring and reporting obligations, liability and financial security provisions, and a process enabling the closure and long-term stewardship of storage sites.

In Canada, where regulatory competence for developing legislation is shared between national entities and provincial or territory bodies, the design and implementation of CCS-specific regulatory frameworks has principally occurred at the provincial level. Alberta's legal and regulatory regime is perhaps the most comprehensive CCS-specific model developed within the country to date (Legislative Assembly of Alberta, 2010). Similarly, in the United States, both federal and state authorities have undertaken development of CCS-specific law and regulation (e.g., EPA, 2010 a and b). These approaches serve as templates for other nations or regions considering how to provide clarity to project developers and investors.

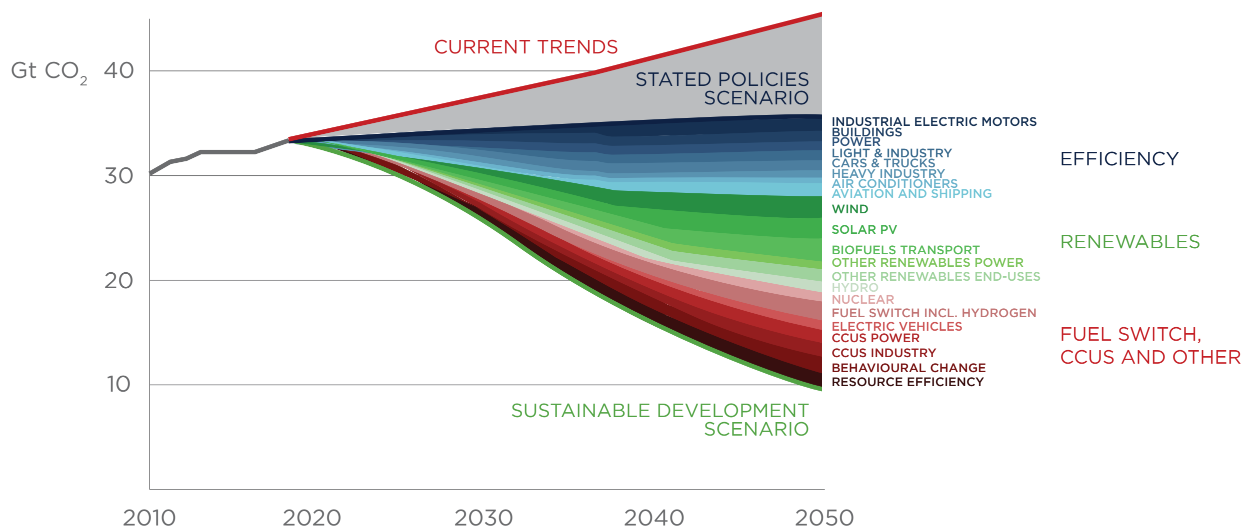
Because of these and related legislative developments, it is now possible for policymakers and regulators to reflect upon the critical legal challenges and intricacies involved in regulating the CCS process. While the ambition and complexity of the legislation developed to date varies greatly, several common areas stand out, and core legal and regulatory elements ("building blocks") will be required if regulatory regimes are to address concerns of investors and public stakeholders.

Only a small number of jurisdictions worldwide have well-defined and comprehensive CCS-specific frameworks. This will be insufficient to achieve net zero by midcentury and requires cultivation of regulatory frameworks. These jurisdictions and their regulatory models offer excellent examples of the challenges to be faced in designing and implementing CCS-specific legislation. For global deployment targets to be met, many more jurisdictions will need to develop their regulatory response to the technology, and the time required to undertake the process must not be underestimated. The urgency of this activity will prove increasingly acute in view of the timeframes contemplated to meet global climate change commitments and net-zero ambitions, including 2030 targets.

PROJECTS: THE CORE MEASURE OF PROGRESS AND POLICY-FINANCE FOCUS

To address climate change, climate models have generally recommended a combination of measures with greater contributions from CCS technology in scenarios that have more ambitious carbon targets, especially those which target net-zero emissions by 2050. For example, the IEA's Sustainable Development Scenario estimates 9 percent of the emissions reductions will come from CCS. While this figure may appear relatively small, the challenge of deploying CCS to meet it is significant. ***The 9 percent figure represents roughly 4 Gt CO_2 and a build rate of between 70 and 100 capture facilities per year***, in parallel with necessary transportation and storage infrastructure.

Figure 6: Energy-related CO_2 emissions & reductions in the Sustainable Development Scenario



Source: IEA World Energy Outlook (2019).

This means finance. CCS facilities are capital intensive, requiring hundreds of millions to billions of US dollars. Between now and 2030, capital support from governments will prove necessary to attract private capital. However, the sheer volume of capital required to achieve wide-scale deployment means private funding, both debt and equity. This is commonly the case for early deployment of clean energy technology deployment (see the offshore wind example later).

To date, CCS projects have not been able to attract private funding to meet high deployment rates. Most parts of the world lack solid, market-aligned policies for CCS, which limits financial viability. Most CCS projects are funded in public-private agreements involving a single corporation (or a fully owned subsidiary) that develops the project and places all financial costs (and risks) on its balance sheets. While this makes the entire process of corporate finance attractive in terms of cost of capital and speed of implementation, too few companies are large enough to develop projects in this way, and corporate finance cannot deliver the projects needed to meet the targeted number of CCS projects for 1.5°C or 2°C scenarios.

The alternative, and more scalable funding model, is project finance. Capital for the project is raised on the basis of future cash flows with multiple investors in a single project, so both equity and debt investors are exposed to any uncertainty in performance of the project.[4] Unlike corporate finance, project financiers have no recourse to the assets of project owners and need stable, predictable returns to place their capital risk. This is particularly true of institutional investors (e.g., pension funds and sovereign wealth), which commonly accept low rates of return for low-risk investments, and to attract small- and medium-size investors (i.e., companies that lack large balance sheets). Reducing risks also reduces costs of capital, which will enable participation of smaller companies in the CCS sector.

The Role of Institutional Investors

Institutional investors—those that invest on behalf of third parties, such as mutual funds, pension funds, and insurance companies—will play an important role as CCS deployment ramps up. Institutional investors are attracted to investment in infrastructure projects because these provide secure, long-term cash flow while also providing a yield pickup (an investment strategy whereby bonds with lower yields are traded for bonds with higher yields) on the low returns available from government bonds.

Like all large-scale infrastructure projects, CCS projects will have a varying risk profile across the different phases of construction and operation. Once a project is commissioned, its risk profile falls because risks are highest during the construction phase and lower during operation. This drop in the risk profile of a project can lead to the refinancing of a project's debt with more favorable terms of lending being applied, which reduces project cost, bringing institutional investors to refinance or acquire projects that have entered operation.

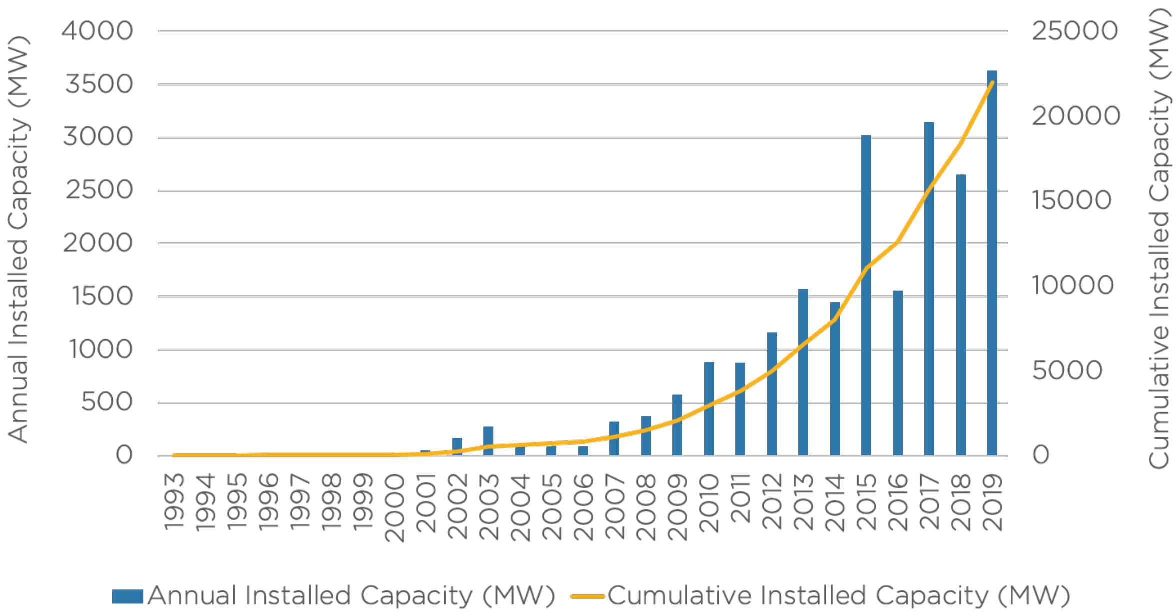
Lessons from European Offshore Wind

The European offshore wind sector is the most advanced in the world, and its recent development provides insights as to how project financing can be leveraged for large-scale CCS projects to increase the rate of deployment.

During the early 2000s, there were very few offshore wind projects in operation, similar to the status of CCS projects today. Once the EU confirmed offshore wind as a critical technology to meet the bloc's emission reduction targets, it implemented multiple policies to accelerate the rate of deployment of offshore wind farms. Private investors received a range of government subsidies in conjunction with other financing policies from the EC, including feed-in tariffs, green certificates, contracts for difference, and other "offtake agreements."

Each of these served the purpose of delivering a sufficiently high and stable revenue stream to offset project risks and generate acceptable returns. These incentives together de-risked investments in offshore wind overall and established a learning curve for the technology, creating more opportunities for smaller investors. As the offshore wind sector has evolved, investors have become more comfortable with project risks, so the participation of financiers has diversified, with commercial lenders playing a more prominent role than during the early stages of deployment. This had led to dramatic increases in the number of projects (Figure 6). Today, investments in offshore wind consist predominantly of conventional project finance.

Figure 7: Cumulative offshore wind installations from the early nineties until 2019



Source: Wind Europe

Although there are significant differences between offshore wind and CCS projects, there are important similarities, including novel, bespoke infrastructure and large corporate first-movers that fund projects on their books. With proper market-aligned policies, CCS could follow a similar trajectory.

POLICY OPTIONS

Without strong and predictable policies, market failures translate to market risks. If the cost of capture, transportation, and storage of CO_2 is greater than the value provided by climate policies, there is no incentive for investing in CCS. The value must be both stable and relatively predictable, and that predictability must ultimately be long-lived.

There are, however, additional challenges that require government intervention to get projects built, given the early stage of CCS ecosystems and networks:

- **Interdependency or cross-chain risk**: CCS facilities may involve one source, one sink, and one pipeline. These engender higher costs as well as a significant interdependency risk for disaggregated business models. This risk manifests as a higher cost of capital for potential financiers and represents a significant barrier to project investment.
- **Long-term liability risk**: While the risk of leakage from an appropriately selected storage resource is extremely low, unlimited or long-duration liability obligations make it very difficult for private sector investors to accept, particularly in jurisdictions where experience or access to geological data is limited. If these questions are not clarified through policy, even very low-risk projects may be difficult to launch.

Overcoming these risks will be essential to achieving 2030 rates of deployment. Thankfully, well-understood options are available as means to better manage or mitigate these risks so as to create an enabling environment for the private sector to invest in CCS.

Valorizing CO_2

Applying CCS at points of emission rapidly and profoundly reduces emissions. CCS does not, however, make products like steel or electricity, create revenues, or reduce energy consumption. In fact, capturing, transporting, and injecting CO_2 commonly adds costs and energy requirements. To merit investment, policies must place a sufficiently high value on the emissions reduction to incentivize investments. To date, the chief way this has occurred has been through the sale of human-made CO_2 for Enhanced Oil Recovery (EOR) rather than through environmental or clean energy policy mechanisms. Of the 21 projects currently in operation, 16 sell CO_2 for EOR (CO_2-EOR), a process whereby CO_2 is injected into oil reservoirs.

Widespread deployment of CCS will require a sufficiently high value to be placed on CO_2 emissions reduction independent of (and possibly as substitutes for) CO_2-EOR opportunities. This can only be achieved through market-aligning policies. Many options are available, and many examples exist supporting CCS deployment. Each jurisdiction determines the policy mix that best suits the local market.

- **Cap and trade**: These policies work by placing a limit on the total emissions—a regulatory cap—allowed for a given industry or the whole economy. The cap is split into transferable allowances, so companies can decide whether to contain their emissions or purchase additional allowances from others. Over time, governments may reduce the cap so that there are less allowances available, thereby increasing demand for low-carbon interventions. By their nature, cap-and-trade schemes reward the most cost-effective forms of mitigation first. The European Emissions Trading Scheme (ETS) is one example, and a variation on cap and trade (baseline accreditation), the California low-carbon fuel standard, is a second (GCCSI, 2019). While cap-and-trade schemes provide a great deal of certainty over emissions reductions, they may carry significant uncertainty regarding the commercial value of these reductions. For example, the ETS value remains below the investment threshold for CCS investment and is not projected to meet it before 2030 (European Commission, 2018; CarbonTracker, 2018).

- **Carbon tax**: A carbon tax is a fixed cost imposed on CO_2 emissions. The pricing of the tax can be optimized to achieve reductions in line with targets for specific areas of the economy, and it can be increased over time to drive down emissions. For CCS, such taxes can be directed at large emitters and priced higher than the cost of capture. Like all taxes, however, their effectiveness is subject to their longevity. The Norwegian government introduced a carbon tax in 1991, which incentivized the development of the Sleipner and Snøhvit CCS projects. At the time, \$17/t CO_2, the cost of injecting and storing CO_2 for the Sleipner project, was much less than the \$50/t CO_2 tax penalty for CO_2 vented to the atmosphere (Massachusetts Institute of Technology, 2016; Herzog, 2016).

- **Tax credits and other incentives**: Governments may grant incentives such as tax credits to promote investment in a low-carbon technology. Credits can be investment-based (investment tax credits), performance-based (e.g., production tax credits), or both in combination. Tax credits have the benefit of being well-established climate change policies, having been used to drive significant investment in renewables over the past two decades. The US has used tax credits to stimulate renewable investments, including the wind production tax credit and the solar investment tax credit. In 2018, the US amended a performance-based tax credit for CCUS, 45Q (EFI, 2018; GCCSI, 2019). A similar mechanism, contract for differences (CfD), provides additional revenues for low-emissions production of electricity and acts as a production credit. The UK CfD for low-carbon electric power generation is an example that would support CCS deployment there (BEIS, 2020).

- **Green bonds**: One promising investment vehicle, sustainable bonds, allows investors to attach purpose to their investments, reconnecting finance with hard assets in the economy. In recent years, there has been significant growth in sustainable bond investments, particularly those issued to raise financing for climate-friendly investments. In terms of financing sources, there may prove to be substantial potential if projects are structured correctly. To this end, specialist funding sources (i.e., multilateral agencies and export credit agencies) play an important role in providing impact financing, especially during the earlier stages of deployment.

- **Regulated reductions**. Enacting legislation to reach climate targets provides transparency and accountability. To this end, several countries have mandated emissions reduction targets through legislation. Many countries have legislated net-zero emission commitments by 2050: France, the United Kingdom, Sweden, Denmark, Netherlands, Iceland, and New Zealand. At the subnational level, California and New York in the US and Victoria in Australia have all enacted legislative commitments to net-zero. Some commitments are economy-wide; others are sector-specific (e.g., electricity). Commonly, these regulated reductions are paired with incentives and supported by advisory or statutory bodies (e.g., the UK's Climate Change Committee, created by the Climate Change Act of 2008). Some countries with net-zero commitments have overtly provided policy support for CCS deployment. In the Netherlands, CCS has been highlighted as a crucial technology in the electricity sector, and accompanying policy packages have allocated subsidies to assist with deployment.

- **Procurement policy**: Public procurement has emerged as an important instrument of innovation policy. Governments are one of the largest buyers of materials and services and can have a significant influence over the development of markets. In OECD nations, public procurement accounts for 12 percent of GDP, and up to 30 percent in many developing countries (Hasanbeigi et al., 2019). In the context of CCS, this is most relevant for hard-to-abate sectors, from which governments procure either directly or indirectly in large volume, including cement, steel, paper, and fuel. Traditionally, governments have bought the first generation of clean energy technologies, playing a key role in creating supply chains, stimulating innovation investments, and reducing initial costs. However, many policies that guide procurement predate the Paris Agreement and restrict the adoption of low-carbon choices. Governments must modify procurement policies and standards accordingly.

Costs and Avoided Costs

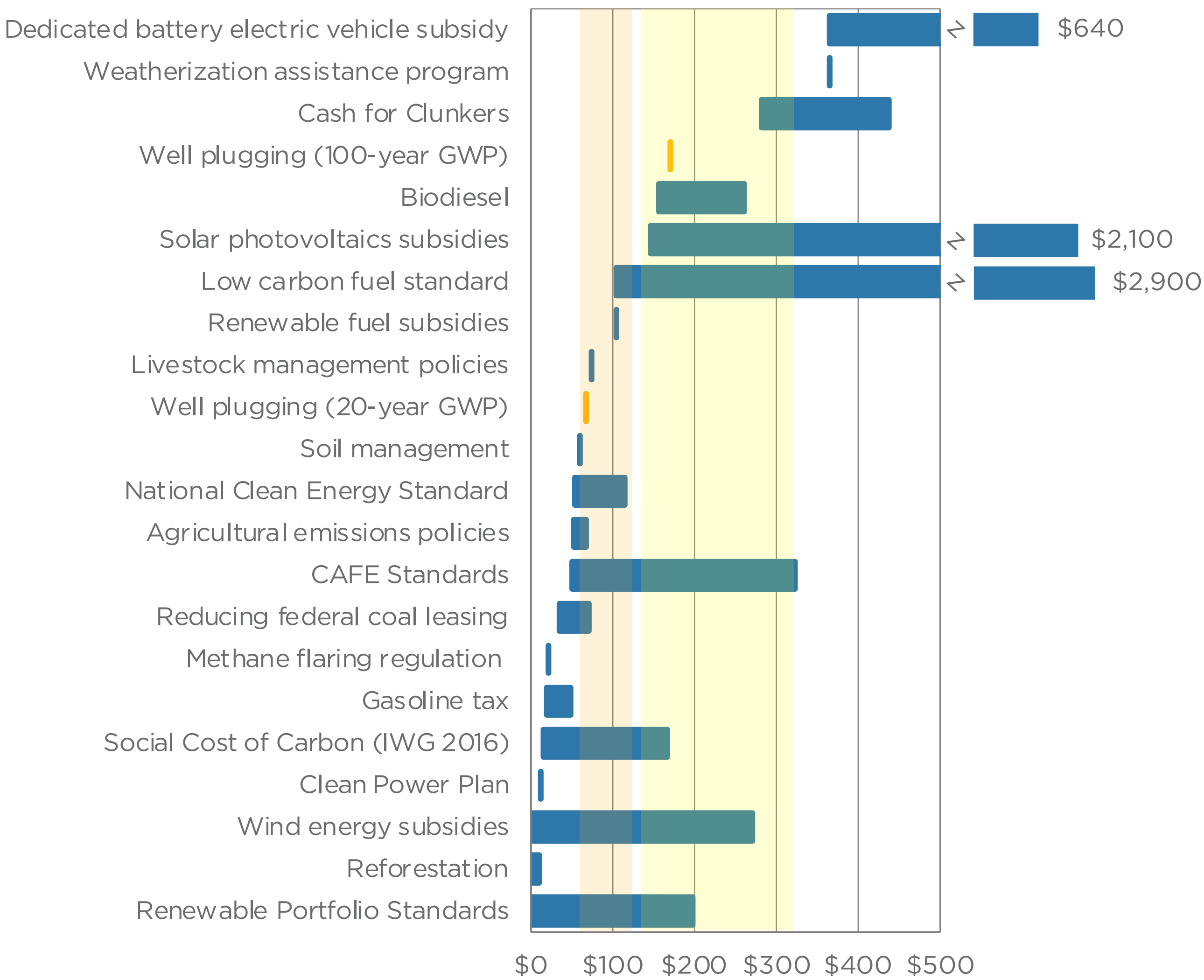
In considering what policy mix can achieve a net-zero economy and how to value emissions reductions, two key questions emerge: What should we do first, and how much will this cost? Focusing on 2030 as a near-term milestone underscores these questions: the longer the delay in reducing CO_2 emissions towards zero, the larger the likelihood of exceeding a 1.5°C increase, and the heavier the implied reliance on net-negative emissions after midcentury to return warming to 1.5°C.

In this context, CCS has two specific values: low total costs in comparison to other options and avoided costs of climate change impacts through rapid mitigation and emissions reduction.

The Energy Transitions Commission (2018) states that achieving net-zero emissions in hard-to-abate sectors without CCS "will probably be impossible, and certainly [be] more expensive." It describes CCS as the most cost-effective route to decarbonizing chemicals, steel, and hydrogen production. One advantage CCS has is the ability to retrofit existing facilities without their premature retirement. Attaching CCS operations to emitting plants allows continued operation and production in existing infrastructure and logistics chains, preventing the capital losses associated with premature decommissioning (Friedmann et al., 2020). The prize can be substantial—applying carbon capture to the most feasible individual fossil power generators in the US would capture approximately 200 million MT per year (Brown, 2019) and at lower system costs than other low-carbon options (Jenkins et al., 2018; NPC, 2019).

To compare CCS with other clean energy options requires a common metric. To determine the relative abatement costs associated with carbon removal technologies and policies, Friedmann et al., (2020) propose a levelized cost of abatement (LCCA). LCCA provides specific quantitative measures regarding the cost and abatement associated with specific investments, technologies, or policies, allowing "apples-to-apples" comparisons between CO_2 reduction and removal options. Gillingham and Stock (2018) compare these costs across many carbon reduction or removal policies, revealing that CCS remains cheaper than many decarbonization pathways. (Figure 7)

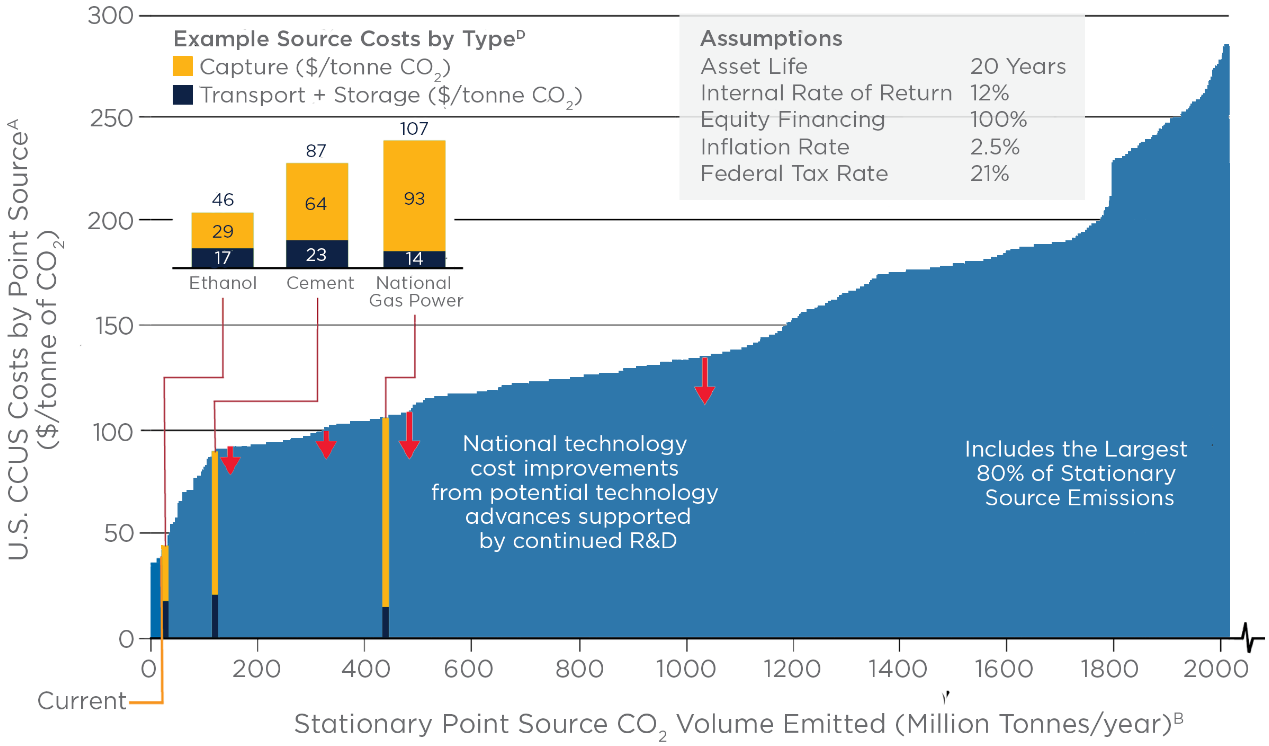
Figure 8: Estimated CO_2 abatement costs from selected US policies. Most of these policy options cost much more than the cost of carbon capture (orange shading) or even direct-air capture (yellow shading). Data from Gillingham and Stock, 2018. CCS cost data from GCCSI 2019 and NPC 2019. DAC costs from Rhodium Group, 2019.



Source: Bordoff et al., 2020.

The recent NPC (2019) report estimated the marginal abatement costs (MAC) for virtually every large emitter in the US, creating a MAC curve for CCUS deployment (Figure 8). It represents specific US facilities and builds the curve with individual costs assuming a specific existing technology and casts them in the context of policy ambition. Their estimates indicate that almost half a gigaton of reduction is possible for less than \$110/ton CO_2, again substantially less than other options discussed by Friedmann et al., (2020) or Gillingham and Stock (2018).

Figure 9: Marginal abatement cost (MAC) curve for application of carbon capture and storage technology to individual existing US point sources (both power and industrial sites).



Source: NPC, 2019

Finally, it is important to remember the likely costs and consequences associated with inaction. Stern and Stiglitz (2017) estimate enormous costs associated with climate change, ranging from 5–20 percent of global GDP. The estimated costs and impacts on health, infrastructure, and biodiversity are enormous even under a 2o C scenario (IPCC 1.5o C report, 2018). In this, CCS provides an option that takes advantage of existing infrastructure at lower marginal cost and lower system cost (IEA, 2020).

Ecosystem Support

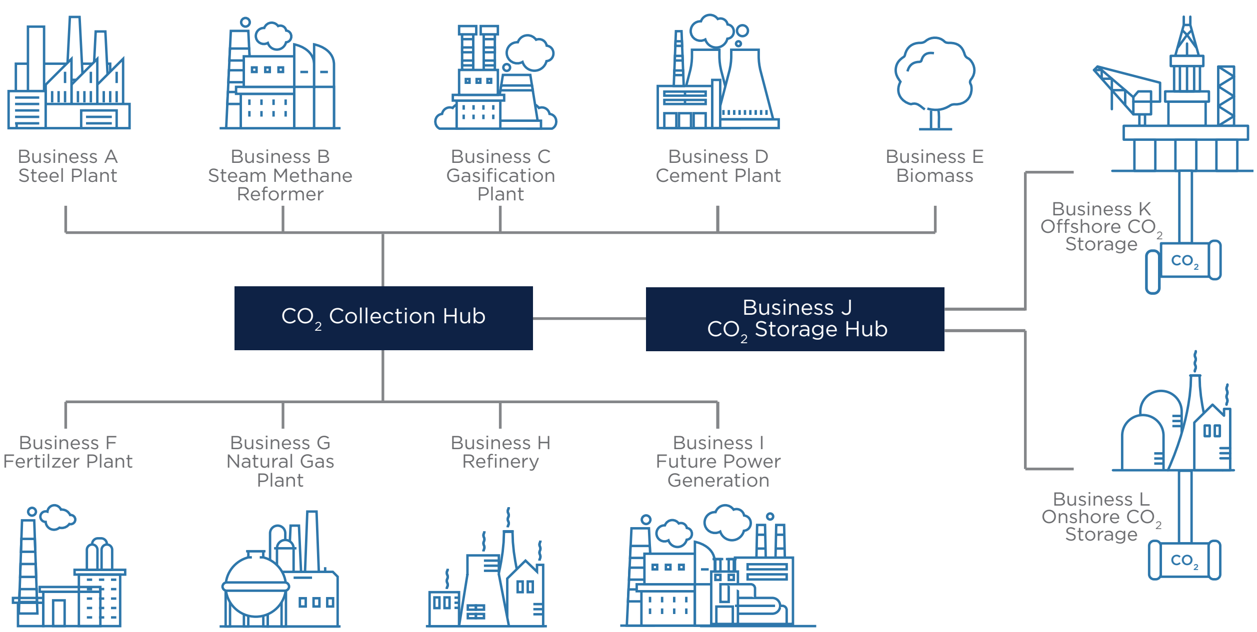
Some clean energy technologies, such as hydropower or biofuels, enter mature markets with well-developed infrastructure, legal, and regulatory systems. That mature market ecosystem has helped speed adoption rates. Between now and 2030, components of the CCS ecosystem require support, clarification, and development to facilitate deployment.

Infrastructure: Pipelines, Storage Centers, and Minimizing Cross-Chain Risk

CCS facilities may involve one source, one sink, and one pipeline. In a disaggregated business model, there is significant cross-chain risk for all members of the value chain. This risk is a significant barrier to investment and manifests, ultimately, as a higher cost of capital and higher project costs. Common infrastructure dramatically lowers costs and risks to market entry and lets participants focus on their core business and skills. Shared transport and storage networks significantly improve the economics of CCS facilities because of the benefits of economies of scale and overall de-risking, and developing this infrastructure is essential to achieving widespread deployment of CCS systems (GPI, 2020).

An important option (discussed earlier) is the hub and cluster model (Figure 9). Here, value is provided through risk reduction across the value chain. A transport and storage network gathers CO_2 and manages disposal with a single entity, which significantly reduces unit cost of CO_2 disposal, enables market entry for new players, and reduces cross-chain risk by creating multiple customers for the operators of the CO_2 transport and injection business. Hubs and clusters offer high levels of operational flexibility, clear and constant prices for CO_2 services, reduced operational risk, and can serve to attract additional local investment, production, manufacturing, and jobs.

Figure 10: Hub and cluster model



Early investors in a new transport and storage network will face all the costs and risks of a single source until others join the network. This exposes them to cross-chain risks, greatly limiting numbers of early-movers. Guarantees must be provided for revenue during the early stages of development, as they are for new power transmission lines or new natural gas pipelines. For CCS projects in most jurisdictions, the balance of risk and return is insufficient to attract private sector investment in a CO_2 transport and storage network, requiring government investment or loan guarantees early on. The benefit to governments, beyond rapid and profound emission reduction, would include new investment attracted by the infrastructure and associated jobs and community support.

This model of government making the initial investment in infrastructure followed by later privatization is proven in other sectors such as road and rail transport, power generation and transmission, and telecommunication. Alternatively, governments could invest in establishing a regulatory framework that provides the private sector with the right incentives to invest in transport and storage networks. This may be preferable in regions where this is already common among infrastructure providers and where governments are restricted in funding transport and storage networks.

Long-Term Liability

A significant barrier to investment in CO_2 storage is risk associated with long-term liability. If there are no limitations on liability, either magnitude or duration, storage operators will face indefinite obligations of uncertain size. It is very difficult for private sector investors to accept essentially unlimited and perpetual liabilities. To mitigate this risk, it is critical for governments to implement a well-characterized legal and regulatory framework that clarifies operators' potential liabilities.

Multiple governments have adopted a remedy, whereby the storage operator bears the risk of short-term liability during the operational period of the project and for a specified post-closure period only. The Australian government provides one example:

> Following the completion of a period of at least 15 years, from the issue of the Site Closure Certificate, the title-holder may apply to the Minister for a declaration confirming the end of the 'Closure Assurance Period'. A declaration at the end of this period concludes the title-holder's liability for the storage site. Importantly, the Offshore Petroleum and Greenhouse Gas Storage Act also provides the former title-holder with an indemnity from the Commonwealth Government for any liability accrued after the Closure Assurance Period (Havercroft, et al., 2015).

This approach has been replicated in a number of other jurisdictions including the Australian states of Victoria and Queensland, the European Union, and the Canadian province of Alberta. It recognizes that the risk of leakage from a geological storage resource is highest during injection of CO_2, reduces immediately upon cessation of injection, and continues to reduce with time. Consequently, the risk accepted by governments starts small and shrinks thereafter.

Another proposed option is for governments to bear some or all of the risk during and after storage operations. This mechanism has been adopted in many states in the US, which have legislated policies that accept liability for early projects. Under this arrangement, the private sector operator would be responsible for risks incurred below a cap, while government would take responsibility for all additional risks above a cap (Pale Blue Dot, 2018). Note that all risks, not just long-term liability risks, could be subject to risk-sharing under this model.

Amendment of International Marine Law

Enormous opportunities exist to store CO_2 offshore, most importantly in Europe and Australia. Even in the 1990s, many early analyses focused on the maritime setting for CO_2 injection and storage activities. Initial legal and regulatory assessments of CCS operations identified international and regional marine agreements as potential barriers to the technology's deployment, notably the 1972 London Convention and its proposed Protocol, a key element of the CCS ecosystem that merits diplomatic attention and work. The Protocol (the first international agreement codified to protect marine environments from wastes) adopts a stringent, precautionary approach to the disposal of wastes, with parties required to prohibit the dumping of all wastes at sea, save for those listed in the Protocol's Annex.[5]

The completion of various CCS-focused legal and technical reviews and the Protocol's entry into force in 2006, resulted in several parties submitting a proposal to amend the Protocol's Annex to allow the storage of CO_2 in sub-seabed geological formations. At the first meeting of the contracting parties to the London Protocol in November 2006, a formal resolution was adopted and entered into force in 2007. This category consists of "Carbon dioxide streams from carbon dioxide capture processes for sequestration" and provides a formal basis for the regulation of CO_2 sequestration in sub-seabed geological formations under the Protocol's mechanisms.

Shortly after the 2006 amendment, it became apparent to parties who were keen to export their CO_2 for storage or to host storage projects within their territory that these activities were not permitted under the Protocol. While principally aimed at preventing the export of wastes to non-parties, Article 6 of the Protocol had the effect of prohibiting transboundary transportation of CO_2 for geological storage. The position was confirmed by a technical working group, who recommended proposed text to amend the Protocol, introduced in October 2009 as a formal amendment. The amendment has yet to enter into force due to insufficient signatories. Although an agreement was reached in 2019 to allow the provisional application of the 2009 amendment as an interim solution, ratification of the 2009 amendment remains important.

Beyond 2030

Given the long lead times associated with developing CCS projects, the steps taken between now and 2030 will determine whether CCS technology will be deployed at the scale necessary to meet net-zero emissions by 2050. The arithmetic similarly demands that between 2030 and 2050 the rate of deployment of CCS grows exponentially. This implies that a rapidly growing demand for CCS projects emerges from debt and capital markets before 2030. For this to happen, investments in CCS must be significantly de-risked during the intervening years.

Governments must also anticipate the logistical barriers to be overcome by 2030. This will involve planning and investment at large scale, such that the infrastructure to enable private investments in capture facilities is already available by the time the CCS market is de-risked and financiers are primed to invest. A handful of countries may already be on this path and will be well positioned to host projects beyond 2030.

Nonetheless, significant work remains to ensure that key nations, ones for which CCS will be an essential component of their climate objectives, follow suit. Parts of the world lack the capacity to develop the necessary infrastructure, human capital, or policies. In many cases (e.g., Southeast Asia) high cost of capital will severely limit investment potential. Novel arrangements should be explored to create options for these regions. One idea is for a group of OECD and non-OECD countries to cooperate in creating trade-based hubs and clusters enabled through shipping CO_2. Each country could then play to its strengths to create a cost-effective network of low-carbon goods, services, and infrastructure. International engagement, both bilateral and multilateral and in some cases long-lived, will be important to lay the foundations for projects and trade networks of this kind. Similarly, work is needed now to identify and assess viable geological storage options in regions like India, Southeast Asia, and Latin America. This may involve capacity building exercises, data transparency, and joint international surveys as the rest of the policy framework for geospheric return matures.

Such approaches can only succeed through robust policy measures and the availability of affordable financing. Developing countries will be at a disadvantage, and in some cases country risks would translate into a high cost of capital. To overcome these barriers, support from OECD countries, e.g., through climate finance mechanisms, may prove essential. This support can only become available if there is a concerted effort from within the international community to target large-scale planning and implementation of CCS projects globally.

SUMMARY – IT'S ABOUT TIME

The benefits of the modern energy system are many and varied, including wealth, health, art, and growing equity. The emissions from this system, past, present, and future, present a grave threat to these benefits and to the natural world. **Urgent action is required to achieve net-zero emissions and ultimately to remove legacy emissions** from our air and oceans. The work is pressing, mammoth, and enduring.

For this work, there is no substitute for carbon management. Both conventional CCS and engineered CO_2 removal are essential contributors to a net-zero global economy. All of the above starts with the world "all." **Throughout the next 10 years**, specific investments in infrastructure and innovation and specific policy actions will determine if net-zero is possible in our lifetimes. The focus must be on returning any carbon taken from the geosphere back to the geosphere and enabling policies that can hasten deployment. The most important policy options are as follows:

- ***Invest in CO_2 transportation and storage infrastructure***, most importantly CO_2 pipelines, industrial hubs and clusters, and qualified storage sites.
- ***Provide financial support to projects***, either through incentives (e.g., contract for differences, grants, tax credits, green bonds) or regulation (e.g., mandates, emissions standards, cap and trade).
- ***Clarify key regulatory and policy issues, such as pore-volume access***, long-term liability resolution, and the amendment of the London Convention of the Seas.

Due to the urgency of the climate crisis, time is of the essence. There are no important technical barriers to scale-up. The costs are well within the conventional boundaries of global energy investments and the policy options well understood. The next ten years will prove decisive – if the governments of the world are to meet their climate goals, these key policies must enter into force with deliberate speed.

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NOTES

1. Assuming solar PV capacity factor of 0.25 for 20 MW PV capacity, 10 MW electrolyzer and 50 kWh per kg of H_2 produced and necessary large scale battery storage.
2. Assuming 50 kWh of electricity per kg of H_2 produced.
3. 90 percent of this potential was via net-negative hydrogen production, combining biomass gasification with CCS.
4. The ratio of debt to equity in a project can vary significantly, by project specifics, availability of capital, and risk profile of the project owners.
5. The International Maritime Organization (IMO) acts as the secretariat for both the Convention and Protocol and views the Protocol as a key element of the international community's response to climate change.

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