Comparative State Economic Interventions in the Carbon Capture and Storage Market

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VIEWPOINTS

Abstract: An essential element in the portfolio of climate solutions required to rapidly achieve net zero emissions is flue gas carbon capture and storage, whereby carbon can be sifted from emission streams before it enters the atmosphere and safely sequestered in geologic storage systems. Despite its importance in the climate tool portfolio, flue gas capture capacity is currently much less than reasonable estimates of its potential. States around the world are searching for policies by which to incentivize emitters to invest in carbon capture and storage (CCS) and hasten the technology's rollout. We survey five leading polities (United Kingdom, Netherlands, Norway, United States, and California) in their efforts to kick-start the deployment of CCS and assess the strengths and weaknesses of each territory's scheme.

INTRODUCTION

Why CCS is necessary: Mitigation — reduction in the emission of greenhouse gases — remains the urgent and primary strategy by which to forestall further climate change, and adaptation will prove essential to lessening the negative impacts of climate change on future generations. However, global decarbonization of both the energy supply and industrial processes will take many decades, and if the flues associated with these facilities remain unremediated, their effluent will add substantially to the climate problem. Even after the world achieves net zero, it will likely be cheaper to recapture emissions from certain recalcitrant industrial sectors than to eliminate them from the upstream processes.

These circumstances require the rapid and urgent build-out of carbon capture facilities at fixed-point emission sources (hereafter referred to as CCS) around the globe. However, these technologies remain "obstinately unused."[1] with a mere 27 commercial facilities operative today, capturing less than 40 Mt CO_2 per year.[2] This is less than 1/100th of the estimated capture capacity required by 2050 to reach Paris Agreement goals.[3]

The impediment to accelerating scaling is not technological, but financial. There is a utilization market for only a tiny portion of our annual carbon production, and "natural" climate solutions such as afforestation and bioenergy are poorly scaled to the enormity of the climate challenge. The ultimate catalyst for widespread CCS adoption will of course be high carbon prices, though these are not yet at the level required to make CCS an economically viable proposition for the average emitter.

CCS vs DAC: Flue gas capture is distinct from direct air capture (DAC), wherein carbon is captured from ambient air rather than flue gases. In either case, CO_2 is chemically extracted from a stream of gas, but whereas carbon concentrations in flues emanating from industrial facilities and power plants may range from 5% – 30% CO_2,[4] those in ambient are in the range of 410 parts per million — less by three orders of magnitude. Therefore, capturing a given amount of CO_2 from ambient air requires handling and scrubbing a vastly larger volume of air at substantially higher cost. Since it will always be more efficient to capture carbon from flues, until such time as virtually all the large flues in the world have either been eliminated or remediated, the economically efficient focus of carbon capture efforts should be flue gas rather than direct air.

Carbon storage: Irrespective of the source from which the CO_2 was recovered, the front-end capture mechanism must be linked to a back-end transportation and storage network that can transport the purified and compressed CO_2 to an appropriate storage location. It can thereafter be pumped underground into essentially permanent geologic sequestration. As with natural gas, the most efficient transportation method for large quantities of CO_2 would be pipelines, and several thousand kilometres of CO_2 pipelines already exist in the U.S. and elsewhere.[5] The most abundant sequestration sites will generally be depleted oil and gas fields, where the geology is well suited to the injection and permanent storage of such fluids, or saline aquifers, for which there is little expected future human use. There are abundant potential storage sites all over the earth, such that storage capacity is not understood to be a meaningful constraint.[6] A well-managed carbon storage operation would also entail monitoring infrastructure to ensure that the sequestered carbon does not inadvertently return to the surface and atmosphere.

History of CCS around the world: The earliest large-scale efforts towards commercialising carbon capture technology were for enhanced oil recovery (EOR), which remains by far the largest use of the technology today. Since the 1970s,[7] energy majors in North America have used both captured and mined carbon to support "tertiary recovery," by which more oil is driven out of an existing field.[8] While EOR projects have propelled the commercialisation of CCS technology, from a climatic perspective they offer very little benefit, as they newly dredge up almost as much carbon as they put in the ground.[9]

However, carbon capture technology has also been used for more climatically positive interventions since the mid-1990s, and this trend has inched forward as more governments have recognized the need for CCS. Norway has led the charge, introducing a carbon tax in 1991, followed by the world's first offshore storage of CO_2 at the Sleipner facility in 1996.[10] Subsequently, other governments have invested in CCS demonstration projects and full-scale commercialisation.

Why governments must intervene to scale up CCS: While the technology for both capture and storage is relatively mature,[11] the business case is anything but. The central challenge is that there is market-demand for less than 1% of the CO_2 that the modern global economy produces.[12] The remainder is simply an unwanted industrial waste that is vented into the atmosphere, creating huge climate damages in the future. This necessitates government intervention either to internalize this externality into traditional markets or to fund CO_2 capture projects directly.

In the longer term, the ultimate driver of the CCS industry will be governmental mandates that place a price on carbon, whether in the form of carbon taxes, emissions trading schemes, or (implicitly) through direct regulation. Once the price of emitting a ton of CO_2 becomes higher than the marginal cost of abatement, economic actors will find ways to reduce or recapture emissions. However, for the vast majority of the world, that is a distant prospect. While a growing list of countries have put in place carbon pricing (UK, EU, Norway, China, Canada for instance), price levels are not nearly high enough to incentivise CCS on a large scale. The European Union ETS price (somewhat of a global benchmark) has traded throughout 2021 in the €50-60 range.[13] While this range does cover early CCS opportunities in sectors with cheaper capture costs like natural gas processing, fertilisers, and bioethanol production, it falls well short of the capture costs of €90 and above per ton associated with fossil fuel-based power generation and cement, iron, and steel production.[14]

Further, with processing, transport, storage, and monitoring adding another €15-60 per tonne, current carbon prices are insufficient to drive the CCS industry.[15] Hence, several countries have pursued bespoke incentives and funding schemes to jump-start their carbon capture industries, such that when those presumed higher carbon prices arrive, the supporting infrastructure, regulations, financial community, other ancillary services, and society at large will be ready.

Unfortunately, the results of such early market interventions to date have been mixed. While nations such as the UAE[16] and Norway[17] have successfully stood up CCS facilities, there have been as many failures as successes. Both the UK[18] and the Netherlands[19] have attempted to fund carbon capture projects that ultimately fell apart when it became clear that either the business case or the societal/political alignment was insufficiently strong to justify a full investment. The Global CCS Institute reports that only about one-quarter of the CO_2 capture capacity under all levels of development materialized into operating projects over the last decade, with the overall capacity under development decreasing steadily every year between 2011 and 2017.[20]

However, in the last few years, particularly in the context of recent net zero commitments by many nations, jump-starting carbon capture markets has again risen to the top of many environmental policy agendas. With lessons learned from previous failures as well as renewed and strengthened political desire to reduce emissions quickly, this new generation of CCS projects may stand a greater chance of success.

POLICY SUPPORT FOR CCS AROUND THE WORLD

We focus on five polities that are furthest along on scaling up domestic CCS industries: the United Kingdom, the Netherlands, Norway, the United States, and California. Of course, other countries are making headway on CCS. Australia, Japan, China, Saudi Arabia, the UAE, Qatar, Canada, and Brazil have all invested in demonstration projects, grants to operators, direct funding via state-owned enterprises, regulatory performance standards, and/or tax incentives. However, these efforts have been on a more limited scale (generally linked to individual projects), often without an overarching regulatory framework, and hence are of less relevance to this analysis of what is needed to kick-start carbon capture on a larger scale.

United Kingdom: Driven both by European fears in respect of seismic activity resulting from onshore carbon storage and by the abundant offshore regional oil and gas prospecting operations, three North Sea-facing nations have become the European leaders in CCS development. The UK government announced in November 2020 the goal of capturing 10 Mt CO_2 per year by 2030.[21] This is a mere drop in the ~40 Gt bucket of global CO_2 emissions, and constitutes less than 5% of UK's total CO_2 emissions, but would nonetheless constitute a meaningful forward step.

To support this ambition, the UK has announced funding of up to £1bn for at least four "clusters," with the aim of (at least) two clusters being operational by 2025 and a further two by 2030.[22] Each cluster will link several industrial and power emitters, as well as hydrogen production sites, to a network of transportation pipelines leading to an offshore sequestration site. From the UK government's perspective, facilitating clusters of emitters rather than individual sites drives economies of scale, reduces the cross-chain risk on the transport and storage (T&S) network, and helps build local political support for the projects.[23] Each of these strategies derives from "lessons learned" from prior failed attempts to spur CCS development in the UK.

In response to a governmentally sponsored competition, five different clusters across the north of England and Scotland submitted bids for to be among the first to be developed — the so called Phase-1 Clusters.[24] The winners were the HyNet Cluster and East Coast Clusters, with the Scottish Cluster chosen as a reserve.[25] The HyNet Cluster, in North West England and North Wales, is backed by the Italian oil and gas company, Eni, while the East Coast Cluster is centred around the Humber and Teeside regions of Northeast England and will see participation from BP, Eni, Equinor, National

Grid, Shell and TotalEnergies.[26] As of August 2022, the UK government had also identified a list of individual emitters within and adjacent to these clusters that are eligible for support under the program.[27] It is envisioned that these large point source emitters in the industrial, power, or hydrogen sectors will be linked into the T&S network such that their future emissions can be sequestered.

To fund the cluster operators, the government is instituting four business models, each specific to the type of operator — industrial, power, T&S, and hydrogen.[28] The subsidy model for industrial and power emitters is the Contract for Difference (CfD), whereby the government provides a top-up payment to the operator over and above the cost to emit a ton of CO_2 via the (projected) UK ETS price. This top-up payment takes into account the operator's cost of capture, T&S fees, and a rate of return on capital investment, alongside co-funding of initial capital expenditure to build out the capture equipment.[29] The CfD model was pioneered by the UK government in the highly successful spool up of the offshore wind industry in the 2010s, providing optimism that investors will be comfortable with the structure for CCS.[30]

For power generators, the support contract is the Dispatchable Power Agreement (DPA), which builds on the CfD noted above. Rather than a single difference payment, in the DPA the payment is split into parts — an availability payment and a variable payment. Given the demand uncertainties inherent in power generation, the availability payment provides a constant fee for stand-by low-carbon power generation capacity. The variable payment is activated whenever the plant dispatches electricity and is akin to the standard CfD payment in that it compensates the operator for the added CCS costs (operating costs, T&S fees, higher gas costs etc.).[31] However, the variable payment is structured such that the CCS operator is economically incentivised to generate ahead of an unabated (high emissions) operator, but not to displace renewable energy sources such as solar and wind.[32]

The revenue model for the T&S network is based on a "User Pays" model, reflecting the fact that a T&S vendor would both own and operate the onshore transportation and offshore storage network.[33] It is envisaged that industrial and power users of the network will be charged both a connection fee and a usage fee based on the volume of CO_2 each user supplies. The UK government has committed itself to fund the T&S fees of the emitters, either directly or via the CfD and DPA payments (to be determined).[34] The goal is to stand up a fully functioning T&S network for each cluster that future emitters could plug into.[35]

The bespoke nature of the business models for the emitters as well as the distinct model for the T&S networks represent major policy innovations in the CCS space. Previous attempts to spur CCS development in the UK failed principally because too much responsibility and funding was put towards a single self-contained "mega-project".[36] The cluster approach is an implicit recognition that the various economic and operational risks are too great to be concentrated upon a single party and are better divided up along the CCS value chain. While the UK government still has an important role to play in assuming risks that are otherwise difficult to mitigate (such as long-term liability for storage leaks), the various cluster business models are designed for private sector operators to assume standard commercial risks, such as operating performance and cost overruns.[37] From the government's perspective, striking an appropriate balance of risks coupled with sectorally differentiated business models should give businesses maximum visibility of their cash flows and therefore maximize private sector investment in the clusters.

Norway: Norway was one of the early pioneers in the CCS industry, with the Sleipner facility running since 1996 and its cousin Snøhvit since 2008 (both operated by the state-owned energy company Equinor, formerly Statoil).[38] Norway occupies a unique and privileged position as a major oil and gas producer with a small and prosperous population, and is therefore capable of pioneering initiatives that few nations have been able to match, including the introduction of a carbon tax in 1991.[39] The Norwegian government has consistently strived to lead in CCS, creating a state-owned enterprise dedicated to CCS (Gassnova) and a research and development program (CLIMIT) to support technological advancement.[40] However, Norway has recently gone further to create an industrial carbon capture hub.

The resulting Longship project will see the installation of capture equipment on the HeidelbergCement Norcem plant and Fortum Oslo Varme (a waste-to-energy plant), both in southern Norway, with transport of CO_2 by ship and pipeline to an offshore storage location. The offshore storage facility (known as Northern Lights) will have an estimated annual capacity of 1.5 Mt ton/ CO_2, with a future potential for 5 Mt.[41] The more limited scale of the project (relative to other nations considered here) reflects the facts that Norway has few industrial emitters of large scale, and that most of the country's electricity derives from hydroelectric power.[42] Hence, from the government's perspective, the intent for Longship is both to demonstrate global leadership on CCS as well as to develop Northern Lights as a potential storage location for CO_2 sourced from across Northern Europe.[43] The capture unit at Norcem is scheduled to become operational by 2024,[44] whereas the waste-to-energy plant is projected to start capturing its emissions in 2026.[45] Each of these plants has a planned capture capacity of 400,000 tons per year.

The subsidy model for the Longship program is primarily based on direct state funding. Both the construction costs for the capture equipment and ongoing operational expenses for the emitters will be fully covered up to an agreed cap, beyond which the operator must cover 25% of the costs.[46] Northern Lights has a similar scheme, but interestingly will charge no T&S fees to the Norwegian emitters, giving it an incentive to sell capacity to other capture projects across Northern Europe.[47] Finally, in contrast to the UK approach, which explicitly subsidizes a rate of return for investors, in the Longship program, 50% of the net cash flow over a lower return rate and then 75% above a higher return rate must be shared with the state.[48]

The current surplus capacity in the Northern Lights T&S, along with the room for expansion in the second phase, is already attracting attention from other European countries. Recognizing this, the EU has identified the Northern Lights as a Project of Common Interest and allocated funds through the Connecting Europe Facility for the front-end engineering design studies for the expansion of the T&S capacity.[49] Additionally, Northern Lights is now collaborating with Aker Carbon Capture to provide full value-chain offerings to emitters looking for decarbonization solutions.[50] Aker, which is already working with the Norcem cement plant,[51] hopes to complement the Northern Light's T&S-as-a-service with its carbon-capture-as-a-service to accelerate CCS deployment across Europe. Furthermore, in a bid to allow more of Europe to access its offshore storage sites, the Norwegian government has recently awarded Equinor with two separate licenses to develop storage facilities on its continental shelf.[52] The investment decisions on these new projects are yet to be finalized.

Netherlands: The Netherlands is also seeking to become a leader in the CCS space. While the country's smaller size means its direct emissions are on a limited scale, plentiful offshore storage in the form of depleted gas wells and a deep experience in the energy space set the Netherlands up well for CCS. The Dutch government has tried three times to get CCS facilities up and running in the past two decades, all of which failed due to political, societal, and economic challenges.[53]

However, the government has recently committed to ambitious climate targets as well as a new carbon tax, starting at €30 per ton this year and planned to reach €125 by 2030.[54] Notably this tax will act essentially as a backstop to the EU ETS price (not on top of it), and hence, by the end of this decade, the Netherlands will have some of the highest carbon prices in the world.[55] Recognizing that CCS will play a crucial role in the country's emissions reduction targets, in 2020, the Dutch government created a new avenue for CCS funding via the SDE++ program. This will function similarly to the UK's CfD model such that the state will pay the difference between the emitter's cost of capture and the prevailing carbon tax.[56] The European Union has also provided funding to individual carbon capture projects (via the Connecting Europe Facility initiative), which will go towards construction costs of the capture equipment.[57]

The most advanced CCS project in the Netherlands, and the only project to receive SDE++ funding in the initial (2021) round, is Porthos, centred around the Port of Rotterdam. Porthos was awarded almost half of the total subsidies awarded under the 2021 SDE++ scheme, demonstrating the Dutch government's enthusiasm for CCS.[58] Four operators (Air Liquide, Air Products, ExxonMobil, and Shell) will receive a combined total of up to €2.1bn in subsidies over 15 years under the SDE++ scheme to capture CO_2 from their respective facilities near Rotterdam. The CO_2 will then be piped offshore to a depleted gas field in the North Sea.[59] Intended to be operational by 2024, the project will initially store approximately 2.3 Mt/year at a little under €60 per ton of CO_2,[60] and is targeting 5 Mt CO_2 storage per year by 2030.[61] There are further projects centred around the ports of Amsterdam and Den

Helder that hope to receive SDE++ funding in the future, but both are still in the planning phase.[62] With the Dutch government currently calling for applications for another round of the SDE++ subsidy scheme for 2022, more funding for CCS projects can be expected.[63]

United States: The political situation in the U.S. with regards to environmental policy is markedly different than that in Western Europe. Much of the population remains skeptical of the causality and severity of potential climate impacts, and, partly as a result, substantial carbon taxes or other ambitious mitigation measures similar to those in Europe are for now politically infeasible, at least on the federal level. Ironically, political support for carbon capture is quite strong in both parties, as it is linked to enhanced oil recovery (EOR). As discussed in the introduction, EOR is the only use of captured carbon that has gained significant scale.[64] While the net sequestration resulting from EOR is only a tiny fraction of what CCS is intended to sequester elsewhere, its utility to the oil and gas industry in driving tertiary recovery from existing fields has ensured bipartisan political support.[65]

The primary instrument of policy support for CCS in the U.S. is the "45Q" federal tax credit. Initially established in 2008, it has been expanded and bolstered several times thereafter by both Democratic and Republican administrations.[66] In its current form, it gives a tax credit per ton of CO_2 to operators who either utilize the CO_2 for purposes such as EOR (up to $35 / ton) or for secure geologic storage (up to $50/ton).[67] The credits increase linearly over time up to $35 and $50 levels in 2026, and projects must start construction by January 2026 to be eligible.[68] The U.S. Department of Energy has also been instrumental in granting financing to many "first-mover" CCS projects, enabling technological innovation.[69] Moreover, the United States has plentiful onshore storage locations and decades of experience in using carbon capture technology for EOR. Hence it should come as no surprise that the U.S. leads the world in active large scale CCS facilities, with 12 of the world's 27, and another 36 in various stages of development.[70] Despite its association with fossil fuel production, EOR has undoubtedly helped the CCS industry mature and enabled the U.S. to become a world leader in the technology.

In addition, over $6 billion was authorized under the U.S. Energy Act of 2020, which allocates various amounts (to be spread over five years) towards developing large-scale and commercial projects, carrying out R&D on nascent technologies, and exploring carbon storage and validation.[71] Other legislation in various stages of consideration include: enhancements to the existing 45Q credits to boost the value of captured carbon, along with introducing separate credits for carbon from direct air capture; and the Storing CO_2 and Lowering Emissions (SCALE) Act, which looks to provide support towards enhancing the transport and storage of CO_2, while also easing the permitting process for sequestration wells and expanding CO_2 usage into markets beyond EOR.[72] Additionally, the U.S. has already began looking into a hub-based model for direct air capture (DAC) with the Department of Energy seeking to deploy $3.5 billion between FY2022-2026 to finance the development of four DAC hubs.[73] Separately, the recently passed Inflation Reduction Act of 2022 improves on the 45Q tax credits increasing the credits to $85 per ton of CO_2 stored in secure geologic formations and $60 per ton of CO_2 utilized otherwise from current levels of $50 and $35 per ton respectively.[74] Furthermore, the act will also extend the construction deadlines for CCS facilities, lower the emissions threshold at each facility to access the credit, and will provide developers an option to collect the credit value as direct compensation instead of tax credits.

California: The state of California has led the rest of the United States in much of its climate policy and is ahead of the game on carbon capture as well. The state's Low Carbon Fuel Standard (LCFS) places carbon intensity targets on all transportation fuels sold in California. Those that do not meet the targets generate deficits, while fuels with a lower carbon intensity than the target generate tradable credits, akin to an ETS scheme.[75] In 2018, the California legislature modified the LCFS to enable carbon capture projects to generate LCFS credits, both for flue gas and direct air capture.[76] Crucially, the flue gas capture project can be located anywhere, provided the associated transportation fuel is sold in California.[77] The credits are significantly more valuable than their counterparts in other ETS schemes, trading in the $175-200 / ton range over the last year.[78] This has created a compelling economic case for CCS facilities, particularly in conjunction with the federal 45Q tax credit, and many of the CCS facilities in development in the United States have used LCFS credits to build their business models. These include the 2,000-mile pipeline network proposed by Summit Carbon Solutions and another 1,200-mile pipeline network across the U.S. Midwest proposed to be built by Navigator CO_2 Ventures.[79]

DISCUSSION

Hereafter we analyze key themes that emerge from the review above.

Utilization vs pure sequestration: Perhaps the most glaring divergence we note is between polities that have pursued CCS in conjunction with EOR and those that seek only geologic sequestration. In the former camp sits the United States (both 45Q and projects that use California's LCFS), but also Canada, Brazil, the UAE, Saudi Arabia, and China.[80] In the latter sits the United Kingdom, Norway, and the Netherlands, along with Australia and Japan.[81] While EOR is of little or no net benefit to the climate, it is a strong commercial driver for CCS projects, in that it provides a crucial private market revenue stream and spur for technological innovation. EOR is the primary reason why North America leads the world in operational CCS capacity.[82]

Nonetheless, on the scale of the global energy markets, it is still a minnow. EOR using CO_2, from both captured and naturally occurring sources, currently makes up only about five percent of overall U.S. crude oil production.[83] While a vast majority of the CO_2 used in EOR is mined rather than captured from the atmosphere, McKinsey expects the use of captured CO_2 in the EOR industry to increase up to 80 Mt annually by 2030 — more than twice the current global CCS capacity.[84]

Nor is EOR the only use case for CO_2. Of the roughly 230 Mt of CO_2 (both captured and from other sources) used every year annually across all industries, the largest proportion is in fact in the fertilizer industry for the manufacture of urea (130 Mt), followed by EOR (70-80 Mt).[85] Other markets such as concrete, aggregates, and algae fuels have the potential to scale up in the next decade to the point that they could make a meaningful difference to the business case for CCS (for individual facilities).[86], [87] Hence while there is relatively little CCUS going on in most of the world at the moment (necessitating government intervention to create a business case for private operators), that could conceivably change over the next 10-20 years.

Market-wide vs bespoke approach: The approaches of our five polities can also be differentiated in respect of whether the policies are targeted at specific projects and / or differentiated based on specific actors, or whether they apply uniformly throughout the market. The tax credits in the U.S. make no distinction on the basis of cost of capture associated with various emitters or whether the government support is required for setting up capture facilities or constructing T&S networks. On the contrary, the British, Dutch, and Norwegian policies are targeted at specific projects, and tailor the level and nature of their support to different actors within the CCS value chain.

The bespoke approach allows for greater governmental oversight, reducing the chances of project failures and giving greater certainty to private sector actors to invite investment. In contrast, the market-wide approach invites individual actors to build their business cases around a fixed amount of government support, requiring less oversight to manage but with a higher chance of failure for individual operators.

Clusters vs. standalone projects: Another significant difference in approaches to CCS policy is the specific focus of government schemes. Norway, Australia, Japan, and the Gulf countries remain focused on capturing emissions from individual emitters. However, after earlier failed attempts to do the same, the UK and the Netherlands have shifted to the creation of "clusters" linking multiple closely-located emission sources to a common T&S network.

Among single-emitter focused states, some smaller scale programs such as Norway's Longship seem designed to function much more as demonstration projects than enablers of full-scale commercialization, whereas in countries such as Australia and Japan with large-scale domestic emissions sources, early projects appear more likely to serve as stepping stones toward a wider scale-up of CCS. While such a project's success can reassure investors (and voters) that the technology is safe and investable, setbacks on the scale of Australia's Gorgon facility[88] can have the opposite effect.

In contrast, the UK and the Netherlands are highly focused on commercialization, and hence have opted for the cluster approach, seeking to leverage economies of scale and create resilience, lowering the collective risk of stranded assets. However, it is important to note that this approach explicitly prioritizes the resilience of the network over the cost of capture, given that both relatively low-cost flues (such as natural gas processing) and higher cost flues (such as the cement industry) will be captured and included in the same network.

The hands-off tax credit approach favored by the United States does not favor one approach over the other, although historically most American projects were isolated. However, with the increase of 45Q and LCFS credit values, clusters are beginning to emerge. For example, the Summit Carbon Solutions pipeline network plans to capture emissions from over 30 biorefineries, while the Heartland Greenway Pipeline plans to transport captured CO_2 from 20 ethanol and fertilizer manufacturers across the Midwestern U.S..[89, 90]

CCS as one industry or two: Another emerging distinction in CCS is between vertically integrated capture and storage projects versus ownership configurations that divorce the two functions. Most legacy North American CCS projects were vertically integrated, whereas the CCS clusters being spun up in the UK, Norway, and the Netherlands envision T&S operators that have been split out from the emitters themselves under different business models and incentives tailored to each sector.

Unbundling capture and T&S should facilitate a more efficient risk allocation, allowing entities to focus on their core competencies and for the T&S network to maximize economies of scale.[91] Such an approach would also reduce the risks of cross-chain failures, where the obstruction of any one of the capture, transport, or storage infrastructures would result in the whole project being stranded.

Furthermore, in the case of Norway and to some extent the Netherlands, splitting out the T&S network from the capture equipment also allows the T&S organizations to pursue customers outside of their home countries, becoming an offshore storage hub for CO_2 from across Northern Europe.

Public vs private finance: With an estimated USD 655 – 1,280 billion required for CCS to achieve global climate targets by 2050,[92] all of the countries surveyed here are eager to bring as much private finance into their CCS projects as possible. While the desire to demonstrate value-for-money in use of taxpayer funding is undoubtedly a strong motivator, there is also a desire to get private financing sources comfortable with the technology so that access to finance is not a barrier to scaling up CCS. Major financial institutions such as Société Générale, HSBC and Lloyds Bank have declared their interest in the CCS market.[93] The status of CCS as a climate/ESG project has generated interest in the technology, and major institutions are keen to get in early as the technology develops.[94] In North America, where a stable tax credit regime and supplemental EOR revenues have solidified the investment case, substantial funding has been obtained.[95] On the other hand, Europe is several years behind this, with few facilities fully operational and the terms of trade still unfolding.

CONCLUSIONS

We pivot here to the question of what lessons other aspirational polities may discern from the current state of play in CCS. The first is that almost no CCS activity will organically arise absent substantial state nudges. Even in high carbon-cost Europe and the UK, carbon prices are not yet high enough and utilization cases are not robust enough to stimulate an organic market for CCS absent additional state support.

As regards the nature of those interventions, sticks would likely prove more effective, but it is carrots that are proving more feasible politically. Though a stable carbon price exceeding €100 would turbocharge the CCS market, that seems a distant prospect in most of the world. Failing that, carrots such as government grants, tax-credits, and activity by state-owned enterprises have been the primary paths forward.

If it is government policy rather than private markets that will be required to stimulate CCS scaling, the consistency and reliability of that state support will prove critical to the matter of bringing private capital to the table. Large CCS projects operate on multi-decade time scales, and carbon repositories are meant to function in perpetuity. With such long-lived capital deployments, private capital will decline to participate until governments convincingly demonstrate that their market-making carbon policies will prove durable.

In the current decade, the challenge will be to develop local expertise, local renewable energy sources, locally deployed technology, and local storage repositories in nations and regions all over the globe. Descending the learning-by-doing cost curve in the absence of a functioning market can only be done via government leadership and financial support.

Prior failures in several countries illustrate the benefit of clusters that link several emission sources to a common T&S network. The business model for capture facilities will resemble those for industrial installations and power plants respectively, with the state underwriting the added costs necessary for carbon capture and storage. The T&S network will operate more like a regulated common carrier utility, charging fees for use.

To bring substantial private capital to bear, a careful parsing of risks will be required. Unlike oil and gas wells, where healthy early profits create a financial incentive for drillers to accept the long-term liability associated with properly abandoning those penetrations, after some minimum time threshold, it may prove necessary for governments, rather than private industry, to assume the long-term storage risk of sequestered carbon.

After many years of stagnation and false starts, the CCS industry is advancing, but it has the potential to contribute much more to global mitigation. Until higher carbon prices stimulate organic market activity, well-crafted state interventions in the carbon economy will be necessary to accelerate the scaling of this essential technology.

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The Harvard Project on Climate Agreements is a Harvard-University-wide initiative established in 2007 to identify and advance scientifically sound, economically sensible, and politically pragmatic public policy options for addressing global climate change. Drawing upon leading thinkers from around the world, the Harvard Project conducts research on policy architecture, key design elements, and institutional dimensions of international and domestic climate-change policy. The Harvard Project is directed by Robert N. Stavins, A.J. Meyer Professor of Energy and Economic Development, Harvard Kennedy School. For more information, see the Harvard Project's website: www.hks.harvard.edu/hpca.