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PERSPECTIVE

Carbon capture and storage in the USA: the role of US innovation leadership in climate-technology commercialization

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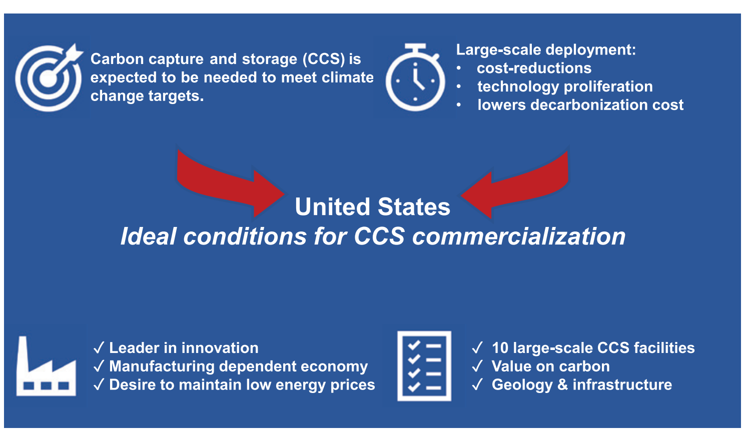
Abstract

To limit global warming and mitigate climate change, the global economy needs to decarbonize and reduce emissions to net-zero by mid-century. The asymmetries of the global energy system necessitate the deployment of a suite of decarbonization technologies and an all-of-the-above approach to deliver the steep CO_2-emissions reductions necessary. Carbon capture and storage (CCS) technologies that capture CO_2 from industrial and power-plant point sources as well as the ambient air and store them underground are largely seen as needed to address both the flow of emissions being released and the stock of CO_2 already in the atmosphere. Despite the pressing need to commercialize the technologies, their large-scale deployment has been slow. Initial deployment, however, could lead to near-term cost reduction and technology proliferation, and lowering of the overall system cost of decarbonization. As of November 2019, more than half of global large-scale CCS facilities are in the USA, thanks to a history of sustained government support for the technologies. Recently, the USA has seen a raft of new developments on the policy and project side signaling a reinvigorated push to commercialize the technology. Analysing these recent developments using a policy-priorities framework for CCS commercialization developed by the Global CCS Institute, the paper assesses the USA's position to lead large-scale deployment of CCS technologies to commercialization. It concludes that the USA is in a prime position due to the political economic characteristics of its energy economy, resource wealth and innovation-driven manufacturing sector.

Graphical Abstract



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Introduction

The USA is one of the top emitters globally and remains highly dependent on fossil fuels to satisfy its primary energy demand. In light of ambitious and necessary climate goals enshrined in the Paris Agreement, bringing the decarbonization of the country's economy on track is extremely important. The 2018 release of the UN Intergovernmental Panel on Climate Change's (IPCC) 1.5°C Report on Global Warming [1] has bolstered the need for urgent climate action, calling to reduce emissions as soon as possible and to net-zero by mid-century. After a decline of emissions of several years, greenhouse-gas emissions rose sharply in 2018 by 3.1% in the USA, outpacing global emissions growth almost by a factor of two [2]. Emissions were driven by more frequent hotter and colder days prompting higher demand.

A suite of clean-energy technologies that has recently experienced renewed policy support through incentive structure innovation and legislative initiatives is carbon capture and storage (CCS). The technologies, which capture carbon dioxide (CO_2) from industrial and power plants, and transport and permanently and safely store it underground, are commercially viable and deployment-ready. Direct air capture (DAC), which captures CO_2 from the ambient air to deliver negative emissions, has also gained increasing attention. The USA has also historically been a leader in innovation, particularly with regard to policy driving private-sector action, designing novel business models and inventing new-energy and clean-energy technologies. For the past decade, the country has been a leader in energy-supply investment and the second largest destination for energy investment after China [3].

Due to a renewed push to formulate supportive policy and enhance the existing policy framework across the country, the USA is in a prime position to commercialize these technologies that are expected to be needed widely to fully decarbonize the global economy. As such, US leadership on the deployment of CCS technologies would make significant contributions to the world's reaching its climate and sustainable-development goals. It would also contribute to reducing the cost of CCS—a technology that is essential to meeting climate goals and enabling technology deployment abroad. The paper seeks to provide an overview of CCS deployment in the USA while assessing the maturity of the US deployment framework, including policies and infrastructure.

1 The US decarbonization opportunity

After 3 years of decline, US CO_2 emissions rose by 3.1% in 2018. Its largest emissions sector remains the transportation sector, followed by electricity and industry [4]. From a global perspective, scenarios that lead to a full decarbonization of the world economy include CCS in both the industrial sector and the power sector. For example, the International Energy Agency's (IEA) Sustainable Development Scenario [5] sees 7% [6] of emissions reductions to be delivered by CCS, in almost equal parts in the power and the industrial sectors, by 2040. The IPCC Report on 1.5°C includes CCS in three of four illustrative pathways and negative emissions in all pathways (Fig. 1).

The USA—the second largest CO_2 emitter globally in absolute terms—can be regarded as a microcosm within the global economy. While comprehensive, economy-wide models that forecast a net-zero economy by mid-century are lacking for the USA, most available decarbonization pathways that are compliant with either the Paris Agreement or a net-zero-emissions scenario by mid-century include CCS in the industrial and the power sectors, among a range of other clean-energy technologies. For example, the Union of Concerned Scientists analysed models that will lead to a 90% decarbonization of the US power sector by 2050. In these scenarios, natural-gas power plants retrofitted with CCS comprise between 9% and 28% of the total mix [7].

With the impacts of more extreme weather already being felt across the globe—July 2019 was the hottest month on record to date [9]—the pressure to decarbonize and address rising CO_2 emissions is intensifying. As part of this global challenge, innovation in the energy, industrial and manufacturing sectors must therefore enable sustainable growth. Continued economic prosperity will depend on countries' ability to reduce their energy intensity. Carbon capture is expected to play a key role, particularly due to three key characteristics of the US economy.

The first is the power sector, which is largely seen as the easiest sector to decarbonize vis-à-vis transportation and industry, yet still faces complex challenges. Despite renewable-energy generation more than doubling since 1990, the USA remains heavily dependent on fossil fuels to satisfy energy demand. In addition, the future of its nuclear fleet, which provides more than 60% [10] of the country's carbon-free power, remains uncertain. Analysts expect retiring nuclear to be replaced not only by renewable energy, but also by unabated fossil-fuel additions. These asymmetries, coupled with a young natural-gas fleet of 22 years average age [11] and further unabated, natural-gas capacity underway, underpin the need to deploy carbon capture in the US power sector.

The second is the industrial sector—an often-overlooked sector in terms of decarbonization and CCS deployment. It remains the largest consumer of energy and is responsible for 22% of emissions [12]. In 2017, the sector was also responsible for ~18.2% [13] of US gross domestic product. So far, experts agree that the sector has felt little pressure to decarbonize due to the lack of

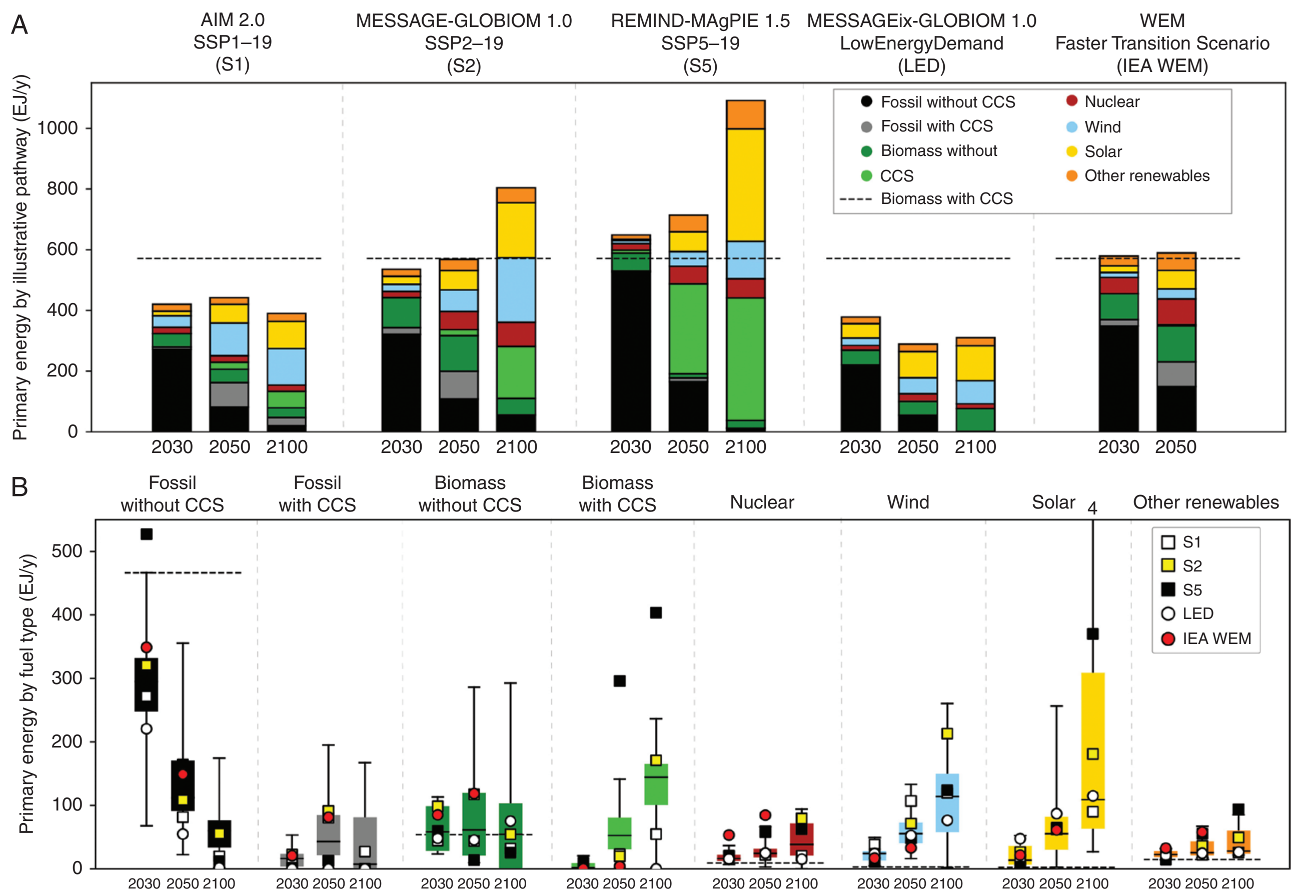


Fig. 1: Primary energy supply for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (a) and their relative location in the ranges for pathways limiting warming to 1.5°C with no or limited overshoot (b) Reproduced by permission from the IPCC [8].

solutions and understanding of the challenge, as well as its significant political economic influence. In fact, the industrial sector offers early deployment opportunities for CCS. As of November 2019, 17 of 19 operating, large-scale facilities globally are in the industrial sector [14]. In the USA, 9 of 10 operating, large-scale facilities are in industry. Furthermore, low-cost applications of CCS are concentrated in industry, amenable to a near-term roll-out of the technology that could result in significant cost reductions and learning-by-doing. For example, processes that produce a pure stream of CO_2 such as ethanol production and natural-gas processing can start at \$15/tCO_2.

Further, CCS can play a key role as a low-carbon heat solution and for process emissions from cement and steel [15]. Industrial heat emissions alone account for 10% of global emissions and research has shown that many decarbonization options are more costly than CCS application [16]. Along these lines, a key to decarbonizing industry could be hydrogen, whose production from fossil resources can be decarbonized with CCS. In fact, the USA holds ideal conditions for large-scale hydrogen production with CCS thanks to the vast availability of low-cost natural gas [17]. A 2014 NETL study showed that almost 70 Mtpa of CO_2 would be available for capture from hydrogen production alone. A total of more than 250 Mtpa of CO_2—almost 10 times the US capture capacity today—would be available for capture from hydrogen, cement, steel, ethanol, ammonia production and natural-gas processing combined [18]. Hence, the industrial sector should be considered a key target for CCS deployment.

The third is the USA's economic structure; the USA is strongly dependent on fossil fuels, providing ideal conditions for CCS deployment. In fact, in 2018, about 80% of the primary energy demand was satisfied by natural gas, coal and petroleum [19]—a share that has been constant for the last decade. Between 1983 and the great recession, the share hovered around 85%. These long-term trends signal strong rigidity of the US energy economy. The USA, due to the shale revolution, has also become the largest natural-gas producer in the world, holding this position since 2009, but also demonstrating its ability to improve techno-economic processes through innovation. Due to its fossil-fuel-dependent economic structure, the USA, along with China and Russia, ranks highest in the Global CCS Institute's Inherent Interest in CCS [20], which is a relative index based on the share of fossil-fuel production and consumption, indicating an economy's suitability for large-scale CCS deployment to diversify and decarbonize its energy production.

However, the USA's energy economy evidences further supporting factors for CCS commercialization in the near-to-medium term, underpinning the country's suitability. The structure of its energy supply has also contributed to low energy prices in comparison to other advanced economies, boosting energy security, while also strengthening the desire by producers, policymakers and consumers to maintain low levels of energy prices [21]. At the same time, for the past decade, the country has been a leader in energy-supply investment and the second largest destination for energy investment, right after China [22], evidencing strong government commitment as well as a capability to attract investment in the sector. On an absolute basis, the USA invests more than any other nation to support clean-energy innovation. It invests more in total clean-energy RD&D ($6.8 billion in 2018) than the next two countries, China and Japan, combined and more in basic energy science than all other nations combined [23]. Therefore, the desire to maintain strong energy security as well as accelerate innovation provides fertile ground for large-scale CCS deployment.

While this outlook, evidencing strong fossil-fuel and manufacturing dependence of the economy, might pose an obstacle to full decarbonization at first sight, it should also be regarded as an opportunity and incentive to transform the sector and develop next-generation clean-energy technologies. Coupled with a strong desire to bolster energy security, demonstrate technology leadership and an innovative edge from a policy, finance and private-sector perspective, the USA is well positioned to benefit from large-scale CCS deployment. Furthermore, the technology, which is also seen as essential to alleviate the existing lock-in of emissions from existing infrastructure, could potentially be exported to other countries, cementing the USA's leadership in innovation. Moving to a lower-carbon economy is inevitable to contain global warming and prevent potentially disastrous effects of climate change. Therefore, the USA's ability to maintain its position as a top natural-resource producer, exporter and its ability to provide energy security will largely depend on the possible transformation of its energy and industrial sectors.

2 CCS in the USA

Currently, as of November 2019, there are 10 CCS facilities in the USA with a combined capacity to capture more than 25 million tonnes per annum. In total, there are 19 operating facilities globally, with a further 28 in various stages of development and 4 under construction (Fig. 2). In the USA, there are 10 operating, large-scale projects and a further 17 under development. One of the operating facilities in the USA is in the power sector, with others in natural-gas processing and fertilizer, hydrogen and ethanol production [24]. In addition, the USA hosts the National Carbon Capture Center—a large public and privately backed test centre allowing new technology providers to test their technologies. The USA also has a history of demonstration and small-scale projects. A prime example is the

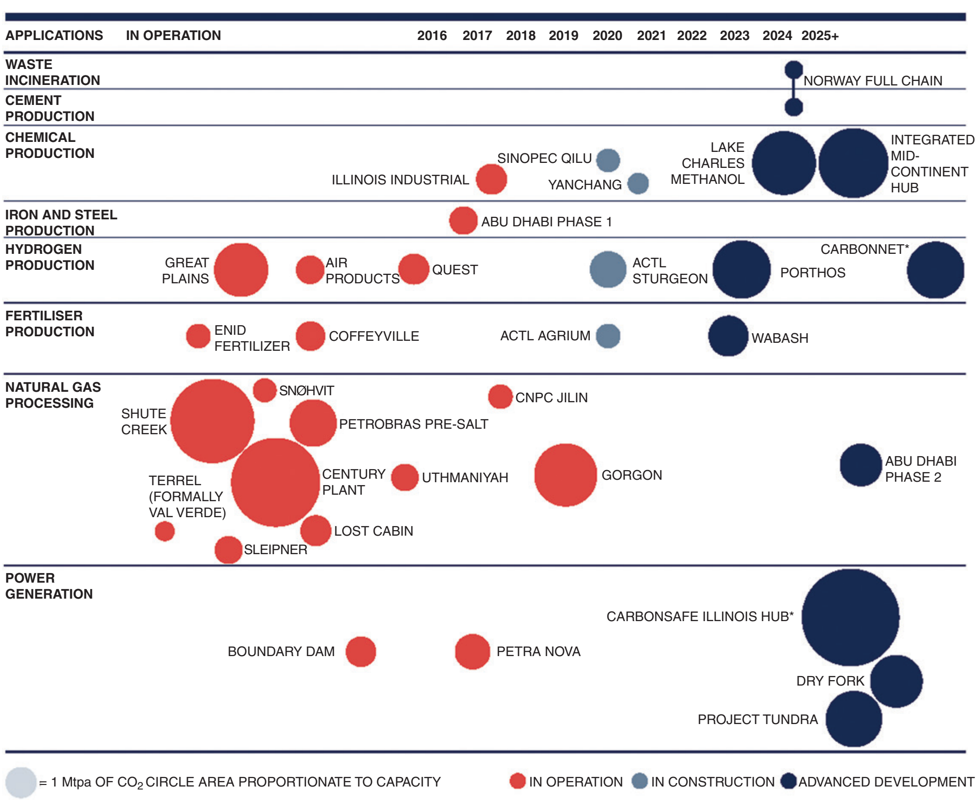


Fig. 2: Large-scale CCS projects by industry and storage type [25]. Reproduced by permission from the Global CCS Institute Ltd.

demonstration of the Allam Cycle, a novel zero-emissions power-plant technology, at a 50MWth facility in Texas.

The USA has traditionally been the leader in CCS deployment. Initial deployment was driven by enhanced oil recovery (EOR), which has provided a value for carbon dioxide. This is complemented by private-sector-technology expertise and a supportive policy framework. The typical price for anthropogenic CO_2 that companies pay is estimated to start at around US$15/t$CO_2$ [26], albeit it is indexed to the oil price. For example, at oil prices of US$70 per barrel, the cost of CO_2 is around US$30/t$CO_2$ [27]. Hence, as a result, multiple CCS projects in the USA have come online during periods of high oil prices; in the early 1980s, two projects started and, in 2013, three CCS projects commenced operation [28]. EOR has demonstrated secure geologic storage, can result in reduced life-cycle emissions per barrel of oil and has provided an incentive to deploy CCS, demonstrating that a value on carbon can drive technology deployment.

3 A framework for analysing CCS progress

The Global CCS Institute, in 2019, has developed a policy-priorities framework [29] through analysing the 23 large-scale operating and under-construction CCS facilities. In particular, the authors assessed their incentive and capital structures, alongside other enabling mechanisms (Fig. 3). The framework lends itself well to analysing the maturity of the USA to accelerate the large-scale deployment of CCS:

1. A value on carbon

   A value on carbon provides policy signals that governments are committed to moving to a lower-carbon world, and reflects the externalities created by pollution. Twenty-two of the 23 facilities analyzed were built or are being built in an environment that provided some value on carbon such as through an emissions credit, a carbon tax or a tax credit, or enhanced oil recovery. For example, two projects in Norway were built as the result of a carbon tax on offshore natural gas production. Only one project, the Gorgon project in Australia, which is also the largest geologic storage project to date, was the result of a regulatory requirement.

2. A framework enabling investment

   Most CCS projects have been enabled through high proportions of grant funding, with little to no debt financing. To deploy CCS at scale, private sector

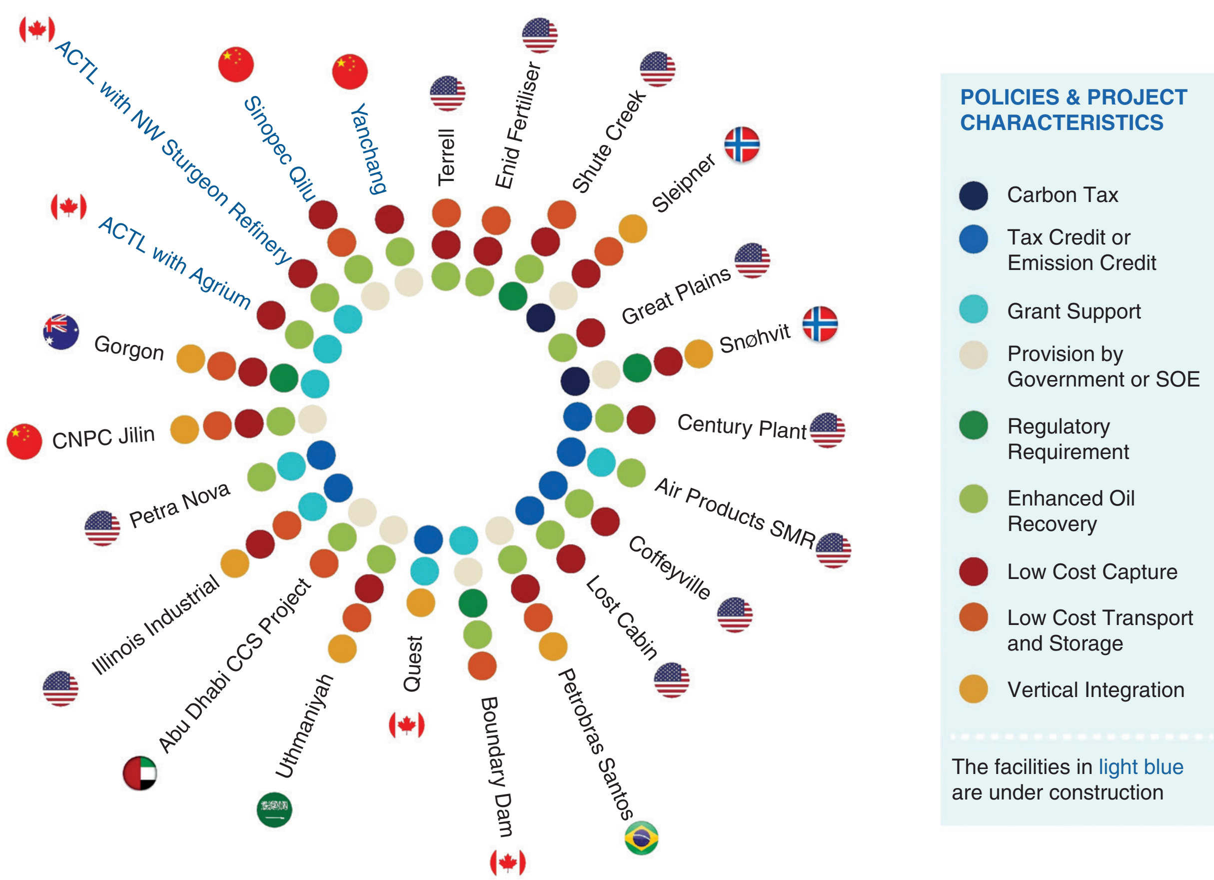


Fig. 3: Key incentives and project characteristics of realized-large-scale CCS projects globally [30]. Reproduced by permission from the Global CCS Institute Ltd.

investment must increase with banks providing debt financing at feasible interest rates. Currently, project risks are perceived by banks as too high, and the cost of capital has a substantial implication for the sanction of CCS projects. As the number of CCS facilities increases, debt finance will become available for CCS projects, thereby reducing the cost of capital. However, in the meantime, governments can provide further grant funding, accelerated depreciation, concessional loans, loan guarantees and other mechanisms to attract private capital. Such instruments reward early investments for the knowledge they create that is available to future project developers. Government investment in public goods such as clean air is important, even if these investments do not make a private financial return, but a distributed societal financial return.

3. Infrastructure access and storage

Most facilities that have successfully commenced operation so far had access to well-developed and characterized storage sites, and low-cost transportation options, such as existing pipeline infrastructure to transport the CO_2. It is therefore an imperative for countries to map and understand their CO_2 storage capacity, and aid the private-sector in the identification of suitable sites. In addition, governments can support the build-out of CO_2 pipeline networks to reduce cross chain risks and enable the establishment of CCS hubs that significantly reduce unit CO_2 storage costs.

4 The framework in the US context

Using the above-mentioned framework to analyse CCS policy and deployment infrastructure provides a clear understanding that the USA is in a prime position to commercialize carbon-capture technologies. These findings are also supported by the Global CCS Institute's CCS Readiness Index, which actively monitors the progress of CCS deployment and identifies nations that are leaders in creating an enabling environment for the large-scale deployment of CCS. The USA ranks in second place, with 70 of 100 points—close to Canada, the global leader [31].

As mentioned above, EOR has provided a value on CO_2, roughly estimated at ~$15 t/$CO_2$. Nonetheless, to date, only about 30% of CO_2 used for EOR is from anthropogenic sources, the rest is being mined from natural resources [32]. Hence, it would be an obvious step to aim for the substitution of mined for anthropogenic sources, opening up a larger market for capture, or to require maximum CO_2 stored per barrel of oil produced [33].

Beyond regional carbon markets, which, for the most part, trade either below $10 t/$CO_2$ or do not allow CCS projects to gain credit, the USA has recently reformed and introduced two significant, CCS-specific values on carbon. Since 2008 [34], the USA has been incentivizing the capture of CO_2 through a tax credit also known as 45Q, named after the relevant section of the US tax code. The tax credit was first introduced in 2008, when it provided $10 t/$CO_2$ for CO_2 stored via EOR and $20 t/$CO_2$ for geologic storage, adjusted for inflation. This credit was significantly expanded and reformed in 2018 (Table 1). The work was led by a bipartisan group of lawmakers, supported by a diverse coalition of environmental groups, trade associations and industry. The credit now provides up to $18/t$CO_2$ for CO_2 used for EOR and $29/t$CO_2$ for CO_2 stored through dedicated geological storage, rising linearly to $35/t$CO_2$ and $50/t$CO_2$ by 2026, respectively, and adjusted to inflation thereafter. The credit is currently being implemented by the internal revenue service and also includes other features, including enhanced transferability that will make it more attractive to the tax-equity market, similar to solar and wind. Projects have to commence construction before 2024 in order to qualify.

Moreover, California's Air Resources Board, anticipating the need for CCS and DAC, amended the state's Low Carbon Fuel Standard (LCFS) [35]—a credit-based emissions-reductions system aimed at reducing the emission intensity of fuels sold in California by 20% by 2030. The regulation was amended with a CCS protocol in September of 2018, after a series of stakeholder consultations and listening sessions, and came into effect in early 2019. Trading at an average of 186.5$/t$CO_2$ during the first 6 months of 2019 [36], the LCFS CCS Protocol credits are stackable with 45Q for projects that reduce the life-cycle emissions of fuel consumed in California. Recognizing that the stock of CO_2 contained in the atmosphere is a transnational problem, the protocol also incentivizes DAC projects globally to spur advancement and technological

Table 1 : The 45Q tax credit for CCS [35]

	Plant size in ktCO_2/yr			Relevant level of tax credit (USD/tCO_2)							
	Power plants	Industrial facilities	DAC	2020	2021	2022	2023	2024	2025	2026	Onwards
Geologic storage	Min. 500	100	100	34	36	39	42	45	47	50	Indexed to inflation
CO_2-EOR-storage	Min. 500	100	100	22	24	26	28	31	33	35	
Utilization dependent on actual emissions reductions	25–500	25	25	22	24	26	28	31	33	35	

innovation in negative-emissions-technology options needed to reach global climate goals (Fig. 4).

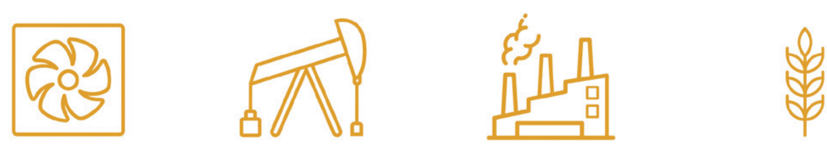
These combinable measures have the potential to significantly change the economics of projects. Current break-even estimates range between \$5 t/CO_2 for natural-gas-processing CCS facilities to \$30t/CO_2 for hydrogen production and coal-to-chemicals processing, as well as \$60 t/CO_2 for power plants equipped with CCS [38]. The incentives are expected to support spurring a wave of new projects at low-cost capture facilities, bringing down the cost of the technology, while also enabling and accelerating infrastructure and industrial hub build-out. In fact, a 2019 analysis has shown that, in the power sector alone, 45Q could drive the deployment of CCS, enabling the capture of 49 Mtpa on coal- and gas-fired power plants [39]. A conservative learning-rate estimate of 10% means that the cost of CCS could halve with large-scale deployment.

Further positive policy signals include the passage of clean-energy standards in seven states, bolstering technology–neutral decarbonization pathways in the power sector and providing an alternative value on carbon through certificate trading. Ambitious emissions-reductions pledges by multiple utilities complement this policy development and could spur CCS deployment in the short-to-medium term [40].

With CCS-specific incentives in place creating an initial business case for deployment, further project support is still necessary. As outlined in the framework, the financing of CCS projects remains challenging due to the perceived and actual risks of these projects. As such, banks are reluctant to lend unless they can be assured that the risk of a proven, yet not widely deployed, technology has been sufficiently mitigated. Therefore, government support is essential to risk reduction enabling financing, which in turn will lead to more deployment, reducing risk and cost. For example, both the Air Products SMR CCS project (a hydrogen-production facility) and the Decatur Illinois project (an ethanol plant) depended on grants to provide more than 60% [41] of their funding. On the other hand, projects like Petra Nova and Lake Charles Methanol were able to secure financing, because their revenues are reliant on the sale and use of CO_2 for EOR. Contributing significantly to enhancing policy confidence, these policies have already resulted in project announcements. This includes an ammonia-production facility set to become the largest geologic-storage project in the USA, as well as a DAC facility in Texas. More announcements are anticipated, pending the implementation of the 45Q tax credit. Currently, there are nine projects at various stages of development, which include ethanol, coal power, fertilizer production and DAC [42].

Nonetheless, large-scale deployment of CCS at the scale necessary to reduce emissions to net-zero will need to be driven by policy measures, just as other clean-energy technologies have been deployed thanks to innovative incentive structures like feed-in tariffs and renewable portfolio standards. These policy measures, at the beginning of large-scale deployment, must be accompanied by further risk-reducing mechanisms.

The Department of Energy (DOE) is largely seen as the global leading agency concerning the support of CCS, having supported the advancement of the technologies since 1997 [43]. The DOE is responsible for R&D and hosts multiple funding programmes for different parts of the CCS-development, -deployment and -commercialization value chain. For example, it provides funding for Front-End



	DIRECT AIR CAPTURE PROJECTS	CCS AT OIL & GAS PRODUCTION FACILITIES	CCS AT REFINERIES PROJECTS	ALL OTHER CCS PROJECTS (E.G. CCS WITH ETHANOL)
Location of CCS project	Anywhere in the world	Anywhere, provided they sell the transportation fuel in California	Anywhere, provided they sell the transportation fuel in California	Anywhere, provided they sell the transportation fuel in California
Storage site	Onshore saline or depleted oil and gas reservoirs, or oil and gas reservoirs used for CO_2-EOR			
Credit method	Project-based	Project-based, under the Innovative Crude Provision	Project-based, under the Refinery Investment Credit Program	Project-based or fuel pathway
Earliest date which existing projects eligible	Any	2010	2016	Any
Requirements	Project must meet requirements specified in the CCS protocol			
Additional restrictions	None	Must achieve minimum CI or emission reduction	None	None

Fig. 4: Types of CCS projects qualifying for credits under the LCFS [37]. Reproduced by permissions from the Global CCS Institute Ltd.

Engineering Design (FEED) Studies, research grants, technology development and related activities, all of which can reduce risk and entry cost. It also provides a loan guarantee for advanced fossil-energy projects that include CCS to support projects in securing affordable financing. In total, there are $8.5 billion in loan guarantees available. So far, one project—the Lake Charles Methanol project, which is the first petcoke-to-methanol facility in the USA—has been offered a conditional commitment to guarantee loans of up to $2 billion [44]. These support mechanisms and structures have helped initial projects to be realized through mitigating risk.

However, stakeholders in the USA representing the climate and CCS community have moved to suggest additional incentives through legislative efforts. These focus on the ability of projects to secure additional financial support, including but not limited to the eligibility for private-activity bonds and master limited partnerships. Other legislative proposals include funding for large-scale CCS-demonstration projects.

To conclude, the USA has a robust framework of policy support through the DOE, as well as multiple potentially fruitful legislative initiatives to reduce the financial risk of large-scale CCS projects. However, more near-term, robust policies to lower perceived and actual risk could accelerate and support the urgently necessary roll-out in light of climate goals.

A key part enabling the large-scale deployment of CCS is a robust CO_2-transportation network. The US CO_2-transport and -storage infrastructure is among the most well developed globally, but not sufficient to support immediate large-scale deployment. The USA already possesses 5000 miles of CO_2 pipelines, which were built primarily for EOR and connect privately owned assets [45]. Several states already provide financial assistance and tax incentives for the build-out of CO_2 pipelines. However, the current amount of pipeline capacity and geographical reach are not sufficient to sustain large-scale CCS deployment. Experts estimate that pipeline capacity needs to grow 3- to 5-fold over the course of the next 30 years to facilitate a CCS industry of the size needed for climate mitigation [45].

In 2015, a working group consisting of different stakeholders suggested five trunk lines to be developed. These trunk lines could connect different CO_2 and industrial hubs, strategically transporting more than 150 Mtpa of CO_2, which is about six times as much as being stored from anthropogenic sources today [46]. Pending legislation such as the USE IT Act can enable the facilitation of and clarify the siting, permitting and planning of the CO_2 infrastructure. However, it remains to be seen how these pipelines can be financed, particularly in the absence of government financing. Analyses suggest a strong role for initial government financing and ownership to reduce cross-chain risk and address the fact that pipelines are natural monopolies. For example, an analysis from 2018 showed that a government-financed pipeline from the mid-west, an ethanol hub, to the Permian Basin could enable an additional 30 Mtpa of CO_2 to be stored, doubling the US storage of anthropogenic sources. Should the government finance only half of the pipeline, CO_2 storage would drop to 19 Mtpa [47]. The study also found that the network would not be feasible without government finance and pointed to the important role of government support overcoming the chicken-and-egg problem. Therefore, while the USA possesses an initial CO_2-transport infrastructure, its overall pipeline system is insufficient to support the scale of CCS expansion needed to transition to a net-zero economy.

With regard to CO_2 storage, the USA has made significant advances in developing its own geologic-storage potential. In the Global CCS Institute's database, the USA ranks as second out of all countries assessed. The USA's storage is thoroughly characterized and there is high confidence in published storage-resource estimates that include 2360–21 200 GT (high likelihood) [48]. Currently, there are >100 sites operating EOR, injecting an estimated 68 Mtpa [49] of CO_2, albeit the majority being non-anthropogenic CO_2 [50]. An excellent example of the US government's leadership on supporting CCS deployment is the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative. These projects focus on the development of geologic-storage sites for the storage of an estimated 50 Mt of CO_2. The projects are aimed at improving the understanding of project screening, site selection, characterization and baseline monitoring, verification, accounting and assessment procedures. Commencement of injection is anticipated for 2026 [51]. States are also seeking to simplify CO_2-storage guidelines and provide regulatory clarity. In addition, multiple CO_2-transport and -storage hubs are in the early stages of development.

Overall, CCS has gained momentum in the USA. Beyond the analysis of its policy framework, multiple initiatives are pending and being proposed, evidencing that the policy gaps for CCS deployment have been well understood and stakeholders are aiming for an optimization of the government's role. For example, several pieces of legislation are aiming to increase the funding and scope of the DOE's carbon capture, storage and utilization (CCUS) programme, including directing funding to CCS on natural-gas power generation. Further legislation seeks to fix the 48A tax credit for efficient coal plants, which, equipped with CCS, are unable to meet the efficiency requirements, establish research programmes for DAC and commercialize CCS within the next decade. Building on the diverse and bipartisan support, lawmakers also introduced legislation aimed at research and development to enable emissions reductions in the industrial sector, including steel, iron, cement, aviation, shipping and petrochemicals. The industrial sector has long been an overlooked climate challenge and reflects a significant policy gap to accelerate decarbonization solutions. In fact, some CCS applications in the industrial sector are low-cost and already competitive today.

5 Conclusion

To conclude, the USA provides ideal preconditions to commercialize CCS technologies due to its strong dependence on fossil fuels and manufacturing, coupled with an innovation-based economy and a desire and pressure to maintain extremely low energy prices. Whilst the USA certainly evidences a very advanced policy incentive and infrastructure framework, not least because it also hosts the most facilities globally, conditions for large-scale CCS deployment on the scale necessary to meet climate goals remain incomplete. The latest movements in terms of policy development in the USA provide a promising outlook, particularly with the implementation of 45Q and further initiatives to address infrastructure shortcomings, access to affordable private capital and storage characterization. Including CCS in regional carbon markets and transition from renewable- to clean-energy standards can further increase policy support for CCS deployment. Further priorities include an emphasis on project deployment enabling technology optimization through more investment in demonstration projects, possibly by the government itself. Emphasis should also be placed on reducing risk through government involvement, clarifying liability and regulatory questions, and enabling the build-out of pipelines between emissions clusters and storage hubs and facilities. Moreover, creative incentive structures to reduce emissions in the industrial sector are needed, as is an innovative business model for CO_2 transport and storage. Finally, if the USA can accelerate the deployment of CCS technologies accelerating the cost-reduction process, similarly to what Germany has done for solar and Great Britain for offshore wind [52], this would not only reduce the collective-action problem that climate change represents, but also bring the world closer to tackling its global emissions problem.

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Conflict of Interest

None declared.

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