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Capture Carbon, Capture Value: An Overview of CCS Business Models

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Introduction

Because of the scale with which it could be applied, carbon capture, and storage (CCS) is identified as a critical technology to reduce CO_2 emissions to achieve global climate goals[1]. Particularly, CCS can reduce emissions from existing assets (such as gas processing plants, power plants, chemical plants) decreasing the risk of stranded assets in a carbon-constrained world; reduce emissions from hard-to-abate sectors (such as cement and steel) where decarbonization technologies are limited and have not been scaled up; enable the production of low-carbon hydrogen which represents a key pillar of decarbonization; and enable the removal of CO_2 from the atmosphere which is needed to reach global climate objectives via technologies such as Direct Air Carbon Capture and Storage (DACCS) and Bioenergy with carbon capture and storage (BECCS)[2].

The potential of CCS as mitigation technology could be substantial. In the IEA's Net-Zero Emissions by 2050 Scenario (NZE), installed capacity of captured CO_2 increases from the current level of around 45 Mt CO_2 per year to 1.2 GtCO_2 per year in 2030[3], and up to 7.6 Gt CO_2 in 2050[4]. According to the Intergovernmental Panel on Climate Change (IPCC), the role of CO_2 capture and storage is even more significant than IEA's NZE with the IPCC's 1.5°C scenarios having a median of around 15 Gt CO_2 per year captured in 2050[5]. Similarly, the Energy Transition Commission (ETC) estimates that by 2050, between 6.9 Gt (base case) and 10.1 Gt (high deployment case) of captured CO_2 per year is required to meet net zero targets[6].

According to the IEA[7], total annual capacity capture capacity in 2023 amounted to 45 Mt CO_2 and although deployment momentum has improved – with around 200 new capture plants announced to be in operation by 2030 – even if all of these are implemented, the total annual capacity will only increase to roughly 400 Mt CO_2 by 2030, well below the levels required to achieve 2050 net zero objectives[8]. This raises some fundamental questions about the characteristics of CCS projects which make them challenging for financing and scaling, even though the technology has been applied for decades particularly in the oil and gas industry.

This paper seeks to identify the main commercial and non-commercial risks associated with CCS and analyze incentive mechanisms, regulatory and legal frameworks, types of industry and ownership structures, and public-private partnerships that are likely to emerge in different parts of the world to mitigate these risks and enable viable business models to scale up the technology. Given that countries have different natural resource endowments, regulatory frameworks, and economic structures and as CCS can be applied to different industries (e.g. cement, steel, oil and gas, power, and chemicals), emergent business models can differ substantially across countries.

1. Key risks involved with CCS

The CCS value chain consists of three main activities: CO_2 capture, transport, and storage. Capturing CO_2 often constitutes the biggest cost component for CCS and is where significant cost reductions, efficiency gains and further technological innovations could be achieved. A key factor in the cost of CO_2 capture is the concentration and overall volumes of CO_2 in the source gas, with costs typically decreasing with increased concentration and volumes of CO_2 in the flue gas flow. In some applications such as ethanol production or

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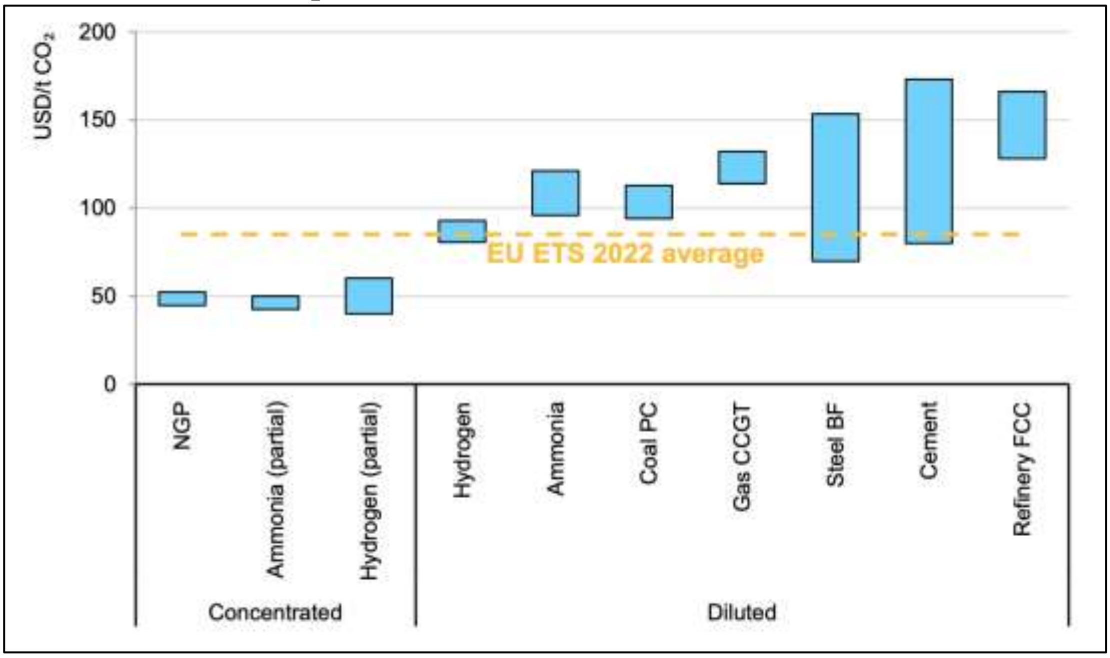
[1] See for instance, Bui, M., Adjiman, C., Anthony, E. et al. (26 more authors) (2018) Carbon capture and storage (CCS): The way forward. Energy and Environmental Science, 11 (5). pp. 1062-1176. ISSN 1754-5692; IPCC, Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
[2] IEA (2020), Energy Technology Perspectives 2020 Special Report on Carbon Capture Utilization and Storage: CCUS in clean energy transition.
[3] IEA (2023). Credible paths to 1.5C. Four pillars for action in the 2020s.
[4] IEA (2021), Net Zero by 2050: A Roadmap for the Global Energy Sector.
[5] (IPCC) (2018), Special Report on Global Warming of 1.5°C (SR15), https://www.ipcc.ch/sr15/
[6] ETC (2022), Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited, July 2022, https://www.energy-transitions.org/wp-content/uploads/2022/07/ETC-CCUS_Executive-Summary_final.pdf
[7] https://www.iea.org/reports/carbon-capture-utilisation-and-storage-2
[8] IEA (2023). CCUS policies and business models.

natural gas processing, CO_2 concentration is quite high (> 95%). In contrast, in applications such as power generation, CO_2 is quite diluted and therefore it is more challenging and costly to capture it (Figure 1). Currently, the most expensive application is capturing CO_2 directly from air (Direct Air Capture)[9].

Figure 1: Levelized cost of CO_2 avoided between CCS and unabated route across sectors



Source: Figure extracted from International Energy Agency (2023), CCUS Policies and Business Models: Building a Commercial Market. Notes: Notes: BF = blast furnace; CCGT = combined cycle gas turbine; FCC = fluid catalytic cracker; NGP = natural gas processing; PC = pulverised combustion.

CO_2 transportation technologies are mature especially via pipelines, as many pipelines are already in operation linked with enhanced oil recovery (EOR)[10]. Large-scale transportation of CO_2 via ships is less established, but the gas industry has plenty of experience in transporting gaseous fuels and this is unlikely to present a technical barrier especially as the technology required is already in use for the transport of other cryogenic liquids such as LPG and LNG[11].

The final stage in the CCS supply chain is injecting and storing CO_2 underground. CO_2 can be stored in saline formations and in depleted oil and gas fields. According to the Global CCS Institute, storage in saline aquifers has Technology Readiness Level (TRL) of 9 and existing projects have shown that CO_2 could be injected, monitored, and stored permanently[12]. Storage in depleted oil and gas fields has a lower TRL (5-8) as projects are yet to operate at a commercial scale[13]. While storage of CO_2 scores high in TRL, the delay and underperformance of some key projects such as the Gorgon CCS project have caused some observers to doubt whether the deployment of CO_2 storage at a large scale and across the globe could be achieved[14]. During this stage, monitoring, reporting and verification (MRV) is key[15]. The injection process needs to be documented and volumes of injected CO_2 need to be verified. It is also important to demonstrate with appropriate monitoring techniques that CO_2 remains contained in the intended storage formation. This has also safety and environmental dimensions. Systems must be put in place to monitor leakage and provide

[9] Costs of DACCS can vary widely from 400-1000 \$/tCO_2. Source: Webb et al. (2023). Scaling DAC: A moonshot or the sky's the limit?
[10] International Energy Agency (2023), CCUS Policies and Business Models: Building a Commercial Market.
[11] Small scale CO_2 shipping already exists under medium pressure conditions.
[12] GCCSI (2021). Technology readiness and costs of CCS.
[13] Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., ... & Mac Dowell, N. (2018). Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science*, *11*(5), 1062-1176.
[14] IEEFA (2022). If Chevron, Exxon and Shell can't get Gorgon's carbon capture and storage to work, who can?
[15] International Energy Agency (2023), CCUS Policies and Business Models: Building a Commercial Market.

early warnings of any seepage or leakage that might require mitigating action and to assess environmental effects.

Several characteristics and risks make financing CCS projects challenging for governments and the private sector alike. These include:

Risk of insufficient revenues: For many projects, the deployment of CCS will exclusively be driven by climate change mitigation goals and lowering emissions. In such projects where CO_2 is captured and stored underground and/or in building materials such as cement and concrete, there are no, or very limited revenue streams associated with CCS that can compensate for the high upfront capital costs and high operation costs (in contrast, for instance, to the case of renewable electricity generation). These operational costs include:

- The cost of capturing and conditioning CO_2
- The cost of compressing/liquefying CO_2 for transport
- The cost of transporting CO_2 via pipelines and ships (or trucks in case of short distances and small volumes)
- The cost of injecting CO_2 into storage sites, and
- The cost of monitoring and verifying the amount of CO_2 stored.

The cost of each of these activities varies widely depending on project specific factors (location, plant size, type of activity, the technology in use, to mention a few) and the literature reports a very wide range of estimates of these costs.

Risk of low and variable CO_2 price/tariffs: In countries that have established carbon pricing, either through emission trading systems (ETS) or carbon taxes, these instruments can provide players with economic incentives, either through avoiding costs or as revenue (e.g. from sale of allowances in an ETS) that would help them recoup part of the capital investment and operating costs. However, such signals may not be stable, and the revenues not large enough to provide incentive for investment in CCS.

Risk of interdependency: One way to reduce risks is to disaggregate the capture, transport, and storage components of the CCS technology chain. On the one hand, this allows different market actors with different strength and risk appetites to collaborate on CCS and to allocate risks more broadly across the chain. On the other hand, this creates interdependency/cross-chain risks as each part of the chain depends on the performance of other components. For instance, if an industrial player invests in CO_2 capture, it is important that the transport and storage infrastructure is in place. It is also important that those players controlling the transport and storage infrastructure do not have unilateral market power to charge excessive fees. At the same time, investors in the transport and storage infrastructure must ensure that there is sufficient and regular demand for their services to recoup capital and operational costs.

Risk of liability: Although the probability of CO_2 leakage from well-selected and managed storage is very low, this risk cannot be eliminated. If this risk is not transferred to the government or through insurance, the project owner would be liable for the risk of leakage for an indefinite period, with the contingent liability most likely to increase in value over time.

Other risks: There are other key risks that face investors in CCS including plant integration risk, technology risks (especially when it comes to the capture technology) and financing risk. There is also a public perception and stakeholder acceptance risk as many remain skeptical about the role of CCS as a climate mitigation technology, citing factors such as high cost, uncertainty surrounding viability, and fears around the safety and permanence of storage. Skeptics argue that CCS can also perpetuate the use of fossil fuels and discourage change in societal behavior and reinforce existing dependencies[16]. It is also argued that CCS could divert funds away from clean technologies[17].

Table 1 summarizes the hurdles faced by players through various parts of the CCS value chain.

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[16] Parmiter, P. & Bell, R. (2020). Public perception of CCS: A review of public engagement for CCS projects.
[17] IEA (2020). A new era for CCUS.

Table 1: Summary of hurdles in the CCS Supply Chain

Capture	Transport	Storage
CAPEX	CAPEX	CAPEX
OPEX	OPEX	OPEX
Low and variable CO_2 price or compensation for CO_2 avoidance	Price risk (tariffs for CO_2 transport)	Price risk (tariffs for storage)
	Volume risk (volume of CO_2 transported)	Volume risk (volume of CO_2 stored)
		Decommissioning risk
	Safety and storage liabilities (CO_2 leakage)	
	Public perception risks	

2. Frameworks to support investment in CCS

In designing frameworks to support investment and scaling up of CCS, the following key elements are essential to mitigate some of the above risks and generate a stream of revenues to make projects attractive for private sector investment:

- Stable and supportive legal and regulatory frameworks
- Mechanisms that allow stacking of revenues for operators in the supply chain, and
- Varying degrees of government participation in the CCS supply chain to enable risk-sharing and risk mitigation.

2.1 Supportive legal and regulatory framework

At the macro level, the government can create an enabling regulatory and legal framework for CCS. Key elements include:

- Setting national/regional CCS targets to signal the governments' commitment for CCS as a mitigation technology. For instance, in the EU, the NZIA establishes an EU-wide objective to achieve an annual CO_2 storage capacity/injection target of 50 Mt CO_2 by 2030, 280 Mt CO_2 by 2040, and up to 450 Mt CO_2 by 2050.[18] In the UK, the government has a target to deliver four carbon capture usage and storage (CCUS) clusters capturing 20 to 30 Mt CO_2 per year by 2030. These targets are intended to reassure entities that wish to invest in CO_2 capture that storage will be available.
- Establishing regulatory frameworks that incentivize investment in low-carbon technologies. Carbon pricing is the main market-based instrument in the policy toolbox to reduce CO_2 emissions. Carbon pricing could be implemented either through a tax on carbon emissions or via an emission trading scheme (ETS), and both options are presently in use. Governments can also introduce specific incentive schemes such as the 45Q tax credits for CCS projects under the Inflation Reduction Act (IRA) in the US and the investment tax credit (ITC) in Canada.
- Establishing a regulatory and licensing framework to address issues of operation, permitting, licensing of storage and CO_2 transport and decommissioning. For instance, the UK introduced the Energy Act 2023 that establishes an economic regulation model for CO_2 transport and storage, including an economic licensing framework under which CO_2 transportation by pipeline for geological storage operations will require a licence. The licence allows the economic regulator to address market failures associated with the natural monopoly characteristics of this network infrastructure. In the EU, the Directive on the geological storage of CO_2 (2009/31/EC), or colloquially the CCS Directive, aims to establish a legal framework for environmentally safe geological storage

[18] European Commission (2024). Industrial carbon management – carbon capture, utilisation and storage deployment.

of CO_2. The CCS Directive is comprehensive and covers areas such as selection of storage sites and exploration permits, storage permits, obligations for operating and closing storage sites, and third-party access (Member States must ensure that potential users have access to CCS infrastructure). The CCS Directive must be implemented in the national legislation with national authorities having some choice on how to implement the Directive. Similarly, in the US, the Underground Injection Control (UIC) program regulates the injection and long-term storage of CO_2 into deep rock formations such as Class VI wells. In Australia, the government introduced the Offshore Petroleum and Greenhouse Gas Storage Act 2006. The Act covers many aspects including the granting of the right to explore, appraise, inject and store a GHG substance, sets out a basic framework of rights, duties, obligations, entitlements and responsibilities of governments and industry, and ensures safe, secure and permanent storage of GHG substance[19].

- Establishing and/or adopting CCS methodologies. Methodologies are needed to ensure the quality and accuracy of monitoring data, the credibility of the crediting baseline, and whether impacts are accurately quantified using conservative and transparent methodologies and which account for potential leakage and reversals and avoid double counting. For instance, the ETS Directive in the EU has developed its rules for the monitoring and reporting of GHG emissions through Regulation 2018/2066, also known as the Monitoring and Reporting Regulation (MRR). MRR establishes compliance procedures and includes reporting and monitoring requirements.[20]
- Establishing a body to coordinate activities across the supply chain if the value chain is not integrated. For instance, in Norway, the government established a state entity Gassnova to act as a project integrator for the CCS Longship project.
- Developing a legal framework which allows for CO_2 to be transported across borders if the country plans to establish itself as a regional or a global storage hub.

2.2 Mechanisms that allow stacking of revenues

While utilization of CO_2 could provide a limited stream of revenues in some contexts[21], government support and incentives are central to make CCS projects viable. Also, since the CCS value chain may include various players with different incentive structure and skills and different appetite for risk, the question of who should be incentivized in the value chain comes into focus. For instance, an industrial plant (an emitter) can be incentivized with the revenues passed through the supply chain. Also, since the costs and the technology/commercial readiness levels varies across the supply chain, the amount and type of support will differ across the various components.

The bulk of revenue streams for CCS comes either through public funding support mechanisms – which is the main funding process for the time being – or through market-based mechanisms, which are likely to grow further in the future as CCS technology and business models mature.

Government funding support mechanisms

Government funding support plays a crucial role in overcoming barriers and mitigating risks which are particularly inherent to First-of-A-Kind (FOAK) CCS infrastructure, beyond simply reducing the investment contribution required from the private sector. Support can be provided in several forms and at various stages throughout the development, execution and operation of the CCS project. This support is required to overcome the barriers and mitigate the risks of technology, value chain coordination, low and volatile carbon pricing, environmental risk from CO_2 leakage, counter-party risk and the cost of capital for financing the projects. In terms of policies, incentives and levers which are currently being employed by governments globally, they can be categorized into three main buckets:

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[19] Australian Government, National Offshore Petroleum Titles Administrator, 'Offshore Petroleum and Greenhouse Gas Storage Titles: An introduction to the Greenhouse gas (GHG) storage legislative framework', May 2023, https://www.nopta.gov.au/_documents/guidelines/Introduction-to-the-offshore-petroleum-and-GHG-titles-framework.pdf
[20] MRR deals partially with CCU where the CO_2 converted into products must be reported.
[21] This paper does not focus on the utilization options. The IEA notes that 'the market for CO_2 use is expected to be relatively small in the short term, but also acknowledges that 'early opportunities can be developed'. See: IEA (2019), Putting CO_2 into Use: Creating Value from Emissions.

- Subsidies for specific CCS projects, through elements such as tax incentives/breaks, support agreements, competitions and direct CO_2 storage procurement,
- Emitter-targeted policies which drive demand for CO_2 capture and storage such as carbon pricing and ETSs (as noted earlier, representing an incentive for operators to reduce their emissions to avoid paying the carbon tax and/or allow operators to trade emission reduction certificates and generate revenues in the market), and/or imparting producer responsibility to sequester CO_2, and
- Public sector low-carbon procurement requirements, private sector procurement commitments, and standard-setting and regulations for low-carbon products.

Table 2 summarizes four main government funding mechanism that are currently being utilized by governments supporting the development and deployment of CCS globally. Each mechanism possesses specific advantages but also constraints.

Table 2: Government funding support mechanisms for CCS

Government funding support mechanism	Description	Advantages	Disadvantages
Direct capital grant subsidy	Direct subsidy of the CCS project CAPEX to the investor/project sponsor (not required to be paid back)	Reduces private sector's CAPEX investment requirements. Reduces project cost of capital (WACC) through risk sharing. Improves bankability through the sharing of the project execution risk between the government and the private sector.	Development risk and expenditure retained by project sponsor and therefore CCS development contingent on securing subsidy which ends up potentially constraining the CCS value chain pipeline. Public finances are exposed to downside risk with no potential for upside benefit from the project. Limited scalability in that finite amount of capital grant subsidy is available which ultimately ends up limiting the number of projects and constrains scalability. Fewer projects can be deployed and therefore limited economies of scale and cost optimization potential. Lengthy process coupled with uncertainty since public funding processes tend to be bureaucratic and subject to changes in government policy, and therefore has the potential to increase the lead-time and uncertainty to Final Investment Decision (FID). Technology risk; subsidy payments are not driven by the performance of CCS to capture and sequester CO_2 but aligned with project execution milestone deliverables.

Revenue support (OPEX/tariff subsidy)	Government payment made either to the: **Capturing entity:** Subsidy paid to the emitter capturing the CO_2 at a predetermined rate for a predetermined period based upon the CO_2 captured and sequestered, to contribute to operational costs and/or to mitigate uncertainty/volatility in the compliance carbon market price. **Transport & storage operator:** Payment made to T&S operator/company to mitigate the coordination risk of delay, shortfall or non-payment of transport and storage fee from the emitters.	Performance dependent: if there is no capture and sequestration, there will be no payment. Sharing of technology and operational risk between the government and the private sector. Reduction of cost of capital through risk sharing. Potential for enhanced scalability (relative to the direct capital grant subsidy). This is because the public funding support is spread over several years.	Development and execution risk is retained by the operator/project sponsor. Determining the optimum level of subsidy in that direct payment or tax credit may limit the drive for cost optimization and may even increase costs in the medium term. Essential to set an optimal level of subsidy to prevent such an eventuality. Note that while a direct payment option (such as the US 45Q credit) carries this risk, it has the advantage of being quick to activate (i.e. deployment-focused). This risk can be mitigated by employing a CCfD-type (Carbon Contracts for Difference) mechanism which incentivizes competitive bids; but may nonetheless involve a lengthy process.
Preferential government loan	Capital loan from Government for a portion of the project capital requirements on terms which are more favorable than the private sector in terms of the interest rate, period of debt repayment and/or start of debt repayment.	Transparency: enhances public transparency on the project economics, accounts and risks. Improving bankability through sharing of the project execution risk between government / state and private sector Reducing cost of capital: reduces project WACC, through risk sharing. Scalability: as loan is repaid and therefore funds available to invest in other projects.	Development, Technology, Execution & Operation Risk; Government exposed to project technical risks over the full lifecycle of the project at the earliest stages of the sector development. Negotiation of step-in rights; between public and private entities should the project fail at any time through the project lifecycle. Development risk and expenditure; retained by investor/project sponsor and may therefore limit/delay speculative CCS development until loan is secured. Lengthy lead-time to FID; securing of investment necessarily subject to rigorous governance and administration processes which may prolongs the lead-time and uncertainty to achieve FID.
Government equity investment	Government or Sovereign Investment Fund provides a capital contribution in return for equity in the CCS in the project company.	Project control: shareholder has increased control and transparency of the project throughout its lifecycle from development,	Development, Technology, Execution & Operation Risk: Government exposed to project technical risks over the full lifecycle of the project at the

		execution, operation and through to post closure. Transparency: enhances public transparency on the project economics, accounts and risks. Sharing of upside between public and private investors / shareholders of potential project profits as well as sharing project downside from potential losses. Reducing project WACC through risk sharing. Enhanced scalability as profits can be reinvested and funds can be recycled if shareholding is divested at a later stage of operation.	earliest stages of the sector development. Negotiation of step-in rights between public and private entities should the project fail at any time through the project lifecycle. Lengthy lead-time to FID; securing of investment necessarily subject to rigorous governance and administration processes which may prolongs the lead-time and uncertainty to achieve FID. Potential conflict of interest as the Government may be both the regulator and CCS project investor at the same time.

Market-led revenue streams

Revenues through utilization of CO_2: Revenue streams for captured CO_2 could be generated in some industrial applications where CO_2 could be utilized (examples include cement, food and beverage). But these opportunities remain very limited in scope and the vast proportion of the captured CO_2 will have no intrinsic economic value[22]. CO_2 could also generate value through its use in enhanced oil recovery (EOR). Currently, this remains the only well-established application of utilizing CO_2 (CO_2-EOR) that has been scaled up and has achieved commerciality in some places[23]. However, the use of CO_2-EOR has attracted wide criticism from environmental groups as it is seen as one of the ways for the oil industry to prolong the use of hydrocarbons. Also, since CO_2-EOR has the effect of increasing oil production and hence oil consumption, there is a public perception that this may ultimately cause an increase in emissions[24]. However, some studies[25,26] argue that it is possible for net reduction in emissions to be realized if the CO_2-EOR operation is appropriately operated and optimized for that purpose. The notion here is that the carbon balance of the project would be negative (net CO_2 stored) in the early stages of injection[27], as more CO_2 is trapped permanently underground and can offset the increase in emissions due to the combustion of the incremental oil due to CO_2-EOR[28].

Low-carbon products: CO_2 emitters have the possibility to sell low-carbon products such as low-carbon steels and cement. This can also include indirect use of CO_2 in products, such as synthetic fuels, chemicals or building aggregates, provided low-emissions energy is utilized for CO_2 conversion. Some of these applications will be or are already in regulated markets; examples include the Low Carbon Fuel Standard (LCFS) and the proposed sustainable aviation fuel (SAF) mandate in the UK[29] which place an obligation to produce a certain amount of an accredited low-carbon product. However, a majority of such standards for decarbonized products, such as ‘green steel’, still rely on voluntary demand where willingness to pay a

[22] IEA (2019), Putting CO_2 into Use: Creating Value from Emissions.
[23] Núñez-López and Moskal (2019). Potential of CO_2-EOR for near-term decarbonization. Frontier in Climate.
[24] Roberts (2019). Could squeezing more oil out of the ground help fight climate change? The pros and cons of enhanced oil recovery.
[25] ibid
[26] Pierru and Motairi (2023). Will government support for CCS-EOR lead to reduced emissions? Published in Oxford Energy Forum edition 138, OIES, Oxford.
[27] Mota-Nieto (2023). Carbon emissions accounting in the context of CCS coupled with EOR. OIES paper CM04, Oxford.
[28] ibid
[29] UK Department for Transport (2023). Pathway to net zero aviation: Developing the UK sustainable aviation fuel mandate.

premium for the lower-carbon alternative may exist, while efforts are underway to protect these premium products against emission-intensive and cheaper imported goods (i.e. carbon border adjustments).

Voluntary Carbon Markets (VCM): CCS project developers can sell carbon credits in the VCM based on certified emissions that have been reduced or removed through CCS. However, the size of the VCM remains quite small and despite the potential for the VCM to grow, many obstacles remain. Particularly, there have been concerns about the quality of the carbon credits which ultimately raised fears of corporate greenwashing.[30] Also, financing through the VCM has been mainly concentrated in a few types of projects, namely, renewable energy and Nature Base Solutions (NBS) avoidance projects.[31]

Tradable CCS or carbon storage certificates: The government can impose an obligation to decarbonize and award CCS certificates per ton of CO_2 abated. Then the obligated entities such as cement and steel companies or fuel providers can either make investments to generate CCS trade certificates to meet the obligation or trade these CCS certificates with obligated entities whose cost of abatement is higher than the price of CCS certificates. This instrument allows for the cost to be shared with purchasers of the product. For instance, car manufacturers could be obligated to use a certain percentage of 'green steel' and producers deploying CCS to produce green steel can sell the certificates to these car manufacturers.[32] The Canadian government issued the Clean Fuel Standard (CFS) regulations in 2022 targeting emission reductions from fuels. Primary suppliers will be required to meet their reduction requirements through the use of compliance credits. One potential pathway for compliance credits under the CFS is to undertake CO_2 emission reduction projects including CCS projects[33]. A drawback is that the price of these certificates is determined by the market and hence is highly uncertain and thus government support would still be needed to ensure a floor on the prices of these certificates. Similarly, a mechanism whereby 'carbon storage units' could be awarded to and traded by storage operators, coupled with an obligation on emitters to sequester certain amount of CO_2 (i.e., carbon takeback obligation – CTBO).[34]

2.3 Diverse approaches: Experiences from different countries

Governments have adopted different approaches as they attempt to establish a sustainable CCS market through contributing capital and sharing costs and risks, recognizing that while one approach may be feasible for a particular country, it may be completely unsuitable for a neighboring country and therefore there is no one-size-fits-all. The approaches that are being adopted by governments across the world can be roughly categorized into three buckets, with a spectrum ranging in between the categories, as shown in Figure 2.

[30] There is a real drive for robust verification and validation of carbon removal and reduction to ensure credible credit claims through the introduction of the Core Carbon Principles (CCP). The CCP are a set of interlinked principles to define a threshold standard to ensure integrity in the voluntary carbon market, focusing on emissions impact, governance and sustainable development.

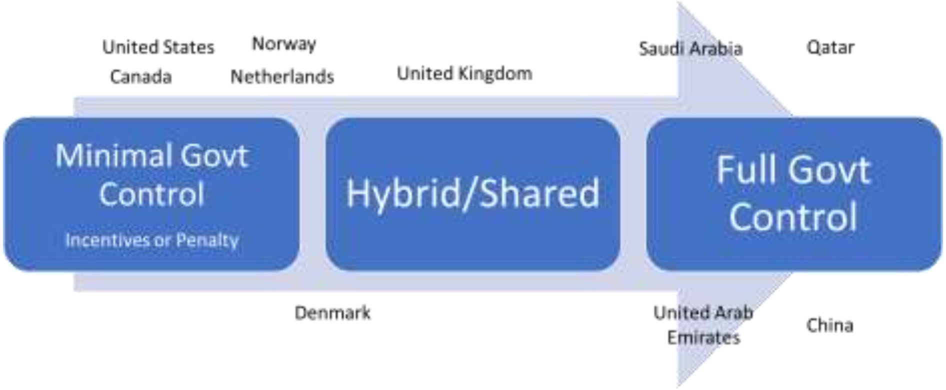
[31] With the inclusion of REDD+ and renewable energy credits, reduction and avoidance credits account for 90% of all credits on the VCM in 2023, according to Carbon Direct (2023). A look at the 2023 voluntary carbon market.

[32] Muslemani, H., Liang, X., Kaesehage, K., & Wilson, J. (2020). Business models for carbon capture, utilization and storage technologies in the steel sector: a qualitative multi-method study. *Processes*, *8*(5), 576.

[33] Duncanson, S. et al (2022), Canada's New Clean Fuel Standard Obligations for Liquid Fuel Suppliers and Low Carbon Energy Producers, OSLER, https://www.osler.com/en/resources/regulations/2022/canada-s-new-clean-fuel-standard-obligations-for-liquid-fuel-suppliers-and-opportunities-for-low-c

[34] Jenkins, S., Mitchell-Larson, E., Ives, M. C., Haszeldine, S., & Allen, M. (2021). Upstream decarbonization through a carbon takeback obligation: An affordable backstop climate policy. *Joule*, *5*(11), 2777-2796.

Figure 2: Varying degree of government involvement in CCS



At one end of the spectrum is minimal government control whereby governments utilize incentives and/or penalties to influence and nudge the private sector to invest in CCS projects without taking ownership of any segment in the supply chain. For example, incentives can involve government subsidies like grants, loans, or tax credits, while penalties encompass taxes or fees for non-compliance. The United States, Canada and the European Union follow this approach, relying on incentives and penalties, such as carbon pricing, to drive CCS investment.

In a hybrid setup, governments do not solely rely on the market for incentivizing private sector decisions. For capital-intensive activities with uncertain revenue streams, governments may share costs and risks with the private sector. This approach suits large infrastructure projects but requires sustained government support. In these countries, various parts of the supply chain are heavy regulated, and the government plays a key role in coordinating activities across the supply chain. The United Kingdom, Norway and Denmark, in varying degrees, are examples of the hybrid approach.

At the far right of the spectrum is the full government control where countries leverage their state-owned and/or national oil companies to invest in and potentially operate CCS projects. China, Saudi Arabia, Qatar, and the United Arab Emirates exemplify this approach, where most CCS projects involve state owned companies and with some private sector involvement depending on the country. The full government control approach model can overcome some of the obstacles such as cross-chain risks and other risks such as construction or underutilization risk. However, this approach raises the issue of how to fund these projects which could be through general revenues (oil/tax revenues) or through state-owned enterprises (SOEs) building and operating the transport and storage infrastructure and charging users a regulated tariff.

It is important to note that governments and countries adapt their approaches as a CCS market evolves. For example, in the United Kingdom and Norway, while there is significant government intervention in the current CCS market to initiate the process, government policy aims to become less interventionist as the CCS commercial market matures, for instance as outlined in the UK's CCUS Vision published in December 2023[35].

The United States

The US has supported CCS primarily through grants, subsidies and tax credits. The 45Q Tax Credit, first introduced in 2008 and enhanced in 2018, has been instrumental in progressing CCS. In 2022, the Inflation Reduction Act (IRA) was passed into law and further reformed the 45Q. The credit values as they stand now are listed below. 45Q tax credits will be inflation-adjusted post-2026.

- Point-source capture & dedicated storage: increased from US$50/tonne to US$85/tonne
- Point-source capture & EOR/utilization: increased from US$35/tonne to US$60/tonne
- DAC & dedicated storage: from US$50/tonne to US$180/tonne

[35] Carbon Capture, Usage and Storage, A Vision to Establish a Competitive Market, Department for Energy Security and Net Zero, 20 December 2023 (https://assets.publishing.service.gov.uk/media/6594718a579941000d35a7bf/carbon-capture-usage-and-storage-vision-to-establish-a-competitive-market.pdf)

- DAC & EOR/utilization: from US$50/tonne to US$130/tonne

Also, as part of the IRA, the construction start date window has been extended by seven years to 2033. Credits will be granted for 12 years of operation.

The Infrastructure Investment and Jobs Act (IIJA), passed in 2021, provided over US$12 billion for CCS and related activities over the next 5 years, including:

- US$2.5 billion for carbon storage validation
- US$8 billion for hydrogen hubs, including blue hydrogen, and
- over US$200 million for CCS technology development.

The IIJA also amended the Outer Continental Shelf Lands Act, directing the Department of Interior to develop regulations for establishing a permitting framework for offshore CO_2 storage.

Canada

Canada hosts many CCS projects. The development of CCS has been supported by policies and government incentives, both at the federal and provincial level. The Canadian Net-Zero Emissions Accountability Act, which became law on June 29, 2021, enshrines in legislation the country's commitment to achieve net-zero emissions by 2050 and reduce emissions by 40-45% from 2005 levels by 2030. The Canadian government also set a target of at least 15 mtpa of CO_2 reductions using CCS technology through 2030. This includes capturing and storing CO_2 emitted from oil sands facilities (8 mtpa), refineries (3 mtpa), and gas plants (4 mtpa). In addition, the "Healthy Environment and a Healthy Economy" policy document, published in 2020, proposed the development of a Canadian CCS strategy and launched a Net Zero Challenge for large industrial emitters to encourage plans for net zero emissions by 2050. The Hydrogen Strategy for Canada was also released in 2020 by Natural Resources Canada, citing CCS as part of an expanded, low carbon intensity hydrogen strategy. A "Strategic Innovation Fund – Net Zero Accelerator" was also announced to fund initiatives up to 8 billion Canadian dollars including decarbonization projects for large emitters [36] using CCS. The Energy Innovation Programme is also funding CCS Research Development and Demonstration (RD&D) to the amount of 319 million Canadian dollars over seven years. The Canada Growth Fund with funds of 15 billion Canadian dollars is being designed to attract private capital into clean technologies and decarbonization projects including CCS. These are in addition to support at the provincial level such as Alberta's Carbon and Capture Storage Fund[37].

In 2018, the Canadian government adopted the Greenhouse Gas Pollution Pricing Act (GHGPPA). This is made up of a federal fuel charge for all fossil fuels paid by either the producer or distributor in a province and a performance-based system for industries known as the output-based pricing system (OBPS) designed to ensure there is a price incentive for industrial emitters to reduce their GHG emissions while mitigating the risk of carbon leakage and competitiveness impacts. These are linked to a carbon pricing schedule that is \$65/tCO_2e in 2023, with escalating annual increases of \$15/tCO_2e until it reaches \$170/tCO_2e in 2030 [38]. In addition, the 2022 budget proposed an investment tax credit (ITC) for businesses that incur CS expenses on projects that capture and permanently store CO_2 through an eligible use. This includes dedicated geological storage and storage of CO_2 in concrete but excludes EOR. The tax credits for investment became effective immediately, with the following rates set through to 2030:

- 60% in DAC equipment
- 50% in capture equipment
- 37.5% in equipment for transportation, storage and use
- 10% in refurbishment costs

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[36] https://ised-isde.canada.ca/site/strategic-innovation-fund/en/net-zero-accelerator-initiative

[37] International Energy Agency (2023), CCUS Policies and Business Models: Building a Commercial Market.

[38] See Ihejirika et al, (2023), Scaling CCUS in Canada: An Assessment of Fiscal and Regulatory Frameworks, OIES Research Paper, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/04/Scaling-CCUS-in-Canada-CM02.pdf

The credit can be claimed on eligible expenses in the year in which the expense is incurred, regardless of when the equipment becomes available for use. From 2031, the rates will be reduced by 50%.[39] However, there is still uncertainty regarding the time frame in which these credits will be paid. In its 2023 fall economic update, the Canadian government also introduced carbon contracts for difference, which would result in funding up to $7bn Canadian dollars out of the $15bn Canada Growth Fund to backstop carbon pricing mechanisms, in a bid to provide more assurance to project developers.

The United Kingdom

The UK approach is based on the regulation of emitters/industrial and transport and storage (T&S) operator (see Table 3). The UK government has introduced business models/commercial arrangements for different emitters (e.g. industry, waste-to-energy, power sector). The emitters are selected through a competitive tender and granted contracts (for instance, for the industrial sector, these are referred to as Industrial Capture Contracts (ICC)). The contract (a 10-year contract with the option for up to five one-year extensions) provides emitters subsidies in the form of capital grants from the Carbon Capture and Storage Infrastructure Fund and ongoing revenue support scheme with payment covering CAPEX (including a return), OPEX, T&S fees. The revenue stream is based on the price difference between a reference price (based on the UK-ETS) and a strike price (the cost of abatement). Through these contracts, emitters are also protected against some cross-chain risks.

The transport and storage segment is regulated separately and is funded through the Transport & Storage Regulatory Investment (TRI) business model. The business model establishes an economic regulatory regime (ERR) linked to a user-pays revenue model plus a government support package (GSP) and mandates open access networks. Under this business model, a private company is established (the T&S company or T&SCO) which will be responsible for construction, financing, operation, maintenance, and decommissioning of the T&S network. Within the context of the ERR, the regulator (Ofgem) provides a licence to the T&SCO based on key parameters including allowed revenue. The users of the network will pay fees for T&SCO and through these fees, the company will recover its allowed revenues. The T&S fees will be set by a methodology that allowed the company to recover its costs plus an allowed return. The GSP protects the company from some events such as CO_2 leakage if commercial insurance schemes are not available.

Table 3: CCS support mechanisms in UK

Regulatory and Legal Framework	**Financials**		**Risk Mitigation**	
	Emitters	T&S	Emitters	T&S
• 20-30 million tonnes of carbon dioxide captured, per year, by 2030 • CO_2 transport and storage licensing framework • Adoption of EU CCS Directive • Financial assistance • Business models	• Capital Grants (CCS Infrastructure Fund) • Carbon Pricing (UK-ETS) • CCfDs • Subsidy for payment of T&S services	• Capital Grants • Regulated Asset Base (RAB) Model	• Risk of failures and delays caused by the T&SCo	• Decommissioning risk • Leakage of CO_2

[39] See Ihejirika et al, (2023), Scaling CCUS in Canada: An Assessment of Fiscal and Regulatory Frameworks, OIES Research Paper, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/04/Scaling-CCUS-in-Canada-CM02.pdf

Norway

The country has a relatively long history with CCS where the Sleipner project has been in operation since 1996, followed by Snohvit CCS in 2008 and CO_2 Test Center (TCM) opening in 2012. As such, Norway has over 28 years of operational CCS experience with around 22 million tonnes of CO_2 stored so far. There is high-level and consistent political support for policies that have helped achieve this. This began with legislating a carbon tax in 1991, which effectively led to the Sleipner and Snohvit CCS projects. The general CO_2 tax on mineral oil currently sits at NOK 952/tonne (US$91). Proposals are in place for it to rise steadily, reaching NOK 2000/tonne (US$220) by 2030.[40] Norway participates in the EU ETS and energy use that is subject to the EU ETS is generally exempt from the CO_2 Tax on Mineral Products or benefits from a reduced carbon tax rate[41].

In addition, regulations for transport and storage of CO_2 are mature and have been in place since 2014. Following completion of CO_2 injection, the storage licence will be transferred to the state government no less than 20 years later. The operator will be liable for funding 30 years of Monitoring, Measurement and Verification (MMV) costs post-closure. This must be paid into a fund upfront.

A key CCS project is Longship in Norway which covers the entire CCS supply chain. The CO_2 is to be captured from a cement plant (Norcem) and waste-to-energy plant (Hafslund Oslo Celsio) (industrial partners). The CO_2 transportation and storage infrastructure would be developed in a partnership between Equinor, Shell, and TotalEnergies known as Northern Lights. The CO_2 is to be transported in liquid form by ships to the project's CO_2 receiving terminal on the Norwegian west coast. The liquefied CO_2 will be then transported by pipeline to an offshore storage location under the North Sea for storage. The Longship annual storage capacity stands at 1.5 million tonnes of CO_2 per annum, which exceeds the 800,000 tonnes of CO_2 allocated to Norcem and Celsio and therefore Northern Lights will have the capacity to receive CO_2 volumes from other sources. Northern Lights already signed the world's first commercial agreement on cross-border CO_2 transport and storage where, from early 2025, it is planned to capture some 800,000 tonnes of CO_2 from an ammonia and fertilizer plant in the Netherlands[42].

Longship constitutes an interesting case study on how to enable the establishment of a CCS hub. The state/government support has been vital to kickstart the industry and bridge the financing gap for this first-of-a-kind full chain CCS commercial project. The Norwegian government provided funding of US$1.8 billion, covering 80% of the Northern Lights' cost through state aid agreements.[43] It was difficult for the project to get commitment from industrial emitters to build capture plants without having storage, but the project required commitment from emitters to justify building the storage. State support was therefore critical during the market development phase. The government established a state entity Gassnova that promotes technological development, builds CCS competence and acts as a project integrator for the Longship project including administering the public funding to industrial partners, coordinating the overall project schedule and managing the cross-chain risks and functionality[44]. The government also participates indirectly in CCS projects through Equinor (majority ownership by the government of Norway). However, the government seems to be keen to keep a distance in future projects and while oil and gas operators need to be on each licence this may not involve Equinor.[45]

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[40] See Kevin R. Kaushal and Hidemichi Yonezawa (2022), Increasing the CO_2 tax towards 2030: Impacts on the Norwegian economy and CO_2 emissions, Statistics Norway. https://www.ssb.no/natur-og-miljo/miljoregnskap/artikler/increasing-the-CO2-tax-towards-2030.impacts-on-the-norwegian-economy-and-CO2-emissions/_/attachment/inline/fbd324c2-1490-44bd-9848-3328a7cdffa9:7a60a2ab12e794a969d8fa010a648ad541661586/RAPP2022-43.pdf

[41] OECD, Taxing Energy Use 2019: Country Note – Norway, https://www.oecd.org/tax/tax-policy/taxing-energy-use-norway.pdf

[42] See: https://totalenergies.com/media/news/press-releases/norway-northern-lights-project-signs-worlds-first-commercial-agreement

[43] Ole Ketil Helgesen, Norway takes aim at CCS with huge government investment, Upstream, 21 September 2020,

[44] See: https://ccsnorway.com/publication/regulatory-lessons-learned/

[45] In 2023, exploration licences were awarded including one to Sval Energi AS, Storegga Norge AS, and Neptune Energy Norge AS, one to a group consisting of Aker BP ASA and OMV (Norge) AS and one to a group consisting of Wintershall Dea Norge AS and Altera Infrastructure Group through its subsidiary Stella Maris CCS AS. See: Davide Ghilotti, Norway awards trio offshore CO_2 storage licences, Upstream, https://www.upstreamonline.com/carbon-capture/norway-awards-trio-offshore-CO2-storage-licences/2-1-1503361

Denmark

In Denmark, CCS is a relatively recent development where pre-2020, injection of CO_2 into the Danish subsoil was prohibited under legislation, and all previous attempts at launching CCS had been publicly opposed. The change happened in 2020 when the Danish government passed the Danish Climate Agreement for Energy and Industry, committing the country to a 70% reduction in GHG emissions relative to 1990 levels by 2030. The agreement acknowledged CCS as a critical component to achieve the target and a CCS target was set at 4-9 mtpa of CO_2 storage by 2030. In addition, the Danish government has allocated approximately €5 billion of support to projects across the CCS value chain with around €4 remaining.[46] Additional amount of approximately is €350 million is also available under the Negative Emissions CCS Fund.[47] Danish CCS projects are also eligible to apply for funding from the EU Innovation Fund, which aims to allocate over €38 billion towards low-carbon technologies by 2030. The state company Nordsøfonden will have a 20% interest in all future CO_2 storage licences. The state will receive a share of future profits and also invest in the project (sharing the risk) with investors.

In January 2022, the Danish Marine Act was amended to exclude geological storage of CO_2 under the seabed from the prohibition and carriage of materials and substances for dumping. In October 2022, a bilateral agreement was signed under the London Protocol between Belgium and Denmark, which allowed for cross-border transportation of CO_2 between the two countries. In January 2023, the EU commission approved a €1.1 billion Danish scheme to support the role out of CCS technologies[48]. This is in addition to the remaining tenders under the restructured CCS fund worth approximately €3.6 billion[49].

The rapid change in Denmark's CCS journey resulted in the initiation of CO_2 injection at the Project Greensand pilot in March 2023. This was the first cross-border CO_2 to be stored in the North Sea, and the first CO_2 to be stored in a depleted North Sea reservoir[50]. The Greensand pilot received funding of 197 million DKK (€26 million) from the Danish Energy Agency. Also, Ørsted has commenced the construction of two carbon capture facilities in Denmark as part of the Ørsted Kalundborg CO_2 hub. The project has been awarded a 20-year contract by the Danish Energy Agency in 2023 and is expected to capture 0.43 Mt CO_2 per year of biogenic CO_2 from the beginning of 2026. Once captured, the CO_2 will be transported and stored by Northern Lights Joint Venture in the Norwegian part of the North Sea.[51]

The Gulf Cooperation Council (GCC)

In the Gulf Cooperation Council (GCC), the two biggest CCS projects currently in operation are Uthmaniyah in Saudi Arabia and the Al-Reyadah/Emirates Steel Industries (ESI) in the UAE. The Uthmaniyah project, owned and operated by Saudi Aramco, captures CO_2 from a natural gas and production plant (Hawiyah NGL plant). The captured CO_2 is transported via 85 km pipeline to the injection site. Since 2015, the CCS project has been capturing and injecting 0.8 Mt CO_2 per year for enhanced oil recovery (EOR). Saudi Aramco has also developed an elaborate monitoring and surveillance programme to evaluate the performance of the project. In the UAE, the ESI CCS project captures up to 0.8 Mt CO_2 per year from the Emirates Steel plant. The CO_2 is transferred to Al-Reyadah plant for compression and dehydration which is then transported through a pipeline (43 km) to two onshore oil fields for enhanced oil recovery.

These two projects have a few features in common:

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[46] Lockwood, T. (2024), Designing Carbon Contracts for Difference: A comparison of incentives for carbon capture and storage in Europe,

[47] Lockwood, T. (2024), Designing Carbon Contracts for Difference: A comparison of incentives for carbon capture and storage in Europe,

[48] European Commission, State aid: Commission approves €1.1 billion Danish scheme to support roll-out of carbon capture and storage technologies, https://ec.europa.eu/commission/presscorner/detail/en/ip_23_128, Press Release January 12.

[49] ibid

[50] See: What is project Green Sand? https://www.projectgreensand.com/en/hvad-er-project-greensand

[51] Ørsted begins construction of Denmark's first carbon capture project, December 4, 2023. https://orsted.com/en/media/news/2023/12/oersted-begins-construction-of-denmarks-first-carb-13757543#:~:text=The%20%E2%80%98%C3%98rsted%20Kalundborg%20CO%3Csub%3E2%3C/sub%3E%20Hub%E2%80%99%20project%20aims%20to,from%20the%20straw-fired%20unit%20at%20Aved%C3%B8re%20Power%20Station

- Both projects operate in environments where there is no carbon pricing or regulations to reduce emissions from industrial plants. However, both Saudi Arabia and UAE have announced net zero targets for their overall economies.
- In both projects, the cost of capturing CO_2 is relatively low given the high concentration of CO_2 in the flue gas.
- In both projects, the captured CO_2 is transported through pipelines to be used for enhanced oil recovery in mature fields.
- Neither of these projects relies on market-based instruments such as CfDs or CCS certificates. There are no carbon credits issued on the back of these projects. The main form of support is through government/state owned entities' financing.
- In both projects, the interdependency risk is low. In the case of the Uthaminyah project, Saudi Aramco controls the entire supply chain from capture to transport and storage. In case of ESI CCS project, the ownership is more complex, but the interdependency risk is also low. The Al-Reyadah is a joint venture project between ADNOC and Masdar (with Masdar itself owned by three government entities: ADNOC, Mubadala Investment Company, and Taqa). Emirates Steel is owned by Abu Dhabi's General Holding Corporation (Senaat), a subsidiary of sovereign wealth fund ADQ.

In terms of opportunities, GCC oil and gas exporters could establish competitive advantage in CCS given their natural resources. These include geological storage capacities, access to depleted hydrocarbon reservoirs and deep saline formations, and the utilization of existing infrastructure. Also, these exporters have the technical resources (expertise in subsurface technology) through decades of hydrocarbon exploration. These include site characterization which is prerequisite to safe geological storage of CO_2 and monitoring and verification. Verifying the quantity of injected CO_2 and demonstrating with appropriate monitoring techniques that CO_2 remains contained in the intended storage formations are key components of any CCS project.

Indeed, many GCC countries have ambitious plans to scale up CCS projects. For instance, Saudi Arabia has announced a plan to develop a major CCS hub with a capacity to store 9 million tons of CO_2 annually starting in 2027 with further plans to scale it up to 44 million tons of CO_2 per year by 2035. This constitutes an important step in the Kingdom's efforts to reduce its emissions and meet its climate targets. The details of the project remain scant, but the hub will be developed by Saudi Aramco. An agreement was signed between SLB and Linde to develop a 9 million ton/year CCS hub. But unlike the Uthmaniyah project, the hub will be open to multiple industry users including Saudi Aramco, which will contribute to around 6 Mt CO_2 annually and the rest will come from other industrial sources. From Aramco's perspective, this is a main component of its efforts towards developing a blue hydrogen industry.

The challenge for the countries in the region is how to finance and scale up CCS activity without having a big impact on public finances and economic growth. Unlike Norway where the government has provided incentives for private players and where there is a price on CO_2 emissions, the players in the CCS supply chain in the GCC are mainly government entities (either those capturing the CO_2 or those transporting and storing the CO_2). Thus, the additional cost for implementing CCS is born ultimately by the government in the form of lower revenues and can be thought of as a carbon tax on its own emissions. The government can mandate obligated entities (whether state or privately owned) to capture all or part of their emissions. The associated costs could be borne by the obligated entities (which will impact their profitability and competitiveness) and/or the government can incentivize these entities through the provision of public funds to compensate for the upfront and operation costs. To offset some of the costs on the obligated entities, the cost of transport and storage of CO_2 could be borne by the national oil company (NOC) through the creation of a storage hub. The NOC has the knowledge and the expertise and the infrastructure to develop such a hub and is an importance supplier of CO_2 from its own activities (refining, gas processing plants, blue hydrogen developments, chemicals). This also has the added advantage of minimizing coordination costs. In addition to infrastructure, the NOC will put in place the appropriate monitoring regimes for CO_2 leakage and reporting and verification standards. The NOC could pass the cost of building the CCS hub and transport and storage to the main shareholder i.e., the government or the NOC could generate revenues through the utilization of CO_2 and/or through the issuing of high quality and verifiable carbon credits against these reductions.

3. CCS Business Models

3.1 Overview of business model theory

There is a significant body of work and literature on definitions, interpretations and theories of business models. Thinkers and academics such as Hayek[52], Osterwalder and Pigneur[53], Boons and Lüdeke-Freund[54], Doganova and Eyquem-Renault[55], and many others, have written extensively on the subject, and an analysis and review of the different theories are beyond the scope of this paper. However, for the purposes of this paper, the term "business model" will simply refer to a company's strategy for achieving profitability. It encompasses elements such as the:

- products and/or services the company intends to offer,
- its target market,
- the market gap it aims to address,
- anticipated expenses, and
- a financial model for sustainable operation.

Traditionally, the primary objective of publicly traded firms is profit maximization for shareholders; yet, there has been a shift towards integrating social and environmental sustainability as key drivers for innovation in business models. In addition, business models do not only serve to ensure revenue certainty, but also address specific risks, allocating them in a fair and balanced manner, such as between governments and private sector entities in the context of CCS.

A significant element of any business model is its value proposition, which must be clearly articulated. In the case of CCS, determining its value is crucial for establishing a functional business model. The value of CCS revolves around either:

- Emissions reduction or removals through the introduction of a carbon price (carbon tax, ETS etc.), and/or
- Economic revenues generated from the sale of captured CO_2, and/or
- The creation of low-carbon products

The value proposition of CCS may vary, depending on the policy instrument a government has utilized to drive the deployment of CCS. A model focused on meeting climate targets will be influenced by government regulations, while one emphasizing economic return will aim to boost revenues and cut costs. Currently, many of the operational CCS plants have derived value from utilization of CO_2, predominantly for EOR.

3.2 CCS business models

CCS business model falls into two main project types:

i) Full chain model, or

ii) Partial chain model

This essentially describes the extent of the integration of the CCS value chain within the project. Within the two overarching business model descriptions, project ownership can either be public/state-owned, private or a public-private partnership (PPP). Financing of the project can either be through government sources such as grants, tax credits, loan support or through private financing such as revenue from direct use of

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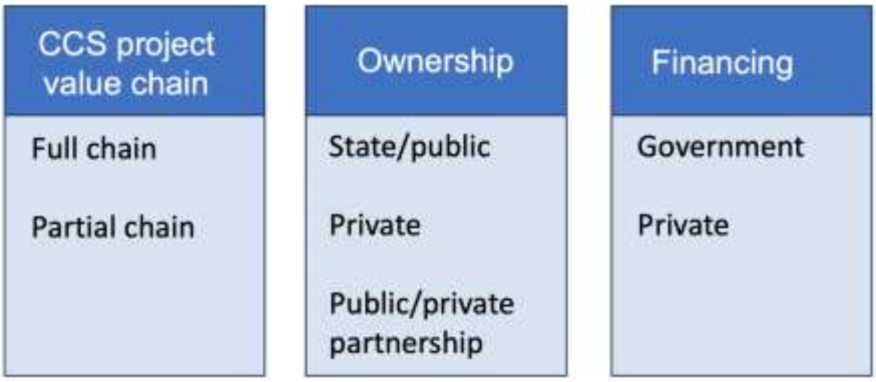
[52] Hayek, F.A. (1967). Studies in Philosophy, Politics, and Economics. University of Chicago Press, Chicago.
[53] Osterwalder, A., & Pigneur, Y. (2010). Business model generation: a handbook for visionaries, game changers, and challengers. John Wiley & Sons.
[54] Boons, F., & Lüdeke-Freund, F. (2013). Business models for sustainable innovation: state-of-the-art and steps towards a research agenda. Journal of Cleaner Production, 45, 9-19.
[55] Liliana Doganova, Marie Eyquem-Renault, What do business models do?: Innovation devices in technology entrepreneurship, Research Policy, Volume 38, Issue 10, 2009, Pages 1559-1570, ISSN 0048-7333 (https://www.sciencedirect.com/science/article/pii/S0048733309001668)

CO_2 or low-carbon products and voluntary carbon markets (see Section 3.2). An overview of the different possible configurations is highlighted in Figure 3.

Figure 3: CCS value chain, ownership and financing



Different configurations can be adopted utilizing the above descriptions. For example, a partial chain model may be privately owned with government subsidies, or it may be fully government-owned and subsidised. A full chain model may also be either state-owned or privately-owned or consisting of a PPP, dependent on the approach a government has taken to establish a viable and sustainable market for CCS. For example, in China, NOCs such as Sinopec, PetroChina, CHN Energy and CNOOC dominate nearly all CCS projects, except for the Karamay methanol plant, operated by the private Dunhua Oil Company. Similarly, in the Middle East, NOCs such as Saudi Aramco, Qatar Energy (in collaboration with ExxonMobil) and ADNOC hold sway over the regional operational of CCS projects. Examples of public-private partnerships include Norway. The Norwegian Government is the majority shareholder in Equinor, which boasts almost three decades of experience operating commercial CCS projects.

Both full chain and partial chain models can be developed through a joint-venture structure, where a new joint venture company, owned by the participating stakeholders, is created. This is usually the ownership model behind CCS hubs and clusters and applies to private as well as public stakeholders. In a joint venture, financial risk is usually shared between the partners. Alignment and agreement are also required on where and how other risks are best tackled and is essential to guarantee alignment among the various steps of the CCS chain.

Full Chain Model

The majority of CCS projects currently in operation adopt the full chain model, whereby the captured CO_2 is transported from one capture facility to one injection site. The project is usually developed, owned and operated by a single entity, as shown in Figure 4. It is commonly adopted for EOR projects and for demonstration sequestration projects where the operator is able to control the development, execution and operation of full value chain from emissions to storage site.

This is a natural model for a first-of-a-kind (FOAK) project to prove the concept with capture-ready emitters and usually accompanied by government subsidy to bridge the funding gap. The advantages of such a model are the limited development and coordination risks, due to one entity operating the entire chain, although the operator bears all the liabilities and must possess the technical and operational expertise in all areas of the CCS chain.

However, this model may fail to meet some of the key characteristics for a viable CCS model, in particular scalability, providing open access to the network and incentivizing competition. Breaking up the CCS value chain can potentially help mitigate the highlighted risks, allocate the risks across players, as well as avoid monopolistic behavior. Examples of projects which have utilized the full chain model are provided in Table 4.

Figure 4: Full Chain Model Concept

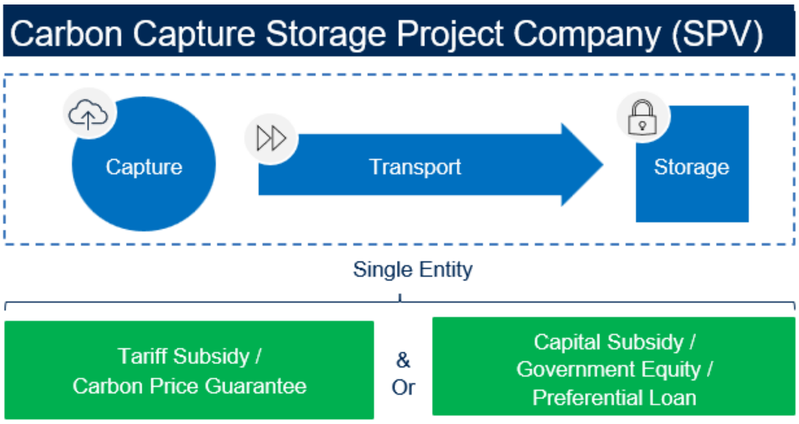


Table 4: Full Chain Model Projects

Project name	Country	Partners	Operation	Announced capacity (high) (Mt CO_2/yr)	Sector	Carbon Sink
Gorgon CCS	Australia	Chevron (47.3 per cent, operator), Shell (25 per cent), ExxonMobil (25 per cent), Osaka Gas (1.25 per cent), Tokyo Gas (1 per cent), Chubu Electric Power (0.417 per cent)	2019	4	Natural gas processing	Dedicated storage
Illinois Industrial Carbon Capture and Storage (IL)	United States	ADM	2017	1	Biofuels	Dedicated storage
Qatar LNG	Qatar	Qatar Petroleum, ExxonMobil	2019	2.1	Natural gas processing	Dedicated storage
Quest (ALB)	Canada	Shell (60%), Marathon oil (20%), Chevron Canada (20%), CNRL	2015	1.2	Other fuel transformation	Dedicated storage
Sleipner	Norway	Equinor, Eni	1996	1	Natural gas processing	Dedicated storage
Snohvit CO_2 capture and storage	Norway	Equinor, Petoro, TotalEnergies,	2008	0.7	Natural gas processing	Dedicated storage (EOR)

		Neptune, Wintershall				
Uthmaniyah CO_2 EOR Demonstration Project	Saudi Arabia	Saudi Aramco	2015	0.8	Natural gas processing	Dedicated storage (EOR)
Al-Reyadah/Emirates Steel Industries	UAE	ADNOC, Masdar and Emirates Steel Industries	2016	0.8	Steel	Dedicated storage (EOR)

Partial Chain Model

Different models are now appearing whereby the CCS value chain is split or broken up, with partial chain projects focused on capture, transport and/or dedicated storage developing in connection to emerging shared infrastructure within CCS hubs. There are several advantages to splitting the CCS value chain, including better management of risk where it is allocated to specialist entities that are best placed to bear it. Governments will need to support the deployment of these new models in areas including in coordinating the stakeholders involved as well as addressing the long-term liability concerns related to CO_2 storage and establishing reliable revenue streams where a profitable market does not exist yet.

Partial chain models offer a strategic advantage by enabling emitters to delegate the expertise in capture, transport, and storage to specialized companies. This is particularly pertinent for capture applications where CO_2 is not inherently separated as part of the process, such as in natural gas processing or ammonia production, necessitating dedicated capture equipment.

The establishment of CCS hubs further enhances the efficiency of these models. By consolidating resources and expertise, hubs can significantly reduce lead times for connecting to shared infrastructure. This not only streamlines the overall process but also cuts costs through heightened competition within a specialized corporate landscape and the sharing of infrastructure expenses. Additionally, the hub model facilitates the connection of more dispersed and smaller emitters to CO_2 transport and storage, leveraging economies of scale for enhanced accessibility and affordability.

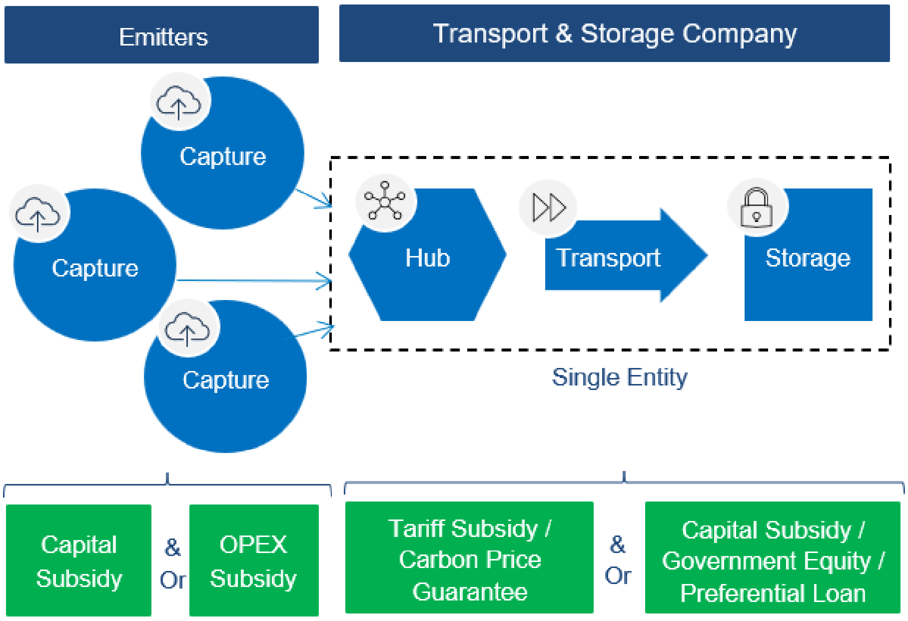
As discussed previously, the risk associated with partial chain models include increased cross-chain and coordination risk whereby multiple entities are involved and responsible for constructing, owning and operating different elements of the CCS value chain, and the timings and operational arrangement for how they interact will be difficult to align. In addition to that, the 'chicken and egg' situation arises whereby emitters are reluctant to invest in capture facilities unless they have certainty on where the captured CO_2 will be taken and stored and transportation and storage operators will not invest in transportation and storage infrastructure unless there is a critical mass of customers (emitters) who have committed to investing in capture plants. This uncertainty makes financing such projects a challenge, and this is where some governments have stepped in with financial and regulatory support and incentives to provide a certain degree of certainty to encourage investment. Again, as highlighted earlier partial chain models may be government-owned, privately-owned or through a public-private partnership. Several different partial chain models are being developed, some of which are highlighted below.

Partial Chain Model - Single Hub

This is the model currently adopted by many of the European countries developing CCS, including the UK, Denmark (Project Greensand Phase 1 and Bifrost), some of the projects in Norway (Northern Lights and Havstjerne) and the Netherlands (Aramis and Porthos), as well as the Gulf countries, including Abu Dhabi's CCS project and Saudi Arabia Jubail CCS hub.

The key feature of this model is that the ownership and operation of the transportation and storage (T&S) infrastructure is carried out by a single entity (or a consortium of companies potentially including state-owned enterprises), forming a natural monopoly and therefore requiring regulation of fees and access[56] (see Figure 5). This means that this model relies on substantial government participation, as the case with Denmark, or via a regulated asset base model such as the case with the UK. In terms of emitters, several would be involved, all feeding into the shared infrastructure of the CCS hub. While the aggregation of the T&S elements simplifies interface risk between the segments and therefore de-risks development of the T&S infrastructure, there is significant coordination risk due to the multiplicity of emitters, including commercial and financing complexity. The model does possess an inherent flexibility for expansion, which is a positive.

Figure 5: Partial Chain Model – Single Hub Concept



As noted earlier, the transport and storage elements may require regulation to avoid monopolization of the infrastructure and overcharging for the CO_2 disposal services. In addition, in the case of the emitter, direct subsidy of both the capital (CAPEX) and operational (OPEX) expenditure is required. A CAPEX subsidy is needed to bridge the investment case for building the capture plant and an OPEX subsidy is also required to bridge the funding gap for the T&S charges. In addition, some form of subsidy or equity investment in the T&S infrastructure is required to share the project risks and reduce the Weighted Average Cost of Capital (WACC) and effectively reduce the T&S tariff. A T&S agreement is negotiated directly between the T&S operator and each individual emitter.

There is also an option for government to take equity in return for capital contribution in T&S infrastructure to gain insight and control over development, as is the case in Denmark, where the state company Nordsøfonden takes a 20% interest in all future CO_2 storage licences. The Danish state will receive a share of future profits, but must also directly invest in the respective project, sharing the risk involved for the other stakeholders. In addition, if the CO_2 is sufficiently priced and a long-term purchasing contract is in place, the CO_2 transport and storage operator would face low risks. With state ownership, there is easier access to finance, usually at lower rates than those faced by private organisations when operating alone.

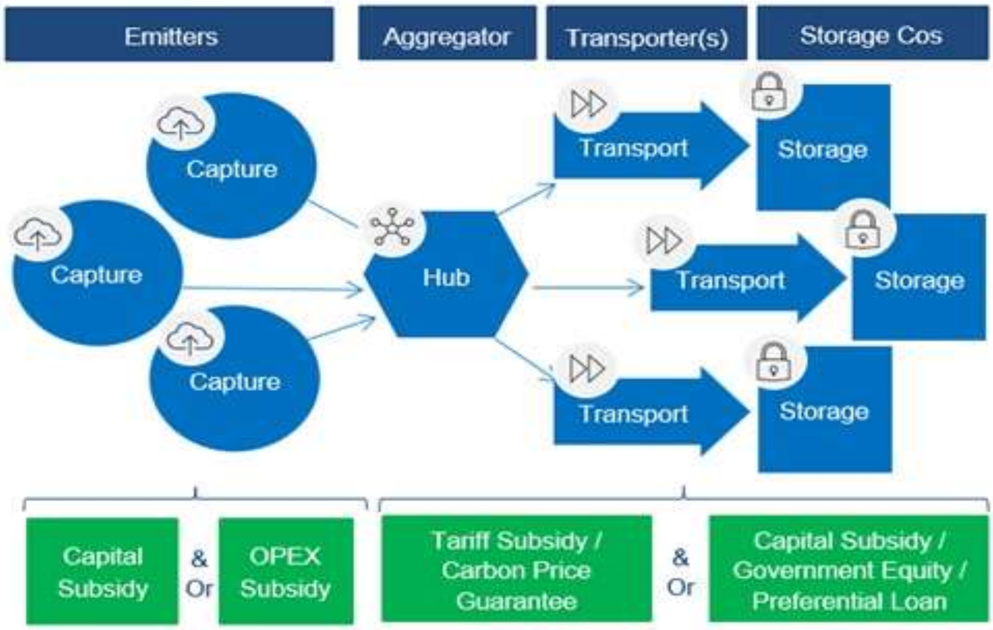
Partial Chain Model – Offshore CO_2 Transport

The main feature of this model is the separation of the collection hub from the transportation element (see Figure 6). It is most commonly applied where domestic emissions are collected for transboundary export and sequestration, necessitating a separate entity to own and operate the shipment of CO_2. In this regard, the value chain is split into four separate components: 1) Emitter, 2) Aggregator, 3) Transport and 4) Storage. The Aggregator designs, builds and operates the aggregation infrastructure and integrates the

[56] In the UK, T&S fees are regulated through the economic regulator, Ofgem.

CCS value chain as well as negotiates offtake agreements with emitter(s), transporter(s) and storage operator(s).

Figure 6: Partial Chain Model – Offshore CO_2 Transport Concept



This model is exposed to significant coordination risk as many stakeholders are involved including multiple emitters, transporters and storage providers. However, the model possesses an inherent flexibility for expansion. The aggregation element of the model will have to be regulated to avoid monopolization of the infrastructure and overcharging for CO_2 disposal services. With regards to pipeline transportation and storage of the captured CO_2, the collection and transportation segments of the value chain would not be split.

As was the case in the single hub concept model, direct subsidy will be required for both the emitters' CAPEX and OPEX to bridge the investment case to build a capture plant and a subsidy for the OPEX element to bridge the funding for the aggregation and T&S charges. A government subsidy or equity investment in the aggregation infrastructure will assist the aggregator in sharing the financial project risk and therefore reduce the aggregator's WACC which effectively results in a reduction in the aggregation tariff. In addition, the government may take equity in the project in return for capital contribution in the aggregation infrastructure and therefore gains insight into project development and participates in the decision-making process.

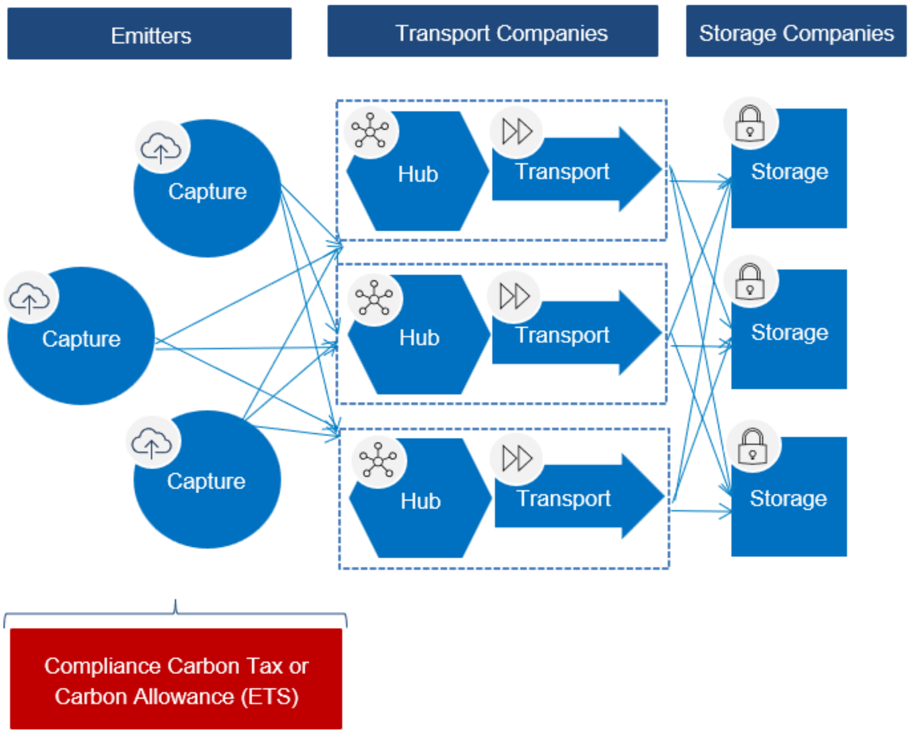
An example of a project utilizing this model is the Altera Stella Maris CCS Project in Norway. The project, led by Altera Infrastructure, is planned to be a large-scale, flexible, scalable maritime logistics solution for captured CO_2 from industrial sources. The ambition of Stella Maris CCS is to provide cost efficient floating CCS infrastructure solutions for a global market. However, the initial plan aims to collect, transport, inject and store 10 million tonnes per annum of CO_2 using collection hubs and large CO_2 carriers for transport to permanent storage sites in the North Sea.

Partial Chain Model – Free Market

This model, in principle, would promote open competition between the operators to provide T&S services, enabling the emitters to choose between a variety of T&S service offerings (see Figure 7). Ultimately, it may be the case that emitters are able to negotiate disposal of CO_2 on a cargo basis in contrast to the situation today where it is necessary to sign long-term agreements.

In such a model, there is significant coordination risk and complexity in terms of commercial and financing arrangements due to the presence of multiple emitters. Each emitter is required to negotiate with the storage operator for T&S services and the storage operator negotiates separate transportation agreement with the pipeline operator. In addition, there is limited or no government subsidy to build the infrastructure while a subsidy or incentive is provided to the emitter and dispersed to the storage and transportation entities via T&S tariffs. Moreover, the T&S infrastructure would most likely be regulated for environmental compliance, but the owners and operators would potentially have full commercial freedom to offer assets or capacity as required. There is potential for monopolization of the existing pipeline or corridors, which would need to be assessed by the authorities if it becomes a significant issue.

Figure 7: Partial Chain Model – Free Market



Examples of the 'Partial Chain– Free Market' model are highlighted below in Table 5. All the examples are from the US market which fulfil many, but not all, of the model characteristics and is currently the closest to achieving this type of market structure. The Appendix provides an overview of three different US companies deploying slightly modified versions of this model in interesting ways.

Table 5: Examples of Partial Chain - Free Market projects

Project Name	Partners	Operation	Announced capacity (high) (Mt CO_2/yr)	Carbon Sink
Midwest Carbon Express (NE, SD, ND, MI, IA)	Summit carbon solutions (SK E&S 10%)	2024	12	Dedicated storage
Denbury Ascension Parish sequestration (LA)	Denbury Carbon Solutions (Acquired by Exxon)	2025	12	Dedicated storage
ExxonMobil Vermilion parish storage (LA)	ExxonMobil	2025	2	Dedicated storage
Central Louisiana Regional Carbon Storage (CENLA) Hub (LA)	CapturePoint Solutions, Energy transfer	2027	10	Dedicated storage
Gulf Coast Sequestration Hub Lake Charles (LA)	Gulf Coast Sequestration	2030	2.7	Dedicated storage

Conclusions

CCS is a key mitigation technology for the global energy system to reach its net zero target and is one of the decarbonization pillars identified by the IEA (in addition to energy efficiency, behavioral changes, electrification, renewables, hydrogen and hydrogen-based fuels, and bioenergy). Despite the role that it is expected to play in the transition, scaling up CCS has proven challenging, and its contribution to meeting climate targets has been limited so far. This has caused some to argue that CCS represents a 'fairytale solution'[57].

However, as shown in this paper, there has been considerable progress in the design of government support mechanisms, market instruments and legal and regulatory approaches that could help the private sector manage some key risks and enable viable business models that are necessary for scaling up CCS. This has already resulted in the number of CCS projects in the pipeline rising fast with 198 new CCS facilities added to the project pipeline since 2022[58]. What is also becoming clear is that there is no one CCS business model that fits all projects or sectors. Instead, there is an emergence of various business models with different degrees of integration in the supply chain, including varying degrees of government support, multiple support mechanisms, and various mixes of ownership structures and public-private partnerships. These variations are to be expected given the wide differences across countries in terms of resource endowments, industrial structures and energy sectors, dominance (or lack thereof) of a national company, the importance of CCS in meeting government's climate objectives, the health of public finances, public acceptance of CCS, and whether a country has a system in place to price CO_2 emissions. Yet, business models are not static, and as policies, technologies, players' objectives, and the legal and regulatory environment evolve so will business models, and they may witness more convergence over time.

[57] See for instance, Stuti Mishra (2023), Too much focus on 'fairytale solutions' at Cop28 climate talks, warn activists, The Independent, December 10, 2023.
[58] Global CCS Institute (2023), Global status of CCS 2023. https://www.globalccsinstitute.com/wp-content/uploads/2023/11/GSR23-Executive-Summary_PDF.pdf

Appendix: Case studies

The case studies below provide an overview of three different US companies operating in the CCS space. They are all utilizing a modified version of the 'partial chain – free market' model. The three have been selected intentionally to highlight the interesting and nuanced ways in which each company is applying the model to different parts of the CCS value chain.

EnLink Midstream

EnLink Midstream provides integrated energy infrastructure services for natural gas, crude oil, condensate and NGLs. This includes gathering and transportation pipelines, processing plants, fractionators, barge and rail terminals, product storage facilities, and brine disposal wells. EnLink is actively developing CO_2 transportation in Louisiana with the aim of providing a fee-based services utilizing the existing connections to provide a link between CO_2 emission sources (emitters) and permanent sequestration sites (sequestration owner operators). EnLink is focused on Louisiana as the state has all the attributes necessary for large scale CCS, which include a high concentration of emissions, proximity to storage and existing pipeline infrastructure. EnLink is aiming to become the CO_2 transporter of choice through their operational expertise and have highlighted the following factors as advantageous in their quest to achieve their aim[59]:

- Focused on Transportation: Allows EnLink to provide transportation services on a non-preferential basis without competitive concerns and eliminates potential long-term liabilities associated with permanent sequestration.
- Familiar Commercial Model:
    - Fee-for-service, no commodity exposure.
    - Commercial contracts are very similar to midstream contracts (Reserved capacity, minimum volume commitments, long-term, service levels).
    - Eases path to commercialization when all parties are familiar with expected terms.
- Broad Customer Base: Sequestration site owners needing pipeline transportation from a contracted emissions source and Emissions sources needing pipeline transportation to contracted sequestration sites.

EnLink expects the CCS business to have benefits on their overall business plan by providing a long-term stable cash flow as the CO_2 output of industrial emitting facilities does not decline over time (unlike producing wells). EnLink expects first cash flows from their CCS business beginning in 2025.

Denbury

Denbury was recently acquired by ExxonMobil in November 2023 in an all-stock transaction valued at just under US$ 5 billion[60]. Until its acquisition, Denbury was an independent energy company with operations and assets focused on CCS and EOR in the Gulf Coast and Rocky Mountain regions in the US with over 20 years' experience utilizing CO_2 in its EOR operations. Since 2012, Denbury was also active in CCS through the transportation and storage of captured industrial-sourced CO_2. Denbury had over 1300 miles of CO_2 pipelines (largest owned and operated CO_2 pipeline network in the US) and have transported, injected and stored 4.3 million metric tons of industrial-sourced CO_2. Denbury highlighted three different commercial structures for CCS as shown below and expected CCS to be self-funding in 2026/2027.

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[59] EnLink Midstream Investor Presentation May 2023 (https://d1io3yog0oux5.cloudfront.net/_9b1b02cf1c8912bced979ae6306061e2/enlink/db/2227/21554/pdf/EnLink+Midstream+May+2023+Presentation_vF.pdf)

[60] https://corporate.exxonmobil.com/news/news-releases/2023/1102_exxonmobil-completes-acquisition-of-denbury#:~:text=SPRING%2C%20Texas%20%E2%80%93%20Exxon%20Mobil%20Corporation,price%20on%20July%2012%2C%202023.

Table A1: Denbury Business Model

Types of Emissions Agreements	Transportation ***Leverage Denbury pipeline system to move CO_2 to 3rd party storage***	Transportation & Storage ***Connect lateral to industrial customer; move CO_2 to Denbury owned and operated secure storage***	Capture, Transportation & Storage ***Turnkey operation for customers who prefer full-service solution***
% of anticipated Denbury volumes	5-10%	80-90%	5-10%
Agreements announced (Mtpa)	4	18.5	-
Anticipated avg revenue (US$/tonne)	US$5-15	US$15 – 25 (sequestration) $0 – 10 (EOR)	US$85 45Q (less market-priced fee paid to industrial customer)
Term length (years)	Up to 20	12 – 20	12+ (45Q term)
Capital intensity	Low	Medium	High

California Resources Corporation

California Resources Corporation (CRC) is an independent energy and carbon management company based in California. CarbonTerraVault Holdings (CTV), a joint venture between CRC and Brookfield, provides capture, transport and storage of CO_2 services. CTV is engaged in a series of CCS projects in California that inject CO_2 captured from industrial sources into depleted underground reservoirs and permanently store CO_2 deep underground. CRC is focused on California due to the fact that the US Environmental Detection Agency's (EPA) Permitted (Class VI) pore space is a scarce resource in the value chain in the state, in addition to the other elements highlighted in Figure 6[61]. The company has also laid out a variety of go-to-market business models in which it can operate in and highlighted in Table A2[62].

The models highlighted by CRC encompass the different levels of project integration and service provision, from the provision of CO_2 storage services only to the full end-to-end integrated value chain, requiring the most of CRC's capital investment. An example of CRC's joint venture business model is their CO_2 Management Agreement with Lone Cypress Services, an independent energy company specializing in development of hydrogen generation, waste-to-energy plant solutions and traditional oil and gas midstream facilities. Lone Cypress will construct a 65 tonnes/day blue hydrogen facility. The CTV JV will provide permanent sequestration for 205k Mtpa, including the lease of land for the blue hydrogen facility with commercial operations targeted to begin in late 2025. The CTV JV will receive an injection fee to be paid on a per tonne basis and the storage project and Lone Cypress hydrogen facility will be eligible for the federal Sequestration Tax Credit (Section 45Q) or Clean Hydrogen Production Tax Credit (Section 45V) and the California LCFS credits. As part of the agreement, the CTV JV has the right to participate in the blue hydrogen facility up to and including a majority equity stake.

[61] CRC December 2023 Presentation (https://s202.q4cdn.com/682408967/files/doc_events/2023/Dec/07/crc-december-presentation_final.pdf)
[62] CRC Investor Presentation, January 2022 (https://s202.q4cdn.com/682408967/files/doc_presentation/2022/01/CRC-Jan-2022-Investor-Presentation-Final.pdf)

Figure A1: CRC Business Model

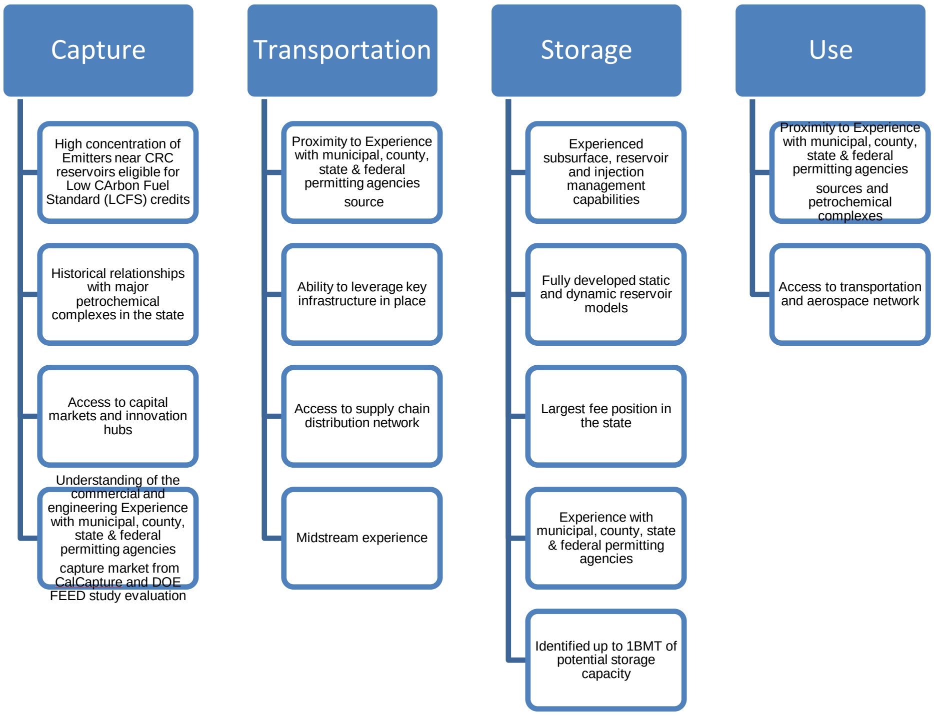

Table A2: CRC Business Model

Business Models	Emission	Capture	Conditioning (Liquifaction/ compression/ purification)	Transport	Storage
End-to-end value chain	CRC owns and operates emission assets	CRC manages & operates capture & conditioning Manufacturing/tech development, EPC & installation & facility start-up are outsourced		Transportation may or may not be necessary as some assets co-located	Carbon Terravault
CCS Service	3rd party owns and operates emission assets	CRC manages & operates capture, conditioning & transportation Manufacturing/tech development, EPC & installation & facility start-up are outsourced			Carbon Terravault
Joint Venture	3rd party owns and operates emission assets	CRC establishes JV with emissions producer and/or engineering firm to develop, manage & operate capture, conditioning & transportation processes			Carbon Terravault
Carbon Storage	3rd party owns and operates emission assets, capture, conditioning and transportation				Carbon Terravault