Advanced Carbon Capture for steel industries integrated in CCUS Clusters

Innovation action

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D6.5 Report describing short-listed business models in detail

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ERM's diverse team of 8,000+ world-class experts in over 150 offices in 40 countries and territories combine strategic transformation and technical delivery to help clients operationalize sustainability at pace and scale. ERM calls this capability its "boots to boardroom" approach - a comprehensive service model that helps organizations to accelerate the integration of sustainability into their strategy and operations.

The authors of this report sit within ERM's Sustainable Energy Solutions team which provides a wide range of services in industrial decarbonisation, including a profound understanding of techno-economic drivers of CCS adoption. Close collaboration with a wide range of industrial sites on their decarbonisation strategies has given ERM invaluable insight into the drivers and barriers to CCS uptake in heavy industry.

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Context

Introduction to C^4U

Funded by the European Union H2020 programme, the C^4U project aims to demonstrate two highly efficient solid based CO_2 capture technologies as well as considering the safety, environmental, societal, policy and business aspects for successful adoption of CCS in the North Sea Port industrial cluster.

This report is a deliverable of Work Package 6. The aim of this work package is to develop long-term business models to support the adoption of CCS through market, stakeholder, and scenario analysis. Knowledge gained from a wide variety of stakeholder insights has contributed into the development of viable business models for CCS adoption presented in this report.

WP6 deliverables

This report forms the final deliverable of Work Package 6. It brings together the learnings from earlier deliverables and uses these to assess various business model configurations, with the aim of identifying the most appropriate business models for CCS and further developing these concepts. The report focuses on the business model elements of revenue model, ownership structure, and capital financing / funding sources. Wider deliverables associated with WP6 and which have informed this work include:

- D6.1 - Literature review on CCS risks and challenges
- D6.2 - UK learnings and case studies
- D6.3 - Stakeholder engagement
- D6.4 - Business Model Innovation Framework and Scenario analysis

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Version log

Version	Date	Released by	Nature of Change
0.1	02/02/2024	ERM	Initial draft for external review
0.2	13/02/2024	Reviewer	Comments provided
0.3	20/03/2024	ERM	Comments addressed. Final draft submitted to UCL
0.4	16/07/2024	ERM	References re-formatted
1.0	19/07/2024	ERM	Final version

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Definition and acronyms

Acronyms	Definitions
CCUS	Carbon capture, (transport), utilisation and storage
CCS	Carbon capture, (transport), and storage
CO_2	Carbon Dioxide
EOR	Enhanced Oil Recovery
SAF	Sustainable Aviation Fuel
CfD	Contracts for Difference
ETS	Emissions Trading Scheme
SPV	Special Purpose Vehicle
PPP	Public-private partnership
T&S	CCS transport and storage infrastructure
T&SCo	Entity which operates the CCS transport and storage infrastructure
NEP	Northern Endurance Partnership
CCaaS	Carbon Capture as a Service
H-DRI	Hydrogen Direct Iron Reduction

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1 Importance Of Business Models in CCS Adoption

The goal of the Paris Agreement is to keep the **increase in global average temperature to well below 2°C** above pre-industrial levels and, in doing so, to pursue efforts to limit the increase to 1.5°C. In line with the EU's commitment to global climate action under the Paris Agreement, the EU aims to have **net-zero greenhouse gas emissions by 2050** through a socially fair transition in a cost-efficient manner.

Carbon capture, utilisation and/or storage (CCUS) refers to a suite of technologies that enable the mitigation of carbon dioxide (CO_2) emissions. The EU Commission's vision for a climate-neutral EU recognises that **CCUS deployment is necessary, especially in energy-intensive industries**.[1] It is predicted to play a key role in reaching net zero targets, particularly through the decarbonisation of hard-to-abate sectors, such as iron and steel. Furthermore, the EU's Net Zero Industry Act sets a target of 50 million tonnes (Mt) of annual CO_2 storage capacity by 2030, to facilitate and enable CCS projects.[2] The EU Commission's Industrial Carbon Strategy is expected to increase this target capacity to 200 $MtCO_2$ by 2040.

Whilst CCUS has been deployed since 1970s, mainly for the purpose of Enhanced Oil Recovery (EOR), **deployment solely for the purposes of emission reduction is limited**. One example of CCUS for emissions reduction is the Sleipner gas field, which is driven by the incentive to avoid Norwegian CO_2 taxes. Through this work package, the C^4U project has reviewed literature, conducted stakeholder engagement, collected information via attendance of conferences and industry events, and conducted analysis on the challenges of CCUS deployment and engaged with industrial stakeholders in the North Sea Port to understand why CCUS deployment for emissions reduction is limited.

Our findings from previous research revealed that technical challenges related to CCUS can be overcome, but **challenges in financing infrastructure, generating revenue,** and **allocating the risks associated with deployment** have hindered widespread deployment of CCUS for emissions reduction thus far.

To kick-start the CCUS market for emission reductions, support such as that available through the US Inflation Reduction Act and the EU Net Zero Industry Act may encourage first movers in the CCUS industry. In the longer term, **a self-sustaining CCUS market may be**

[1] European Commission Communication. (2018). A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773

[2] European Commission. The Net-Zero Industry Act. Internal Market, Industry, Entrepreneurship and SMEs. https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

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achieved through design and implementation of viable business models that generate revenue from CCUS, share risks equitably and provide financing for the upfront costs.

This report is **focused on business models for carbon capture and storage (CCS)**, rather than those which involve utilisation. How the proposed business models may differ for CCU is discussed separately. **Long-term CCS business models should be competitive with conventional industrial product value chains** to enable widespread CCS deployment. Given an effective business model, CCS also has the potential to create and safeguard millions of jobs, as well as raising productivity and competitiveness of industrial regions. The support of both the local public and the government may mitigate some risks associated with CCS adoption and increase uptake – these influences and their feedbacks are discussed further in other deliverables for the C⁴U project.[3]

What is a business model?

The definition of a business model varies greatly across publications. For the purpose of this deliverable, a business model is the method by which a particular business or entire industry creates and delivers value for its customers.[4] A viable business model is one that allows a business to charge a certain price for the value it is creating, such that the business brings in enough money to continue operating and make a profit. For a product-focused business, the objective is to sell as many units of the product as possible for as high a price as a customer is willing to pay, maximising profitability. Innovative business models can support the adoption of sustainable practices and new technologies such as CCS.

Key players in CCS Business Models

To ensure a CCS business model is financially viable, industry, governments and many other stakeholders need to work together. One of the key challenges to developing the CCS infrastructure is that many different technologies, companies, and regulators are involved. Different parts of the value chain will likely be driven by companies and sectors that may not have worked together before.[5]

Figure 1 shows a simplified version of the value chain for low-carbon industrial production with CCS, distilled into a series of key players who will be required to collaborate to establish a business model for CCS. This value chain can be divided into different sections:

[3] Deliverables - C⁴U Project. (27 November 2023). C⁴U Project - Advancing Carbon Capture for the Steel Industry. https://c4u-project.eu/deliverables/

[4] 8 Types of Business Models & the Value They Deliver. (26 May 2016). Business Insights Blog. https://online.hbs.edu/blog/post/types-of-business-models

[5] Burrows, et al, CCS value chains and market development. https://www.dnv.com/focus-areas/ccs/ccs-value-chains-market-development.html

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1 **A product branch**, including the industrial plant, initial consumer, and final consumer, will determine **how revenue is generated** when manufacturing low-carbon products.
2 **A CO_2 branch**, including the industrial plant undertaking CCS, the capture plant, the transport infrastructure, and the storage (or utilisation) components of the value chain, which represent the **infrastructure to be owned and operated** for CCS.
3 A section for **the investors** who may provide capital funding for the CCS infrastructure developed.

CCS applicability will likely be much broader than the case presented below, which focuses on industrial plants from a simplified perspective. Deployment of CCS for power generation decarbonisation, ccs-enabled hydrogen production, or carbon removals may include similar stakeholders as for industrial capture, albeit with some key differences (e.g., hydrogen offtakers, buyers of carbon credits).

The key components of the sections alongside the expected motivations of influential players are discussed in greater detail below.

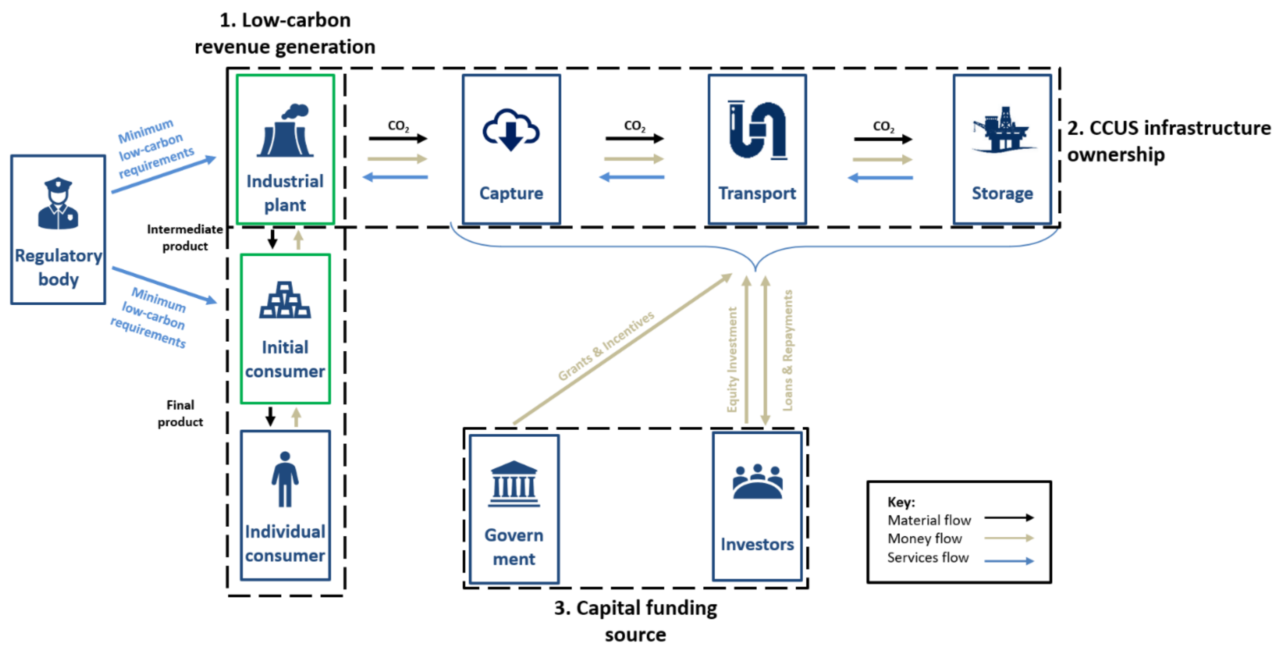

Figure 1: A simplified value chain map for low-carbon industrial production with CCS.

Industrial plant

Products are manufactured at industrial plants and then subsequently sold to generate revenue. The sites themselves are often complex with several buildings containing machinery and other equipment required to manufacture the product. During the manufacturing process, CO_2 is emitted, typically in large quantities, such that decarbonisation processes such as CCS will be required to reach net

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zero. For a CCS business model to be acceptable to the industrial plant, stakeholder engagement found that the following factors should be considered:

- **Revenue incentive** – there should be a financial incentive to justify the additional cost of CCS compared to continued emission. Business models need to provide a guaranteed return on investment, financial support, or increased certainty of demand.
- **Industry competitiveness** – the industrial plant manufacturing zero-carbon products needs to maintain its competitiveness with other industrial plants manufacturing the unabated product.

Capture plant

The capture plant will offtake CO_2 from a process stream (pre-combustion or post-combustion) of the industrial plant, and capture and compress it. This capture plant will likely be located on the same site as the industrial plant and could potentially be owned by the same entity as the industrial plant itself, but this is not essential. The capture plant will be supported by material providers, who will provide items such as sorbents, solvents, and other chemicals. They in turn will rely on IP from technology developers who will develop the carbon capture technology and will be supported by others contributing technologies such as compressor developers and R&D organisations such as universities. From stakeholder engagement and literature reviews, it was concluded that for a CCS business model to be acceptable to the capture plant operator the following factors should be considered:

- **Capital availability** – installation of carbon capture needs to be facilitated by access to grants or low-cost financing to cover the high initial capital costs.
- **Operational cost uncertainties** – the costs of carbon capture and competitiveness within the sector are impacted by uncertainties in OPEX, and energy prices. The level of incentive provided by the business model should account for these uncertainties by, for example, linking directly to incurred costs or using 'pain-gain' risk sharing[6].

CO_2 transport

The CO_2 transport operator will move the compressed CO_2 from the capture plant to the storage or utilisation facility. Pipelines are likely to be the most common way of transporting the large quantities of CO_2 involved in CCS.[7] However, shipping, trucking and rail are also alternative options. A business

[6] Pain-gain risk sharing is an agreement between two parties in which one party agrees to shoulder some of the other party's pain in exchange for a share of any gains that may result.

[7] Fact sheet: Transporting CO2. www.globalccsinstitute.com. https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Transporting-CO2-1.pdf

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model should consider the following factors to ensure that it is acceptable to CO_2 transport operators:

- **Capital availability** – the construction of large pipeline networks and/or specialised ships/trucks/railway carriages will require access to grants or low-cost financing for the initial capital costs.
- **Guaranteed return on investment** – there needs to be a steady and predictable supply of CO_2 to cover costs associated with the transport facilities, both to justify upfront capital costs and to cover operating costs.
- **Future market demand** – the scale of CO_2 transport infrastructure could potentially be oversized to meet future market demand. A business model which considers demand certainty may be important to CO_2 transport operators.

CO_2 storage (or utilisation)

Geological CO_2 storage operators will work together with the industrial plant, capture plant and transport operators to sequester the CO_2 in the subsurface over long-time scales. Alternatively, the CO_2 could be used for utilisation. These companies may be regulated by a variety of environmental agencies, permitting bodies and planning authorities. Their major source of revenue will likely be from the industrial plant paying for the offtake of CO_2, except for any revenue generated through CCU. A business model which is acceptable to CO_2 storage and utilisation companies will require:

- **Capital availability** – drilling of wells for CO_2 storage or building of new facilities to utilise the CO_2 will require access to grants or low-cost financing for the initial capital costs.
- **Guaranteed return on investment** – there needs to be a steady and predictable supply of CO_2 to cover the OPEX costs associated with geological CO_2 storage or CO_2 utilisation.
- **Mitigation of liability for leakage** – there needs to be insurance available, particularly for geological CO_2 storage operators, in case of CO_2 leakage.

Investors

Investors in CCS may include national/regional governments (via taxpayers), investment banks, infrastructure funds, and private equity. These players will provide funds to certain parts of the value chain, potentially in the form of grants, incentives, equity, or debt. However, investors may also perceive early-stage CCS projects as high risk and therefore expect large returns on their investment. Low returns may attract other types of investors, such as pension funds, but any business model should ideally be designed to maximise returns and attract the widest possible range of investors. For the business model to be acceptable to investors it must include:

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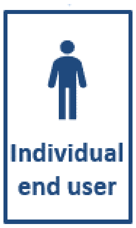
- **Consumer interest** – investors require a return on their investment, so any business model must create and sustain a guaranteed market for CCS, ideally with a large consumer base for low-carbon products. This should lower the perceived risk to investors.
- **Future revenue growth** – as the CCS market grows, there may be potential for higher returns-on-investment in the future – this incentive should further encourage the investor to invest.
- **Transparency** – investors will be more inclined to invest in a market they know and understand. A successful business model for CCS will give confidence to investors and outline a clear investment structure, highlighting where revenue will be generated.

Initial consumer

The initial consumer of the product output by the industrial plant will transform the basic product into something required by an individual end user. For example, in the iron and steel industry, the initial consumer may transform the steel into a car or rolled steel joists for use in building work. For a business model to be acceptable to initial consumers it must include:

- **Green premium incentive** – there should be an incentive to pay if there is a difference in cost between the decarbonised and the unabated product. If there are no additional costs, there does not need to be an additional incentive for consumers to pay the green premium.
- **Technical specifications** – the final product should be able to meet the same expected market standards as products provided through the unabated route.



Individual end user

An individual person/business will be final the end user of the product. For example, in the iron and steel industry, the end user would be the individual who purchases a car, or the owner of a building. For a business model to be acceptable to the end user it must include:

- **Green premium incentive** – there should be an incentive to justify the additional cost of the low-carbon product compared to the cost of the unabated product if such a cost is present and is passed on to the individual end user.
- **Certification** – transparent certification will give the individual consumer confidence in the degree to which the product supply chain has been decarbonised.

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Regulatory body

A regulatory body is an authority that is responsible for licensing and regulating a certain sector. They are often set up to strengthen safety, standards and/or to protect consumers in certain sectors. The regulatory body may be a government authority but could alternatively be an industry-led initiative where members commit to certain standard set by the independent regulatory body. Within a business model, a regulatory body could set-up a regulated market for low-carbon products with certain rules, regulations and standards which need to be met. For a business model to be a success from the perspective of the regulatory body, it will depend on factors such as:

- **Security of the regulatory support** – political or industrial support for a regulated market may vary depending on the vulnerability of the regulatory support to external factors.
- **Size of the regulated market** – the larger the regulated market for low-carbon products that the regulatory body oversees, the larger the customer base is which is covered by the low-carbon requirements.

Government

Governments, including local, regional, national, and multi-international (e.g., EU), may have two potential roles in the business model. The first is as an end user of the final product (e.g., buying fleets of cars or construction of multiple buildings), for which the drivers to CCS acceptability will be similar to those of the individual consumer above. The second is as a provider of grants and incentives to infrastructure within the CCS value chain. This policy support would provide a level of certainty and protect investors from market volatility through government loan guarantees or the use of strike prices. For the business model to also be acceptable to the government the above factors should be balanced with the following considerations:

- **Cost efficiency** – Government support mechanisms should incentivise both efficient operations and cost reductions, to ensure the lowest cost to the taxpayer.
- **Cost pass on** – In the long term, it is advantageous if costs can be passed on to another party (such as individual consumers or other industrial plants), allowing government subsidies to be removed and leaving a self-supporting market.
- **Implementation** – The existence of similar frameworks and the track record of these should be considered. Ideally, business models should be simple and quick to implement, without being significantly slowed by legislative requirements. Any ongoing administrative complexity for governments should be minimised.

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Drivers and barriers to CCS adoption

Stakeholder engagement with players in the North Sea Port region highlighted specific key drivers and barriers for CCS adoption. Key factors that could act as drivers or barriers include (but are not limited to):

- **Value chain integration** – CCS value chains may involve complex relationships among stakeholders. Long-term cooperation and transparent communication among industries will likely be instrumental in ensuring effective emissions reductions at a reasonable cost.
- **Enabling infrastructure** – The high capital cost associated with the infrastructure for CCS projects requires a massive influx of funding to ensure their success. Difficulties may arise from raising the required amount of capital (billions of dollars), particularly for first-of-a-kind projects with large associated risks but there may be the potential for significant reward for early adopters.
- **Certainty and longevity of the business model** – A longer-term business model will likely encourage CCS adoption in industry but the availability of funding for particular business models may vary through time.

Key drivers include:

- **Demand for low-carbon products** – CCS adoption will be driven by demand from the public, both as taxpayers and consumers. Education around the issues associated with CO_2 emissions is a key driver to increasing demand for CCS through increasing political, societal, and corporate willingness to act against climate change.
- **Increasing financial incentive for capturing emissions** - for example through the EU ETS, particularly alongside the SDE++ policy in the Netherlands.
- **Increasing political, societal, and corporate willingness** to act against climate change.
- **Regulations** such as circularity requirements of waste plants and requirements for moving towards low carbon aviation and maritime fuels.
- **Proximity to North Sea storage resources**

Similarly, key barriers may include:

- **Economic challenges** – The lack of market-based incentive instruments may increase the difficulty of commercial deployment of CCS. A strong revenue model is required, particularly to cover high initial CAPEX costs.
- **Policy / regulatory uncertainty** – The CCS industry has a long investment cycle and faces high risks and uncertainties around policy incentives, which may be fatal for such a policy-oriented industry, especially at its initial stage.

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- **Technical challenges** – Uncertainties concerning CCS technologies (e.g., efficiency of carbon capture, safety of CO_2 transport and security of CO_2 storage in the subsurface) may impact the willingness of governments and the general public to pay.
- **Legal challenges** – As CCS is a nascent industry, the legal structure and liability distribution around uncertainties such as leakage will need to be developed to enable CCS adoption.
- **Negative public perception** - whereby carbon capture is perceived to allow businesses to continue using fossil fuels.
- **Extended timelines** for permitting and setting bilateral agreements, especially in densely populated areas and in cluster models involving many stakeholders.
- **Uncertainty and knowledge gaps** for industrial plants on CO_2 transport and storage processes.
- Prohibitively **high costs** of CCS.
- **Lack of regulations** around cross border transport of CO_2 and standardisation of CCS and CCU products.
- **Inherent dependence upon other emerging businesses** along the value chain.

Awareness of potential risks from these drivers and barriers is crucial when designing a business model for CCS projects. The risks associated with the business case of a CCS project can be mitigated by the development of revenue streams, ownership structures, and funding mechanisms that will accommodate these risks. Business models may need to accommodate factors such as market variability, plant downtime, cost overruns, uncertain time scales, and future system expansions. The extent to which each of these potential risk factors may have an impact on CCS projects is dependent on the business models used for CCS adoption.

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Case studies of planned and operational CCS projects:

Project	Country	Revenue model	Ownership structure	Capital financing	Status
Longship CCS[8]	Norway	Avoidance of Norwegian CO_2 tax and EU-ETS CO_2 price	Independent Transport and Storage Entity	Public equity funding from Connecting Europe Facility scheme[9] and Norwegian government[10]	Construction has begun
Lake Charles Methanol[11]	USA (Louisiana)	Sale of CO_2 for EOR to Denbury	Vertically integrated	Debt funding from the Department of Energy[12] and private loans	Construction to begin in Q2 2024
Boundary Dam[13]	Canada	Sold for EOR	Vertically integrated	Public funding and industrial plant equity[13]	CO_2 has been captured and stored
Porthos[14]	Netherlands (Rotterdam)	Fee charged for the cost of T&S.	Independent Transport and Storage Entity	National/EU government funding[15]	No final investment decision yet
HyNet[16]	UK (Merseyside)	Sale of hydrogen & government CfD	Independent Transport and Storage Entity	Public funding from UK's Cluster Sequencing[17]	No final investment decision yet
East Coast Cluster[18]	UK (Humber/ Teesside)	Sale of hydrogen & government CfD	Independent Transport and Storage Entity	Public funding from UK's Cluster Sequencing	No final investment decision yet
ADM Ethanol, Decatur[19]	Illinois, USA	Negative emissions credits	Vertically Integrated	$141.5 million from the US DOE (68%)	Operational (>10 years)

[8] CCS Norway - Sharing knowledge from the Norwegian CCS project Longship. (4 July 2024). https://ccsnorway.com/
[9] Northern Lights – EU funding awarded: Northern lights role to support Europe achieve its climate policy objective confirmed. https://norlights.com/news/eu-funding-awarded-nl-to-support-europe/
[10] Helgesen, O. K. (4 January 2021). Norway greenlights $1.2bn funding for Northern Lights carbon transport and storage scheme. Upstream. https://www.upstreamonline.com/energy-transition/norway-greenlights-1-2bn-funding-for-northern-lights-carbon-transport-and-storage-scheme/2-1-931379?zephr_sso_ott=fvqB3A
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2 Components Of CCS Business Models

This study is focused on the development of business models from the perspective of an industrial plant looking to deploy CCS. Business models may consist of many elements which dictate the terms of the agreement and the financial arrangements between the industrial plant, its customers, and the downstream CCS value chain. Key elements for business model adoption for an industrial plant looking to adopt CCS were identified. A viable CCS business model should consist of:

1. A **revenue model** that describes where the income generated to cover the costs of capture, transport, and storage ultimately comes from (e.g., taxpayers, consumers). The aim of the revenue model is to incentivise CCS adoption through the creation of a long-term value proposition.
2. An **ownership structure** that describes which player is responsible for each of the key parts of the CCS value chain. Within the ownership structure, mechanisms will be required to mitigate risks and allocate them between parties.
3. **Capital financing**, which is required to fund the construction of CCS infrastructure. Often, the industrial plant will have insufficient capital and/or credit rating, so may require support from investors/lenders.

Revenue Models

An effective revenue model will provide a value proposition that incentivizes low-carbon production methods through CCS. This study examines three different revenue models (presented below) to describe different routes to establish a market for low-carbon products (e.g., with CCS) alongside a current market for carbon-intensive products. These examples are focused on revenue generation from an individual end user of the decarbonized product and are not exhaustive. A final viable business model may potentially include a combination of each of these revenue models. Key criteria for generating sufficient revenue for the industrial plant to cover the costs of deploying CCS are outlined below:[20]

- **Cost neutrality** – the industrial plant should not be worse off for having implemented CCS relative to industrial plants who have not yet implemented CCS.
- **Continuous decarbonised operations** – Each revenue model should continue to generate revenue across the whole project lifetime. There should also be a desire by the industrial plant to operate efficiently, driving costs of decarbonisation down.

The three revenue models presented here describe different routes that could help establish a market for low-carbon products (e.g., with CCS) alongside carbon-intensive products.

[20] Industrial carbon capture business models. Final Report. Dusurut, E., & Mattos, A. (2018). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759286/BEIS_CCS_business_models.pdf

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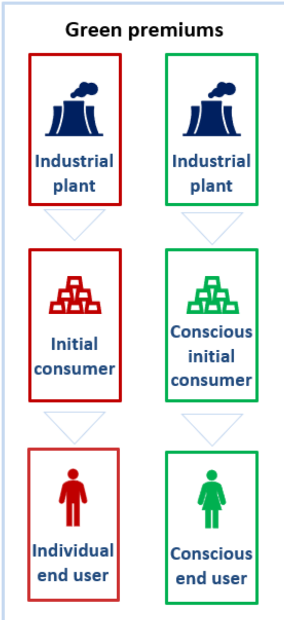

Green Premiums

Revenue is generated to cover the additional costs of CCS because both initial consumers and end users are **willing to pay more** (a premium) for the low-carbon product rather than the unabated alternative. Higher willingness to pay could be driven by several reasons, including climate change consciousness, corporate responsibility, reputational reasons, or ability to absorb a premium. This premium should be designed to cover the additional costs associated with undertaking CCS. For example, typical premiums expected by retrofitting CCS to iron and steel production are an increase in total cost of around €113 per tonne of crude steel (11-14% more than typical European steel prices). [21,22]

This revenue model may be **strongly influenced by the level of societal support for low-carbon products**. Generally, a smaller green premium (lower overall cost) should be accompanied by a higher willingness/ability to pay and drive higher demand. Conversely, the revenue stream may be **vulnerable to fluctuations in the cost of CCS.** This risk could be mitigated by establishing long-term offtake agreements with key consumers to provide certainty of revenue.[23]

This revenue model can be **supported by low-carbon certification**. Through certification, end users can trust that they are paying for a genuinely decarbonised product. However, for certification to be effective, it needs to be transparent, easily traced by consumers and cannot be short-circuited by other fake certificates. In addition, the standards for certification must be credible and able to be obtained globally. Cost neutrality is reached by passing on additional costs of CCS to the conscious consumer. The incentive to efficient operation is supplied by the desire for a greater number of conscious consumers, by reducing the green premium.

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[21] Aliyu, A. (31 May 2024). Clean Steel: Environmental and Technoeconomic Outlook of a Disruptive Technology - IEAGHG. IEAGHG.https://ieaghg.org/news/clean-steel-environmental-and-technoeconomic-outlook-of-a-disruptive-technology/

[22] MEPS Europe Steel Prices MEPS Europe Steel Prices | EU Historical Steel Prices. MEPS International Ltd. https://mepsinternational.com/gb/en/products/europe-steel-prices

[23] Green Steel Demand is Rising Faster Than Production Can Ramp Up (26 June 2023). https://about.bnef.com/blog/green-steel-demand-is-rising-faster-than-production-can-ramp-up/

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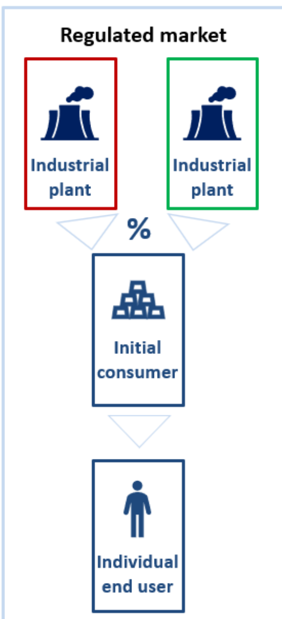
Case Study: SteelZero Initiative[24]

- SteelZero is a voluntary global initiative to expand the customer base of green steel (certified via the ResponsibleSteel International Standard[25]).
- Members make a public commitment to voluntarily buy 50% low-emission steel by 2030 and set a pathway to 100% net zero steel procurement by 2050.
- The initiative aims to raise public awareness about sustainable steel production, facilitate sharing of best practices among businesses and governments.

Regulated Market



In this revenue model, a regulating body (e.g., governments, trade bodies) specifies **minimum low-carbon requirements when awarding procurement contracts or legally mandates the use of certain amounts of low-carbon products**, either at a sectoral level or by individual companies. This regulating body will lead the way and encourage decarbonisation of industrial production lines in high-impact sectors such as iron and steel.

The success of this revenue model may depend on factors such as the political **security of the regulatory support**, which in turn may depend on societal support for CCS. It may also depend on the size of the regulated market covered by the low-carbon requirements, whether their customer base is guaranteed.

This model will generate revenue from low-carbon products by limiting cost-based competition with the unabated option, based on procurement mandates. Cost neutrality is therefore achieved by passing on the additional costs of CCS to the consumer in the regulated market. Efficient operation is incentivised by competitive bids for contracts.

[24] Building demand for net zero steel. Climate Group. https://www.theclimategroup.org/steelzero?gclid=CjwKCAiAkp6tBhB5EiwANTCx1Dv8JcCdHgcqh1aSt500cEGWeydSICPmcEF2Eg7BZCzCpEdm-qwtVxoC0BoQAvD_BwEvvvvv

[25] ResponsibleSteel International Standard. challenge.greenhouse.tech. https://challenge.greenhouse.tech/nearzerosteel2030/responsible-steel-standard

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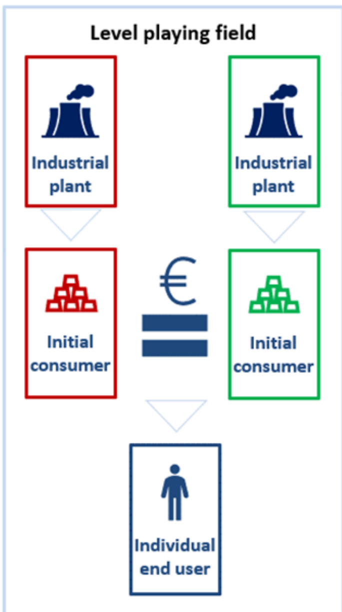
Case Study: ReFuelEU Aviation - Sustainable Aviation Fuels (SAF) mandate[26]

- There are minimum shares of SAF that must be supplied within the EU.
- This mandate applies in 5-year steps from 2% in 2025, to 63% by 2050 to gradually increase the share of SAF used in the aviation sector.
- This mandate provides a dedicated market for SAF producers in which their products only compete with other SAF suppliers' products, allowing them to pass on costs to consumers and generate revenue within the SAF market.



Level Playing Field

In the level playing field revenue model, **low-carbon products are cost competitive with the counterfactual carbon-intensive unabated options**. To ensure this cost competitiveness a variety of revenue incentives could be used/combined including:

1. **Subsidisation of the low-carbon product** where the additional costs may be borne by the government (or other subsidising body)
2. **Taxation of the unabated product** such that both products generate the same amount of net revenue and costs are passed onto the consumer of the high carbon product.

In either case, competitiveness is retained as there will be no price difference between the abated and unabated products for the initial consumer and/or end user. The incentive for efficient operation arises from competition with other industrial plants producing similar products, who may receive different revenue incentives.

[26] European Green Deal: new law agreed to cut aviation emissions by promoting sustainable aviation fuels. (23 April 2023). European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_2389

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Case Study (CO_2 pricing): The EU-ETS

- The EU ETS is a "cap and trade" system designed to gradually increase the cost of emitting CO_2 and incentivise cost-effective emissions reductions.
- An upper limit is specified for the annual CO_2 emissions of individual entities, in the form of "emission allowances" (one allowance = 1 tonne CO_2e).
- Emitters that exceed their allotted allowances must face a fine, or purchase allowances from another emitter. Conversely, emitters below their allowance limit can sell allowances to others.
- The emission limit is set to decrease every year (linearly at 2.2% for 2021-2030) such that the total number of emissions allowances, and therefore overall emissions, falls over time.
- In line with this, the price of allowances (and therefore the cost of emitting) is projected to increase over time, based on supply and demand.

Case Study (low-carbon technology subsidy): The SDE++ in the Netherlands

- The SDE++ subsidy works on a Contracts for Difference (CfD) model, where the difference between the CO_2 price (i.e., the ETS price) and cost of deploying CCS, is subsidized to cover CAPEX and OPEX over a 15-year lifetime.
- The aim of the SDE++ subsidy is to bridge the cost gap between production with and without CCS, thus levelling the playing field for the industrial plant receiving the revenue incentives.

Ownership Structures

Historically, oil and gas companies have been leaders in CCS development and ownership of the value chain. They own five of the eight dedicated CO_2 storage projects in operation and most of the existing CO_2 pipelines.[27] However, specialised players are emerging from the constituent components of the CCS value chain, including:

1. **Existing companies** expanding their portfolio to CO_2 management, for example:
    a. Gas infrastructure developers building and retrofitting CO_2 pipelines,
    b. Liquefied natural gas shipping companies expanding into CO_2 shipping,
    c. Chemical companies developing proprietary capture technologies for their own facilities and third parties and,
    d. Engineering companies also developing capture solutions with modular capture units.

[27] How new business models are boosting momentum on CCUS – Analysis. (24 March 2023). IEA. https://www.iea.org/commentaries/how-new-business-models-are-boosting-momentum-on-ccus

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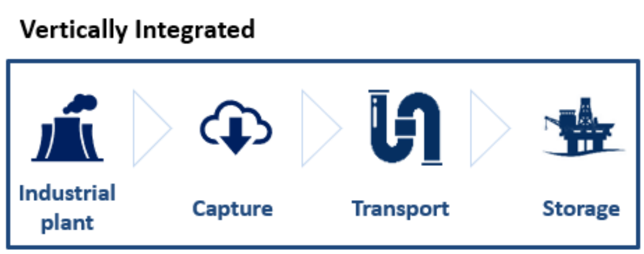
2. **New companies** specialising in certain parts of the value chain, for example by:
    a. Offering capture-as-a-service to industrial plants as developers, owners, or operators,
    b. Providing CO_2 transport and storage infrastructure solutions.

This diversity in specialised players is leading to the development of a wide range of viable ownership structures for CCS. Within the ownership structure each component could be private (e.g. via a Special Purpose Vehicle, SPV), a public-private partnership (PPP) or public.

However, CCS deployment can be hindered by the significant risks associated with being first movers in a nascent industry. To develop a viable business model for CCS, it is therefore paramount that risk is carefully managed.

For each entity in the value chain, the risk of undertaking CCS will depend on the proportion of the value chain they are responsible for, and the agreements made between parties. Certain parts of the value chain may be associated with higher overall risks (e.g., a storage site with long-term risks associated with leakage). Underwriting of risks by governments, for example, could decrease the amount of risk a particular entity and/or the whole value chain will have to take on.

Three possible ownership structures (non-exhaustive) from the perspective of the industrial plant have been considered, with variation in what proportion of the downstream capture, transport and storage value chain that is owned by the same entity as the industrial plant. The exact ownership structure would depend on the capabilities of the different players involved in the project, strategic assets, ability to access capital, as well as the policy context (e.g., certain parts, particularly T&S infrastructure, may be designed as a regulated asset by policymakers).



Vertically Integrated

In this ownership structure, the entity which already owns the industrial plant or emission source, uses their in-house technical and commercial capabilities to support all elements of the CCS infrastructure chain. The entity operates the capture and storage/utilisation site as well as having a means to transport the CO_2.

In this ownership structure all the upfront capital investment will arise from one single entity and/or their investors. The **single entity is responsible for all risks along the value chain**. It is assumed that in the vertically integrated ownership structure, the industrial plant has liability for the CO_2 from capture/compression, through the transportation stage until it is permanently stored. The cost to the industrial plant of implementing the vertically integrated

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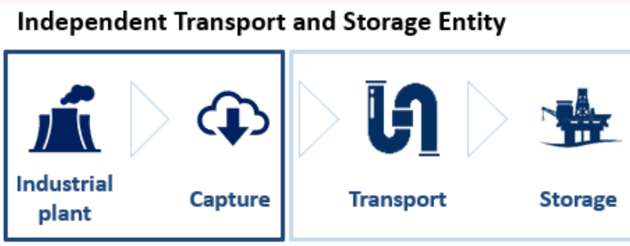
ownership structure should reduce reliance on external services and vulnerability to price variations of service providers which may have a monopoly. However, this type of model is not very often encountered as very rarely one company has capabilities to cover the full value chain.

Case Study: Sleipner, Norway[28]

- Since 1996, the Sleipner field has been used as a facility for carbon capture and storage by Equinor (operator) and a group of partnering companies.
- Each year about 1 million tonnes of CO_2 is captured from the natural gas extracted at the Sleipner field and then stored at the same site, but in a different geological layer (the Utsira formation).



Independent Transport & Storage Entity (T&Sco)

The Independent Transport and Storage Entity ownership structure is based on a partnership between the industrial plant (also liable for the capture plant) and an external entity who operates the transport and storage (T&S). There is a clear distinction between the two parts of the value chain – the responsibility and CO_2 liability of the industrial plant stops at the gate. Upfront capital investment is split between the industrial plant who fund the development of the capture plant, and the independent T&S entity. **Operational risk and upfront capital are shared between the two entities**.

In some cases, the profit requirements of a T&S entity may lead to service price markups compared to the costs of vertically integrated CCS development. However, it is likely - particularly as the industry matures - that **T&S companies can leverage economies of scale** by offering T&S services to multiple entities, lowering the overall CCS cost for the industrial plant. This is particularly true for industrial clusters where multiple industrial plants share land/infrastructure in close proximity. T&S companies may also require long-term contracts for CO_2 storage, tying in industrial plants to guaranteed volumes over the period of the contract.

The success of a project with this ownership structure **depends on successful coordination** between the two entities, including deployment/development timing, agreement of CO_2 purity and flow rate. A key risk that may impact the success of the project is stakeholder withdrawal.

[28] Sleipner partnership releases CO2 storage data - equinor.com. (12 June 2019). https://www.equinor.com/news/archive/2019-06-12-sleipner-co2-storage-data

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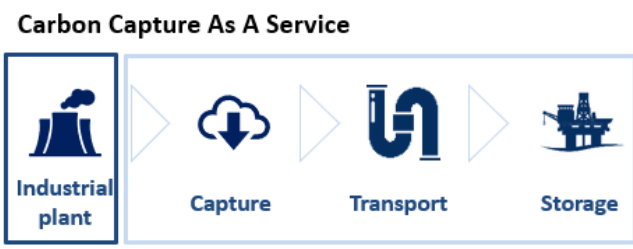
It could also be the case that the transport and storage components of the value chain are independent from one another. From the perspective of the industrial plant, however, this ownership structure will operate in a similar way. Coordination between the industrial plant and T&Sco could be achieved both via private interactions (between the two parties) but also macro-level strategic planning by Government (e.g., UK Cluster Sequencing).

Case Study: Northern Endurance Partnership, UK[29]

- The Northern Endurance Partnership (NEP) was formed through a collaboration of bp, Equinor and TotalEnergies as a CO_2 T&SCo.[30]
- The NEP will collaborate in joint ventures to deliver the onshore and offshore infrastructure needed to transport CO_2 to the Endurance offshore storage site in the UK North Sea, where it will be permanently sequestered.
- It was selected as part of the priority cluster in Phase 1 of the UK Government's CCUS Cluster Sequencing process to decarbonise Teesside and the Humber.



Carbon Capture as a Service (CCaaS)

In the carbon capture as a service ownership structure, a **dedicated CO_2 handling entity** charges the industrial plant a fixed fee to capture, transport and store/utilise the CO_2 produced. This entity has dedicated technical and market expertise so is best placed to decide what the ultimate use for CO_2 is or whether it should be stored. In terms of both capital financing and operational risk, the majority is taken on by the entity providing carbon capture as a service. However, from the perspective of the industrial plant, there may be coordination risks with the CCaaS entity, particularly with deployment/development timing and the risk of stakeholder withdrawal. This ownership structure may also result in price mark-ups by the CCaaS entity which may have to be paid by the industrial plant.

The carbon capture as a service entity may choose to delegate part of the downstream value chain to a different entity, but from the perspective of the industrial plant a fixed fee would be paid to cover any of these downstream costs. This ownership structure might be the preferred model for dispersed sites, smaller sites, those without capital, or those without the technical expertise to operate a capture facility.

[29] Northern Endurance Partnership | Net Zero Teesside. (26 April 2023). Net Zero Teesside. https://www.netzeroteesside.co.uk/northern-endurance-partnership/

[30] Northern Endurance Partnership – changes to equity structure. (24 April 2023). https://eastcoastcluster.co.uk/press-release/northern-endurance-partnership-changes-to-equity-structure/

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Case Study: Aker Carbon Capture[31]

- Aker Carbon Capture aims to provide an easy carbon capture solution to an industrial plant (i.e. CO_2 emitter) who simply select the carbon capture service which best suits their needs and pay per tonne of CO_2 captured and stored.
- Aker promise to commission and operate the carbon capture plant as well as handling the transportation and storage value chain through strategic partnerships.
- Their service also allows for the growth of carbon capture through the addition of capture plants at the industrial facility.
- Agreements are put in place to handle changes and allow for flexibility in the system.

Capital Financing

Due to the large capital outlay associated with CCS infrastructure, and the limited ability of each part of the value chain to fund investments of this size and timescale, any CCS business model must account for the availability of capital to fund individual projects.

The capital financing options available to a project will depend on multiple factors such as: the scale of the project, its technology, the number of offtakers and where it is located. These factors together determine the trade-off between the perceived risk of the investment and the returns an investor may expect. Generally, if there is sufficient certainty of revenue and perceived risks are minimised, low-cost private capital financing will be readily available. However, if a CCS project has a very high level of perceived risk coupled with low returns, this is unlikely to be an investable condition and/or an investor may demand higher returns, so support may be required from public investors (e.g., governments). Factors influencing whether capital financing can be raised for a project are outlined below:

1. **Perceived risk vs expected return** – any capital expenditure on CCS should be well managed, provide value for money and ultimately minimise risks to the investor. If risks to the investor are minimised, capital financing is more likely to be available to the industrial plant for CCS deployment since the project is more likely to offer a high enough return for the risk being taken, in comparison to other investments.
2. **Revenue visibility** – investors require a return on their investment, or a lender requires interest repayments, so each will want to ensure that the CCS project will generate sufficient fixed revenue over its lifetime. If an industrial plant can show that long-term revenue can be generated by deploying CCS (e.g., through offtake contracts), more capital financing options should be available.

[31] Carbon Capture as a Service – Aker Carbon Capture. (2024, June 20). Aker Carbon Capture. https://akercarboncapture.com/offerings/carbon-capture-as-a-service/

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The four capital financing options (non-exhaustive) presented here describe different potential routes which could be followed to source the money required to be spent on CCS infrastructure. There are various other methods by which capital financing could be raised, but this study is limited to three broad and likely sources available for CCS financing. It is likely that multiple sources of capital financing will be collated to raise the necessary amounts needed to deploy CCS, the best combination of which is likely to depend on the security of revenue generation for the low-carbon product. For example, Sweden's H2 Green Steel has signed debt financing agreements for €4.2bn, raised nearly €300m in equity and secured a €250m EU Innovation Fund grant.[32] This was partially achieved by the project having a very low electricity price fixed through long-term PPAs, to power the electrolysers and steel production, thus enabling hydrogen-based steel production which is competitive with traditional steel production routes. This certainty in electricity price, combined with revenue certainty from offtake contracts provides revenue certainty to support the raising of capital funds.

Public Grants, Loans and Loan Guarantees

A government or other institution (e.g., development banks) may decide to offer grant funding, public loans, or loan guarantees to finance the large capital investment required for CCS.

- **Grant funding** = A sum of money awarded to an organisation to use for an agreed purpose. Often this money is non-repayable but may require match-funding from the industrial plant itself. Importantly, this option is unlikely to be sustainable in the long-term due to its reliance on taxpayers' money.
- **Public loans** = Money that is also awarded to an industrial plant for a particular CCS project, which is repayable, but often at a favourable interest rate. This option is unlikely to be sustainable for widespread CCS deployment as governments tend not to have access to as much capital as the private sector.
- **Loan guarantees** = Where a third-party (e.g., a government) promises to assume the debt obligation of the borrower, if that borrower defaults. A guarantee can be limited or unlimited, making the guarantor liable for only a portion or all of the debt.

From the perspective of the industrial plant, public funding often:

- Favourable loan rates, loan guarantees and/or potential for grants allow for a **lower cost of debt**.
- A **government may also take on some of the risk** associated with CCS.
- May allow the industrial plant to have full ownership of the CCS infrastructure.

[32] Currie, C., & View, H. (29 January 2024). H2 Green Steel signs €4.2bn debt financing agreements for Boden plant. H2 View. https://www.h2-view.com/story/h2-green-steel-signs-e4-2bn-debt-financing-agreements-for-boden-plant/2104900.article/?utm_source=dlvr.it&utm_medium=linkedin&utm_campaign=rss

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However, obtaining public financing may have drawbacks such as:

- A potentially **lengthy application process** with various hoops to jump through which may dictate operational requirements of the CCS infrastructure and/or the ownership structure through which CCS is delivered.
- **No guarantee that money will be issued**, even following a lengthy application process, particularly if there is political instability (e.g., a new government takes power).
- Governments must balance the cost of CCS with other government spending so **grants in particular are likely to have limited availability**, as they rely on taxpayers' money.
- Loans may also be limited in availability due to limited capital from the public sector.

Case Study: European Innovation Fund, European Commission[33]

- The European Innovation Fund offers grants to finance low-carbon technologies and aims to allocate over €38 billion by 2030.
- ANRAV-CCS was one of the CCS projects awarded a grant of €190 million to establish a complete CCS value chain in Eastern Europe from capture at the Devnya Cement Plant (Bulgaria) to storage in the Black Sea.

Private Equity Financing

Private financing can be in the form of an equity investment in the project for example through private equity firms or individual equity investors. The motivation for private equity finance is to achieve a financial gain from return via capital appreciation, dividend payments or the addition of shares, usually for an extended period, and increased asset value upon exit. Nascent industries are often a target for venture capital firms providing private equity in the hope that the industry will grow and generate large returns on investment.[34] From the perspective of the industrial plant, private equity finance is often:

- **Readily available** – if there are interested/willing investors, there should be no limit to the amount of capital available.
- Unlikely to have a lengthy application process compared to obtaining public funding, although a through due diligence process will likely be required. An industrial plant should not need to wait a significant amount of time to access the funding.
- Up to an individual/private firm whether to invest– costs do not have to be justified.

[33] Innovation Fund projects, European Commission, Energy, Climate change, Environment. https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/innovation-fund-projects_en

[34] From Solutions to Scale: Considerations and Insights for Investing in Nascent Climate Technologies. Yale Center for Business and the Environment. https://cbey.yale.edu/research/from-solutions-to-scale-considerations-and-insights-for-investing-in-nascent-climate

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- Has an **emphasis on economic viability and value creation** to generate returns.
- Comprised of a Joint Venture between two companies with capital which can bring complementary capabilities to the development of a CCS project.

However,

- Typically, **returns of 15-20% are expected for private investors** to compensate for the risk of investing.[35] Infrastructure investors may demand lower returns (i.e., 5-10%) as they typically invest in low-risk projects. The level of risk associated with CCS projects may limit the potential pool of investors, depending on the returns demanded.
- Since a **private equity investor would own a share of the company, they may seek to gain influence and/or control over the operations** of the entity they are investing in.

Case Study: Heineken and Siemens – Green Fertiliser production[36]

1. Siemens and Dutch Heineken have launched a joint venture to form new company (FertigHy) to decarbonise the European fertiliser industry.
2. Their plant in Spain will produce 1 Mt/yr fertilisers from green hydrogen and renewable energy
3. FertigHy has consortium of investors operating on both the supply and demand side– guaranteeing offtake of the green fertilisers.

Private Debt Financing (Private Loans)

Capital finance could be raised by the CCS project developers using debt financing (i.e., taking out a loan). This private financing through raising debt can be provided through a bank or another lender. Since the loan would likely be provided to the industrial plant itself or a special purpose vehicle (SPV) for the CCS project, the loan provider will likely investigate the entity's credit history. From the perspective of the industrial plant, taking out a loan:

- Can **provide certainty in the cost of raising capital** if a fixed rate loan is taken out.
- The entity will **keep control over the business** and will not be held accountable to investors or governments.
- Loan guarantees can be used to protect the entity in case it defaults on its payments.

[35] Return on equity ratio (ROE). (24 March 2023). BDC.ca. https://www.bdc.ca/en/articles-tools/entrepreneur-toolkit/financial-tools/return-on-shareholders-equity#:~:text=While%20average%20ratios%2C%20as%20well,ratio%20would%20be%20considered%20low.

[36] Martin, P. (4 July 2023). "Pioneer" | Heineken and Siemens launch joint venture to decarbonise EU fertiliser production with green hydrogen. Hydrogen Insight. https://www.hydrogeninsight.com/industrial/pioneer-heineken-and-siemens-launch-joint-venture-to-decarbonise-eu-fertiliser-production-with-green-hydrogen/2-1-1479482

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However,

- The entity will then have to **pay interest on the amount which they have borrowed**, so will need to generate enough revenue to cover the cost of the borrowing. Any changes in interest rate may significantly affect the cost of raising capital.
- Loans with **variable interest rates can fluctuate with market forces** but an industrial plant should look to minimise the impact of this with hedging strategies or fixed interest rate loan.
- Industrial plants **may have insufficient credit rating** to obtain debt financing.

Case Study: H2 Green Steel[37]

- H2 Green Steel plant in Boden, northern Sweden aims to produce steel powered by green hydrogen to reduce CO_2 emissions by 95%.
- The capital for the project is mostly from debt financing & private equity.[38]
- Debt financing agreements have been made with over 20 lenders for €4.2 billion. Export credit agencies are used to provide loan guarantees (80-95% of loan value) in the case that H2 Green Steel cannot pay back its debts.
- A diverse private equity pool has also raised €2.1 billion. Many of H2 Green Steel's equity investors are themselves consumers that have signed offtake agreements (i.e., they will buy a certain amount of the steel produced).[39] Combined with predictable costs via long-term PPAs for electricity, the risk to equity investors is lowered making a predictable, but lower, return on investment acceptable.
- €250 million grant from the EU Innovation Fund, funded by the EU-ETS, is also supporting

Industrial Plant Equity

The industrial plant may have some capital themselves which can be used to fund the CCS project. From the perspective of the industrial plant, using its own equity is:

- **More likely if it is a larger corporation operating in an industry with significant profit margins** as the magnitude of industrial plant equity is more likely to be on a scale of that required for CCS.
- Unlikely to have a lengthy application process, which should minimise the time which an industrial plant has to wait to access the funding.

[37] About us page, H2 Green Steel. H2 Green Steel, Norra Stationsgatan 93A 113 64 Stockholm. https://www.h2greensteel.com/about-us
[38] Steel, H. G. S. H. G. (22 January 2024). H2 Green Steel raises more than €4 billion in debt financing — H2 Green Steel. H2 Green Steel. https://www.h2greensteel.com/latestnews/h2-green-steel-raises-more-than-4-billion-in-debt-financing-for-the-worlds-first-large-scale-green-steel-plant
[39] Quinn, C., Bhat, S., & Salazar, A. (21 August 2023). Five Lessons for Industrial Project Finance from H2 Green Steel. RMI. https://rmi.org/five-lessons-for-industrial-project-finance-from-h2-green-steel/

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- Up to the industrial plant itself whether to invest or not – unlike government grants or private funding, costs do not have to be justified to the taxpayer/investor.
- The industrial plant will **keep control over the business** and will not be held accountable to investors/governments.

However,

- Often the **industrial plant has insufficient capital**, so may require additional support (e.g., through government grants, private funding) to fund the upfront costs of CCS alongside the equity of the industrial plant.
- Project returns will have to meet the minimum internal rate of return required by the industrial plant.

Differences in Business Model Components for CCU and GGRs

The focus of the development of the business model components has been in the case where CO_2 is permanently stored in the sub-surface (CCS). When utilisation of the captured CO_2 is considered, for example to manufacture low-carbon fuels, chemicals or building aggregates, the business model for this carbon capture and utilisation (CCU) may differ from those that are exclusively for CCS. Undertaking carbon capture for Greenhouse Gas Removals (GGRs), for example through Bioenergy with CCS (BECCS) may also require different business models compared to those for CCS.

One of the primary differences between a business model for CCS and one is that is for CCU or GGRs, is the potential for additional revenue stream (e.g., through the sale of low-carbon fuels or negative emission credits). This additional revenue stream means that the **revenue model** component for CCU or GGRs may differ from the CCS revenue models by:

- Reducing the amount that the playing-field needs to be levelled by due to the additional revenue from for example the sale of low-carbon fuels, or negative emissions credits.
- Providing a clearly defined market for regulation associated with certain CCU or GGR sectors (e.g. UK SAF mandate).
- Altering the potential viability of Green Premium based on the public perception of CCU and GGR projects, for example if carbon accounting is not clearly defined and disseminated.

Furthermore, the **ownership structure** may vary, particularly for projects involving CCU as the utilisation may take place on the same site as the industrial and capture plants, thus mitigating the need for CO_2 transport infrastructure. Storage will also not be required. However, for GGRs reliant on permanent geological sequestration, the ownership structures are likely to remain similar to those for CCS.

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In terms of **capital financing**, given the increased certainty of revenue generation, it is more likely that CCU and GGR projects will be able to generate a return on investment for private equity and/or be able to pay interest on private loans. Therefore, public funding for CCU and GGR business models may be less important, compared to the need for public funding for the CCS business models.

Case Study: Steelanol

- ArcelorMittal Ghent has developed a €200 million plant for trapping and using carbon from CO_2 as part of the Steelanol project.[40]
- Funding was obtained from various sources including:
    - The Flemish government
    - An InnovFin Energy Demonstration Project loan (guaranteed by the European Commission).[41]
    - A grant of €10.2 million from EU's Horizon 2020 program.[42]
    - Some private funding from ArcelorMittal.[43]
- The plant makes use of carbon recycling technology and biocatalysts to transform carbon-rich waste gases from the steelmaking process and from waste biomass into ethanol.
    - This ethanol can be used to produce a variety of chemical products including transport fuels, paints, plastics, clothing, and cosmetics.
- The plant has the capacity to produce 80 million litres of advanced ethanol and the potential to reduce carbon emissions at the Ghent plant by 125,000 t_{CO2}/year according to ArcelorMittal.[44]

[40] ArcelorMittal inaugurates flagship carbon capture and utilisation project at its steel plant in Ghent, Belgium. ArcelorMittal Europe. https://europe.arcelormittal.com/newsandmedia/pressreleases/5935/Steelanol-inauguration
[41] Steelanol bioethanol project - Industeel. (8 March 2023). Industeel. https://industeel.arcelormittal.com/story/steelanol-bioethanol-project/#:~:text=The%20project&text=Commissioning%20and%20first%20production%20are,under%20grant%20agreement%20No%20656437.
[42] ArcelorMittal, LanzaTech and Primetals Technologies announce partnership to construct breakthrough €87m fuel production facility - Latest news | Steelanol. Steelanol. http://www.steelanol.eu/en/news/arcelormittal-lanzatech-and-primetals-technologies-announce-partnership-to-construct-breakthrough-87m-biofuel-production-facility
[43] CCU Projects Database. The STEELANOL project is based on producing bio-ethanol via an innovative gas fermentation process using exhaust gases emitted by the steel industry. https://database.co2value.eu/projects/50
[44] ArcelorMittal announces the first industrial production of ethanol | ArcelorMittal. (16 November 2023). https://corporate.arcelormittal.com/media/news-articles/arcelormittal-announces-the-first-industrial-production-of-ethanol

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3 Risk Factors affecting CCS adoption

Large-scale CCS deployment and industrial decarbonisation comes with significant risks and challenges. In this section, these challenges are represented by a range of key risk factors that can be used to evaluate the robustness of the business models introduced in Section 2. These risk factors were developed through literature review and stakeholder engagement. To allow assessment of the likelihood and severity (i.e. the overall risk) of these risk factors, key driving forces and potential impacts have been identified and discussed for each. The level of risk faced by a CCS project is expected to vary depending on the revenue model, ownership structure, source of capital finance, or some combination thereof.

The risk factors introduced in this section are assumed to apply to an at-scale commercial project. This discussion focuses on CCS-based decarbonisation but may also be adapted to evaluate business models for other low-carbon technologies. The significance of certain risk factors may also change when CCS clusters are considered, rather than a single industrial plant and downstream value chain.

Infrastructure Risk Factors

A CCS project is heavily dependent on successful deployment and operation of infrastructure for each constituent part (capture, transport, storage) of the value chain. Effective coordination between all players in the CCS ownership structure is required to mitigate risks faced by a CCS project. Certain risk factors, such as long-term CO_2 storage liability post-closure, may be prohibitively expensive for any one player, requiring risk-sharing between parties or government underwriting. The main risks faced by the physical CCS value chain arise from scenarios involving temporary or permanent loss of key infrastructure. The overall risks are likely to vary depending on the CCS ownership structure.

Delay in Infrastructure Deployment

Timely completion of infrastructure deployment at each stage in the CCS value chain is required to avoid delays in CCS deployment and thus keep the overall costs down. Industrial plants looking to deploy carbon capture face commercial risks if they lack timely access to transport and/or storage. Similarly, CO_2 transport and/or storage operators face a commercial risk if they lack access to an industrial plant's captured CO_2. Infrastructure deployment may be delayed by:

- **Poor stakeholder coordination/timing.**
- **Stakeholder withdrawal** due to financial reasons or changes in ambition.
- **Skilled worker shortages** and **supply chain bottlenecks** for materials/equipment due to, e.g., political instability or pandemics.

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- **Land use constraints** driven by permitting issues, public perception (e.g., NIMBYism), safety concerns, lack of space etc.
- **Insufficient utility connections.**
- **Regulatory challenges**, including cross-border regulatory barriers.

The above issues may culminate in a range of impacts. Some impacts may simply involve a delay, but certain cases (e.g. supply chain bottlenecks), may require significant additional capital expenditure to resolve. Possible impacts of infrastructure deployment delays include:

- **Continued emissions** may lead to an inability to meet low-carbon standards, potentially leading to delay in obtaining low-carbon certification or being eligible for certain subsidies and/or regulated markets and therefore a delay in the willingness of consumers to pay a premium for the product. Continued emissions may also require the continued payment of carbon taxes or emissions allowance by the industrial plant
- **Deployment of CCS infrastructure in a different location** than originally planned.
- **Additional capital costs** associated with new planning and permitting processes, and redeployment of infrastructure.
- **Sunk costs** associated with infrastructure already deployed that is now unusable ("stranded assets").
- **New stakeholders** may be required to deploy parts of the CCS value chain.
- **Challenges in obtaining capital investment** due to uncertainties in project schedule and therefore uncertainty in revenue generation.
- **Delay in other industrial sites' decarbonisation** if the CCS project is an anchor project in an industrial cluster.

Temporary Infrastructure Downtime

The CCS value chain from capturing CO_2 at an industrial plant to long-term sequestration at a geological storage site is a process with multiple steps (e.g., compression, pipeline transport, shipping, etc.). Each of these steps may be temporarily disrupted by a range of scenarios, such as:

- **Pipeline corrosion/leakage** due to material failure, potentially caused by changes in CO_2 purity or flow rate.
- **Failure of CO_2 loading/unloading infrastructure.**
- **Technical storage infrastructure issues** e.g., wellhead blockages, thermal stress cracking.
- **Capture material shortage** – CO_2 capture materials can degrade over time.[45] If the capture material is not replenished, the rate of achievable CO_2 capture will gradually decrease.

[45] CCS: amine degradation rates? THUNDER SAID ENERGY the research consultancy for energy technologies. thundersaidenergy.com. https://thundersaidenergy.com/downloads/ccs-amine-degradation-rates/

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Any of the scenarios above may result in temporary shutdown of operations to allow for repairs or replacement of the infrastructure. The impact of any temporary shutdown of operations may include things such as:

- **Paying the CO_2 price** for any CO_2 emitted during the temporary shutdown or pausing industrial production to avoid emitting any CO_2.
- **Temporary loss of low-carbon certification or eligibility for certain subsidies and/or regulated markets** and therefore the willingness of consumers to pay a premium.
- **Increase in operating costs** associated with the CCS infrastructure since maintenance may have to be carried out.
- **Changes in public perception and/or political support** for CCS, particularly if the temporary shutdown affects the wider community and/or the perceived effectiveness of the technology.[46]

Permanent Loss of Infrastructure

A more severe issue may lead to the loss or absence of infrastructure somewhere in the value chain which may occur during planning, commissioning, or operation phases of the project. Scenarios potentially leading to a loss of infrastructure may include:

- **Stakeholder withdrawal** – potentially leading to a loss of capture, transport and/or storage infrastructure availability.
- **Transport pipeline failure** – if a pipeline fails in such a way that renders the ground unsafe or unusable (e.g., landslide or earthquake), re-deployment may be required along a different route.
- **Storage infrastructure failure** – CO_2 storage infrastructure faces risks of failure due to damage or blockages. If the cause of failure cannot be resolved, an alternative storage site will be required.

The permanent loss of infrastructure on CCS deployment may involve impacts such as:

- **Liability for CO_2 that was previously stored** but is no longer secure if the permanent loss of infrastructure occurs at the storage site.
- **Paying the CO_2 price** for emissions from the industrial plant on a long-term basis.
- **Exploring alternative decarbonisation technologies.**
- **Premature abandonment of the CCS project**.
- **Deployment of alternative CCS infrastructure** which would likely bring significant delays to decarbonisation ambitions and extra costs**.**

[46] Matthews, W. (2022). Failure Investigation Report - Denbury Gulf Coast Pipelines, LLC – Pipeline Rupture/ Natural Force Damage (US Department of Transportation). https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf

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Economic Risk Factors

The profitability of a CCS business model depends strongly on the production cost and sale price of the decarbonised product relative to the unabated option, as well as the total market size. CCS deployment and operation come with significant CAPEX and OPEX requirements, fluctuations in which may impact the profitability of a project and/or the availability of capital finance. External market forces, such as CO_2 pricing, consumer spending power and public perception of CCS may further affect the competitiveness of CCS-decarbonised products with the unabated option, or with products decarbonised via non-CCS routes.

CCS CAPEX Increase

Particularly for first-of-a-kind projects, there is a large uncertainty in the capital cost which will be required for CCS, thus there is a risk of the project going over-budget. Capital costs are estimated to range from €66-79/tCO_2 for the capture plant,[47] €63-143/tCO_2 for the pipeline (depending on length)[48] and €1-20/tCO_2 for storage.[49] Several factors have the potential to vary capital costs, such as:

- **Material costs** – any fluctuation in cost of materials (cement, steel, etc.) is likely to affect the capital costs associated with building the infrastructure.
- **Availability of utilities** – the additional power and heat required for CCS may not be readily available and establishing new grid connections may require additional CAPEX.
- **Regulatory barriers** – may restrict deployment of the most cost-effective CCS infrastructure configurations due to constraints in land use regulations, planning permission, etc.
- **Skilled worker availability** – a shortage of skilled workers may mean that additional investment is required for training.

[47] Aromada, S. A., Eldrup, N. H., & Øi, L. E. (2021). Capital cost estimation of CO2 capture plant using Enhanced Detailed Factor (EDF) method: Installation factors and plant construction characteristic factors. International Journal of Greenhouse Gas Control, 110, 103394. https://doi.org/10.1016/j.ijggc.2021.103394

[48] Dusurut, E., & Joos, M. (2018). Shipping CO2 – UK Cost Estimation Study. Final report for Business, Energy & Industrial Strategy Department. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761762/BEIS_Shipping_CO2.pdf

[49] The Costs of CO2 Capture, Transport and Storage. Post-demonstration CCS in the EU. Zero Emissions Platform. Retrieved July 15, 2024, from https://zeroemissionsplatform.eu/wp-content/uploads/Overall-CO2-Costs-Report.pdf

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Increases in the capital investment needed for CCS may have impacts on deployment such as:

- **Excluding funding from sources with limited capital**. In particular, government grants may be limited to a fixed amount - any increase in the capital investment needed for CCS may exceed this amount.
- **Reducing cost-competitiveness with the unabated option,** potentially altering the number of consumers willing to pay a premium for the low-carbon product.
- **Reducing cost-competitiveness with alternative decarbonisation options,** meaning other low-carbon production methods (e.g., electrification) could become more viable.

CCS OPEX Increase

Any variation in CCS operating costs is likely to affect the total production cost. Sudden increases in OPEX could therefore impact a revenue model's viability, and may be driven by scenarios such as:

- **Increase in energy costs** affecting business case, since CCS is an energy-intensive process.
- **Increase in capture material cost** such as for specialised and/or proprietary chemicals and materials.
- **Monopolistic CO_2 infrastructure price markups** – industrial plants could be vulnerable to excessive fees if CO2 transport and/or storage monopolies are not effectively regulated.
- **Over sizing of infrastructure** – poor coordination across the CCS value chain may result in over-sizing of infrastructure which could increase maintenance costs.
- **Technology lock-in** – due to long technology & infrastructure lifetimes, CCS operators may be committed to higher operating costs, e.g., if transport infrastructure is improperly sized.

The impact of increasing operating costs for CCS infrastructure include situations such as:

- **Consumers unable to pay the green premium** – the number of conscious consumers may decrease so revenue from CCS deployment may also decrease.
- **Inability to recover additional operational costs,** if the CCS business case is based on long-term fix-price contracts.
- **Reduction in returns on investment** may reduce the number of investors investing in CCS operations.
- **Unable to keep up with interest repayments** could prevent more loans being taken out to finance the capital costs of CCS.
- **Exploring alternative decarbonisation technologies.**

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Reduction in the Cost of Emitting CO_2

A possible long-term driver of CCS revenue is the increasing cost of emitting CO_2. A sufficiently high CO_2 price may mean that CCS deployment carries lower cost than unabated CO_2 emissions. However, CO_2 prices are subject to significant uncertainty and variability, for example, the EU-ETS price fluctuated between €60-100/tCO_2 in 2022-2023.[50] Changes in CO_2 price within certain Emissions Trading System (ETS) schemes may also be affected by the variation in supply and demand of the emissions allowances. Any reduction in the cost of emitting CO_2 may impact CCS deployment such as by:

- **Low-carbon product becomes less cost competitive** with the unabated option, potentially reducing the number of conscious consumers willing to pay the green premium.
- **Decrease in revenue availability through the CO_2 price** may deter private investors and thus reduces the amount/diversity of capital funding available for CCS.

Reduction in Investor Confidence

Most infrastructure operators in a CCS value chain are unlikely to have sufficient capital to fund infrastructure deployment and will often require financial support from private equity investment. Private investors and private equity firms are more likely to provide equity if they perceive that there will be a high return on their investment. Several external factors could influence the availability of private equity financing for CCS, such as:

- **Availability of other finance** – Private investors may be more likely to invest if match/top-up funding is supplied through public grants.
- **Success of first-of-a-kind projects** – if the first CCS projects are successful and the industry grows rapidly, greater confidence of investment returns may widen the pool of available investors.
- **Investor confidence & perceived risk** – any potential accidents associated with CCS being a novel technology (e.g., concern around potential leakage from geological store in first-of-a-kind project) may deter investors with a moderate or low appetite for risk.

Any reduction in investor confidence could have impacts on CCS deployment such as:

- **Reduced availability of private equity finance** which may prohibit CCS deployment if not enough capital is available.
- **Increased costs of private equity finance** since the perceived risks may be higher to the investor compared to the potential returns that may be generated.

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[50] EU carbon price tops €100 a tonne for first time. Financial Times. https://www.ft.com/content/7a0dd553-fa5b-4a58-81d1-e500f8ce3d2a

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Increasing Cost of Debt-Based Private Finance

Capital funding for CCS could also potentially be supported through taking out private loans. Several external factors could influence the overall cost of private debt financing for CCS, such as:

- **Increasing interest rates** – any change in interest rate greatly impacts the overall cost of borrowing.
- **Reduced lender confidence & perceived risk** – lender interest rates can vary significantly depending on the perceived project risks, the risk appetite of the lender and perceived changes in inflation.
- **Strict repayment schedules** – certain lenders may have strict repayment schedules, further increasing the costs associated with debt-based finance.

The risks associated with increased costs of debt-based finance include impacts such as:

- **Lack of affordable capital funding** if debt cannot be raised to fund the CCS infrastructure.
- **Reduced investor confidence** if alternative sources of capital funding cannot also be relied on.
- **Reduced revenue generation** if the industrial plant is having to pay more to cover debt.

Negative Public Perception & Willingness to Pay for CCS

Revenue generation is often tied to consumers' willingness to pay a certain price for a product. For products decarbonised with CCS, this willingness to pay also determines the amount of green premium that can be charged. Consumer willingness to pay may be impacted by several factors, including:

- **Societal support for CCS** – levels of societal support for CCS are strongly affected by concerns around the safety of CO_2 storage, the possibly of leaks and potential environmental impacts and the perception of CCS as an enabler of continued fossil fuel use.
- **Increase in cost of CCS-decarbonised product** – any unexpected increase in either the capital or operational costs of CCS will likely be reflected in a higher product price, shrinking the pool of consumers who are willing to pay.
- **External economic risks** – a change in spending power, e.g., due to increased cost of living, is also likely to affect consumers' willingness to pay.
- **Availability of alternative low-carbon products** from other decarbonisation technologies which may offer lower cost and/or lower carbon intensity products.

The consequences of negative public perception and/or willingness to pay for CCS could have impacts such as:

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- **Reduction of revenue** available through a green premium's revenue model.
- **U-turns on certain policies/regulations** underpinning government incentives for CCS.
- **Decrease in investor/lender confidence** due to uncertainties in revenue generation.

Reduction in Sector-Specific Product Demand

Certain revenue models may rely predominantly on certain end-use sectors. For example, the automotive industry is likely to have a relatively large pool of conscious consumers (via electric vehicle sales), while the additional cost of low-carbon steel yields a small relative increase in the final vehicle price. This implies a good opportunity for the sale of steel that has been decarbonised with CCS, but also risks creating a niche market that is more susceptible to supply chain bottlenecks and external economic forces. Using the automotive industry as an example, sector-specific steel demand may be affected by:

- **Decrease in product demand** – an increase in cost of living may impact consumers' spending power. This is likely to have disproportionate impact on demand for high-value items products like premium-priced private cars.
- **Supply chain bottleneck for other product components** – a shortage of materials required for other vehicle components (e.g., rare minerals required for on-board electronics) may decrease vehicle production capacity, thereby lowering steel demand.
- **Decreased worker availability** – worker availability may be restricted by external forces, e.g., a pandemic.

The above scenarios ultimately result in a decrease in steel demand that may affect the automotive sector more than other sectors (e.g., construction). A business model that relies on a diverse customer base will therefore be more resilient to this risk. The impact of sector-specific product demand on CCS deployment could involve scenarios such as:

- **Revenue from conscious consumers may be reduced** if there is reduced demand in certain sectors which are more favourable to the green premium.
- **Changes in procurement quotas** in a regulated market if there is reduced demand from the sectors covered by the regulated market.
- **Smaller market may reduce investor/lender confidence** due to uncertainties in revenue generation.

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Political & Regulatory Risk Factors

Deployment and scale-up of CCS may be facilitated through government support and risk sharing that increases the value proposition of the technology. Some revenue models (e.g. regulated market, level playing field) may rely specifically on certain policy and regulatory mechanisms and are therefore vulnerable to changes in political support.

Reduced availability/magnitude of Public Finance

First-of-a-kind CCS projects may be reliant on public funding, so any uncertainty in the availability of public grants may hinder the deployment of CCS. Such funding comes in the form of grants, or loans with favourable rates, likely with conditions that focus more on the environmental/social benefits of a CCS project than its economic viability. However, this funding is likely to be limited in availability, potentially with lengthy application procedures and competitions with no guaranteed award. The type and amount of public funding available may be affected by:

- **Project scale/type** – funding sources and supportive regulatory regimes may be restricted to certain projects. Overly prescriptive regulations may run the risk of excluding viable projects.
- **Change in government/policy** – policy changes may either occur due to a change in government or be implemented for short-term political gain.
- **Uncertainty in CCS technology/infrastructure,** particularly for first-of-a-kind projects may deter governments from giving out capital support for CCS projects, due to safety concerns and potential for negative public perception. Conversely, governments could underwrite some of these risks to provide a more attractive environment for investors.
- **Cross-border policy differences** – CCS or product value chains that cross national borders may receive different levels of political support or be subject to different regulations.

The consequences of a reduced availability of public finance for CCS could lead to impacts such as:

- **Reduced value of capital funding** available for CCS.
- **Reduced certainty for private investors/lenders** in reducing the risks associated with investing in CCS.

Reduced availability/magnitude of Revenue Incentives

Subsidies and/or taxation also exist in certain regions to help cover CCS OPEX expenditure (e.g., the EU-ETS and the SDE++ subsidy in the Netherlands). The availability of these may impact the overall cost to the industrial plant of deploying CCS. The availability/magnitude of revenue incentives will be affected by the same factors as the availability/magnitude of

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public finance (listed above). Another factor which may specifically affect the availability/magnitude of revenue incentives is:

- **Strike pricing** – Establishment of a government-backed strike price for low-carbon products could provide some certainty of revenue, around which a viable level playing field revenue model can be designed. However, changes in this strike price will therefore impact revenue generation for certain business models.

The impact of reduced availability/magnitude of revenue incentives could lead to consequences such as:

- **Reduced possibilities for revenue generation** from CCS may affect how level the playing field is between the low-carbon and unabated products and may lead to an increase in the green premium price.
- **Reduced certainty in the return on investment or interest repayments** for private investors/lenders due to uncertainty in future revenue generation.

Lack or delayed deployment of Low-carbon Market Regulations

Certain regulations could be used to guarantee a customer base for decarbonised products (e.g., SAF mandates). If CCS deployment is to be enabled by these low-carbon regulations, then the market should be carefully designed to ensure that products decarbonised using CCS are eligible. Other decarbonisation routes (e.g., electrification, fuel-switching) may also be enabled by the regulated market, potentially creating competition between low-carbon products. The inclusion of multiple decarbonisation routes could be beneficial for driving efficient technology development but equally could constrain CCS deployment if other decarbonisation routes are more effective. The regulated market should also ensure that the eligibility is not too lenient, and that decarbonisation solutions should meet a certain threshold of emissions abatement to participate. Variations in the regulations/eligibility of the low-carbon products will impact the size of customer base available through the regulated market revenue model. The establishment of low-carbon market regulations is likely to be influenced by factors such as:

- **Consumer demand for low-carbon products** (i.e., size of the potential regulated market).
- **Incentives of the regulating body** (e.g., governments, trade bodies) in specifying minimum low-carbon requirements and other regulations.

The impact of a lack of low-carbon market regulations could be consequences such as:

- **Uncertainty in the final consumer** of the low-carbon product leading to uncertainty in revenue generation.
- **Reduction in investor/lender confidence** as there is no guaranteed market for the low-carbon product.

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- **Risk of the CCS project not being eligible** to comply with potential future changes in the low-carbon market.

Unique Risk Factors for CCU-Based Decarbonisation

Deployment of CCU likely carries its own distinct risks and challenges compared to CCS, based on differences in revenue generation mechanisms and degree of CO_2 sequestration. These are outlined below but are not considered individually when it comes to risk mitigation as the focus of the study is on CCS business models.

CCU often has the added benefit of generating revenue through the sale of CO_2-derived products like sustainable aviation fuel (SAF), olefins, polymers/plastics, mineral carbonates and even protein. Except for mineral carbonates and some polymers, however, most CCU products do not permanently sequester CO_2 in the same way as CCS. This means that many CCU pathways lead to eventual re-emission of the captured CO_2 and are likely to be liable for CO_2 pricing. Another difference between CCS and CCU is that CCU tends to operate at smaller scales and/or involve on-site (or nearby) utilisation of the CO_2, so may not require transportation infrastructure. These differences are likely to cause some variation in the business model structure and/or risk factor impacts.

Revenue Model

The sale of CO_2-derived products represents a separate revenue from the main low-carbon product (e.g., steel) being decarbonised. This additional revenue stream may be subject to different consumer bases, regulations, and market forces. However, since CCU products currently often come at a higher price than fossil-derived counterparts (e.g., SAF vs conventional jet fuel), the revenue models discussed in this work are likely to be similarly viable for the CCU value chain (e.g., regulated market mandating use of SAF in jet fuel).

Product Value Chain

The product produced via CCU may not be for the same market as the traditional products produced by the industrial sites (e.g., ethanol produced at the Steelanol plant at ArclorMittal's Ghent plant). Product development may also require different expertise to the current operations of the industrial plant. These added challenges may potentially require collaboration between companies in differing market sectors.

Ownership Structures & CO_2 Value Chain

The CO_2 value chain for CCU is expected to have a different structure than for CCS, likely with lower infrastructure requirements and therefore CAPEX. Long-term CO_2 storage infrastructure is likely not required for CCU or will exist in a very different form (e.g., landfill at end-of-life for plastics and mineral carbonates). Conversely, insufficient (or overly costly) CO_2 storage

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capacity may influence industrial plants to adopt a CCU-based decarbonisation pathway. Transport infrastructure may also not be necessary, as the location requirements for CO_2 utilisation are much more flexible than for CO_2 storage (i.e., CO_2 utilisation may occur near the emission site, as with Steelanol[51]). A capture plant is most likely still required unless the CO_2 stream is already sufficiently pure for the utilisation process. However, the product derived from CO_2 (e.g. SAF) would require market and revenue certainty (e.g. supported by policies, mandates, or long-term offtake agreements).

Capital Financing Sources

The potential for an additional source of revenue from CCU will likely impact the type and amount of available capital financing. The increased certainty of revenue generation (depending on the profitability of the CCU product) may mean that private equity investors are more likely to invest in the project. Increased revenue generation may also allow a wider range of sources for debt financing. However, CCU projects may not be eligible for some public CAPEX support (e.g., CCU projects are not supported by the UK's Cluster Sequencing support).

[51] Home page, Company website. Steelanol. http://www.steelanol.eu/en

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4 Evaluating business models for Industrial CCS

In this section, the different business model components introduced in Section 2 are evaluated against the risk factors to an industrial plant of deploying CCS introduced in Section 0 (excluding those unique to CCU). The relative ability of each business model component to mitigate each risk to an industrial plant (either reducing its likelihood or lowering its impact) was qualitatively assessed. This assessment used the base-case assumption of an industrial entity (plant or cluster of nearby plants) that has chosen to deploy CCS. The scoring is summarised as a Risk Mitigation Matrix (Table 1) and the key drivers of the scores are discussed briefly in the next section.

The results of this were then used to evaluate how each business model component may vary with time and to create decision trees that are designed to help an industrial plant choose the most viable business model(s) for CCS deployment that best mitigates most risks at a certain point in time. In reality, all combinations of all business model components could exist. It is very likely that the viability of these business models will evolve over time as the CCS market grows and matures and certain risks are mitigated.

Risk Mitigation Matrix

As discussed in Section 0, each risk factor considered here represents a type of challenge that a CCS project may face. These risk factors each have a range of possible drivers, and a range of possible impacts. The scores in the risk mitigation matrix below (Table 1) reflect the ability of each business model component to mitigate the total risk, by lowering the likelihood and/or reducing the impact of each risk factor.

A **green tick** (✓) indicates good mitigation of the risk being assessed and/or resilience to its impacts. This good risk mitigation should allow greater flexibility in choosing other business model components since impacts associated with the particular risk should mostly be mitigated.

An **amber tilde** (~) indicates partial risk mitigation and/or some resilience to the associated impacts. This does not ensure business model viability by itself and likely requires careful choice of other business model components to help fully mitigate the risk.

A **red cross** (×) indicates poor risk mitigation and vulnerability to the associated impacts. The choice of other business model components should be considered carefully to ensure that the risk is mitigated by another business model component.

For example, a level playing field can mitigate many risks associated with revenue uncertainty by ensuring costs are competitive with the unabated production route (e.g., through subsidies or carbon tax), and so compensates for the poor mitigation of these risks when private debt is used as a source of finance. Conversely, the green premiums business

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model is more likely to be vulnerable to these risks and may require a source of finance that carries fewer overall risks, such as public grants/loans.

Table 1. Risk mitigation potentials of business model components from the perspective of the industrial plant, across all risk factors. Interactions with highly uncertain or undefined risks/impacts have been left blank.

Risk Factor	Revenue Model			Ownership Structure			Capital Financing			
	Green Premiums	Regulated Market	Level Playing Field	Vertically Integrated	T&Sco	CCaaS	Public Grants / Loans	Private Equity	Private Debt	Industrial Plant Equity
CCUS OPEX Increase	×	~	✓	~	~	~	✓	~	×	~
CCUS CAPEX Increase	×	~	✓	~	~	~	~	✓	~	×
Reduction in Cost of Emitting CO_2	×	✓	~	~	~	~	✓	~	×	~
Reduction in Investor Confidence				×	~	✓	~	×	~	✓
Increasing Cost of Debt-based Private Finance				×	~	✓	✓	✓	×	✓
Negative Public Perception & Willingness to Pay	×	~	~	~	~	~	~	~	×	~
Reduction in Sector-specific Product Demand	×	~	✓				✓	~	×	~
Delay in Infrastructure Deployment	×	~	✓	~	~	~	~	~	×	×
Temporary Infrastructure Downtime	~	~	~	~	✓	✓	~	✓	×	✓
Permanent Loss of Infrastructure	×	×	×	×	~	~	~	~	×	×
Reduced Availability of Public Finance	×	~	✓	×	~	✓	×	~	~	✓
Reduced Availability of Revenue Incentives	✓	✓	×							
Lack of Low-Carbon Market Regulations	✓	×	✓							

✓ = Mitigates risk/impact ~ = Partially mitigates risk/impact × = Does not mitigate risk/impact

This risk mitigation assessment (from the perspective of the industrial plant) reveals that certain business model components offer significantly higher risk mitigation potential than others, but that these are likely subject to availability of necessary political/regulatory support and/or existence of specialist CCS entities. Each choice of business model component comes with various caveats and nuances, which are discussed in more detail below.

Revenue Model

The **Level Playing Field** revenue model appears the most resilient to risks involving cost fluctuation (both CAPEX and OPEX) as well as sector-specific variability in product demand. A well-design level-playing field will likely use a combination of subsidies, carbon taxes and/or CO_2 pricing to ensure certainty in revenue generation in the event of OPEX fluctuation or changes in product demand. This ideal level-playing field model should also be resilient to CAPEX fluctuations because the certainty in revenue should allow investment from private sources to be obtained more easily. The main relative vulnerability of this revenue model is the availability of revenue incentives (i.e., subsidies, carbon taxes, CO_2 pricing) upon which it

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relies. While a level playing field should ensure cost-competitiveness with the unabated option even if the cost of emitting CO_2 drops, a sustained drop in CO_2 price may affect the security of the revenue incentives if these are funded through CO_2 taxation. There may also be a risk to CCS adoption from other low-carbon production methods which could be eligible for the same/similar government revenue incentives.

A **Regulated Market** revenue model is less resilient to cost fluctuations (compared to the level-playing field revenue model), as additional costs are passed onto the consumer within the regulated market, which may affect their ability/willingness to pay. Similarly, sector-dependent market shrinkage is a risk, particularly for those sectors covered by the regulated market. However, this revenue model appears most resilient to changes in CO_2 pricing; if consumer base is guaranteed through the procurement obligations of the regulated market, then a drop in CO_2 price (i.e., lowering in cost of the unabated option) should not affect competitiveness of green product, and may even increase consumers' spending power.

The **Green Premiums** revenue model exhibits the highest vulnerability to cost fluctuations, market size and public perception, as revenue generation is directly tied to consumer preference and ability/willingness to pay. This revenue model is likely limited to niche markets and may require further de-risking, e.g. via consumer offtake agreements for the low-carbon product. The main benefit of this revenue model is its wide and immediate availability due to lack of reliance on governmental regulatory or revenue market mechanisms.

The **certainty of the revenue model of generating sufficient revenue is likely to influence the risks and availability of capital financing**, particularly private finance (see Capital Financing discussion, below). A revenue model with more certain revenue generation should provide greater stability. This revenue certainty should improve the risk/reward ratio for sources of capital financing, such as private equity or debt financing. Conversely, a less certain revenue model may restrict sources of capital financing to those who are willing to take on higher risks, potentially for lower rewards.

Ownership Structure

The expected differences in upfront cost between ownership structures means that the amount of available capital strongly influences which ownership structures are possible from the perspective of the industrial plant.

A **Vertically Integrated** ownership structure is expected to carry the highest CAPEX requirements for the industrial plant, making it less resilient to fluctuations in funding availability than the other ownership structures. A potential benefit of this ownership structure is that the industrial plant retains control over the whole project. However, this ownership structure also likely comes with higher risks, and greater CO_2 storage liability for the industrial plant – this is reflected mainly in the poor mitigation of the "permanent loss of infrastructure" risk factor.

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An **Independent Transport & Storage Company (T&Sco)** ownership structure likely comes at lower capital cost to the industrial plant than vertical integration, and so better mitigates risks associated with availability & cost of capital financing. This ownership structure also carries fewer risks for the industrial plant in terms of storage liability and other infrastructural issues. If the T&Sco is a mature company with significant expertise and/or can leverage economies of scale by working with multiple industrial plants in a cluster, overall CCS costs may be lower than for a vertically integrated project. This is not guaranteed, however, since the industrial plant no longer has control over the way in which T&S infrastructure is deployed, which may lead to higher overall costs in some cases. Risks associated with changes in CCS CAPEX & OPEX have therefore been assessed as partially mitigated on average.

A **Carbon Capture as a Service (CCaaS)** ownership structure outsources most of the CCS deployment/development responsibility to a third party and therefore carries even fewer CAPEX and infrastructure-related risks to the industrial plant than a T&Sco ownership structure. As above, outsourcing of CCS operations has implications for control and pricing; CCaaS may offer lower costs to an industrial plant than a Vertically Integrated ownership structure, but this is again not guaranteed and should be re-assessed based on the individual project.

Capital Financing Source

The overall risks surrounding capital financing are likely to be strongly influenced by choice of both revenue model and ownership structure. The magnitude and certainty of revenue generation is likely to significantly impact the numbers of investors willing to finance the CCS infrastructure. The higher CAPEX requirement for the industrial plant in a Vertically Integrated ownership structure increases the importance of any capital financing decisions, while outsourcing some or all the CCS infrastructure development lowers this importance for the industrial plant.

Public Grants/Loans are expected to carry the lowest capital financing risks for the industrial plant, likely due to fewer repayment or equity requirements, and/or favourable interest rates. This risk mitigation may improve the viability of CCS projects using revenue models with higher risk levels (e.g., Green Premiums). The most impactful risk for public funding is the magnitude of capital available, which may be limited by for example, the amount of taxpayers' money which can be used for CCS grants. There may also be risks associated with meeting the eligibility requirements of the public funding (e.g., the UK's Cluster Sequencing for Industrial Carbon Capture requires a capture rate of >85%).

The feasibility and risk mitigation potential of capital funding via **Industrial Plant Equity** depends strongly on the required CAPEX and therefore ownership structure. If the industrial entity has sufficient capital to withstand any cost fluctuations, the risk mitigation of this option may be high as the industrial plant is not beholden to third-party lenders or investors. This option may be limited to industrial plants with sufficient financial resources and/or those

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who outsource some CCS development responsibility to an independent T&Sco or CCaaS entity.

Privately financed capital typically has a much larger pool of available funding than public or in-house industrial funds. **Equity-based finance** is likely to involve some risk sharing between industry and investor and should offer some resilience to cost & revenue fluctuations, as the industrial plant is not beholden to interest payments. The main restricting/deciding factor around capital availability is investor confidence – the perceived viability of the other business model components, particularly the revenue model, is expected to influence this.

Debt-based private finance will require regular interest payments, potentially at higher interest rates and with a stricter repayment schedule, compared to public loans. This type of finance is therefore expected to be much more vulnerable to fluctuations in production cost, revenue, and interest rates. Therefore, it is likely only viable in combination with a secure revenue model. CAPEX fluctuations may also affect the total cost of borrowing.

Real-life Business Model Component Interactions

In addition to the risk mitigation potentials of the individual business model components described above, more complex interactions are expected when a combined business model is exposed to a real-life scenario. These may arise due to:

- **Site variability** - certain risk factors (and driving mechanisms thereof) are likely to depend highly on the individual site and must therefore be appraised on a case-by case basis. For example, the decision of whether an industrial plant is *able* to develop and deliver a vertically integrated CCS value chain will be influenced by the combined availability of capital, land, utilities, skilled workers, shared infrastructure, etc.
- **Compounded impacts** - some risk factors can act in concert with others and magnify the combined impacts. For example, a drop in public perception & willingness to pay may also affect investor confidence and/or political support (and therefore availability of capital funding & revenue incentives).
- **Common driving mechanisms** - conversely, a single driving mechanism may increase the likelihood of multiple risk factors. For example, energy costs may affect CCS OPEX, but also consumers' willingness and/or ability to pay.
- **Interdependence of business model components** - the impact of certain risks upon one business model component may be directly influenced by the choice of another. For example, risk factors affecting the relative viability of different capital financing models (e.g., degree of investor confidence) are themselves strongly affected by the chosen revenue model.

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Business Model Deployment

From the perspective of a present-day industrial plant deploying a first-of-a-kind CCS project within a small-scale CCS market, the choice of CCS business model will likely be informed by the combined relative risk mitigation potential of its components, as discussed above. However, a business model that currently presents the fewest risks to the industrial plant may be underpinned by taxpayer-funded government financing & revenue support mechanisms. These are currently not widely available (e.g., the SDE++ subsidy is available in the Netherlands, but only to a limited number of projects through a competitive bidding process), and are unlikely to offer sufficient funding for sustaining a widespread and mature CCS market in the long term.

This section first outlines the CCS business model with the lowest risk to the industrial plant (i.e., highest risk mitigation potential) in the current CCS market. This is accompanied by a discussion of the political and societal implications of such a business model, and the circumstances in which it may be viable.

Following this, the longer-term viability of these business models is then discussed. Over time, as the global CCS market transitions towards a widespread, self-sustaining market, the relative viability of different CCS business models is expected to evolve. External risks to the wider political and societal systems of CCS deployment will also have to be mitigated, in addition to those risks to the industrial plant itself.

Business Model with the lowest risk to the Industrial Plant

Based on the results of the Risk Mitigation Matrix, the business model with the lowest risk (from the industrial plant's perspective) uses a Level Playing Field revenue model with Capital Financing provided by Public Grants/Loans, and an ownership structure that outsources some or all CCS operations. The truncated risk mitigation matrix in Table 2 indicates effective mitigation of many of the risks by one or more of these business model components, as discussed in the previous section.

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Table 2. Truncated matrix illustrating risk mitigation ability of the CCS business model with the lowest risk from an industrial plant's perspective.

Risk Factor	Revenue Model	Ownership Structure	Capital Financing		Overall risk mitigation potential
	Level Playing Field	CCaaS	Public Grants / Loans		
CCUS OPEX Increase	✓	~	✓		✓
CCUS CAPEX Increase	✓	~	~		✓
Reduction in Cost of emitting CO_2	~	~	✓		✓
Reduction in Investor Confidence		✓	~		✓
Increasing Cost of Debt-based Private Finance		✓	✓		✓
Negative Public Perception & Willingness to Pay	~	~	~		~
Reduction in Sector-specific product demand	✓		✓		✓
Delay in Infrastructure Deployment	✓	~	~		✓
Temporary Infrastructure Downtime	~	✓	~		✓
Permanent loss of infrastructure	×	~	~		~
Reduced Availability of Public Finance	✓	✓	×		✓
Reduced Availability of Revenue Incentives	×				×
Lack of Low-Carbon Market Regulations	✓				✓

Considering the Overall Risk Mitigation Potential column, the business model components chosen mostly have good risk mitigation potential against the risk factors to an industrial plant. However, there are a few risk factors which are not well mitigated.

The **Reduced Availability of Revenue Incentives** remains as a key risk factor. This is because the Level Playing Field revenue model is likely to depend heavily on the availability of revenue incentives (e.g., carbon taxation or subsidies). Subsidies which currently available are limited in extent (e.g., SDE++ only in the Netherlands for certain industrial sectors, limited to 15 years) due to their reliance on taxpayers' money. For CCS deployment at the scale required for net zero, subsidies for CCS are likely to be a major financial burden to the government if applied at scale. Alternative methods of levelling the playing-field, for example through CO_2 pricing schemes (e.g., the EU ETS) can encourage deployment of CCS. However, these are currently

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insufficient (due to, e.g., price volatility and free allowances) to guarantee long-term revenue generation for decarbonised products.

Negative Public Perception & Willingness to Pay is a risk factor which is only partially mitigated by this business model. This is partially due to the reliance on public funding sources which will likely require public backing by the electorate given the potential reliance on taxpayers' money if public grants are used to finance the project.

The final risk factor which is only partially mitigated by the business model is the **Risk of Permanent Infrastructure Loss**. This risk to the industrial plant should be mitigated as much as possible by prior identification of multiple alternative storage sites, combined with government underwriting of long-term CO_2 storage liability.

This combined business model is which mitigates the most risk to the industrial plant is likely to be helpful for catalysing CCS deployment in the current CCS landscape for first-of-a-kind projects. However, it likely cannot be used to deploy CCS at the scale required to achieve net-zero due to its reliance on public money.

Towards a Self-Sustaining Business Model

To achieve a self-sustaining commercial CCS market large enough to significantly lower industrial emissions, a portfolio of CCS business models will likely be required. Certainty and longevity of a particular business model is likely key to its adoption from the perspective of the industrial plant, although variations through time and how this may influence each business model component may impact CCS uptake.

Each business model component has the potential to play a key role as the CCS market matures and evolves over time. A possible pathway for this evolution is illustrated in Figure 2, and the implications for each business model component discussed further below.

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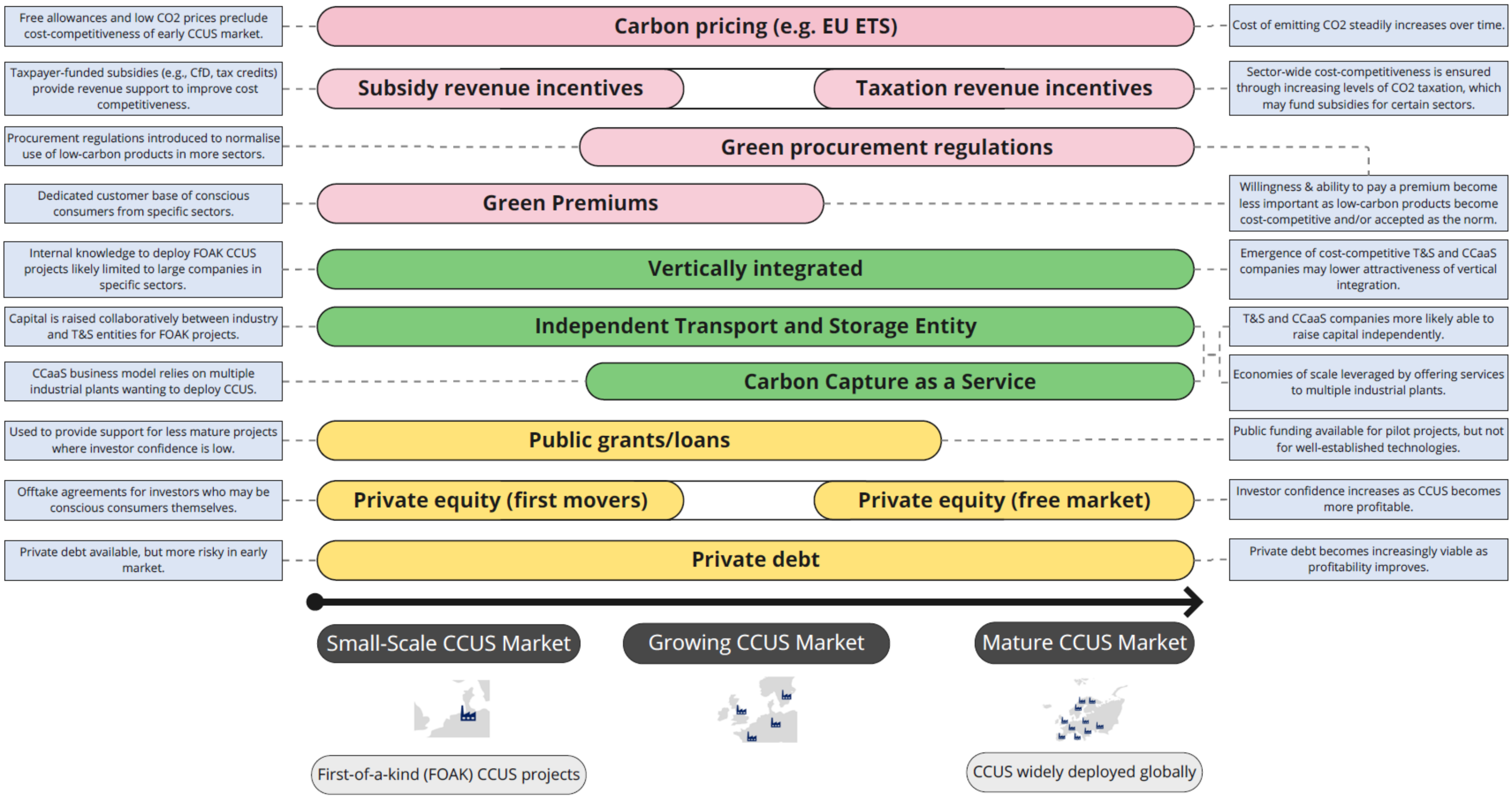

Figure 2. Possible timeline outlining evolution of CCS business model components as the CCS market matures.

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Revenue Model

In the long-term, a Level Playing Field revenue model is still likely to offer the lowest risk to the industrial plant across the widest possible market, provided it can be implemented reliably & sustainably, and includes CO_2 taxation as well as (or instead of) subsidies. To improve the reliability of this revenue model, more certainty is required around both the cost of emitting CO_2, and availability of financial support for low-carbon industrial production. To ensure sustainability of this revenue model, it should be implemented in such a way that minimises the financial burden on the government and passes costs onto consumers. To ensure social license to operate, this cost pass-on should be implemented gradually to minimise shocks to the market and ensure equitable distribution of costs across consumers.

Currently, CO_2 prices are not far-reaching enough to level the playing field across all geographies and sectors, and subsidy-based revenue support for CCS is limited. As such, other revenue models should be utilised where possible to allow the CCS market to develop. While a Regulated Market involving green procurement regulations exists for certain low-carbon products like sustainable aviation fuel, this is not yet the case for many other energy intensive industries (e.g., iron & steel or cement). Depending on the cost margins and competitiveness of certain product sectors, implementation of such regulations may be met with commercial, political, and societal resistance if introduced too quickly. Therefore, while a regulated market could increasingly drive CCS deployment in the medium/long term, it also cannot be solely relied upon to catalyse initial growth of a CCS market.

Until more favourable regulatory conditions exist, CCS deployment in a young, small-scale CCS market may still employ a Green Premiums revenue model. Despite the higher risks to the industrial plant than the other revenue models, Green Premiums still may be viable in certain key cases. For example, revenue may be guaranteed by signing offtake agreements (contractual obligations to purchase a certain amount of product) with key conscious consumers prior to project development. This revenue certainty may then help to boost investor confidence and increase the availability of capital financing beyond that provided by public funds. Investment and investor confidence may be further reinforced by selling equity stakes to offtakers.[52]

Market penetration of low-carbon products and the conscious consumer customer base may be improved by education and public awareness campaigns to communicate importance of industrial decarbonisation and strengthen public perception of CCS. Education may also be particularly important to improve public understanding around the safety and

[52] Bhat, S. (2 October 2023). H2 Green Steel has raised billions in 3 years: a case study of Industrial Project Finance - Energy Post. Energy Post. https://energypost.eu/h2-green-steel-has-raised-billions-in-3-years-a-case-study-of-industrial-project-finance/

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efficiency of CCS, and potentially to change the narrative around the perception of CCS as simply an enabler of continued fossil-fuel use. Initial demonstrations of supply and demand for CCS-decarbonised products may also help to normalise CCS and low-carbon products.

The Green Premiums revenue model will likely be limited to niche applications and unlikely to foster widespread decarbonisation. However, it is currently the most widely available revenue model and has the potential to penetrate a small but not insignificant portion of low-carbon product markets. As such, it can act as a useful tool to initiate CCS deployment and pave the way for more far-reaching revenue models.

As the Green Premiums business model matures, policymakers and/or regulating bodies may slowly introduce and ramp up green procurement regulations to facilitate deployment of CCS in sectors where decarbonised products may be less competitive. Alongside this, robust certification should be developed to improve consumer trust, and provide transparency around the embedded emissions of industrial products. A Regulated Market could encourage wider growth of the CCS market, which could serve to further normalise the market presence of low-carbon products and bolster public acceptance of industrial CCS.

Meanwhile, the cost of emitting CO_2 may increase over time, such that a level playing field will eventually develop as the prices of unabated products rise to match (or exceed) those of low-carbon products. At this stage, carbon border adjustment mechanisms are also expected to minimise carbon leakage to economies with lower (or absent) CO_2 taxation. For sectors with low-carbon products that remain uncompetitive, government income generated by higher rates of carbon taxation may be used to fund subsidies to maximise the commercial feasibility of CCS across the whole market.

In a mature, developed CCS market, Green Premiums and Regulated Market revenue models may become less important as low-emissions industrial products become the default. In this situation, the cost of emitting CO_2 (both commercially and socially) may be high enough that unabated production is no longer competitive; the main market competition faced by CCS-decarbonised products would instead be products decarbonised via other routes.

Ownership Structure

The ownership structure with the lowest risk to the industrial plant currently involves outsourcing some or all of the CCS responsibility to a separate entity. However, this outsourcing is dependent on the existence of such an entity and its willingness to collaborate. Currently, very few independent T&Sco or CCaaS entities are operational, and the range of expertise required to deploy CCS means that a Vertically Integrated ownership structure is restricted to large companies with the necessary resources and knowledge.

Several first-of-a-kind projects currently under development involving third-party transport and storage entities (e.g., Ghent Carbon Hub, Northern Endurance Partnership), are formed of

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existing companies with expertise in various aspects of CCS deployment. These projects typically involve close collaboration and joint fundraising.

In a more widespread & mature CCS market, projects may involve a dedicated CCaaS company (e.g. Aker Carbon Capture). In this more mature market, established T&Sco or CCaaS entities may be more able to independently acquire the capital and resources required for CCS projects. Such a scenario may require less collaborative risk-sharing on the industrial plant's part and simplify interactions across the CO_2 value chain.

To facilitate creation and sustainable operation of specialised CCS service entities, certain outstanding risks should be mitigated. For example, guidelines and standards may be developed to:

- Determine appropriate mechanisms by which to underwrite long-term CO_2 storage liability, whether by governments or private insurers.
- Encourage the standardisation of transportation equipment to facilitate flexibility in CO_2 storage options.
- Encourage competitive CCS services and avoid T&S monopolies (e.g., T&S fee regulation, regulated asset base models).

As the CCS market matures, the increasing presence of dedicated CCS service operators may accelerate development of the above. A competitive market with multiple CCS third parties may also alleviate risks to the industrial plant associated with stakeholder withdrawal from a CCS value chain. A maturing CCS market is also expected to come with an increasingly robust supply chain for key materials associated with CCS deployment (e.g., amine sorbents for capture plants).

Capital Financing

Public grants/loans, while offering a degree of risk mitigation for first-of-a-kind CCS projects, are unlikely to be a sustainable source of capital financing for a widespread and mature CCS market due to their reliance on taxpayer money. To transition to a market in which CCS can be reliably financed from private funds, investor confidence must be improved and/or use of private debt de-risked.

A key driver associated with raising private capital is security in revenue generation. Adopting a revenue model which generates sufficient revenue to provide investors with a return on investment or covers costs associated with debt financing will likely allow more private funding to be raised. Learnings and developer confidence associated with successful infrastructure deployment as well as underwriting of key risks (e.g., those associated with long-term CO_2 storage) may also increase the amount of capital funding which can be raised from private sources as the CCS market matures. Raising equity from the offtakers of a project can also ensure some security in revenue generation for them as investors. In

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addition, loan guarantees (e.g., backed by governments) could be established to de-risk debt financing. Alternatively, CO_2 taxation could be used to fund public grants, allowing them to be more sustainable in the long-term.

Decision Trees for CCS Business Models

The most appropriate CCS business model for an individual industrial plant will depend upon a multitude of decisions that the plant must make, considering factors such as their individual market & in-house expertise, the political & regulatory environment, and opportunities for capital funding. This section aims to illustrate the decision-making process that an industrial plant may need to go through to determine the most appropriate business model for their situation. This is done through the development of decision trees for revenue model, ownership, and capital financing.

Each decision tree starts from the point at which CCS is established as the best solution for the plant and the design of the decision trees is informed by the results of the Risk Mitigation Matrix. Interconnections between other business model components and external influencing factors (e.g., the political support available to an industrial plant to deploy CCS) are highlighted to emphasise how other players, both within and external to, the CCS market can affect the decision-making process. The focus of the decision trees is on CCS, with high-level options/considerations for augmentation of revenue with CCU.

The most appropriate business model is likely to change over time depending on market conditions for both the unabated and low-carbon product, availability of expertise (both in-house and external), the political & regulatory environment, and opportunities for capital funding. It is likely that these external factors may change the risk mitigation potential of each business model, such that these decision trees should be re-evaluated periodically.

These decision trees have the following key elements:

- **Key decision points** - yes/no questions that help determine whether a certain business model component is feasible and/or viable. For example: “is capital funding available?”
- **Actions** - recommended actions the industrial plant may take to improve the feasibility and/or viability of the business model. For example: “conduct campaigns/lobbying to improve political support for CCS”.
- **Decision-making factors** - factors that collectively contribute to the outcome of a key decision point. For example, the outcome of the key decision point “can the industrial entity deliver the entire CCS value chain?” depends on a range of site-specific factors, including availability of capital, land, skilled workers & utilities, and whether the industrial entity is an isolated site or part of a cluster.

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- **Business model component** - the endpoint of the decision tree. Each business model comes with a range of considerations to be managed on a case-by-case basis, as described in Section 2.

The **revenue model decision tree** initially asks whether the decarbonised product is cost-competitive with the unabated option, to determine whether an additional revenue model is specifically required for the low-carbon product. If an additional revenue stream for CCS is required, the next step is to determine whether a Level Playing Field (the revenue model with the lowest risk to the industrial plant) is feasible - i.e. does a government revenue incentive (e.g., subsidy) exist that can cover the additional costs? The answer to this depends on whether the CCS project is eligible for the revenue incentive, the political security of the revenue incentive (including the length of time the support is available for), and the amount of funding (i.e., whether it would cover CCS costs). If a Level Playing Field is not feasible, then similar decisions need to be made involving the feasibility and viability of the Regulated Market revenue model. If no external support is available, only then does the decision tree direct the user to the Green Premiums revenue model (the least preferred revenue model due to its high risk to the industrial plant).

The **ownership structure decision tree** first assesses the ability of the industrial plant to deliver the entire CCS value chain; this includes a consideration of whether capital financing is available, and whether this capital financing is associated with any ownership structure requirements. If vertical integration is deemed feasible, next comes the decision of whether the industrial plant *should* develop/own all CCS infrastructure, with decision-making factors to be considered including the operational risks of CCS versus the cost/possibility of outsourcing to another entity. If vertical integration of CCS is not feasible or viable, then the Vertically Integrated option is eliminated and similar considerations (e.g., finance, risk versus price markups etc.) are applied to the choice of whether to develop a capture plant and outsource the T&S or outsource all CCS infrastructure entirely. In some cases where the industrial plant may be unable to deliver sufficient CCS infrastructure by itself, there may also be no T&SCo or CCaaS entities available for CCS outsourcing. In this case, different decarbonisation options should be considered instead (e.g. fuel-switching to hydrogen or electrification).

The **capital financing decision tree** begins with key decision points that first determine the ability of the industrial plant to self-fund the CCS project (the capital requirements of which depend on ownership structure) and, if this is feasible, the viability of this decision. If additional capital financing is required/desired, the availability & viability of different funding sources is then assessed, in order of risk mitigation potential (public grants/loans > private equity > private debt). The availability of different funding sources is likely to be strongly dependent on both the revenue model (i.e., security of revenue generation) and the ownership structure (i.e., magnitude of investment required) chosen.

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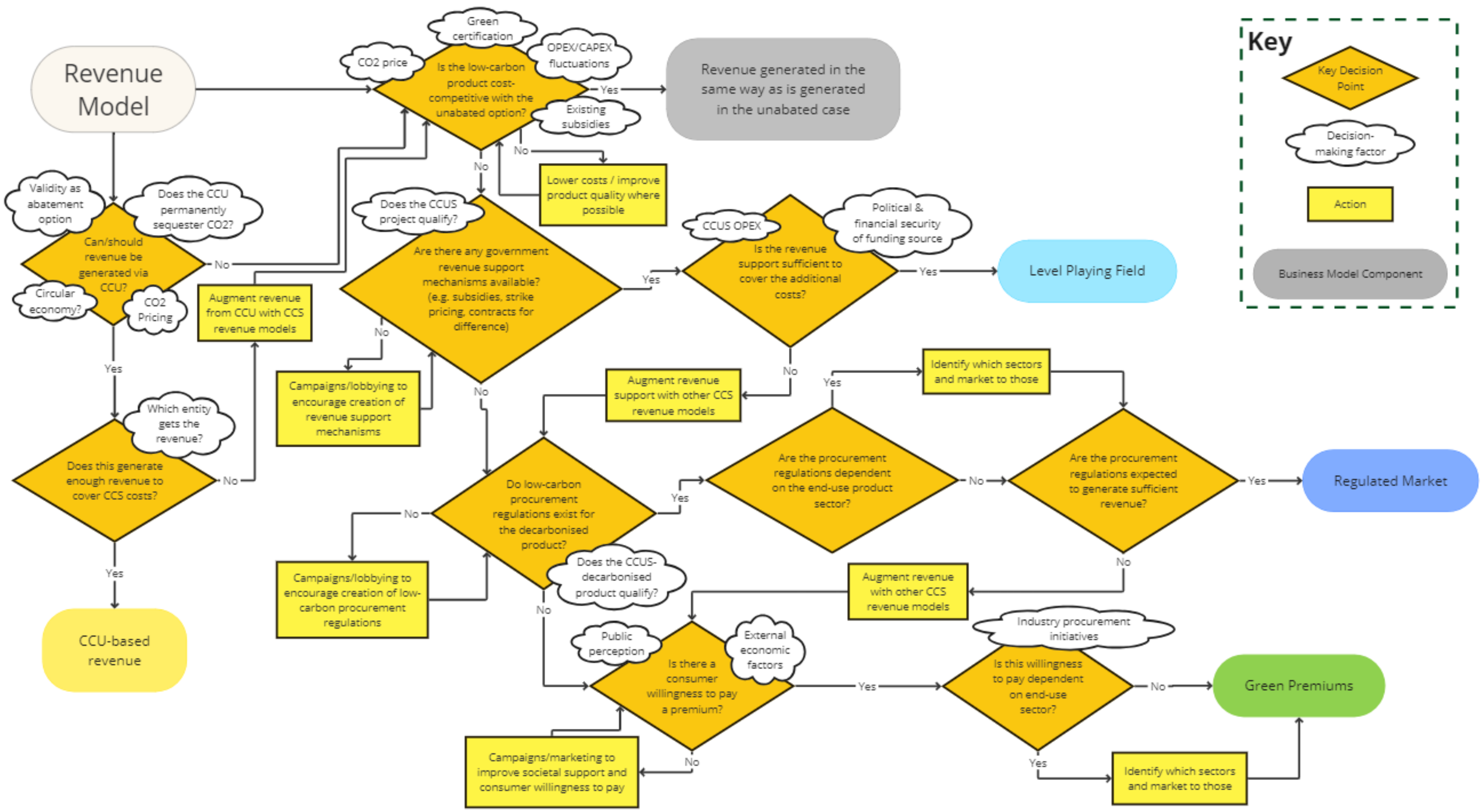

Figure 3: Illustrative Decision Tree to choose a revenue model for an industrial plant deploying CCS at a given point in time.

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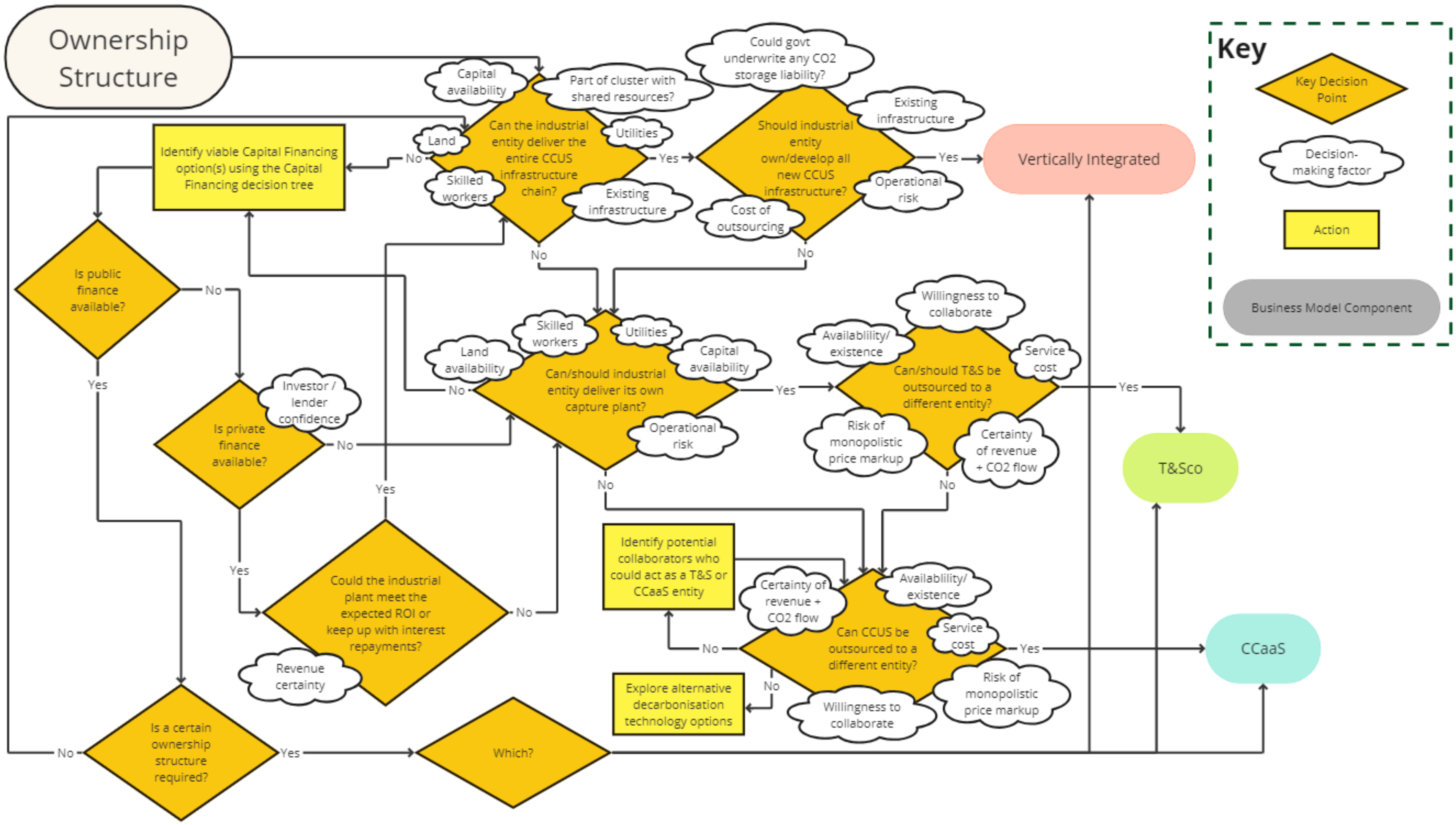

Figure 4: Illustrative Decision Tree to choose an ownership structure for an industrial plant deploying CCS at a given point in time.

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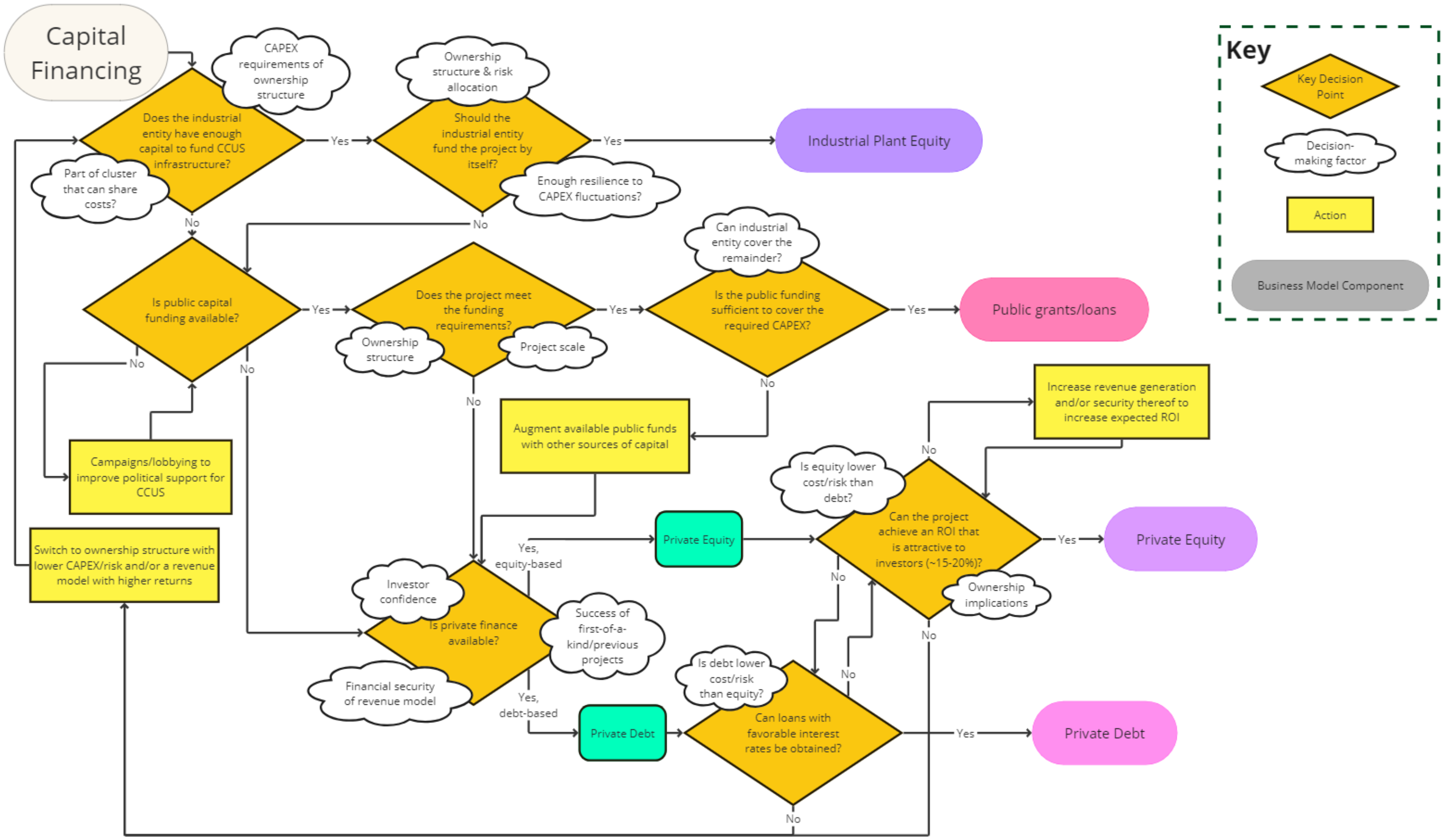

Figure 5: Illustrative Decision Tree to choose a capital financing model for an industrial plant deploying CCS at a given point in time.

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5 Conclusions, key takeaways and recommendations

CCS is a necessary technology to reach net zero, but widespread commercial deployment in a self-sustained market is currently challenging.

- To reach the EU's target of net zero emissions by 2050, the EU Commission's Industrial Carbon strategy is expected to set a target of 200 $MtCO_2$ to be captured and stored by 2040. This target will require widespread deployment of CCS, particularly by energy-intensive industries.
- Although CCS has been deployed since 1970s, mainly for the purpose of Enhanced Oil Recovery (EOR), deployment solely for the purposes of emission reduction is limited.
- The C^4U project has reviewed literature on the challenges of CCS deployment and engaged with industrial stakeholders in the North Sea Port to understand why current CCS deployment for emissions reduction is limited.
- Our findings from this research revealed that technical challenges related to CCS can be overcome, but challenges in both financing CCS infrastructure/generating revenue and allocating risks between players have hindered widespread deployment of CCS for emissions reduction thus far.
- To kick-start the CCS market, governments are currently trying to support initial CCS deployment, for example through the US Inflation Reduction Act and the EU Net Zero Industry Act.
- However, to ensure a self-sustaining CCS market in the long-term, viable business models that generate revenue from CCS, share risks equitably and provide financing for the upfront costs need to be designed and implemented.

A viable business model for CCS should consider the motivations of all players in the CCS value chain.

- A viable business model is one that creates and delivers value for its customers while enabling the business to continue operating and generate profit.
- There are a number of key players in the value chain for low-carbon industrial production with CCS, each with differing motivations – de-risking CCS deployment for each of these players through a viable business model should underpin widespread infrastructure roll-out.
- Stakeholder engagement with key players in the North Sea Ports region highlighted drivers to CCS adoption (e.g., financial incentives for CCS, increasing willingness to act against climate change) as well as barriers (e.g., policy/regulatory uncertainty, technical challenges and negative public perception associated with continued fossil fuel use).

There are three key components of a viable CCS business model – low-carbon revenue generation, infrastructure ownership and capital financing source.

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1. A **revenue model** that describes where the income generated to cover the costs of capture, transport, and storage ultimately comes from (e.g., taxpayers, consumers). Three routes are proposed which can be taken to establish a market for green products:
    - **Green Premiums** where revenue is generated because both initial consumers and end users are willing to pay more (a premium) for the low-carbon product rather than the unabated alternative.
    - In a **Regulated Market** revenue model, a regulating body (e.g., governments, trade bodies) specifies minimum low-carbon requirements when awarding procurement contracts or legally mandates the use of certain amounts of low-carbon products, either at a sectoral level or by individual companies.
    - In the **Level Playing Field** revenue model, low-carbon products are cost competitive with the counterfactual carbon-intensive unabated options through incentives such as subsidisation or taxation.
2. An **ownership structure** that describes which player is responsible for each of the key parts of the CCS value chain. Within the ownership structure, mechanisms will be required to mitigate risks and allocate them between parties. From the perspective of the industrial plant, there are three potential ownership structures:
    - In the **Vertically Integrated** ownership structure, the entity which already owns the industrial plant or emission source, uses their in-house technical and commercial capabilities to support all elements of the CCS infrastructure chain.
    - The **Independent Transport and Storage Entity** ownership structure is based on a partnership between the industrial plant (also liable for the capture plant) and an external entity who operates the transport and storage (T&S).
    - In the **Carbon Capture as a Service** ownership structure, a dedicated CO_2 handling entity charges the industrial plant a fixed fee to capture, transport and store/utilise the CO_2 produced.
3. **Capital financing**, which is required to fund the construction of CCS infrastructure. Often, the industrial plant will have insufficient capital and/or credit rating, so may require support through mechanisms such as **public grants/loans, private equity funding, and/or private loans**.

Economic, infrastructure and political risk factors each have varying impacts on how successful a business model is in CCS adoption.

- We have evaluated each business model component against different risk factors to an industrial plant as CCS projects depend on successful deployment and operation of infrastructure, and effective coordination along the CO_2 value chain.
- **Infrastructure risk factors** include deployment delays, downtime, or loss/failure of CCS infrastructure. These risk factors may affect overall capital costs of CCS deployment.

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- **Economic risk factors** involve changes in OPEX & CAPEX of CCS infrastructure, cost & availability of finance, CO_2 pricing, market size and consumer willingness to pay for the low-carbon product. These risk factors may affect the profitability of a CCS business model through variations in the production cost, sale price and consumer demand of the decarbonised product relative to the unabated option.
- **Political risk factors** include availability of public finance, low-carbon procurement quotas, strike pricing, CCS pricing regulations and CO_2 storage liability support. These may influence the deployment and scale-up of CCS if it is facilitated through government support and/or risk sharing.

The level playing field revenue model appears the most resilient to risks associated with CCS deployment to an industrial plant. The most resilient ownership structure depends on the magnitude and availability of capital financing available to the industrial plant.

- A risk mitigation matrix was developed to reflect the ability of each business model component to mitigate the total risk, by lowering the likelihood and/or reducing the impact of each risk factor.
- The Level Playing Field revenue model appears the most resilient to risks. The main relative vulnerability of this revenue model is the availability of the revenue incentives (e.g., carbon taxes, subsidies) on which it relies.
- Revenue models relying purely on green premiums from conscious consumers appear the most vulnerable to nearly all risks considered.
- Different ownership structures come with different risks, but ultimately the preferred structure depends on magnitude of upfront costs which can be covered by the industrial plant through capital financing and the expertise of the industrial plant.
- Public grants & loans appear to offer slightly lower risks than private finance (equity or debt based) but may have more restricted availability, particularly in a long-term, widespread CCS market.
- Availability of private capital financing is likely to be strongly influenced by choice of both revenue model and ownership structure. The magnitude and certainty of revenue generation is likely to significantly impact the numbers of private investors/lenders willing to finance the CCS infrastructure.

Over time, CCS business models are expected to transition from those initially targeted at first-of-a-kind projects that prioritise lower risks for the industrial plant, towards a self-sustaining business model in a widespread, mature CCS market.

- To achieve a self-sustaining commercial CCS market large enough to significantly lower industrial emissions, a portfolio of CCS business model components will likely be required.

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- In the long-term, a Level Playing Field revenue model is still likely to offer the lowest risk to the industrial plant, provided it implemented in such a way that minimises the financial burden on the government (e.g., through CO_2 taxation).
- As the CCS market matures, the increasing presence of dedicated CCS service operators providing carbon capture as a service, and/or transport and storage solutions should de-risk CCS deployment from the perspective of an industrial plant.
- Public grants/loans, while offering a degree of risk mitigation for first-of-a-kind CCS projects, are unlikely to be a sustainable source of capital financing in the long-term. Investor confidence should be improved and/or the use of private debt de-risked by ensuring secure revenue generation
- To de-risk certain business model components governments could:
  - Establish green procurement regulations for a wide range of energy-intensive industries
  - Encourage offtake agreements with key conscious consumers
  - Develop guidance/standards for CO_2 transport and storage

The most appropriate CCS business model for an individual industrial plant will depend upon a multitude of decisions that the plant must make, considering their individual market & in-house expertise, the political & regulatory environment, and opportunities for capital funding.

- Via the development of decision trees, this study has illustrated the decision-making process for an industrial plant to select an appropriate CCS business model.
- Our decision trees start from the point at which CCS is established as the best solution for the plant and then highlighted the interconnections between business model components and external influencing factors (e.g., the political support available to an industrial plant to deploy CCS).
- Our decision trees highlight how the most appropriate business model is likely to change over time depending on market conditions for both the unabated and low-carbon product, availability of expertise (both in-house and external), the political & regulatory environment, and opportunities for capital funding.
- Our decision tress may be used by industrial plants as a high-level guide for choosing a CCS business model, considering the revenue model, ownership structure, and capital financing route. Other players in the CCS market may also use them to influence deployment of CCS at the industrial plant.

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