element energy

Industrial carbon capture business models

Report for

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Terminology

Term	Definition
Capture rate	The % of CO_2 generated that is captured.
Carbon capture (utilisation) and storage (CCS / CCUS)	The process of capturing CO_2 and transporting and storing (or utilising) it so that it is not emitted to the atmosphere.
Carbon leakage	For the purposes of this study, industry relocating to regions with less stringent environmental regulations to reduce costs, thereby simply moving CO_2 emissions abroad, rather than eliminating them. This can be either through physical relocation of a firm's production facilities, or closure of UK facilities due to loss of competitiveness to sites abroad.
CCS certificates	Certificates representing a certified t/CO_2 abated (and stored).
CO_2 (carbon) price avoidance	Avoided emissions costs through reducing CO_2 emissions in a market with a CO_2 price. See page 39 for details.
Consumers	Consumers of goods and services in the economy.
Cost plus	A business model where, for the purposes of this report, all costs are covered by government through open book reporting.
Emissions performance standards (EPS)	A policy instrument which sets maximum emission standards for specified emitters or products.
EU Emissions Trading System (EU ETS)	An EU policy to reduce emissions by setting a cap on the emissions for qualifying activities (large point sources of CO_2). Emissions allowances can be purchased and traded by operators to cover the obligation.
Industrial carbon capture (ICC)	The process of capturing CO_2 from industrial sites, including purifying and compressing it ready for transport.
Levelised cost of abatement (LCoA)	The cost per tonne of CO_2 abated (£/tCO_2) over the lifetime of the project. In this case, it is the equivalent CO_2 price that would be required to financially break even.
Obligations	A policy instrument in which a party is legally bound to fulfil a commitment. For example, to surrender a number of CCS certificates each year or meet certain EPS requirements.
Pain-gain risk sharing mechanism	Parties share in the financial 'gain' of a project's overperformance or the financial 'pain' of a project's underachievement.
Policy instruments	Interventions by the government in the economy to achieve certain objectives.
Private sector	The for-profit sector of an economy, not under direct state control.
Public procurement	The purchasing of goods or services by the government. Note that this refers to the government performing the act of purchase; it may levy the private sector for the necessary financial resources.
Public sector / Government	The sector of the economy controlled by the state.
Scale-up phase	During the scale-up phase of technology development, a technology moves from demonstration to commercial scale. For UK CCS, the first few projects can be considered the scale-up projects.

Regulated Asset Base (RAB)	A RAB model values existing assets used in the performance of a regulated function, for example UK gas distribution, and sets tariffs to pass the costs of these assets on to consumers.
Roll-out phase	Roll-out succeeds the scale-up phase. The technology builds sufficient track record to access capital at reasonable market rates and a sustained industry supply chain develops.
Storage liability	The liability for any environmental damages from storing CO_2.
Transport and Storage (T&S)	The process and infrastructure for transporting captured CO_2 away from an industrial site and storing it permanently.
Tax credits	A policy instrument which provides reductions in the tax liability of a tax payer for fulfilling defined criteria.

Glossary

BAT	Best available technology (technique)
BAU	Business as usual
BEIS	The Department for Business, Energy and Industrial Strategy
Capex	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CfD	Contract for Difference
CfD_C / CfD_P	Contract for Difference on CO_2 price / product price
CHP	Combined heat and power
CO_2	Carbon dioxide
EII	Energy intensive industry
EOR	Enhanced oil recovery
EPS	Emissions performance standard
EU ETS	EU Emissions Trading System
FEED	Front end engineering design
FES	National Grid Future Energy Scenarios
FID	Final investment decision
FOAK	First of a kind
GHG	Greenhouse gas
H_2	Hydrogen
ICC	Industrial carbon capture
JV	Joint venture
LCoA	Levelised Cost of Abatement
Opex	Operational expenditure
PPP	Public-private partnership
RAB	Regulated Asset Base
ROI	Return on Investment
T&S	Transport and storage

Unit	
t	Tonne
Kt	Kilotonne
Mt	Megatonne (million tonnes)
$MtCO_2e$	Megatonnes of CO_2 equivalent

Disclaimer

Contents

1 Executive Summary

Overview

Deep decarbonisation of all sectors of energy use is required to meet the UK's long-term emissions reductions goals. Whilst progress has been made in the power sector, energy intensive industry (EII) presents a particular challenge, both technically due to lack of alternative processes, and economically, due to the internationally traded nature of many products. Carbon Capture Utilisation and Storage (CCUS) has been recognised, both internationally and in the UK, as a key technology in reducing carbon dioxide (CO_2) emissions in industry. In the last 15 years, the annual global CO_2 storage rate doubled to a 2017 value of around 37 $MtCO_2$/year, with most operational projects being industrial CCUS. Importantly, ICC presents many opportunities for the UK, including protecting existing industry from exposure to climate regulations (e.g. CO_2 pricing), attracting foreign direct investment in UK manufacturing and supporting decarbonisation of the heat sector. The International Energy Agency estimates there will be a global CCUS market worth over £100 bn, and even a modest share of this could increase UK GVA by between £5 bn and £9 bn per year by 2030 (The Clean Growth Strategy, 2017).

To unlock the potential for CCUS deployment at scale in the UK during the 2030s, BEIS committed in the Clean Growth Strategy (CGS) to review viable delivery and investment models. As the previous full-chain CCS projects in the UK involved complex risk sharing arrangements, it is important to explore whether "part chain" business models for industrial carbon capture (ICC) are more investable. Element Energy and its partners were commissioned by BEIS to identify the range of business models that could incentivise cost-effective deployment and operation of ICC technology in the UK. Consideration is given to the key barriers currently hindering the deployment of ICC as well as business models used in other sectors and countries that have potential to address these challenges and drive cost reductions.

Key challenges of ICC

There are many challenges to the deployment of ICC, but these challenges can be successfully addressed to unlock the opportunities ICC brings and enable a cost-effective decarbonisation pathway for industry. To identify the key challenges to the deployment of ICC in the UK, the study draws on expertise from a broad range of stakeholders and the considerable literature outlining market failures and barriers to CCS, including learnings from unsuccessful UK CCS projects.
These challenges were evaluated and categorised as follows:

- **Technical and operational:** Risks and challenges associated with the ICC technology and its performance (e.g. the capture rate is lower than expected) and risks and challenges to the industrial operations associated with integrating the capture plant (e.g. industrial plant downtime).
- **Economic and market:** Risks and challenges associated with the capital and operational costs, including the market uncertainties and international competitiveness. For example, uncertainties around operational costs (opex) and fuel prices.
- **Political:** risks and challenges associated with policy and regulation. For example, the uncertain CO_2 price signal given by the European Emissions Trading System (EU ETS).
- **Cross-chain:** Risks and challenges associated with the integration and coordination of parts of the CCS chain. For example, the risk of transport/storage counterparty default.

As this study focuses on part-chain business models for industrial carbon capture, some of the most important risks under the "cross-chain" category are expected to be addressed via the decoupled transport and storage (T&S) business model and by the introduction of government backing. The remaining technical and operational risks are expected to reduce over time during the 'scale-up' phase[1] and can be addressed contractually. The economic, market and political risks should be addressed by the ICC business models and are therefore directly included in the business model assessment.

[1] The scale-up phase comprises the first few projects as CCS develops from demonstration to commercial scale.

Business model characterisation and selection

ICC business models were characterised to define the key elements which differentiate the mechanisms: revenue model, funding source, risk management, capital options and ownership model. The full set of options available under each of these elements is summarised in Figure 1-1.

Figure 1-1 Summary of the options available for each of the ICC business model elements

Revenue models

- Contract for difference on CO_2 price
- Cost plus open book
- Regulated asset base
- Tradeable tax credits
- Product CO_2 taxes (redistributed)
- Tradeable CCS certificates
- EPS + tradeable CO_2 credits
- Low carbon product market creation
- CO_2 utilisation & EOR *(not considered as primary drivers for UK ICC)*

Risk management

- Loan guarantees
- Insurer / buyer of last resort
- Stable policy or long-term contracts
- Price floor & ceilings
- Revenue guarantees
- Border adjustments
- Public underwriting of risks
- Pain-gain sharing mechanisms
- T&S fee regulation

Funding source

- Exchequer
- Emitters
- Fossil fuel suppliers
- Energy consumers
- Purchasers of low carbon products
- CO_2 sales for utilisation

Capital & ownership

Capital:
- Public grants or loans
- Emitter equity
- Debt (commercial & multilateral funds)

Ownership could be private, PPP or public *(public ownership is considered unlikely for capture plants).*

The **revenue model** is the income generated by the emitter through capture, with the aim of covering the costs of capture plant operation (e.g. opex, fuel, CO_2 T&S fees). Industry input highlighted that the fundamental ICC barrier from the private sector perspective is the absence of a value proposition. The revenue model is the central element in creating value for ICC, so was used as the basis for the business model, building other necessary elements around it. The **funding sources** available for each revenue model may be different. For example, for models such as a tax credits, the funding comes from government, whether that be through general taxation or levies. Alternatively, a CCS certificate obligation, or other tradeable CO_2 certificate scheme, allows cost to be passed on to all obligated parties, including fossil fuel suppliers, giving a wider pool of funding options. The funding sources available for each model will contribute to political acceptability. Revenue models may inherently address some of the risks associated with ICC, and the remaining risks must be mitigated through additional **risk management instruments,** developed to support each business model.

The revenue model and the risk management options added will have an impact on the sources of capital financing available for development and construction of the capture plant. Where the revenue model provides certainty of returns and the private sector is shielded from the most significant ICC risks, commercial debt finance may be available at low cost. In addition, the business model *may* also benefit from grants or capital loan guarantees from government in the scale-up phase where required. The ownership model of the capture plant includes ownership of the plants assets, with responsibility for their operation and maintenance, and may be distinct from the ownership, operation and maintenance of the T&S infrastructure.

Business models were evaluated for their acceptability to industry and government through the development of selection criteria. The assessment utilised the key criteria shown in It should be noted that 'cost to government' represents the level of subsidy required from government; this is distinct from the *source* government chooses to fund that revenue (subsidy), as above. The mechanism to 'collect' revenue for redistribution determines which parties the costs are passed on to. For example, exchequer funding passes costs to taxpayers, fossil fuel supplier levies to fuel consumers, and the distribution of EU ETS certificates (or equivalent) to ICC transfers costs to polluters.

Figure 1-2, which was developed with input from industry and government. The industrial criteria evaluate the strength of the revenue model and how well the model protects industry from the key risks. The government criteria aim to evaluate how cost-effective the policy could be for the public sector, as well as the potential burden of policy implementation. It should be noted that 'cost to government' represents the level of subsidy required from government; this is distinct from the *source* government chooses to fund that revenue (subsidy), as above. The mechanism to 'collect' revenue for redistribution determines which parties the costs are passed on to. For example, exchequer funding passes costs to taxpayers, fossil fuel supplier levies to fuel consumers, and the distribution of EU ETS certificates (or equivalent) to ICC transfers costs to polluters.

Figure 1-2 Criteria used to evaluate ICC business models

'Acceptability to industry' criteria	'Acceptability to government' criteria
1. Capital availability or low-cost financing	1. Cost: efficiency promotion
2. Strength of revenue incentive	2. Cost: ability to pass costs on
3. Industry competitiveness & carbon leakage	3. Policy track record
4. Flexibility for operational cost uncertainties	4. Speed and simplicity of implementation
5. CO_2 price level and uncertainty	5. Ongoing administrative simplicity
6. Simplicity and transparency for industry	• Applicability to industrial sectors
	• Applicability to CCS phases

Promising ICC business models

The key to a successful mechanism is balancing the private and public sector requirements and allowing this balance to change as the market matures. After the analysis, six of the business models were considered sufficiently promising to recommend for further investigation.

Contract for Difference CfD_C CO_2 certificate strike price

The emitter with ICC is paid (or refunded) the difference between a CO_2 strike price contractually agreed, in £/tCO_2 abated, and the prevailing CO_2 market certificate price. The quantity of CO_2 'abated' is determined relative to an industry benchmark (see page 62) to ensure that best available technologies (BAT) are deployed where possible and the deployment of high emissions technologies is not incentivised through CO_2 revenue. The CfD_C strike price is fixed for the duration of the contract (e.g. 15 years), but each contract may have a different strike price.[2] For early projects, the strike price may need to be higher due to the greater uncertainty and risks. Risk management may include index linking of the strike price to fuel prices, pain-gain risk sharing mechanisms[3] for deviation from expected costs, and capital loan guarantees in the scale-up phase. The main advantages of this mechanism are that it is capable of providing a strong and certain revenue incentive and the 'cost to government', if well designed, is only the net amount required (above the carbon price avoidance) to compensate the emitter and protect industry competitiveness. In addition, operational efficiency is incentivised, the model is broadly applicable across the industrial subsectors, and the model can transfer the construction and performance risks to the private sector in the roll-out phase as the strike price is fixed and the incentive is not paid until the ICC plant is operational. However, costs are not passed on to consumers or other parties directly, so the government funding would need to be recovered through general taxation, levies or other mechanisms. The policy track record is good, as evidenced by

[2] The strike price is likely to be set on a site by site basis in the scale-up phase through bilateral negotiations, but the roll-out phase may introduce a competitive bidding process.
[3] Parties share in the financial "gain" of a project's success/overperformance or the financial "pain" of a project's underachievement. Parties therefore have a shared interest in the overall success of the project.

parallels with the power CfD mechanism. Adaptation of the power CfD may allow more efficient policy development & implementation, although sector or site specific CfDs would add complexity.

Cost Plus open book (adapted from Teesside Collective, 2017)
The emitter is directly compensated through government grants for all properly incurred operational costs and any emitter capital investment is paid back with agreed returns. The corresponding CO_2 certificate value would be deducted, partially or fully, from the payments, as unused certificates can be sold by the ICC emitter. This mechanism provides a very strong incentive for industry, as ICC costs are fully covered with guaranteed returns and it is also simple and transparent. However, cost to government (recovered through taxes, obligations or other schemes), is likely to be high as costs are not passed on to consumers and efficiency in project selection and operation is not incentivised. Therefore, the model requires efficiency incentives such as pain-gain sharing mechanisms, a robust project selection process and monitoring of capex and opex for early identification of cost overruns. The policy track record is reasonable. The model can be implemented rapidly for early projects, but ongoing administration is potentially complex due to the need to evaluate every project annually, making it less sustainable in the roll-out phase, where the number of ICC projects may reach into the hundreds.

Regulated Asset Base (RAB)

All investments made by the industrial site are valued and costs are recovered from 'consumers' under regulation. The RAB model is thought to be primarily applicable for hydrogen production for heat, where the cost recovery is through gas consumer bills[4]. The mechanism provides a solid incentive for industry as ICC costs are fully covered under the regulated model, passing risks on to consumers. The likely low returns may attract a different type of investor (e.g. pension funds) and there is a need for robust project selection and efficiency incentives, for example by allowing the value of cost reductions to increase investor returns. While the cost to government and taxpayers is low, affordability concerns should be addressed around consumer gas bills, including gas price impacts on EII competitiveness. The policy track record is good as the RAB model is successfully functioning in the UK energy market and other infrastructure markets. Implementation requires creation or repurposing of regulatory body and administration may be relatively complex due to the need to evaluate every project annually.

Tradeable tax credits for CCS
Tax credits are reductions in the tax liability of firms which implement ICC, in £/tCO_2 abated, and may taper through the contract. The credits must be tradeable to allow full realisation of their value and a government buyback guarantee may be required, as well as capital support. If the credits are of sufficient depth, longevity and certainty, they provide a strong incentive to emitters and the required certainty to investors. The mechanism is also relatively simple and transparent for industry. The cost to government is moderate as efficiency and low-cost project selection are incentivised, but costs are not passed to consumers. Some emitters may be overcompensated if a blanket tax credit is applied to all industrial subsectors, but subsector or site specific tax credits would add complexity. The policy track record of tax credits is strong, but the tradeable element remains unproven. Implementation may be relatively quick and administration for a blanket tax credit would be less complex than many mechanisms. Tax credits may ultimately work best in combination with other business models.

Tradeable CCS certificates + obligation

Tradeable CCS certificates are awarded, per tCO_2 abated, and obligated parties are obliged to surrender a set number of these certificates, which may increase over time. Certificates are freely traded, so obligated parties without CCS may purchase them from ICC emitters. The certificate price may be highly uncertain and volatile, resulting in a weaker incentive for industry and lower investibility; creation of a price floor through a government buyout price and a price ceiling through penalties may partially mitigate this. The CCS obligation may be on emitters and/or fossil fuel suppliers, allowing the

[4] Other industrial subsectors are subject to competition both domestically and internationally, so cannot pass costs on to consumers in the same manner. However, if a proxy was created for the consumer base (likely the exchequer), a similar regulated model could be used in place of 'cost plus' for the other industrial subsectors.

financial burden to be shared more widely and passed on to other parties, reducing the cost to government. As this is a market mechanism, it also incentivises efficiency of operation and low-cost project selection. The policy has a reasonable track record (e.g. Renewables Obligation) as well as providing a route to decreased government involvement over time, provided there is sufficient trading for a functioning market. While market creation is relatively complex, the administrative burden on government may be low, assuming government does not act as an intermediary in any transactions. However, if the certificate market is not liquid enough, government intervention may be required to stabilise it through alteration of the price floor/ceiling, the level of obligations or combination with the CfD_C mechanism. Consideration should also be given to how the CCS certificate price would/should interact with the EU ETS CO_2 price and how this could be controlled (see page 49).

Creation of low carbon market

Creation of a low carbon market in the UK through certification, public procurement of low carbon products and regulation of end uses (e.g. buildings) allows a price premium for low carbon goods through guaranteed demand. The key advantages of this model are that the cost to government is low and it directly incentivises efficient production of low carbon products through a market led mechanism. However, the strength of the revenue incentive of early projects is uncertain before the market develops sufficient supply and demand to promote competition and allow the price premium to stabilise. Equally, while demand creation partially addresses carbon leakage (see Terminology), the regulated demand is not present outside the UK, so firms with ICC would be less competitive on exports without financial support. The model may be strengthened through additional elements such as tax credits for competitively exposed industry, tax credits for end-use, or a price premium guarantee. The mechanism has little track record, although public procurement and end-use regulation are common practise. It is likely to be complex to implement & potentially administer if applied to a large number of end-products, although government support could be gradually removed as the market matures. Creation of a European or global low carbon market would be more effective; however, a UK low-carbon market would also create demand and strong signals for CCUS deployment, especially for the UK industries with lower export proportions such as cement.

Three of the models above are broadly applicable: **CfD_C** on CO_2 price; **tradeable tax credits**; and **tradeable CCS certificates**. The other three have limited applicability or require further research. **Cost plus** is a promising model for the scale-up phase but may not drive the desired cost reductions in the roll-out phase. **RAB** performs well under the evaluation criteria but is primarily applicable to hydrogen and raises affordability concerns around heating bills. Finally, **low carbon market** creation is considered to have potential; however, the concept requires further development to better understand the instruments required for success.

Further discussion of business model requirements

The characteristics of the CCS market maturity phases define their differing requirements. The scale-up phase, consisting of the first few ICCS projects, requires specific government involvement, both in terms of risk ownership and financial contribution, to create a strong and certain revenue model capable of incentivising ICC investment. The aim is that the business model should allow this support to be gradually removed over time as the market matures and costs are passed to consumers (e.g. through raised product prices). Models such as '*Cost Plus'* perform well in the scale-up phase, providing revenue certainty, but may not be the most cost-effective solution for government in the roll-out phase[5]. Market led mechanisms, such as '*tradeable CCS or CO_2 certificates'*, are likely to allow reduced government involvement over time and drive cost reductions in the roll-out phase most successfully. However, they may require supporting mechanisms in the scale-up phase to provide sufficient revenue certainty for industry. Mechanisms which can be applied effectively to both CCS market phases (scale-up and roll-

[5] The roll-out phase succeeds the scale-up phase. The technology should build sufficient track record to access capital at reasonable market rates and a sustained industry supply chain develops.

out) include *CfD_C, tradeable tax credits and RAB*. Using the same business model for both CCS market phases has benefits and allows the model to be tested and improved during scale-up.

The models also differ in their allocation of construction and performance risks, which may be a key consideration in model selection. In the roll-out phase, the private sector is expected to take these risks in four of the promising models: CfD_C, Tradeable tax credits, Tradeable CCS certificates and Low carbon market. In Cost Plus, the government accepts a larger share of the construction and performance risks and in RAB they are indirectly held by the energy consumers (hydrogen). However, in the scale-up phase, it is likely that the government would have to accept at least partial liability for these risks in all models, through mechanisms such as loan guarantees and pain-gain sharing mechanisms. It is also worth noting that some additional operational risk sharing may occur under index linking of incentives e.g. strike prices index linked to fuel prices.

The industrial subsectors are diverse, with differing processes, locations, scales and product markets, however the risks and challenges to ICC deployment in these subsectors are broadly similar. A few key differences are relevant to ICC market development:

- **Sites emitting high purity CO_2**, such as ammonia, hydrogen and some other chemical sites do not require sophisticated capture technologies[6]. As a result, they have the lowest capital cost of ICC, but they may also be of small scale with dispersed sources.
- **Impact of ICC on production costs (%)** is dictated by factors including the carbon intensity and value of product and ranges from 3% - 70% across the EII subsectors analysed. Where the relative impact is low, a proportion of ICC costs *may* be borne by the emitter over time, provided the profit margins are sufficient to allow this.
- **Carbon leakage risk is not applicable to hydrogen for heat**, allowing costs to be passed to consumers in business models such as a regulated asset base (RAB). Most other major EII sectors are exposed to carbon leakage risk, so the models must address this. For hydrogen, there is also greater opportunity to fit ICC technology during construction, rather than retrofit, allowing a more cost-effective application (albeit along with the significant undertaking of hydrogen production, distribution and appliance conversion).
- **Some subsectors can be supported by UK regulations more effectively**. For example, new building regulations or regulations on infrastructure construction, where low carbon materials are used and sold domestically. In contrast, for other manufacturing sectors where the end product is sold internationally, such as vehicle manufacture, regulations around use of low carbon materials may put the manufacturers at a competitive disadvantage.

Whilst CO_2 utilisation is currently not considered a primary driver for ICC in the UK, it could provide an additional revenue source and business models could be adapted to incorporate or promote this – considering whether the technology achieves CO_2 reuse or CO_2 sequestration. For example, the section 45Q tax credit in the US contains different incentive rates for utilisation (primarily EOR in the US) and storage. If contracts for the sale of CO_2 can be negotiated with UK ICC projects, the level of incentive offered by government may be lowered accordingly. However, some of the additional revenue from sale of the CO_2 may be retained by the emitter (subject to State Aid), to increase their returns and provide an incentive to sell the CO_2 for utilisation where demand is available.

Industrial CCUS clusters improve economies of scale, including sharing T&S costs; some business models may allow additional benefits to clusters. For example, a CfD_C model may provide one **single incentive contract** to a cluster of emitters, which could reduce complexity for government, allowing negotiation on a cluster basis, rather than a site basis. Mechanisms incentivising low carbon products would require separate contracts, agreements or regulations for each product type, so the benefits of clusters administratively would be minimal. The terms of the business model could also be written to promote particular clusters. For example, additional incentives or regulatory measures could be applied to sites which can connect to existing infrastructure or sites in a strategic location.

[6] https://hub.globalccsinstitute.com/publications/carbon-capture-and-storage-industrial-applications-technology-synthesis-report/31-high

Consideration of hybrid models may enable further cost reductions and broader model applicability. Whilst this study outlines a range of discrete business models and highlights which of those models have promise, hybrid models could also be considered, utilising aspects from more than one of the models assessed. As an example, CfD_C can be combined with CCS certificate obligation, by either using the obligation to fund some of the CfD subsidy, or by putting the CfD on CCS certificate price (similar to a price floor). This would provide greater certainty over revenues for the industrial emitter, and the cost to government in the CfD_C model can be reduced through the CCS obligation.

It will be important to consider the wider implications of business models on all parties involved, as well as the broader economy. Consideration should also be given to potential unintended consequences of the models, and protection from these should be added. For example, product related mechanisms may incentivise other decarbonisation measures over ICC, thereby delaying the deployment of ICC and reducing its potential. The range of incentives or regulations in place will have an impact on the attractiveness of the UK as a location for industrial operations, so care should be taken to protect or improve the appeal. The impact of any policies on taxpayers and/or bill payers should be considered and efforts made to maintain affordability, particularly of consumer heating bills where hydrogen for heat is concerned. There will be many repercussions on the economy that are even further removed from the parties directly involved in the business model. For example, material substitution in construction and manufacturing industries to avoid higher material prices or comply with carbon regulations may impact the quality and lifetime of homes or vehicles. As a result, economic analysis is required to fully understand the benefits and potential risks.

Recommendations for further work

Additional studies or research should be completed to develop the promising models further and understand the implications of each for industry, government, consumers and the wider economy.

- Investigation into the **legislative requirements and implementation timeline** associated with each business model, as well as the requirement for a **delivery body or regulatory body**.
- **Cost-benefit analysis of various options**, including their implications on the wider economy and potential unintended consequences. This should include economic analysis on the impacts of these policies and business models on the attractiveness of the UK as an industrial location.
- **Further quantitative analysis on the selected business models.** Examples include reviewing the profits and tax liabilities of UK industries to assess the feasibility of tax credits; impact of low-carbon market creation on product prices; pricing mechanism of CCS certificates.
- Further research on **market creation for low carbon products,** including the contribution of additional mechanisms, such as price premium guarantees (CfD_P) or tax credits.
- **Further engagement with UK clusters and industries** to identify which models would be most effective and acceptable for the UK clusters. Detailed research into **how mechanisms could be applied to industrial clusters** and used to promote cluster development.
- Analysis on further development of the **CO_2 utilisation market** and incorporation of CO_2 utilisation into the ICC business models is recommended.
- Work around the most effective way to account for the **CO_2 price uncertainty** considering the CO_2 pricing mechanism(s) the UK government intends to implement in the short-term.
- Analysis on the **funding source** should be completed to understand the feasibility and 'optimal' combination of funding sources for each model. The potential option of passing costs on to polluters, thereby reducing subsidies, through additional allocation of tradeable certificates to ICC projects (e.g. EU ETS certificates) should be explored.
- Potential for **evaluation of hybrid models**, including those outlined in section 6.2.
- Research on integration of the ICC business model with the **T&S business model** will be important to ensure robust full-chain integration.

2 Introduction

2.1 Background

Deep decarbonisation of all sectors of UK energy use is required to meet the legally-binding emission reduction goals. Energy intensive industries (EIIs) are a particular challenge to decarbonise due to the lack of alternative production pathways and the globally competitive nature of many of the product markets.

Carbon Capture, Utilisation and Storage (CCUS) involves capturing carbon dioxide (CO_2) produced, often from power plants or industrial sites, and either utilising it or transporting it to sites where it can be permanently stored to prevent emissions to the atmosphere. In the last 15 years, the annual global CO_2 storage rate doubled to a 2017 value of around 37Mt/year, with 21 large-scale plants operating, or in construction, across the world. However, no projects have yet reached completion in the UK and the technology remains pre-commercial. It is commonly suggested that CCS is a key component of a cost-effective route to decarbonise industry sufficiently to meet climate targets by 2050 (Oxburgh, 2016). However, there is currently no clear delivery and investment model available in the UK to incentivise industry or other private parties to invest in the required technology and infrastructure. Just as in the development of the UK wind and solar industries, financial support is required to incentivise early projects and drive cost and risk reductions, which can then allow CCUS to compete with other decarbonisation options.

Despite continued government investment in CCUS internationally, there have been a number of set-backs to the deployment of CCS in the UK, including the failure of the UK CCS Competition in November 2015. The UK Government's statutory advisors recommended a part-chain approach, whereby the support for capture is separated from the support for transport and storage (Parliamentary Advisory Group, 2016). The CCS Cost Challenge Taskforce (2018) also recommended the Government consider reviewing the split-chain model to better manage risks, develop shared infrastructure and create an investible business model. In this study we look at part-chain business models to incentivise industrial carbon capture (ICC) deployment, in line with The Department of Business, Energy and Industrial Strategy (BEIS) commitment in the Clean Growth Strategy (2017) to review the delivery and investment models for CCS. In addition, the Government will spend up to £100 million from the BEIS Energy Innovation Programme to support industry and CCUS innovation and deployment in the UK, including £20 million of funding available for a CCU demonstration programme.

2.1.1 The value of CCUS

The Cost Challenge Taskforce Report (2018) highlighted the need for CCUS deployment to meet climate ambitions as well as the opportunity to improve productivity and competitiveness of our industrial centres through clean growth. CCUS unlocks widespread opportunities across the energy system, including the **decarbonisation of power and industry, production of low carbon hydrogen for heat and, potentially, a pathway to negative emissions in combination with bioenergy** (e.g. biomass combustion/gasification with CCS). Early deployment of CCS can also buy us significant 'carbon budget' for a time in the future that we may have to reduce CO_2 at a much greater speed and potentially much greater expense. The International Energy Agency estimates there will be a global CCUS market worth over £100 bn, and even a modest share of this could increase UK GVA by between £5 bn and £9 bn per year by 2030 (The Clean Growth Strategy, 2017). Analysis by the Committee on Climate Change (CCC, 2018) indicates that CCUS will be **the only way** to decarbonise certain key industrial sectors before 2050; they recommend that **10 $MtCO_2$ should be stored annually by 2030**, 3 $MtCO_2$ of which are from industry, to maintain the option of high levels of deployment by 2050, potentially over 100 $MtCO_2$/year. To enable this, business models and T&S infrastructure must be in place by the early 2030s or earlier (Parliamentary Advisory Group, 2016). The ETI reports that **successfully deploying CCS could save tens of billions of pounds on the cost of meeting carbon targets** (Energy Technologies Institute, 2015). ICC has a crucial role to play in realising these savings and safeguarding UK industry ready for a world undergoing significant climate transformations.

2.2 Objectives

The key aim of this study is to identify and evaluate a range of potential business models to drive cost-effective investment in part-chain industrial carbon capture. The work identifies core issues behind the slow development of CCS, and focuses on policy instruments with the potential to address these challenges and market failures, considering these during the development of business models.

The work builds on a large amount of available literature on CCS, both around the current challenges and the potential business models to address these. A comprehensive range of literature was reviewed and many stakeholders across industry, government, finance, consultancies and academia were consulted through interviews and a workshop. Additionally, CCS experts were included in the project team to provide practical real-world expertise and experience of CCS projects. This allowed a broad range of perspectives and input to ensure all key risks and potential business models were considered.

The study aims to prioritise the challenges and market failures identified, through discussion with the authors and the practical expertise of the project team. Consideration is given to the industrial subsector specific challenges and their impact on the business model requirements and options in these subsectors. The work also quantitatively evaluates the potential impact of these challenges and risks through cashflow analysis to enable an objective understanding of their influence on the required risk mitigation options. This analysis allows a stronger business case to be developed, with clearer information for private sector investors. ICC costs, risks and investment profiles may vary between subsectors, so analysis allows a high-level understanding of the differential impact on these subsectors.

A broad range of global CCUS business model case studies were reviewed, as well as UK infrastructure examples, with the goal of identifying all potential business model elements which could contribute to a successful UK ICC business model. The study characterises the business models into the key features which fundamentally differentiate models from each other and assess how well the different models address the key challenges.

The work aims to provide a robust and objective appraisal of a sub-set of feasible business models and associated policies against certain selection criteria. These criteria were proposed and prioritised through a stakeholder workshop, as well as being tested through collaboration with BEIS and the other CCS experts, to ensure there was no bias in the method or findings. The aim of this process is to develop and select business models which can effectively incentivise industry to deploy ICC, whilst driving cost-reductions and providing value for government and taxpayers. The advantages and disadvantages of the business models were presented, accompanied by discussion around the requirements for each model to be successful. The applicability of the models to CCS market maturity phases and different industrial subsectors is also considered and discussed. Recommendations around the most promising UK ICC business models are shared, to give guidance for further, more detailed analysis and model development.

Government and industry already recognise that CCS deployment is a shared endeavour, yet the distribution of responsibilities and risks between them has not yet been resolved, creating a barrier to deployment. Therefore, this work examines the business model challenges and opportunities from both public and private perspectives, exploring the key requirements and for acceptability to both parties.

It is important to create a path for ICC deployment through the early, scale-up projects to the roll-out phase. The study aims to consider the differing requirements of these market maturity phases and the ability of different models to transition between them or gradually remove public-sector support over time. Clarity in the direction of policies and obligations is important to enable decision making and investment in a technology such as CCS, which has a large capital outlay and relies on a long operating lifetime.

2.3 Scope of work

This study is focussed on incentivising the deployment of part-chain industrial carbon capture, with the associated work around transport and storage (T&S) being undertaken separately (Pale Blue Dot, 2018). The scope covers CO_2 capture across all industrial subsectors in the UK and is focussed on the incentives, models, and policy instruments rather than the technical requirements. The aim is a high-level evaluation of the potential business models and their associated advantages and disadvantages. This report considers the wide range of literature available on CCS challenges and business models, and builds on this, reflecting the current UK market and industrial outlook.

3 Industrial carbon capture requirements and challenges

Industrial carbon capture (ICC) involves capturing, purifying and compressing CO_2 produced on industrial sites, which would otherwise be released to the atmosphere. This CO_2 is produced primarily by either combustion of fossil fuels to produce heat and power or directly as a by-product of the industrial process. The waste gases often contain many other components and impurities, which must be separated out before the CO_2 can be transported to storage. This separation (often included in the term 'capture') can be completed using a variety of chemical and physical techniques, with varying technological maturity. Processes which produce pure CO_2 streams, such as the production of ammonia and hydrogen, often don't require sophisticated separation technology, reducing the cost and complexity of implementing ICC.

There are many processes of capturing CO_2. Post-combustion capture is the process of absorbing CO_2 produced through combustion in a suitable solvent. The CO_2 is then liberated from the solvent for transportation. A pre-combustion system involves converting the fuel into hydrogen and CO_2 before combustion using a process such as 'gasification' or 'reforming'; the hydrogen can then be combusted without producing CO_2. Oxy-fuel combustion uses pure oxygen for fuel combustion, rather than air, diluted with recycled flue gas. This results in a flue gas containing mainly CO_2 and H_2O, which can be more easily purified[7].

There are also many technologies and materials which have been developed for use in these processes. The most mature capture technologies are first generation amine chemical solvents (e.g. Monoethanolamine, MEA) and physical absorption solvents (e.g. selexol and rectisol). Physical solvents require significant electricity for compression of the source gas stream, to provide the elevated operational pressure that these physical solvent absorbents require. First generation amines are available for the scale-up projects in the 2020s, but may be superseded in the 2030s by less costly and more effective alternatives (Element Energy, 2014).

The differing requirements of the CCS market maturity phases and the industrial subsectors must also be considered to ensure business models are broadly applicable, flexible where necessary and provide value for money across a broad range of situations.

3.1 Industrial subsectors

Industrial emissions arise from a broad range of processes and industrial subsectors, each with their own challenges and requirements. Industrial emissions comprise direct emissions from industrial processes or combustion of fossil fuels, and indirect emissions, for example from electricity consumption. The total industrial emissions, direct and indirect, in the UK were estimated to be around 75 $MtCO_2$ annually in

[7] Carbon Capture and Storage Association http://www.ccsassociation.org/what-is-ccs/capture/

2017, which contributes around 20% of UK emissions[8]. The subsectors with the largest emissions contribution in the UK are shown below in Table 3-1.

Table 3-1 Total EU ETS emissions in 2016 of the top CO_2 emitting sectors in the UK

Subsector	Total EU-ETS emissions 2016 ($MtCO_2$ / yr)	Proportion of emissions which are energy-derived (%)[9]
Iron and Steel	12.8	86%
Refining	12.6	60%
Cement & Lime	6.8	36%
Ethylene / Ammonia	4.1	68%
Other chemicals	3.1	68%

Iron and steel

As of 2016, the UK steel industry produced 8 million tonnes of steel annually, employed 32,000 people and has an economic output of £1.6 billion, 0.1% of the UK economy[10]. However, it has been struggling against a fall in international demand for steel and lower production costs overseas, resulting in the closure of the Redcar production facility in 2015. As iron and steel can be globally traded in a competitive market, the subsector is at risk of carbon leakage. Carbon leakage is where UK firms may become uncompetitive internationally due to higher production costs or more stringent environmental regulations. This results in UK operations being displaced by operators in other countries not subject to the same controls, and thus CO_2 emissions simply being relocated, rather than eliminated.

Iron and steel are produced on a huge scale in factories such as that at Port Talbot in South Wales, owned by Tata Steel. Many of the processes are energy intensive, such as the extraction of iron in the blast furnace, which requires high temperatures and coke for reduction. Expected emissions from each of the UK's largest integrated iron and steel blast furnace plants are in the range of 5-8$MtCO_2$/yr. There are likely to be multiple sources of CO_2 for each site, which increases the complexity of carbon capture implementation. Generally, it is economic to capture around half of the emissions of a site, with minimal integration and base process redesign. These emissions will likely be those from Blast Furnace Gas and flue gas from a combined heat and power facility (CHP). Overhaul periods for blast furnaces are typically more than 7 years, providing constraints to the implementation of carbon capture technology (Element Energy, 2014).

Chemicals

The chemicals subsector is a highly diverse field, including the manufacture of materials such as polymers (plastics), bulk chemicals, ammonia and personal care products. It comprises around 2500 small and medium enterprises (SMEs) making up 97% of the subsector, and is primarily concentrated in the five main clusters – Humber, Merseyside, Teesside, Runcorn and Grangemouth. These clusters are already connected by a pipeline for a key feedstock, ethylene. The UK chemicals sector contributed £12.1 billion to the UK's economy and 99,000 jobs in 2016[11]. The chemicals sector trades globally, so faces challenges of competition from low cost production facilities, particularly in China.

[8] BEIS UK Greenhouse gas national statistics 2017 https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2017
[9] BEIS Industrial pathways models
[10] UK Steel industry: statistics and policy, briefing paper 2018
[11] Chemical sector report, House of Commons Committee, 2017 https://www.parliament.uk/documents/commons-committees/Exiting-the-European-Union/17-19/Sectoral%20Analyses/7-Sectoral-Analyses-Chemicals-Report.pdf

Production facilities in the chemicals sector are typically small, with multiple, heterogeneous CO_2 streams. They are likely to only be economic for CCS where a cluster can be formed to provide the economies of scale. However, a high proportion of the CO_2 can be captured and familiarity with CO_2 separation technologies is high at some chemicals facilities (Element Energy, 2014). Ammonia is one of the key chemicals within this sector and is of particular interest as the CO_2 stream has high purity, so capture technology is less costly to implement. This key distinction means ammonia will not face some of the challenges of ICC at other plants in the chemicals sector, so can be considered separately.

Refining

The refining subsector is responsible for transporting and processing crude oil and natural gas into end-products, using processes such as distillation and reforming. The sector contributed £2.3 billion to the UK economy in 2013 and the subsector is highly competitive globally, with companies predominantly owned by international businesses headquartered outside the UK[12].

A typical full UK refinery site emits 2-3 $MtCO_2$/yr of CO_2, depending on the extent to which site CHP plants are included. Refining sites are typically relatively heterogeneous and may have multiple flue gas vents, which must be brought together to capture a high proportion of emissions, as well as a low CO_2 stream purity. It is suggested that around 90% of the CO_2 produced could be captured cost-effectively, if the challenge of high site complexity and disperse vents can be overcome. The refining industry may be familiar with the use of a wide range of separation technologies. Overhaul periods are typically 5-7 years, placing an additional restraint on ICC implementation (Element Energy, 2014).

Cement

The cement-making process consists of heating raw materials, such as limestone, to produce clinker, then grinding clinker with gypsum and other materials to produce cement powder. The limestone must be heated to high temperatures, around 1,450°C, which both results in considerable fossil fuel combustion and direct production of CO_2 through disassociation from limestone, with process emissions accounting for around 65% of total sector CO_2 emissions[13]. In 2016, the cement production in Great Britain was 9.4 Mt annually and the annual UK revenue was around £0.95 billion in 2017, employing around 4000 people[14].

Typical cement sites have CO_2 emissions of 0.2Mt CO_2/yr – 1 Mt CO_2/yr. However, only three to four sites in the UK are in a position where transport and storage of CO_2 is realistic by 2025; these four sites (in Scotland, Yorkshire, and NW England) each currently emit approximately 0.5 Mt CO_2/yr. The CO_2 stream purity is moderate, at around 24%, and it is suggested that almost all of the emissions could be cost-effectively captured (Element Energy, 2014).

Hydrogen production

Whilst hydrogen production in the UK is still at relatively small scale, this has the potential to rise significantly if hydrogen is used to support the decarbonisation of heat, transport and industry. The most cost-effective source of bulk low carbon hydrogen is likely to be steam methane reforming (SMR), which reacts a natural gas feedstock with steam under high pressure, to produce hydrogen, with CO_2 as a by-product (Sustainable Gas Institute, 2017). Carbon capture can then be used to reduce the carbon intensity of the hydrogen produced. Electrolysis using low-carbon electricity is an alternative hydrogen production method but is currently considerably more costly.

Hydrogen production offers significant CCS deployment potential due to the possibility for rapid growth in the subsector, the advantage of a pure CO_2 stream and cost-effectiveness of fitting capture technology

[12] Industrial decarbonisation and Energy Efficiency Roadmaps to 2050, Oil refining, BEIS, 2015.
[13] Industrial decarbonisation and Energy Efficiency Roadmaps to 2050, Cement, BEIS, 2015.
[14] IBISWorld cement manufacturing UK market research report 2018

during the construction of new plants, rather than retrofit. The recent HyNet North West report (Cadent, 2018) explored the feasibility of implementing hydrogen production with distribution to industry and domestic users in North West England, combined with the UK's first CCS project.

Hydrogen for heating also has the potential distinction that it may be utilised in a monopolistic energy market supplied through a gas grid. This lack of competition allows the product price to change and therefore the costs of ICC could be passed onto the consumer without the risk of carbon leakage. This presents a different set of requirements and opportunities for business models and may allow ICC to develop under a model with considerably less financial support from government.

High Purity CO_2 sources

Currently, operational full-chain industrial CCS is dominated by sources where a high purity CO_2 stream (>95% concentration in flue gas) is available as the by-product of an industrial process. The common sources of high purity CO_2 are natural gas processing, hydrogen, ammonia and biofuel production from fermentation[15]. CO_2 from high purity sources can potentially be captured with limited further CO_2 separation, so the primary barriers are the presence of T&S infrastructure and suitable business models. Once T&S infrastructure is in place, these subsectors can economically utilise the pipelines or can provide the required volumes for the initial infrastructure development. They could therefore be used to test and pilot business models and CO_2 transport and storage networks.

Impact of ICC on production cost

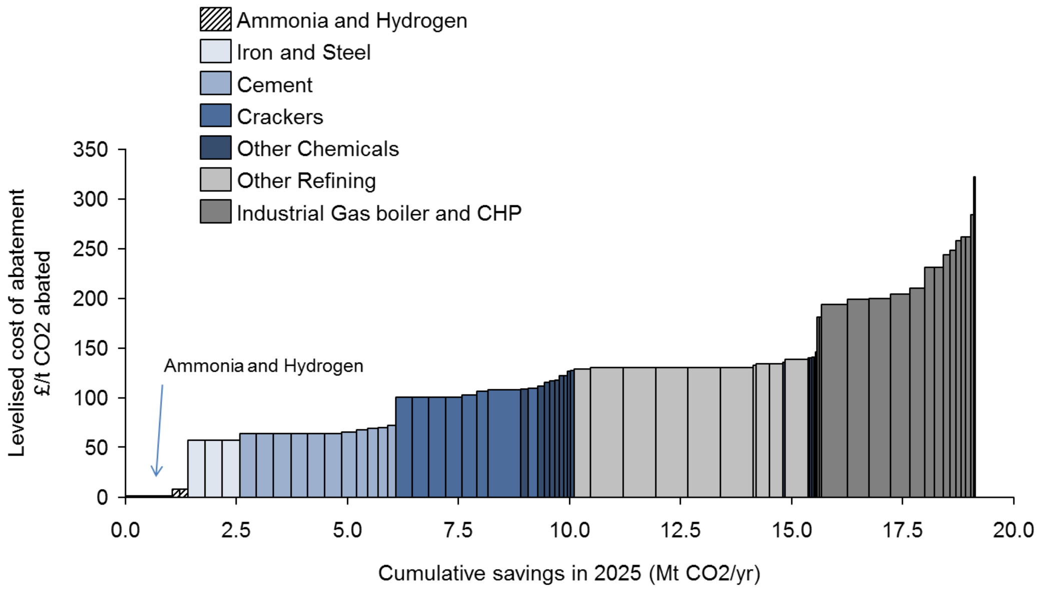
There are significant cost uncertainties associated with deploying ICC across the industrial subsectors. The cost-effectiveness of capture, in £/tCO_2, has 3 primary drivers:

1. CO_2 concentration of source gas streams, where purer streams are less costly
2. Degree of contamination of the gas stream by impurities
3. Mass flow rate of the source, where costs can reduce through economies of scale.

The levelised cost of abatement across the industrial sectors has previously been studied (Element Energy, 2014), with results summarised in Figure 3-1. The high purity CO_2 streams provide the lowest cost abatement opportunities. Beyond those the steel and cement sectors provide significant opportunity of some 5 MtCO_2 abatement potential at a cost below £75 /tCO_2. For most capture facilities, the costs are very sensitive to electricity and gas price due to the energy required for heating and compression. It should be noted that these previous estimates are based on the cheapest capture technologies that are expected to be available in the future, and exclude compression, T&S and financing costs.

[15] Carbon Counts (2010) CCS Roadmap for industry: High purity CO_2 sources: Sectoral assessment – final report for UNIDO.

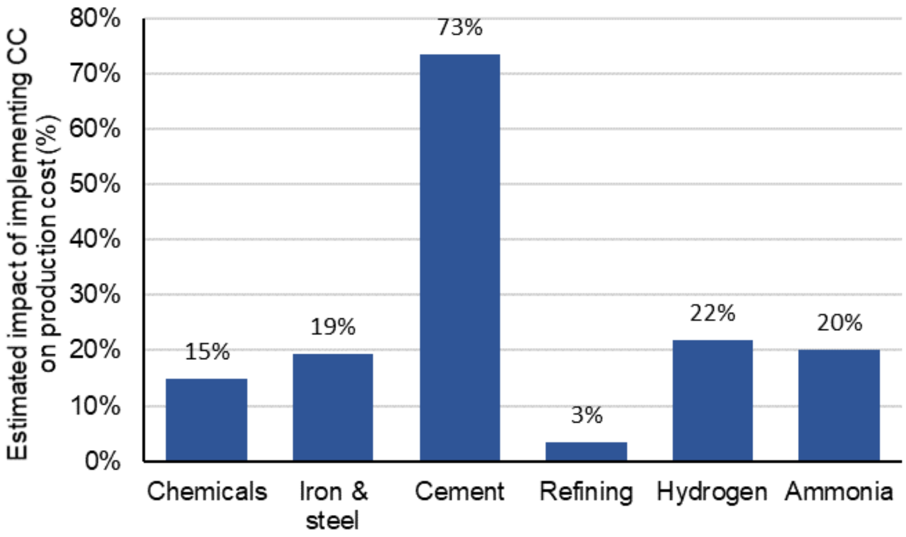
Figure 3-1 Marginal abatement cost curve for different subsectors for projects operational by 2025 (Element Energy, 2014), *excluding the cost of compression, financing and T&S.*



The LCoA is not the only factor to consider in terms of the relative cost difference between subsectors; the proportional impact on manufacture costs also varies according to factors such as product value and carbon intensity. The estimated impact of implementing ICC on production costs is depicted in Figure 3-2[16], assuming the same central carbon price projection for the reference case. For a product such as cement, which has a low market price, the relative cost of implementing ICC is high, leading to an increase in production cost of over 70%. Where a product has a higher carbon intensity, more tonnes of CO_2 are required for capture, and therefore the ICC cost is higher per tonne of product produced. For refining, where the market value of the products is higher, and the carbon intensity is lower, the relative impact on production cost is considerably lower, just 3%. However, even where ICC implementation only has a small relative impact on production cost, the subsector still may not be able to pass this cost on to consumers due to the globally competitive nature of the markets, and may not be able to absorb this effectively due to the low profit margins.

[16] This is calculated by converting the ICC cost (£/tCO_2) to a cost per unit product (£/t product) and then comparing with the current production costs. The assumptions are given in the Appendix.

Figure 3-2 Estimated impact of implementing carbon capture on production costs across industrial subsectors



3.2 CCS phases

Technology development and deployment in the energy sector can be split into four stages: demonstration, scale-up, roll-out and commercial. CCS has passed through the demonstration phase, with around 18 projects operational globally. This phase is focussed on real-world proof of concept, often at a smaller scale. The scale-up phase then requires support for new projects of larger scale; this phase broadens capability and proves viability and deliverability. In the UK, CCS has stalled at the scale-up phase. The market has yet to prove its ability to manage the risks associated with delivery of projects. The public sector is struggling with the rationale behind the significant funding required for scale-up, evidenced by the failure of recent initiatives to proceed. The roll-out phase typically sees the implementation accelerate now that the technology is proven at scale and many of the risks and uncertainties have reduced; this phase aims to establish a sustainable industry and develop supply chains and contracting structures. Finally, the commercial stage is where projects are commercially financeable and require little or no support from the public sector.

The focus of this study is to address the requirements of the scale-up and roll-out phases for ICC in the UK. A summary of the characteristics, aims and requirements of the phases is shown:

Scale-up phase

- Small number of projects deployed
- Phase expected to last ~10 years
- Test technology at scale across a range of applications
- Demonstrate role and value of CCS
- Prove viability of projects and potentially test business model (s)
- Focus on controlling and proving costs.
- Increase stakeholder confidence, including raising public awareness and acceptance.
- Early projects are higher risk, but risks reduce for successive projects.
- Commercial investment is not likely to be available with reasonable returns, so capital support may be required.
- Requires significant public sector involvement, both in terms of risk management and financial support.
- For projects to be operational by mid-2020s, selected policies must be quick to implement
- Projects should focus on deliverability, rather than driving lowest costs.

Roll-out phase

- Larger number of projects deployed more rapidly.
- Phase expected to last ~15 years
- Technology has already been proven and track record is being further developed.
- Building sustainable supply chain.
- Cost reductions and efficiency improvements can be achieved.
- Economies of scale realised as T&S infrastructure is shared in clusters.
- Costs and other parameters are more certain, making projects lower risk and enabling access to commercial investment.
- Likely still requires some public sector support. During this phase some of the risk and financial contributions are passed to the private sector.
- The market should be becoming progressively more independent and an exit route for government should emerge.
- Focus on cost-effectiveness of projects and competition with other decarbonisation options.

It is important to have visibility of a route between scale-up and roll-out phases through appropriate project selection, testing of suitable business models and creation of market mechanisms. The differing requirements of the CCS market maturity phases must therefore be considered to ensure business models are broadly applicable, flexible where necessary and provide value for money across a broad range of situations.

Knowledge sharing is also key to enable subsequent projects to benefit from the experience of the earliest projects, and to increase awareness and confidence for investors and other stakeholders.

3.3 Outline of key challenges

Before identifying and assessing potential business models, it is key to understand the risks, challenges and market failures that are currently preventing the deployment of CCS in the UK. A successful business model must address these challenges to enable realisation of the opportunities industrial carbon capture presents for the UK. An extensive literature review was carried out to identify all risks and challenges proposed for CCS. The findings were then tested through targeted interviews with authors of the reports, as well as CCS experts, policy makers and representatives from industry through a stakeholder workshop. The applicability of the challenges to industrial carbon capture in the current UK climate was considered, accounting for the current phase of CCS, considered to be post-demonstration but pre-commercialisation. The long list of challenges was first simplified by removing those not relevant to ICC, and combining similar challenges with comparable requirements. The remaining challenges were prioritised through stakeholder consultation to those considered the most relevant and important and categorised under the following categories:

Technical and operational:

1. **Technology performance:** Some capture technologies, such as calcium looping, as well as several catalysts, are still in the development phase and are not commercially proven at scale, with resulting performance uncertainty.
2. **Plant integration risks:** Plant integration risks can be considered those which may have an impact on industrial operations. For example, hidden costs of additional downtime or impact on product quality.

Economic & market:

3. **Capital cost uncertainty:** High levels of uncertainty regarding cost of capture in some industries, particularly those with less mature capture technologies being developed, such as cement and iron and steel[17]. Additionally, significant heterogeneity between individual industrial sites limits replicability of solutions and leads to further capital cost uncertainty.
4. **Poor finance terms:** Investors may perceive CCS projects as high risk and therefore expect large returns on their investment. Industries *may* not have sufficient capital themselves to fund the initial outlay, and may have high credit risk, limiting external corporate funding to around 5 years.
5. **Lack of revenue model and insufficient value proposition:** There is insufficient financial benefit to reducing CO_2 emissions as it is currently more cost-effective to emit the emissions. This has a number of fundamental causes, including a low CO_2 price, insufficient CO_2 utilisation opportunities, and lack of other revenue models. Additionally, 'green' or low carbon products currently have no intrinsic added value simply by virtue of having lower environmental impact.
6. **Product demand uncertainty:** Industry has an inherently less stable market, more flexibility in technology and location and shorter investment timeframes than power. Product demand uncertainty leads to uncertainty over revenues and return on investment (ROI).
7. **Industry competitiveness:** Competitiveness of industry may reduce with the burden of carbon capture costs (or increased CO_2 prices), already challenging in the UK due to labour costs, environmental and social regulations. There is therefore a risk of unemployment rise and perceived conflicting industrial and employment goals. Carbon leakage[18] is thought to be a risk for industries with globally traded commodities, due to inability to pass costs of CCS on to consumers whilst maintaining competitiveness. This includes the majority of industry in the UK to some degree, with the potential exception of hydrogen for heat, which may be utilised in a monopolistic energy market.
8. **Operational cost (Opex) uncertainty:** Long-term viability risk due to uncertainties in operational parameters such as operational costs, equipment lifetime, fuel prices and capture plant energy consumption.

Political:

9. **Policy uncertainty:** Policy & regulatory uncertainty, including no comprehensive policy framework and business model to facilitate ICCS.
10. **CO_2 price uncertainty:** Weak and uncertain CO_2 prices of the EU ETS. Sectors deemed to be at risk of carbon leakage (often trade-intensive sectors) are allocated a large portion of EU Allowances for free.

[17] http://www.ccsassociation.org/index.php/download_file/view/274/98/

[18] Industry relocating abroad to benefit from less stringent climate regulations, thereby simply shifting CO_2 emissions rather than eliminating them.

Cross-chain:

11. **Cross-chain integration:** Project-on-project development risk, particularly for timing of completion. Coordination of multiple stakeholders.
    a. Sequential interface and operability risks: Counterparty risks. Volume uncertainties of CO_2
    b. The allocation of risk between parties, CO_2 liability transfer, low risk management capability of EIIs.
12. **T&S fee uncertainty:** T&S monopoly leads to risk of excessive T&S fees. Could be exacerbated by competition for T&S volumes.
13. **T&S availability:** Uncertain availability or performance of T&S, or T&S competition, leads to risk of stranded assets.

This shortlist of categorised risks is summarised in Table 3-2.

Table 3-2 Summary of key risks and challenges

Category		Risks, challenges & market failures
Technical & operational	1	Technology performance
	2	Plant integration risks
Economic & market	3	Capital cost uncertainty
	4	Poor finance terms due to perceived high risks
	5	Insufficient value proposition and lack of revenue model
	6	Industry instability and product demand uncertainty
	7	Competitiveness and carbon leakage
	8	Opex uncertainty including fuel prices
Political	9	Policy uncertainty
	10	CO_2 price uncertainty
Cross-chain	11	Cross-chain integration
	12	T&S fee uncertainty
	13	T&S availability and performance

All risks and challenges can be mitigated through careful design of business models, policies and contracts. The risks should be allocated to the party best able to absorb or manage them, and the industrial emitter should be protected from cross-chain risks, particularly storage liabilities. On the other hand, there is also a need to appropriately balance the allocation of risks between the public and private sector to avoid moral hazard and protect tax payers.

Plant integration risks

Technical plant integration risks are understandably of concern to industrial plant owners, particularly where there could be an impact on operation of their production facilities. Many of these risks are cross-sectoral, but some may have a higher likelihood or severity in some industrial subsectors. Any showstopper integration risks should be addressed and may require contractual consideration e.g. compensation for industrial plant downtime, particularly for early projects. However, the majority of the challenges will simply increase the cost of CCS (and the required subsidy) where they are present, and many are expected to reduce significantly after the first projects, so their relevance for business models in the roll-out phase is reduced. Examples of the key plant integration risks are presented below[19]:

- For large, **continuously operated** facilities (e.g. a blast furnace) the periods between major **overhauls can be very long** which can represent limited windows of opportunity for the development of capture plants and **additional downtime** may be required, leading to high costs.
- **Technology lock-in** is where an ICC and process technology combination locks the plant into a high system cost solution over a long time period.
- Where there are **multiple, disperse CO_2 vents** (e.g. in chemical and refining subsectors), a large duct network would be required, or multiple capture plants, both increasing complexity and cost, as well as requiring significant space.
- Different sectors have different levels of **familiarity and experience** with specific types of processes (e.g. gas separation, solids handling) employed in ICC technologies.
- **Logistical and HSE challenges** e.g. those associated with amine storage and manipulation may elevate COMAH status for some sites which do not already work with the chemicals required for capture.
- **The location of sites** may also impact the availability of cooling water, or the restrictions around new industrial development, particularly relevant to UK cement sites.
- Plant integration risks are considerably lower for **high purity CO_2 subsectors** (hydrogen and ammonia), as they don't require complex capture plants.

More detail on these risks and the applicability to individual subsectors can be found in the Appendix in section 8.2.

Subsector specific challenges

Whilst most challenges apply to all industrial subsectors, the degree to which each subsector is exposed to the key risks and challenges will depend on its characteristics. There are three characteristics in particular which have the ability to differentiate the subsectors.

Does the subsector produce pure CO_2?

For sectors which produce pure CO_2, the costs and complexity of capture will be considerably lower and the cost uncertainties reduced. The investment profile will be different, as the capital outlay is smaller, with the majority of the costs being operational, such as fuel usage for compression and T&S fees. As a result, technical, operational and economic risks are reduced. Two of the key subsectors which produce pure CO_2 are Hydrogen and ammonia production. Therefore, once T&S infrastructure is available, contracts can quickly be awarded to these plants at low cost.

Is the subsector subject to strong, global competition? Can costs be passed on to consumers?

As discussed above, subsectors which compete in international markets are often unable to pass costs on to their consumers unless international environmental policies are aligned. This results in these subsectors being at risk of carbon leakage. Some of the key factors which contribute to carbon leakage risk are:

- Trade intensity
- Carbon costs (or ICC costs) relative to profit margins
- Price sensitivity of demand for output (CCUS may increase product costs).
- Degree of product homogeneity i.e. if products from different plants are significantly different.

[19] More detail can be found at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/312106/Element_Energy_DECC_BIS_ICCS_CCU_final_Report_Appendix.pdf

For competitive sectors, where no revenue can currently be created for ICC through product sales, alternative financing mechanisms and incentives must be available. The majority of the energy intensive industrial subsectors trade internationally, with the exception of hydrogen for heat, which has the potential to be sold in a monopolistic energy market. Therefore, for hydrogen, additional revenue options may exist. One such option is the use of a Regulated Asset Base (RAB), to recover the cost of ICC through consumer energy bills.

How much would ICC impact the production cost (%)?

As discussed in section 3.1, the relative impact of implementing carbon capture on the production costs varies significantly between subsectors. For example, in the cement industry, ICC is estimated to increase production costs by over 70%[20], whereas in the refining industry, the impact is estimated to be just 3%. Therefore, it is more likely that the refining subsector could bear a significant proportion of the ICC costs whilst maintaining a competitive position in the market. However, in highly competitive markets where the profit margins are low, even a small increase in production costs could have a severe impact. Further detail is given on the variation in subsector costs in section 3.1.

Business models developed may be able to incorporate these sector specific risks and differences through flexible financing and benchmarking against the best available technology (BAT) in the sector. However, some business models may prove significantly more cost-effective in certain sectors or may only be applicable to specific sectors. Despite these differences, the majority of the risks and barriers are applicable broadly across industrial subsectors.

Phase specific challenges

As discussed in section 3.2, the requirements of the scale-up and roll-out phases differ. Some challenges will reduce, or even be eliminated, through scale-up:

- **Technical risks** will reduce as a range of technologies are proven at scale
- **Cost uncertainties** will reduce
- Availability of low-cost **capital financing** will increase due to improved confidence and certainty
- **Policy and regulatory uncertainties** should diminish
- **Cross-chain risks** will reduce, particularly where existing T&S infrastructure is available

Therefore, additional support is required in the scale-up phase, particularly to accept liability for significant risks and in provision of capital financing.

3.3.1 Quantitative illustration of impact of risks and challenges

In order to understand the potential impact of the key risks, they were quantified using illustrative cashflows. This allows an objective measure of the influence of each risk on the project financials, allowing a stronger appreciation of the risk mitigation options required in a successful business model. Cashflow analysis also provides clear information and insights for non-expert stakeholders or investors. ICC costs, risks and investment profiles may vary between subsectors, so quantitative analysis allows a high-level understanding of the differential impact on these subsectors.

Method and Assumptions

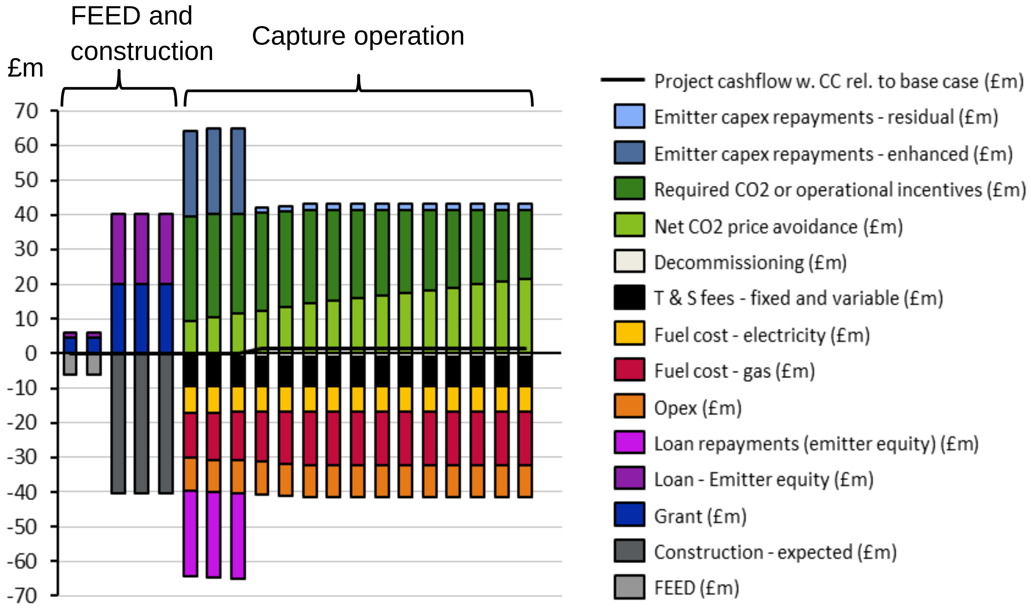
To enable this analysis, a cashflow model was built with data on sector archetypes, capture technologies, fuel price projections and CO_2 price projections. The assumed project timeframe was 15 years, with costs covered primarily by government in the scale-up reference case. Each of the risks

[20] It should be noted that calculations are based on current BAT, but more cost-effective technologies (e.g. calcium looping) and alternative processes (e.g. HIsarna for the steel sector) have the potential to reduce ICC costs significantly once they reach commercial readiness.

was tested in turn, and the impact on key metrics – total CO_2 abated, project cost, levelised cost of abatement (LCoA) – was assessed.

For risks which are not sector specific, a typical cement plant was chosen as a representative industrial site due to its relatively 'central' characteristics in terms of magnitude of emissions, CO_2 stream purity and proportion of CO_2 available for capture. The incentives provided to the emitter in the reference case cashflow are based on the model proposed in the recent Teesside Collective study (Pöyry and Teesside Collective, 2017). The capital financing is 50% grant funding and 50% emitter equity, which is later repaid through operational incentives; the repayment is split into enhanced repayments over the first 3 years of operation and then residual repayments for the remaining operational period to provide an incentive for continued operation. The reference case business model assumes that the financial impact of most risks is borne by government in the scale-up phase and the emitter is protected. The capture operational period is 2025-2040 for this scale-up project and a social discount rate of 3.5% has been applied to all cumulative costs. More detail on the cashflow modelling assumptions can be found in the Appendix. An illustrative cashflow example is shown in Figure 3-3.

Figure 3-3 Illustrative cashflow of ICC project costs and incentives for a typical cement plant[21]



The majority of the risks were quantified using this cashflow analysis and the impact of the risks assessed using the key metrics, such as the impact on LCoA. More detail on the metrics assessed can be found in the Appendix.

The project LCoA is £127/tCO_2 for this cement plant, although across industrial sectors it ranges from £35/tCO_2 (hydrogen and ammonia) to over £200/tCO_2 (chemicals). The incentives required are significantly lower than this total project cost if CO_2 price avoidance is accounted for, were industry exposed to the full cost of emitting CO_2. The government LCoA is an estimate of the required incentive from government or market mechanisms, which ranges from £4 - £168/tCO_2 across the sectors. It should be noted that these figures are a relatively high estimate as they assume a mature, commercially available and higher cost technology (first generation amines), as well as including

[21] It should be noted that the enhanced capex repayments are paid to the emitter to reimburse them for the initial emitter equity investment. This payment is shown as going via the project cashflow.

compression costs, T&S costs and the cost of financing. If calcium looping[22] is chosen instead, which has a lower technical readiness, the project LCoA drops to **£86/tCO_2**. Additionally, removing compression, T&S and financing costs reduces the project LCoA further to £46/tCO_2. For the purposes of this risk assessment, it is the *relative* impact of risks (%) that is most important.

The change in levelised cost of abatement is a clear measure of the impact of the risks quantified, as shown in Table 3-3. However, political uncertainty was considered to be a 'showstopper', which was not quantified. The carbon leakage risk around industrial competitiveness is sector specific and is discussed in section 3.3, and a high-level assessment of the lack of value proposition is assessed in Figure 3-4.

Table 3-3 Summary of the risks quantified and their impact on the government Levelised cost of abatement. More detailed assumptions found in the Appendix.

	Risks and challenges	Illustrative risk quantified	Impact on	Govt. LCoA
1	**Technology performance**	Capture rate only 75%	Climate	**+24%**
2	**Plant integration risks**	3 months plant downtime	Industry	**+2%**
3	**Capital cost uncertainty**	Capital costs 50% higher	Cost	**+14%**
4	**Poor finance terms**	Expensive finance[23]	Cost	**+6%**
5	**Insufficient value**	Capture costs relative to paying CO_2 price	Climate	**-**
6	**Product demand uncertainty**	Product demand only 50%	All	**+25%**
7	**Competitiveness**	Estimate of price impact & carbon leakage risk	Industry	**-**
8	**Opex uncertainty**	Total opex is 25% higher	Cost	**+26%**
9	**Policy uncertainty**	Showstopper	Climate	**-**
10	**CO_2 price uncertainty**	CO_2 price from FES central to low	All	**+19%**
11	**Cross-chain integration**	1 year delay in capture or T&S	All	**+3%**
12	**T&S fee uncertainty**	T&S fee increase by 50%	Cost	**+11%**
13	**T&S availability**	T&S storage capacity limit met 5 years early	All	**+18%**

These results should not be used to 'rank' the risks in order of importance, as the risk likelihood and ease of mitigation are also important factors. However, it is interesting to note that at the risk levels assumed, none of the risks individually has more than a 26% impact on the LCoA. The showstopper risks are those that would prevent the project operating altogether, such as T&S default or removal of the government incentive.

Sector specific comparison of 'lack of value proposition' challenge

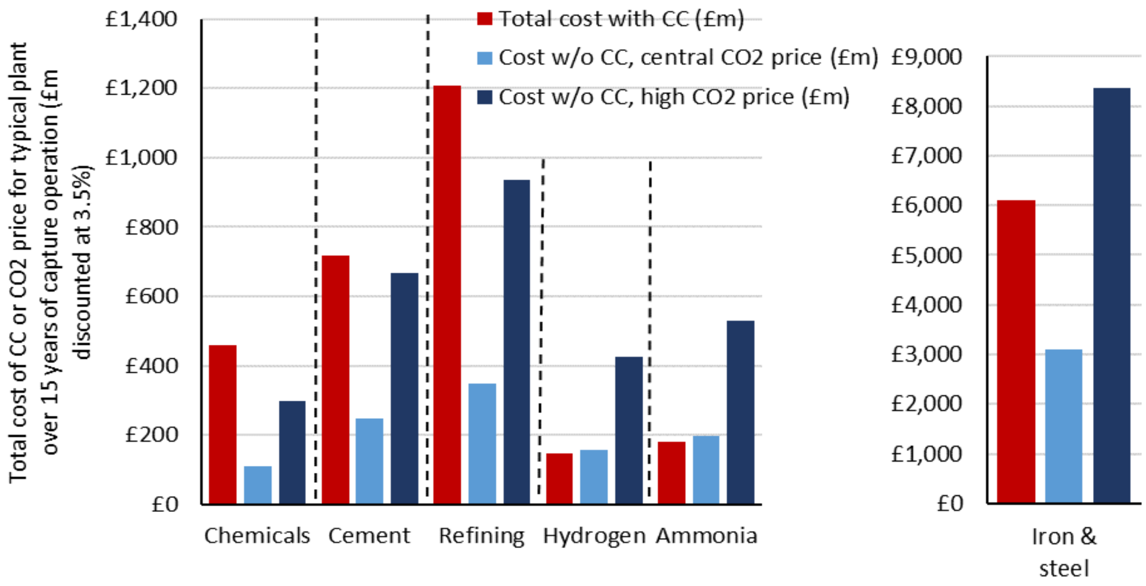
One of the key risks identified is the lack of value proposition and revenue model for industrial carbon capture. A high-level comparison of the total cost to each industrial subsector was completed to understand whether a CO_2 price would provide sufficient incentive for ICC implementation through CO_2

[22]See *Demonstrating CO_2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A Techno-economic Study*, Element Energy, DECC & BIS, 2014 for more details
[23] 100% capex equity (repaid in 3 years at 12% interest + residual repayments at 2.5% per year thereafter) adapted from (Pöyry and Teesside Collective, 2017)

price avoidance. The cumulative cost of ICC operational from 2025 – 2040 was compared with simply paying the CO_2 price, for a central and high CO_2 price projection, as shown in Figure 3-4.

Under the central estimate for the CO_2 price, based on the National Grid Future Energy scenarios 2018 central UK carbon price projection[24], the cost of implementing carbon capture is higher than that of paying the CO_2 price for all sectors, except those which have pure CO_2 streams[25] (Hydrogen and Ammonia). Even in the pure CO_2 stream subsectors, the T&S infrastructure is not currently in place and they are generally of insufficient size to create the economies of scale alone. Under the BEIS high CO_2 price projections[26], the costs with and without capture become more comparable in most subsectors. However, even with a high enough CO_2 price, investors do not currently see CO_2 pricing as a certain and secure enough incentive to invest in carbon capture.

Figure 3-4 An illustrative comparison of the total cost, over the operational period 2025-2040 of implementing carbon capture relative to paying the CO_2 price. Note that the Iron & Steel subsector is separate only due to the different magnitude of the costs.



[24] http://fes.nationalgrid.com/fes-document/
[25] it is assumed that emissions streams with CO_2 purity of 95% or above do not require capture technology, just compression
[26] *The Green Book*, HM Treasury, Data tables, 2017, short term traded high projection

4 Business model options

To develop and select business models for UK industrial carbon capture, the potential mechanisms, instruments and risk management strategies were reviewed through case studies and literature. The business models were characterised into 'elements' which fundamentally differentiate them. In particular, the revenue model is a crucial element to define the success of the business model and to dictate which supporting instruments are required to manage risks and enable capital financing.

4.1 Business model case studies summary

Case studies were selected across a variety of global CCS projects, as well as other UK projects and infrastructure, to ensure a range of mechanisms and instruments were explored across different locations and regulatory environments. Case study canvases, of one to two pages, were used to summarise the information, with input from Carbon Counts, and can be found in the Appendix. Whilst all CCS and infrastructure projects have unique characteristics as a result of their distinct market and regulatory environments, lessons can be learnt around successful attributes with potential to be effective in the UK. The applicability of these models to UK ICC is also discussed, with more detail in the full business model canvasses.

Some of the overarching lessons gathered from this review and accompanying literature can be summarised as follows:

- Ownership models are a mix of public, private and public-private partnerships (PPP). However, full public ownership was only seen in countries such as China and the UAE, which have considerably different political frameworks and markets.
- The revenue model is key to creating the value proposition. The certainty of this revenue also contributes to the investibility of the model and therefore capital availability.
- There are a number of revenue models available for ICC, although currently projects are largely state-supported or receive revenue from Enhanced Oil Recovery (EOR).
- Both tax credits (e.g. 45Q in the US) and CO_2 taxes (e.g. Norway) appear to have been one of the key revenue drivers in their respective projects.
- A Regulated Asset Base (RAB) model is proposed for Hydrogen in the recent HyNet report (Cadent, 2018), allowing costs to be passed to energy consumers and therefore reducing the financial support required from the exchequer.
- Risk management currently involves significant public involvement in the majority of operational projects. Mechanisms such as loan guarantees and public underwriting of risks (e.g. long-term CO_2 liability, Thames Tideway) are thought to be required in the current scale-up phase.
- Joint ventures (JVs) are used successfully in many projects, often involving oil and gas (O&G) companies. However, this is largely due to O&G expertise in infrastructure development, such as transport pipelines, so is more relevant to the T&S.

A summary of the case studies is shown in Table 4-1, highlighting the key business model elements.

Table 4-1 Summary of business model case studies

	Case Study	Sector	Country	Ownership Structure	Investment	Revenue and value	Public involvement	Risk Management	Applicability to UK ICC
1	Quest	CCS – Hydrogen	Canada	Private	Government grants & private equity	CO_2 price avoidance offset credits	Grants and Alberta Offset Credits	Government backed, reduced investment risk. Technical risk held by JV.	Carbon floor price guarantees revenue. Grant funding needed to reduce investor risk
2	Al Reyadah /Emirates Steel	CCS – industrial	UAE Abu Dhabi	Public - Abu Dhabi National Oil Company (was JV)	JV equity	CO_2 use for EOR (avoiding nat. gas use) Oil sales Emissions reduction	ADNOC & Masdar are state owned	State owned. Government bears all commercial and technical risk.	Limited applicability. State owned investors.
3	Petra Nova	CCS – Power EOR	USA Texas	JV owns & operates capture	JV equity \$600m DOE Grant \$190m Debt \$325m	EOR & oil sales Potential 45Q Tax Credit	Small support Japan ExIm Bank export credit guarantee for Japanese lenders	JV holds all technical and commercial risks. Lender exposure minimised through export credit guarantee	Equity interest of CO_2 source in EOR oil revenue stream meant that in this case part-chain model not attractive.
4	Norwegian CCS	CCS - industrial	Norway	PPP likely	Government support and private equity	Avoidance of CO_2 price (Norway) & possible new CO_2 tax, demo.	Promoter & lead developer	Likely largely public risk ownership	Similar challenges to UK CCS, so similar support required
5	Lake Charles CCS	CCS – industrial EOR	USA	Private	Equity investors \$1.8 bn \$2 bn government loan guarantee	EOR: CO_2 sales Chemical sales	DOE loan guarantees Equity investor tax credits	Existing T&S infrastructure, good investment rating. Public private risk sharing	Risk & investment sharing models. EOR less accessible, no existing T&S
6	Sleipner	CCS – industrial / O&G	Norway	Private JV (Petroleum)	JV funded	Avoidance of Norwegian CO_2 tax Natural gas sales	CO_2 taxes	Single party for whole chain. Hasn't addressed long-term CO_2 liability	National CO_2 tax is the main driver for private investment
7	Illinois Basin	CCS - industrial	USA Illinois	PPP DOE and partners	Government grant Partner equity	Potential 45Q Tax Credit RD&D benefits	Majority funder	Tech. and comm. risks largely taken by Government.	Government capital grants and tax benefits
8	Sinopec Qilu Petrochem	CCS - industrial	China	Public (Sinopec state owned)	Likely public – 100% equity Sinopec	EOR Oil sales	State-owned enterprise	State owned. Government bears all risk	Limited as entirely state-owned and EOR driven

9	Rotterdam CCS (Porthos)	CCS - industrial	Netherlands	PPP likely for capture, semi-public T&S	Public incentives & private investment	Avoidance of CO_2 price Govt. incentives (Cost Plus or CfD-like TBC)	Support financially and risk sharing	Public private risk sharing, limited details - pre-FID.	Strong applicability as similar market and challenges
10	CCS Comm. Programme	CCS - power	UK	Private	DECC grant Equity Debt (65%)	Electricity sales (CfD)	Grant funding Risk sharing CfD	Government carries majority of risks (storage, some capital, CfD price)	Directly applicable. Full-chain private model currently not investible.
11	Teesside proposal	CCS - industrial	UK	Capture owned by emitter T&S by government	Government capex and opex support. Emitter equity repaid.	Avoidance of CO_2 price Government incentives and guaranteed returns	Grant funding Opex funding Risk sharing	Government carries capital risk Performance risk shared	Directly applicable financing and risk sharing arrangements.
12	Cadent HyNet	CCS – hydrogen & industry	UK	Uncertain. Likely Cadent partial ownership of chain.	RAB recovery of most costs. Potential public funding for T&S & EII conversion	RAB sales of hydrogen (local and national gas bills)	Ofgem RAB regulation Ownership of key risks Likely funding	Multiple emitters and CO_2 stores. Government will need to take on key risks.	Directly applicable RAB financing and risk sharing arrangements.
13	Merchant CO_2 market	CO_2 utilisation	Global	Multiple sources & customers, who buy from merchants.	Equity: most likely merchants capital.	CO_2 sales which vary from US$30-$300 /t CO_2	None. Call for government intervention to secure supply.	All commercial and technical risks held by merchant. Brokerage means cross-party risks eliminated.	Proven midstream model for CO_2 capture & utilisation. Market benefits of diverse sources.
14	UK Nuclear industry (RAB, CfD, waste)	Power - nuclear	UK	Government often owns nuclear developers.	Developer investment including debt, potentially based off RAB or CfD.	Electricity sales and profit Low carbon so protection from CO_2 price	Often government ownership, regulation & waste liability for a price	Investments de-risked by return certainty May cost consumer more than alternatives	RAB can be used for hydrogen CCS. CfD potentially applied to CO_2 price. T&S waste CO_2 liability transfer.
15	District Heating	District heating waste heat	France Dunkirk	Capture plant owned by industry, heat network by city council	Public – initial capex, then 50% industry second capture facility	Waste heat sales Avoidance of CO_2 price Tax benefits Public perception	Financing & risk of initial heat network. Tax system and heat fund.	Contracts for heat supply & demand. Public investment and capital risk.	Heat capture facility similar to CO_2 capture as investment needed to realise value to industry.
16	Thames Tideway	Waste water	UK	PPP and Private JV + potential RAB later	Equity and public & private loans	RAB Regulated returns from customers	Regulation, some financing & insurer of last resort	Public private risk sharing, government insurance and contingency	Government support to enable private finance Societal benefits

4.2 Characterisation of business models

A business model is predicated on a transaction based on a value proposition. This value proposition, or revenue model, for CCS is currently unclear in the UK. However, the need to reach deep decarbonisation of all energy sectors is widely accepted; hence the real question is, which is the most cost-effective route to decarbonise industry? It has been suggested through many recent pieces of analysis that deploying CCS early could significantly reduce the total cost of decarbonisation to society in the long-run. It is therefore in the interests of government to create a business model which can successfully incentivise ICC whilst protecting UK industry and fairly allocating the cost across society. The value proposition is often assumed to be the 'burial' of CO_2, although the emphasis could instead be placed on the creation of low carbon products; these alternatives are explored further. Identifying the value proposition is the starting point. The other parts of the chain can then evolve around this transaction to see whether they can respond to the price signal offered.

Business models may consist of many elements which dictate the terms of the agreement and the financial arrangements, such as the ownership structure and legal, regulatory, risk, financing, and revenue models. Potential ICC business models were examined to understand which elements fundamentally differentiate the models:

Revenue model: Income related to the emitter capture activities, with the aim of covering the costs of capture plant operation (e.g. opex, T&S fees). The model is designed to incentivise CO_2 capture or the creation of low carbon products through providing a value proposition. A key consideration of the revenue model is the flexibility of this model for changes in the market such as fuel prices and the CO_2 price.

Funding source for revenue: It is important to consider who ultimately funds the revenue stream. For example, tax payers, other emitters or energy consumers. The allocation of the cost will need to be considered 'fair' across society, with consideration of affordability concerns and protection of both UK industry and consumers. The funding sources available for each model will contribute to the political acceptability.

Risk Management: Mechanisms to mitigate risks and allocate them between parties; the required instruments will be dependent on the revenue model in place. Risks are likely to be owned by the party most able to manage each risk. Ownership of high impact, low probability risks should be considered. Risks may be transferred from the public to the private sector as the CCS market matures.

Capital financing: Access to capital for FEED and construction of the capture plant. Often the emitter has insufficient capital and credit rating, so may require support. For example, direct government grants may be available in scale-up, but low-cost loans in roll-out could be enabled through revenue certainty as well as instruments such as loan guarantees.

Ownership structure: The ownership model of the capture plant includes the operation and maintenance of the plant and the possession of the assets. This is likely to be distinct from the ownership and operation of the T&S infrastructure in this part-chain model.

There may be many options within each of the elements above, and these can be combined to form potential business models.

4.3 Discussion of business model elements

A summary of the options available within each of these business model elements is presented in Figure 4-1.

Figure 4-1 Summary of the options available for each of the business model elements

Revenue models	Risk management
• Contract for difference on CO_2 price • Cost plus open book • Regulated asset base • Tradeable tax credits • Product CO_2 taxes (redistributed) • Tradeable CCS certificates • EPS + tradeable CO_2 credits • Low carbon market creation through regulation	• Loan guarantees • Insurer / buyer of last resort • Stable policy or long-term contracts • Price floor & ceilings • Revenue guarantees • Border adjustments • Public underwriting of risks • Pain-gain sharing mechanisms • T&S fee regulation

Funding source	Capital & ownership
• Exchequer • Emitters • Fossil fuel suppliers • Energy consumers • Purchasers of low carbon products • CO_2 sales for utilisation (e.g. EOR)	Capital: • Public grants or loans • Emitter equity • Debt (commercial & multilateral funds) Ownership could be private, PPP or public *(public ownership is considered unlikely for capture plants).*

4.3.1 Proposed revenue models for evaluation

As discussed, the revenue model is the basis for an ICC business model, around which other instruments can be built. Three of the key criteria for an ICC incentive mechanism to perform successfully are outlined below:

1 Cost neutrality: Emitter should not be worse off for having implemented ICC relative to emitters who have not yet implemented ICC i.e. the subsidy must either bridge the gap between carbon cost avoidance and ICC costs, or allow cost pass-on to consumers. Profit margins could be insulated from changes in the price of carbon and potentially other commodities such as fuel.

2 Emitter/investor returns accounting for risk: If the emitter or investor is taking higher risks, they will expect higher returns. The alternative is lowering the private sector risk to allow lower cost of financing. For example, through loan guarantees, T&S fee regulation, government backstops on costs, long term contracts providing revenue certainty.

3 Incentive to continue efficient operation of capture plant: Models may provide front-loaded revenues to give quicker payback but should ensure that emitters have a financial incentive to continue running the capture plant for as long as possible. There should also be an incentive to operate the plant efficiently and drive costs down and capture rate up, which may not be intrinsically present in some business models.

Potential revenue models were identified through the case studies, stakeholder consultation and from literature. The options were tested through stakeholder workshop discussions and filtered accordingly. Certain models were not considered of sufficient strength or feasibility in the UK, and were therefore removed from the analysis:

- **CO_2 utilisation, including EOR**: These sources of revenue are unlikely to be the primary drivers for CCS in the UK, although they may contribute as a supporting element or play a greater role in the longer term. Offshore EOR is high cost and other forms of CO_2 utilisation are currently not of sufficient scale.
- **CO_2 price avoidance**: whilst CO_2 price avoidance is not directly revenue, the avoided costs give a relative advantage over emitters paying for those emissions. Alternatively, if free allowances are provided, they can be sold, rather than surrendered, to realise their value. This is a key supporting revenue for ICC but alone was not considered to provide sufficient certainty and level of returns in the current market to incentivise ICC.

The feasible revenue models were then explored further. As discussed, mechanisms can either incentivise capture and storage of CO_2, or production and sale of low carbon products. Some revenue models could be applied to either, so the distinction is discussed with the associated benefits and drawbacks. Table 4-2 summarises these revenue model options, with explanations below.

Table 4-2 Feasible revenue models or incentive mechanisms

Revenue model based on CO_2 abatement	Revenue model based on low carbon product
Contract for Difference (CfD) on CO_2 price	Contract for Difference on product price premium
Cost plus capture operation	Regulated Asset Base (RAB)
Tax credits for CCS	Product taxes based on CO_2 intensity
CCS certificates (tradeable + obligation)	CO_2 credits for low carbon products (tradeable + EPS obligation)
	Creation of low-carbon product market through regulation

Below is a description of each revenue model. It should be noted that the revenue models require the addition of supporting elements, such as capital financing and risk management, to become full, feasible business models.

Contract for Difference (CfD): A contract for difference is a contract between two parties, typically a 'buyer' and 'seller', creating a guaranteed price for a 'product'. This guaranteed price is called the 'strike price' and one party must pay the other the difference between the strike price and the market price of the 'product'. A CfD mechanism is already used in the power sector; an electricity generator receives a strike price backed by the government-owned Low Carbon Contracts Company (LCCC), which will pay the generator the difference between the strike price and the market price of electricity[27]. The strike price reflects the cost of investing in a low carbon technology and provides certainty of returns to the investors, particularly where market prices can be volatile. For industrial carbon capture, this strike price could be set on the cost of CO_2 abatement, called CfD_C, paid by the government in £/tCO_2 over the market CO_2 price (i.e. the CO_2 price avoidance, see page 39). A mechanism such as this has been proposed in a number of studies, such as that completed by Société Générale (2015). Alternatively, a CfD_P could be on the industrial product price (£/t. product),

[27] https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference

either directly or as a price premium above the market product price. This is more similar to the power CfD in the UK.

Cost plus: This mechanism involves direct operational payments from the government to cover all properly incurred costs annually, on an open book basis, with agreed returns on any emitter investments. In this mechanism, the majority of the risks are borne by the public sector. The mechanism for allocating the unused CO_2 allowances is an area for discussion; if the full value is recovered by the government, industry is still exposed to CO_2 price changes, at the same rate as its competitors within the same CO_2 pricing scheme (currently the EU). A cost plus mechanism is proposed in the recent report on UK industrial CCS support mechanisms, as a strong and certain incentive with a fairer division of benefits between the emitter and government (Pöyry and Teesside Collective, 2017). This mechanism is considered for use in the Rotterdam CCUS project Porthos, where each emitter may be compensated for the incurred additional cost of CCS compared to the avoided CO_2 price.

Regulated Asset Base (RAB): A RAB model values existing assets used in the performance of a regulated function, for example electricity or gas markets, and sets tariffs to pass the costs of these assets on to consumers. The equity risk is low as the revenue risk has been transferred to consumers, for example through future energy bills in a regulated monopolistic energy market. It can be seen as a commitment by future consumers to cover current investment. A possible disadvantage of the RAB model is affordability concerns arising from passing the risk of sunk costs to consumers, particularly for vulnerable consumers. In a RAB system, energy providers may be stimulated to drive cost reductions if they are able to retain funds resulting from cost cutting. While many industrial subsectors are unable to pass costs on to consumers, a proxy may be created for the consumer base, or the model could be applied to hydrogen production for use in the gas grid, as suggested in the recent HyNet report (Cadent, 2018).

Tax credits: Tax credits are reductions in the tax liability of a firm if it meets certain requirements. For example, a firm which implements ICC could receive a tax credit valued for £/tCO_2 abated. A system of tax credits is available in the US (section 45Q) to support CCUS deployment; 45Q was created in 2008 and under a new bill, the credit will be increased to \$35 /tCO_2 used and \$50/tCO_2 stored, by 2026. This mechanism was also suggested in the CCUS Cost Challenge Taskforce report (2018). The level of tax credits, contractual certainty, capital availability and the ability to account for CO_2 prices are important determinants as to the potential success of the policy.

Product CO_2 taxes: Taxing products based on their carbon intensity (in tCO_2 / t. product), relative to a product benchmark, directly incentivises low carbon products. This has the advantage that it promotes production methods with lower emissions (rather than the potential unintended consequence of CO_2 abatement payments of incentivising high emissions processes to allow greater abatement revenue). Another advantage is that if the tax is at the point of sale, it is applied regardless of the country of origin, so within the UK there is a level playing field for domestic and imported goods. However, UK manufactures with ICC would still be at a disadvantage outside the UK, so this mechanism would require financial revenue support for competitive industries. Tax mechanisms are commonly used to alter markets and account for external costs to society such as health or environmental costs; examples include taxes on tobacco or sugary drinks.

CCS certificates + obligation[28]: Tradeable CCS certificates, combined with an obligation to decarbonise, has been proposed as a market led solution. CCS certificates are awarded per tCO_2 abated and emitters are obligated to ensure a certain amount of CO_2 is captured, with the level of obligation increasing over time. Certificates may be used to meet the obligation or traded freely so that parties with higher costs of ICC may purchase cheaper certificates. The price of certificates is determined by the market, so is uncertain, but the government may provide a buyout price, creating

[28] Adapted from '*CCS market mechanisms: Policy mechanisms to support the large-scale deployment of Carbon Capture and Storage*' for OGCI (Element Energy & Vivid Economics, 2018)

a floor price for certificate value; conversely penalties for not meeting the obligation may create a price ceiling. The obligation could be extended to fossil fuel suppliers, to provide additional revenues to industry.

CO_2 credits + EPS: Emissions performance standards on industrial products, or even end-use products, can be combined with CO_2 credits in a similar manner to CCS certificates. The CO_2 credits are awarded on sale depending on the carbon intensity of the product relative to the product benchmark. Again, they could be used to meet the obligation or traded freely, and the government may provide a price floor and ceiling. As with product CO_2 taxes, this has the advantage of directly incentivising low carbon products, but the definition of product benchmarks and trajectories would be a significant administrative undertaking. Additionally, financial support may be required to address the carbon leakage risk.

Low-carbon market creation: A long term solution to decarbonising industry is to create a market for low carbon products, where market mechanisms incentivise decarbonisation over time. There are a number of ways to encourage development of this market. The first is to create standardised certification for low carbon products and raise awareness throughout the economy, including consumers of end-products, of the carbon intensity of goods. The second is through public procurement of low carbon products, directly or through indirect contracts. Finally, regulation on end-products, such as buildings, infrastructure and vehicle manufacture, could include obligations to purchase a certain level of low carbon materials. For instance, new building regulations and Energy Performance Certificates (EPCs) could consider the embedded emissions of the building. These measures would be designed to create a guaranteed demand for low carbon goods, allowing a price premium.

This initial subset of feasible models will be assessed in more detail and combined with additional supporting elements to create a full business model.

4.3.2 Funding source

There are a number of funding sources which could be considered to cover the cost of the revenue models and ultimately contribute financially to ICC. Consideration should be given to the ability and willingness of each party to absorb the costs, as well as the ease with which the funding sources can be implemented and administered. Care should also be taken to protect vulnerable parties, such as consumers at risk of fuel poverty, or industry exposed to international competition.

Exchequer: Direct funding from the exchequer could be recovered through general taxation, with the justification that every member of society benefits from policies to mitigate climate change. However, public acceptability of investing in CCS over other demands on exchequer funding may still make this a difficult sell.

Emitters: Industrial emitters could be the source of funds through obligations or taxes which are redistributed to finance CCS. This would result in a high carbon leakage risk, which would need to be addressed. Instead, all national emitters (power, industry and other emitters) could be the source of funds through obligations or taxes; this could be designed to protect industry from competitiveness implications. This allocation is the ‘polluter pays’ principle and the mechanism could be through (increased) allocation of tradeable certificates (e.g. EU ETS) to ICC emitters, which are then purchased by other emitters. This would reduce the direct government subsidy required.

Fossil fuel suppliers: Obligations could be implemented on all fossil fuel suppliers to store, or pay for the storage of, a given % of the carbon content of the fuel they supply each year. The required % would have an increasing trajectory over time. The justification is that the majority of industrial (and power) emissions are from combustion of fossil fuels, so the cost of reducing emissions from these fuels should be shared by the suppliers.

Gas consumers: Natural gas consumers have so far been protected from much of the climate related cost. As CCS can contribute to the decarbonisation of the gas grid, gas consumers could pay through either taxation or a RAB model. Hydrogen production is an example of where this could work fairly and effectively if the price increase is of an acceptable level. The cost could be spread over direct local consumers or all national gas consumers. Additionally, electricity consumers could contribute to the cost of CCS, to spread the consumer base over which costs are distributed, but this is more likely for the T&S infrastructure than ICC, as T&S may be shared by power CCS.

Industrial product consumers: A price premium could be paid for low carbon products if a market was created through regulations, certification and public procurement of low carbon goods. Alternatively, a price premium could be paid for *high* carbon products, if additional taxation is applied based on product carbon intensity.

CO_2 utilisation, including EOR: Utilisation revenue is another source, for example EOR (fuel consumers), crops and beverages as well as novel production processes utilising CO_2. The volumes and economics are currently unfavourable, so this is considered a supporting option only.

Generally, different revenue models may have different funding sources available to them. For example, a RAB model for hydrogen allows cost pass on to energy consumers and a CCS certificate scheme can use obligations to pass costs to fossil fuel suppliers. However, revenue models should not be restricted to the 'typical' funding sources for that revenue model. A combination of these mechanisms can be used to spread the cost across the parties in the fairest or most acceptable manner.

4.3.3 Risk Management

In a developing industry such as CCS, with high capital investment and significant risks, the risk management is a crucial element of the business model in determining the likelihood of success. Many of the risks in CCS will be managed contractually, particularly the cross-chain risks, but there are additional instruments which can achieve a more effective risk allocation. Some of the key risk mitigation options are summarised below.

Public loan or credit guarantees are guaranteed loan repayments from the government in the event of default, such as those used to support the Lake Charles Methanol CCS project (see case study). They enable a lower cost of debt and improved investibility. However, if there is a cost to the loan guarantee, the reduced debt costs must outweigh this.

Public underwriting of capture operational risks could be caps placed on the liability of private operational parties, where government bears the remainder of the risk.

Stable policy or long-term contracts are required to provide confidence to all parties and guaranteed levels of public support.

Price floors or ceilings (e.g. for CCS certificates) can reduce the risks by providing a minimum return to emitters or a maximum payment.

The government may act as an **insurer of last resort** for high impact risks for which there is no market insurance available. They may act as a **buyer of last resort** for either industrial products or certificates to guarantee a minimum value (similar to a floor price).

Insurance pooling could involve underwriting of risks by one large pool of industries to enable more effective management.

Compensation for BAU disruption may be contractually agreed to protect the emitter from unexpected disruption to their production processes, and therefore provide a more attractive arrangement.

Border adjustments are commonly cited as a potential way to account for differing environmental policies (Vivid Economics, 2014).

Revenue guarantees, as discussed, are crucial to providing an incentive to invest in carbon capture. The stronger and more certain the revenue model, the more investible the project. Examples are CfD or RAB.

Supporting cross-chain options include public backstops on cross-chain default, utilising existing T&S infrastructure, and contractual arrangements such as take-or-pay, and T&S fee regulation. As these are part-chain models, it is assumed that the long-term CO_2 storage liability is accounted for in the T&S business model, particularly as emitters do not have the skills or balance sheet to take on this liability.

The risk mitigation instruments required will depend on the revenue model in question and should be built to support the revenue model and address the remaining risks.

4.3.4 Capital financing

Due to the large capital outlay associated with a capture plant, and the limited ability of industrial emitters to fund investments of this size and timescale, the business model must account for the availability of capital. A summary of the capital financing options is given in Table 4-3.

Table 4-3 Capital financing options available

Capital financing options
Public grants
Public loans
Public equity
Emitter equity
Investor equity
Debt / loans, including Green Bonds
Multilateral public funds

The capital financing options available to a project will depend on the revenue model and the risk mitigation instruments in place. Generally, if there is sufficient certainty of revenue and the risks are minimised, low-cost capital financing (debt) will be readily available. However, in the scale-up phase, this is unlikely to be the case, so public grants, loans or loan guarantees may be required.

4.3.5 Ownership structures

As demonstrated through the business model case studies, the ownership of the capture plant and other aspects of CCS projects is a factor which can have a bearing on the business model. The options are shown in Table 4-4.

Table 4-4 Potential ownership structures

Ownership structures
Private – emitter
Private – non-emitter
Public-private partnership (PPP)
Public – direct
Public – through state-owned enterprise

For an industrial site capture plant in the UK, stakeholders considered it unlikely that public ownership would be an option. The number of capture plants could reach into the hundreds in the long-term and the government is likely to have neither the will nor the resource to manage this number of sites. Secondly, the capture plant is, in many cases, integrated into the industrial processes with complex ties to the operation. Therefore, it was perceived that it is highly likely to be operated by the emitter to minimise risks to BAU operations; at least partial private ownership would facilitate this[29].

All business model elements were discussed and tested at the expert stakeholder workshop, across industry, academia and policy-makers. The feedback was incorporated into the business model development and selection, which is explained further in the next section.

[29] A possible exception to this is in the case of clusters, where a single, large, capture plant may be shared between multiple emitters and therefore operated by an external party (private or public). There is considerable uncertainty relating to this option, so public ownership of capture plants has not been included in the shortlisted business models.

5 Business model development & evaluation

5.1 Process of evaluation

To develop promising business models, it is crucial to understand the requirements of both industry and government. A two-step selection process was developed to understand the potential effectiveness and acceptability of the mechanism first to industry, then to government, as shown in Figure 5-1. Each step involved analysis using a set of 'selection criteria' to evaluate the potential of the model. The majority of the key risks and challenges outlined in section 3.3 are covered in the selection criteria, particularly the economic and market risks and the political risks. Those that are not explicitly evaluated are likely to be either outside the scope of the ICC business model, or covered in the more detailed contractual arrangements:

- **Technical and operational risks** *(risk 1 & 2)*: the technical risks, such as capture rate underperformance, are already reducing through research and demonstration projects and learning from the deployment of ICC globally. Capture plant insurance, either private or through government guarantees, could protect industry from underperformance. Contracts could also include compensation for any unexpected industrial plant downtime due to capture plant construction.
- **Capital cost uncertainty** *(risk 3)*: capital financing agreements are likely to account for potential deviations from the expected costs. For early projects, it may be that the public sector must take on the majority of these liabilities or provide caps on the liability of the private sector (cost backstops). Once in the roll-out phase, there will be more certainty over capital costs, and the private sector may be able to hold this risk.
- **Industry instability** and product demand uncertainty *(risk 6):* this risk is one which is inherent in industry, whether carbon capture is present or not. However, ICC technology may exacerbate financial difficulties should the product demand drop. The cross-chain contracts on CO_2 volumes could be linked to the total industrial product volumes. Additionally, government could act as an insurer of last resort, as in the Thames Tideway model, to ensure the industrial site is not bankrupted by ICC costs when the market is unfavourable.
- **Cross-chain risks** *(risks 11-13):* T&S risks around availability and performance would be covered under the T&S business model and may be backed by government. T&S fees could be contractually covered or regulated to protect industry from excessive fees.

The selection criteria were developed and tested through stakeholder consultation with a broad range of parties across industry, academia and finance. For industry, it was highlighted at the stakeholder workshop that the two stand-out barriers to ICC implementation were the lack of revenue model and the financial impact on international competitiveness. These are assessed through step 1, criteria 2 and 3 respectively. For government, our assessment is that simplicity and cost to government are likely to be two of the key criteria; these form the basis for the step 2 criteria.

For each criterion, the business model was awarded a red, amber, yellow or green rating depending on how well the model mitigated the risk or fulfilled the criteria, as shown in Figure 5-1.

Figure 5-1 Business model evaluation process

Step 1 Acceptability to industry

- Build additional elements and instruments around each *revenue model* to mitigate the remaining risks where possible.
- Assess complete business model using step 1 criteria to understand the acceptability to industry and the model's ability to mitigate risks.

Step 2 Acceptability to government

- Assess the business model policies from public sector perspective using step 2 criteria to understand the acceptability to the government.
- Outline the applicability of the business models across industrial subsectors and CCS maturity phases.

Step 1 criteria

1. Capital availability or low cost financing
2. Strength of revenue incentive
3. Industry competitiveness and carbon leakage
4. Flexibility for operational cost uncertainties
5. CO_2 price level and uncertainty
6. Simplicity and transparency for industry

Step 2 criteria

1. Cost: efficiency promotion
2. Cost: ability to pass costs on
3. Policy track record
4. Speed and simplicity of implementation
5. Ongoing administrative simplicity

- Applicability to industrial sectors
- Applicability to CCS phases

The model does not address this challenge or performs poorly against this criterion.

The model partially addresses this challenge or performs moderately against this criterion.

The model mostly addresses this challenge or performs reasonably against this criterion.

The model can fully address this challenge or performs well against this criterion.

Industry criteria

Capital availability refers to the availability of grants or low cost financing options for the initial capital outlay (addressing *risk 4*). This challenge is not directly addressed by any of the *revenue* models, although those which provide certainty of revenue returns, will reduce the risks and therefore provide access to lower cost financing, allowing orange or green ratings. *Business* models which also provide capital financing or loan guarantees will be green.

The strength of the revenue incentive (& financeability) depends on the total available revenue relative to the cost of capture, and also on the long-term **certainty of that revenue**. This selection criteria refers to *risk 5*. Models with a guaranteed return to cover ICC costs and additional ROI are green. Models with some financial support or creation of demand, but still with uncertainties, will be orange. Models based solely on a regulatory 'stick' will be red.

Industry competitiveness and carbon leakage refers to *risk 7* and can be addressed in 2 ways. The first is a model which **compensates the emitter** for the cost of ICC, and therefore the product production cost does not increase. The second is a model which provides a framework allowing the ICC cost to be passed on (e.g. to the consumer) without impacting competitiveness (e.g. RAB in monopolistic energy market).

Flexibility for operational cost uncertainties refers to *risk 8*, including uncertainties in opex and fuel prices. Does the model insulate the industrial plant from opex uncertainties? If they are not directly accounted for, could they be linked, could a 'pain-gain' risk sharing reduce the impact or could the level of incentive account for this uncertainty?

CO_2 price level uncertainty refers to *risk 9*: some models can account for this uncertainty (e.g. CfD which defines a payment as a top-up to the CO_2 price) and are therefore green. Other mechanisms have more fixed revenue, so the cost-effectiveness to each party depends on the CO_2 price, as explained on page 39.

Simplicity and transparency for industry: how transparent is the model for industry and investors and how simply can they utilise and administer it?

Government criteria

Cost - efficiency: models which incentivise efficiency of project operation as well as low cost project selection will result in the lowest cost to society. Commonly, market led mechanisms drive cost reductions most effectively, whereas public procurement may be less effective. Mechanisms with a fixed incentive e.g. a fixed tax credit, inherently promote efficiency of operation by the private sector to improve their returns. Where this is not the case, for example in a cost plus mechanism, instruments must be added to achieve this incentive.

Cost – pass on: this criterion assesses whether ICC costs can be passed on to another party over time. For example, costs can be passed to consumers if a price premium can be achieved for low carbon products. Alternatively, obligations on fossil fuel suppliers may allow costs to be recovered this way. This is one of the key criteria that determines whether the government support / subsidy can be removed over time leaving a self-supporting market.

Policy track record: have similar policies been implemented effectively to spur capital investment?

Speed & simplicity of implementation: how quickly and simply could the policy be implemented to incentivise the early ICC projects in the 2020's? What are the legislative requirements and their impact on timeframe?

Ongoing simplicity for government: how simple would the policy be for government to administer? Policies which require site specific negotiations and incentives, such as cost plus where all costs must be reviewed annually for every capture plant, would lead to a high level of administrative complexity for government. Market led mechanisms, where once the market matures, government involvement can be gradually removed over time, are likely to result in lower administrative complexity in the longer term.

Applicability to industrial sectors: Could the policy apply to all industrial sectors? This would be green if it could incentivise all sectors effectively. It will be orange if it will only provide strong incentives to some sectors.

Applicability to CCS phases: does the model apply to both scale-up and roll-out phases (allowing government support to be gradually removed as the market matures)? It will be orange if it applies significantly better to one phase.

Specificity to CCS Is the incentive specific to CCS, or does it incentivise industrial decarbonisation through any method? Product related mechanisms, such as applying EPSs on the end-use, generally apply broadly to decarbonisation through any measure, including industrial fuel switching and energy efficiency.

5.1.1 Additional business model considerations

Cost reduction drivers

Effective policies should drive cost reductions in ICC deployment over time to reduce the cost to society and ensure CCS is competitive against other decarbonisation options. A summary of the key factors is presented below:

- **Appropriate project selection:** strategic or low-cost projects must either be chosen through a robust selection process or promoted inherently through the mechanism developed. For example, a fixed tax credit in £/tCO_2 abated, would incentivise the lowest cost projects, as they could generate the highest returns. For publicly procured projects, a competitive bidding process may lead to the best value for government.

- **Operational efficiency:** efficiency must be incentivised within the model. For those with a contractually fixed subsidy, the private sector already has an incentive to drive cost reductions. For mechanisms such as '*Cost Plus'* and '*RAB'*, incentives to drive cost reductions must be included, for example pain-gain risk sharing mechanisms[30].

- **Passing costs on to consumers:** the cost to the exchequer will be minimised if the mechanism can pass ICC costs on to other parties. The only two models which directly enable this are '*RAB*' and creation of '*low carbon markets*', which pass the costs to the consumer of low carbon products. If carbon leakage is addressed, through carbon price collaboration or otherwise, all mechanisms can transfer costs to consumers over time.

- **Passing costs on to polluters:** some mechanisms enable cost to be passed to other polluters through tradeable certificates. *'CCS obligation certificates'* can spread the cost to all obligated parties. e.g. emitters and fossil fuel suppliers and/or buyers through certificate purchase, thereby reducing the cost to government. The potential use of existing carbon trading mechanisms (e.g. EU ETS) could be harnessed by channelling some certificates to ICC operators for onward sale to emitters thereby generating revenues to cover the costs of ICC. NER 300/400 creates the precedent for earmarking certificates for CCS, and ICC implementation frees up certificates, creating flexibility in the UK EU ETS budget.

- **Clusters and economies of scale** have the potential to result in a considerably lower cost of decarbonisation. The mechanism should promote cluster development and infrastructure sharing and government should help enable the required collaboration.

- **Low cost financing:** the overall project cost can be considerably reduced if low cost capital financing is available. A strong and certain revenue model will support this, and financing costs can be further reduced through mechanisms such as loan guarantees.

[30] Parties share in the financial "gain" of a project's success/overperformance or the financial "pain" of a project's underachievement. Parties therefore have a shared interest in the overall success of the project.

State Aid

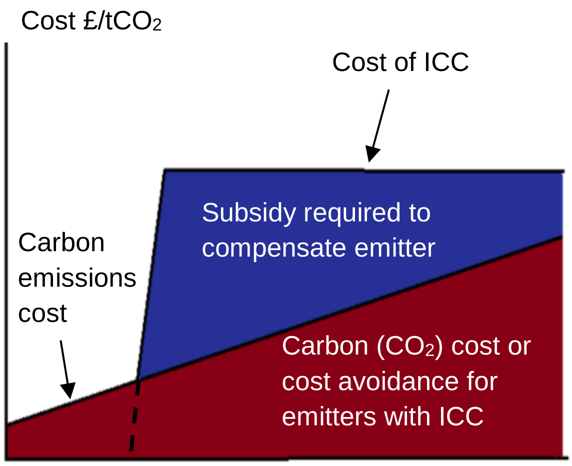
State Aid is defined as an advantage conferred on a selective basis by national public authorities.[31] A company which receives government support may gain an advantage over its competitors. For CCS, there are specific guidelines within the framework under environmental protection[32]. The guidelines recognise the potential contribution of CCS to mitigating climate change and the high costs of the technology. As aid to CCS is considered to address market failure, contribute to the common objective of environmental protection and be appropriate, EEA Guidelines accept that State Aid may be provided. Both operating and investment aid is permitted, and eligible costs are the total funding gap for the CCS technology. If the ICC support mechanism overcompensates the emitter for the costs of ICC, they may gain an unfair advantage over their global competition through reduced production costs. The European Commission would determine whether a specific ICC support mechanism complies with the legislation around industrial support. If an industrial emitter is deemed to have received unfair returns on their ICC investment, they may be obligated to repay some of the profit. Cap and collar mechanisms can be used to impose a cap on the returns, with additional contractual terms outlining the proportion of profits which must be returned to government. This study does not look in detail at the potential restrictions imposed by this legislation. However, in the development of business models, State Aid has been considered and the models are only designed to compensate the emitter for ICC and protect their production costs or margins.

CO_2 price implications

In Europe, the EU Emissions Trading Scheme (ETS) imposes a cost on CO_2 emissions, which is set by the market price of a tradeable CO_2 certificate. As this is a market mechanism, the CO_2 price is uncertain and at the time of writing is around €20/tCO_2. Not only is this too low to incentivise most ICC projects, but it is also too uncertain to spur large capital investments. Currently, many industrial sites are provided with free ETS allowances to avoid the additional financial burden, thereby reducing carbon leakage risk for industries competing against firms outside the EU. Some free allowances are expected to be provided to industry in phase 4 (2021 – 2030)[33], although in the future the number may reduce, particularly if CO_2 reduction policies globally become more stringent.

The aim of many of the business models assessed is to compensate the emitter for the cost of ICC relative to a base case; this base case is assumed to be the emitter continuing to emit CO_2 and paying whatever level of CO_2 price they are obligated to through the EU ETS (or any UK alternative CO_2 pricing mechanism). Through implementing ICC, the emitter avoids these emissions costs, relative to an emitter who has not implemented ICC. A simple schematic illustration is given in Figure 5-2, showing the required subsidy for a given emitter (the ICC cost will vary between emitters). The principle is that as the CO_2 price increases, unabated emitters pass the increasing cost of emissions to their customers; due to the resulting higher product prices, the required subsidy to ICC emitters

Figure 5-2 A schematic illustration of the subsidy required to compensate the emitter for the ICC costs



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[31] http://ec.europa.eu/competition/state_aid/overview/index_en.html and https://www.gov.uk/guidance/state-aid
[32] http://www.justiceandenvironment.org/_files/file/2014/New%20Energy%20State%20Aid%20Guidelines.pdf
[33] https://ec.europa.eu/clima/policies/ets_en

reduces. As a result, the required level of subsidy is related to the current and future CO_2 price to which industry is exposed, and therefore cost-effective mechanisms may need to account for the impact of CO_2 price on profitability levels for the ICC operator.

Models with fixed subsidies do not 'account for the CO_2 price uncertainty', thereby exposing both parties to the future CO_2 price volatility. If CO_2 prices increase more than anticipated in turn increasing product market prices the ICC's profitability increases. Conversely if CO_2 prices stay lower than anticipated, depressing market product prices, the subsidy level may be insufficient to maintain profitability; State Aid would moderate these effects. This leads to uncertainty around the cost-effectiveness to both industry and government. Mechanisms which 'account for CO_2 price uncertainty' are considered to be those which adapt the incentive level as the CO_2 price changes, either through a direct link, such as in CfD_C, or indirectly through market mechanisms. There are four options:

- Emitter contributes to ICC costs to the value of their CO_2 price avoidance
- Emitter contributes a proportion of their CO_2 price avoidance, the rest being covered by the subsidy (shared exposure to the CO_2 price volatility). This could include indexing of the subsidy to the CO_2 price.
- The model compensates the emitter fully for ICC costs, but the emitter returns the corresponding ETS certificates, either in part or full. Financially this reflects the first two options.
- Government and emitters agree upfront a reference (stable) ETS price projection, above which government compensates the additional ICC costs.

If the ETS industry free allowances are reduced, the market cost of industrial products is likely to rise accordingly. The red portion of the ICC cost is recovered from consumers through a rise in product prices. It should be noted that currently EU countries compete with those outside the EU, many of which don't have equivalent CO_2 pricing mechanisms. Therefore, even if the ETS certificate price rises, this does not mitigate the carbon leakage risk unless there is full international collaboration on carbon pricing or protection from imports of cheaper products from countries with less developed carbon pricing policies.

5.2 Full business models

As the revenue models and business models were assessed, additional elements and instruments were included to strengthen their performance. A summary of each of the business models is given below.

CfD_C CO_2 abatement strike price

CfD_C CO_2 abatement strike price	
Revenue model Strike price on £/tCO_2 abated vs. CO_2 price (e.g. EU ETS certificate price), contractually agreed in advance to cover expected ICC costs relative to BAU. Strike price fixed for duration of contract, but level of incentive for new contracts adjusted.	**Risk management** • Long term contract on strike price • Loan guarantees or grants in scale-up • Potential caps (backstops) on emitter liability for unexpected capex and opex if required • Strike price index linked e.g. to fuel price
Funding source options CO_2 certificates purchased by all eligible emitters; government contribution (top-up as required) from exchequer could be funded through general taxation or levies e.g. on fossil fuel suppliers.	**Capital options** • *Roll-out:* Emitter equity and low-cost loans, with loan guarantees if required. • *Scale-up:* additional grants if required.

Description and discussion

A CFD_C strike price will be agreed in £/tCO_2 abated versus an industry standard or benchmark[34] (BAT), based on expected costs of installing and operating the ICC assets, with defined allowable returns to the emitter (State Aid). Once set, the strike price will not change throughout the lifetime of the contract for an agreed period (likely between 10 and 20 years). The emitter sells any excess CO_2 certificates (EU ETS or equivalent certificates) to another 'emitter' at market price and will also be paid the difference between the CFD_C strike price and the prevailing market CO_2 certificate price (see page 62) by a government backed entity. If the market CO_2 certificate price exceeds the strike price, the emitter would be obligated to return the difference. Subsidy is likely to decrease with time as CO_2 price increases. The mechanism provides protection from carbon leakage and mitigates the potential burden on consumers.

In the roll-out phase, the construction and performance risks lie primarily with the private sector, as the strike price is fixed, and the incentive is not paid until the ICC plant is operational. Index linking of the strike price to the fuel price and government caps on emitter liability for unexpected costs both aim to share some risk with government, if this is deemed necessary.

For first mover projects it is likely that bi-lateral negotiations would be needed, requiring a robust process for selecting the lowest cost strategic projects[35]. As the market matures, competitive bidding for the CFD_C strike price could be introduced, once there is sufficient cost certainty and risk reduction. Alternatively, an offered strike price could be set annually for each subsector, but this may result in higher strike prices than necessary (conflict with State Aid rules) or fail to incentivise most emitters (given the variety of emitters/sources), so is not the preferred option. If costs of capture are higher than expected, competitiveness may be impacted. Equally, if costs of capture are lower, competitiveness may improve[36].

The CFDc strike prices will vary between ICC sectors, and potentially within ICC sectors, especially as more complex/diluted/dispersed sources of CO_2 are targeted for later projects. Nevertheless, in general terms strike prices are expected to reduce over time as the market matures and technological improvements and risks reduce.

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[34] See page 61 for more detail on benchmarking.
[35] Given the history of CCS in the UK, it is unlikely a company will take a risk developing an early project without a guaranteed deal in place, due to the uncertainty around policy; this makes competitive bidding / a third competition difficult for the first projects, Additionally, there are currently still significant risks and uncertainties, so detailed contractual arrangements will be required, and it is likely these need to be bespoke in these early projects. Without detailed contractual arrangements and risk sharing, the strike price may have to be very high to mobilise the private sector.
[36] State aid will allow a cap and collar on returns picking up cost over/under runs within a range; the European Commission would determine whether a specific ICC support mechanism complies with the legislation around industrial support.

Public procurement of ICC through CfD contracts provides a strong incentive and socialises risk to some extent. Government is a reliable counterparty and can offer contracting structures to reduce development and operational risk and provide revenue certainty. Public procurement has successfully delivered investment in infrastructure in the past, although has not yet delivered UK CCS. In a large market, public procurement of projects may not allocate resource most efficiency, unless a bidding process is implemented (roll-out only); once operating, there is an incentive to run the capture plants efficiently. In this model, costs are not directly passed on to other parties, unless the CO_2 price rises, and industry is exposed to this price. The government backed entity will therefore require funds to cover the CFDc payment liabilities, especially in the early phases with low CO_2 certificate prices. If there is either international collaboration on CO_2 pricing, or protection (tariffs) against imported products with a high “manufactured carbon content”, the market could transition to a non-subsidised end state with the costs of ICC transferring to consumers. Alternatively, the option of passing costs on to polluters through additional allocation of tradeable certificates to ICC projects (e.g. EU ETS certificates) should be explored. Subsidy payments can then be reduced by the traded value of those certificates (see page 38). The government funding burden could be shared with other parties, such as fossil fuel suppliers, under carbon take-back obligations or through levies on fuel carbon content. For example, a hybrid model with CCS certificate obligations is presented in the Appendix section 8.3.

Acceptability to industry	**Acceptability to government**
• CfD_C mechanisms provides certainty of returns, so provided the strike price is agreed at an appropriate level and contracted for the duration, the incentive is strong. • For early projects, government caps on emitter liability for unexpected capex or opex may be required, and the strike price may need to be index linked to fuel prices to protect from unexpectedly high fuel costs in capture plant. • This mechanism reduces the carbon leakage risk, and if well designed, eliminates it. • Mechanisms is simple and transparent for industry.	• Cost to government, if well designed, is only that required above the carbon price to compensate the emitter and protect competitiveness. Efficiency is incentivised, but costs are only passed on to consumers through a rising carbon price; this may rise sufficiently that the subsidy drops to zero and can be removed. • Policy track record and applicability is high, although power CfD is on product price. • Adaptation of power CfD may allow quicker and more efficient policy development & implementation, although sector or site specific CfDs would add complexity. • Applicable to all industrial sectors and both CCS phases. Could be specific to ICC or include all decarbonisation measures.

CfD$_P$ Product price premium

<table>
<tr><th colspan="2">CfD$_P$ Product price premium strike price</th></tr>
<tr><td>Revenue model

Strike price on £/t product as a price premium relative to CO_2 price avoidance (see page 39). Contractually agreed in advance to cover expected ICC costs relative to BAU. Strike price fixed for contract period but adjusted for new contracts.</td><td>Risk management

• Long term contract on strike price
• Loan guarantees
• Government caps (backstops) on emitter liability for unexpected capex and opex
• Strike price could be index linked to fuel price</td></tr>
<tr><td>Funding source options

Government contribution could be funded through general taxation or levies e.g. on fossil fuel suppliers.</td><td>Capital options

• Roll-out: Emitter equity and low-cost loans, with loan guarantees if required.
• Scale-up: additional grants if required.</td></tr>
<tr><td colspan="2">Description and discussion

A CFD$_P$ strike price will be agreed in £/t product, as a premium[37] over the market price, based on expected costs of installing and operating the ICC assets, with defined allowable returns to the emitter. This premium would be linked to the CO_2 price to account partially or fully for CO_2 price avoidance. Once set, the strike price will not change throughout the lifetime of the contract for an agreed period (likely 15 or 20 years). If the CO_2 price avoidance becomes higher than the price premium agreed, the emitter would pay the difference back to government. The subsidy given is likely to decrease with time.
For the first mover projects it is likely that bi-lateral negotiations would be needed, which requires a robust process for selecting the lowest cost strategic projects. As the market matures, there may be defined price premiums for each product, dependent on carbon intensity; however, the complexities associated with establishing fair price premiums, adapting for market changes, and linking to the carbon intensity, would be considerable. If costs of capture are higher than expected, competitiveness may be impacted, so the government may offer liability caps for unexpected capex or opex. If designed well, the mechanism provides a strong revenue incentive, protection from carbon leakage and mitigates the potential burden on consumers. The government funding burden could be shared with fossil fuel suppliers under carbon return obligations or through levies. If there is protection (tariffs) against imported products with a high “manufactured carbon content”, or international collaboration, the market could transition to a non-subsidised end state with the costs of ICC transferring to consumers. The mechanism could be used more broadly than ICC, as industrial emitters also decarbonising through other routes would receive the price premium. This mechanism does not necessary mandate ICC as the decarbonisation route, so emitters are free to choose the lowest cost option e.g. energy efficiency and fuel switching can contribute. The mechanism is more complex, both on implementation and ongoing administration, than CfD$_C$, due to the large number of industrial products.</td></tr>
<tr><td>Acceptability to industry

• CfD$_P$ mechanism provides certainty of returns, so provided the strike price is agreed at an appropriate level and contracted for the duration, the incentive is strong.
• For early projects, government caps on emitter liability for unexpected capex or opex may be required, and the strike price may need to be index linked to fuel prices to protect from unexpectedly high fuel costs in capture plant.
• This mechanism reduces the carbon leakage risk, and if well designed, eliminates it.
• Mechanism is relatively simple and transparent for industry.</td><td>Acceptability to government

• Cost to government, if well designed, is only that required above the carbon price to compensate the emitter. Efficiency is incentivised, but costs are not directly passed on to consumers.
• Policy track record is relatively high, although power CfD is on a single product.
• Adaptation of power CfD may allow quicker and more efficient policy development, but the large number of products and requirement for benchmarking lead to complexity.
• Applicable to all industrial sectors and both CCS phases. Could be specific to ICC or include all decarbonisation measures.</td></tr>
</table>

[37] A strike price could be used directly as a top up to the market product price. However, this option has been eliminated, as the product prices for many industrial goods may be volatile and it would not be politically acceptable for government to take on this risk. Additionally, prices vary between different product qualities or market locations, so would be complex to define, particularly over a long time period.

Cost plus open book

<table>
<tr><th colspan="2">Cost plus open book (adapted from Pöyry and Teesside Collective 2017)</th></tr>
<tr><td>Revenue model
Emitter is directly compensated for all properly incurred operational ICC costs (deducting CO_2 price avoidance) through government grant funding.</td><td>Risk management
• Robust project selection process and efficiency incentives to ensure value to government e.g. pain-gain sharing mechanism.
• Potential sharing of CO_2 price exposure / avoidance.</td></tr>
<tr><td>Funding source options
Government contribution could be funded through general taxation or levies e.g. on fossil fuel suppliers.</td><td>Capital options
• Scale-up: Partial grant funding upfront and emitter equity, repaid during operation.
• Roll-out: reduced grant funding.</td></tr>
<tr><td colspan="2">Description and discussion
The emitter is directly compensated for all properly incurred operational costs and emitter capital investment is paid back with agreed returns. Repayments may be shaped such that the majority of the emitter capital outlay is recovered by the EII in the first few years, but the EII will only earn a higher return on capital if it continues to operate the plant for the full contract period. The mechanism is specific to ICC as the decarbonisation route and there is no clear route to decreased government involvement over time in the absence of strong and stable carbon pricing. A direct reimbursement contract, such as Cost Plus, is often used where performance, quality or simply delivery are more important than cost; this may be the case for early CCS projects in the UK. May also be used when the design, scope or costs are highly uncertain; in this case a fixed contract price would have to be high to account for this uncertainty. An example of a cost plus contract is that used for Heathrow Terminal 5[38]. Cost plus has also been used in the successful delivery of Defence contracts in the UK; the issue of cost overruns was highlighted as a reason for limiting their use, but many reports now recommend the reintroduction[39].

Government incurs a significant portion of the risks and costs, so this would likely be less politically acceptable, except in the case of early projects, or those of particular strategic value. This mechanism may not allocate resources efficiency in terms of projects and operational cost reductions. To incentivise efficiency, payments could be made against a combination of forecast and actual costs, so that returns to the emitter are higher if they can drive cost reductions (pain-gain sharing mechanism or Cost-plus-incentive-fee). To create a robust selection process, the possibility of a bidding process based on expected costs could be explored.</td></tr>
<tr><td>Acceptability to industry
• Mechanism provides a very strong incentive for industry as ICC costs are fully covered with guaranteed returns. This maintains international competitiveness.
• The mechanism accounts for CO_2 price changes and operational cost uncertainties.
• The mechanism is relatively simple for industry, although less so than CfD_C, and is transparent.</td><td>Acceptability to government
• Cost to government is relatively high as, while the government only pays the required amount to cover additional costs, efficiency in project selection and operation is not incentivised and costs are not passed on to consumers.
• Policy track record is reasonable, with relatively fast implementation for early projects.
• Administration would be complex, particularly in roll-out, due to need to evaluate every capture project annually.
• Political and public acceptability of grants from taxpayer money may be low, so consideration of appropriate funding recovery sources or cost pass-on options should be considered.</td></tr>
</table>

[38] https://www.designingbuildings.co.uk/wiki/Procurement_of_Heathrow_T5
[39] https://publications.parliament.uk/pa/cm200304/cmselect/cmdfence/572/572we13.htm

Regulated Asset Base (RAB)

<table>
<tr><th colspan="2">Regulated Asset Base (RAB)</th></tr>
<tr><td>Revenue model
Product price (Hydrogen) regulated to recover capital and operational costs, likely through consumer energy bills.</td><td>Risk management
H_2 demand guarantees / contracts.
Consumer affordability protection
Requires robust project selection and incentive to drive down costs</td></tr>
<tr><td>Funding source options
Energy consumers, either direct H_2 consumers or spread to all gas (& electricity) consumers.
Government contribution may be required to reduce impact on energy bills.</td><td>Capital options
Roll-out: RAB recovery of capital funded by emitter equity/debt
Scale-up: likely grant support</td></tr>
<tr><td colspan="2">Description and discussion
A regulatory body, such as Ofgem, regulates the product price to allow recovery of ICC asset value and costs, whilst protecting consumers from excessive charges. As a result, the capital equity risk is low, providing there is a certain demand for the product.

It is assumed that this model is only applicable to hydrogen for heat, as suggested in the recent HyNet report (Cadent, 2018), as this is a monopolistic energy market. Other industrial subsectors are subject to competition both domestically and internationally, so cannot pass costs on to consumers in the same manner. However, if a proxy was created for the consumer base (likely the exchequer), a similar regulated model could be used in place of ‘Cost Plus’ for the other industrial subsectors.

In a large market, public procurement of projects may not allocate resource most efficiency. The RAB model requires robust project selection and efficiency incentives; energy providers may be stimulated to drive cost reductions if they are able to retain funds resulting from cost cutting, increasing their returns. This mechanism may also help to spur investment, which may have been deterred by likely low regulated returns. A possible disadvantage of the RAB model is affordability issues arising from passing the risk of sunk costs to consumers, particularly for vulnerable consumers. Mechanisms would need to be in place to protect these vulnerable consumers, or to reduce the impact on energy bills, such as price caps or backstops on gas prices. The acceptability of this policy and resulting increased gas bills to consumers, both commercial and domestic, should be assessed.</td></tr>
<tr><td>Acceptability to industry
Mechanism provides a solid incentive for industry as ICC costs are fully recovered under regulated model making it low risk, provided there is a certainty of product demand. Most risks are borne indirectly by consumers.
Competitiveness and carbon leakage are not addressed but are not an issue for hydrogen for heat.
Model accounts for uncertainties in the CO_2 price and operational costs.
Relatively simple and transparent for industry.</td><td>Acceptability to government
Cost to government is low as costs are directly passed to energy consumers.
Efficiency and cost reductions are not inherently incentivised as well as in market-based mechanisms.
Policy track record & acceptability is high as RAB is successfully functioning in UK energy market.
Implementation requires creation / repurposing of regulatory body & administration may be relatively complex due to need to evaluate every project annually.</td></tr>
</table>

Tradeable tax credits

<table>
<tr><th colspan="2">Tradeable tax credits</th></tr>
<tr><td>Revenue model

Reductions in tax liability of EIIs with ICC in £/tCO_2 abated. The tax credits may be fixed or may taper down over time. Must be tradeable to allow realisation of their full value (See page 55).</td><td>Risk management

• Contracts on minimum credit value for duration.
• Potential HMRC buyback guarantee
• Potential credit value variation with CO_2 price
• Capital tax credits or loan guarantee.</td></tr>
<tr><td>Funding source options

Government contribution could be funded through general taxation or levies e.g. on fossil fuel suppliers.</td><td>Capital options

• Roll-out: Emitter equity or debt + partial capital tax credits
• Scale-up: may also require loan guarantee.</td></tr>
<tr><td colspan="2">Description and discussion

Tax credits are reductions in the tax liability of a firm, in £/tCO_2 abated vs an industry benchmark, to compensate the emitter, partially or fully, for the cost of ICC. Tax credits may begin generously and taper down over time, both within a contract and for offered contracts over time. As the tax liability of many industrial firms is less than the annual cost of ICC, the tax credits must be tradeable to allow firms to realise their full value (See page 55). To provide a strong incentive to industry, the tax credits must be of sufficient depth, longevity and certainty to guarantee ICC costs are covered. Capital availability must also be addressed, either through capital tax credits or loan guarantees. The tax credit level may also vary with the CO_2 price, or the value of the CO_2 price avoidance shared with government, to reduce risk to both parties.

A system of tax credits is available in the US (section 45Q) to support CCUS deployment; 45Q was created in 2008 and under a new bill, the credit will be increased to $35 /t$CO_2$ used and $50/t$CO_2$ stored, by 2026. It is said to have already provided and incentive to the Petra Nova and Illinois CCS projects (see Appendix). This mechanism was also suggested in the CCUS Cost Challenge Taskforce report (2018).
In terms of award mechanism, tax credits, in £/tCO_2, could be of fixed value across industry, be subsector specific, have value varying by factors such as CO_2 purity, be negotiated for each site, or be awarded under a competitive bidding process (roll-out only). Fixed tax credits are simple and promote low cost project selection but may overcompensate some emitters and fail to incentivise others. Tax credits could be used to focus ICC development, for example in specific locations, if the tax credits were more generous in strategic cluster locations, for a strong, efficient supply chain; however, the additional complexity and concerns over fairness makes this less appealing.

The tax credits would be funded by the exchequer, although the cost could be recovered through specific levies for example on fuel consumers or suppliers. The exchequer funding burden could also be reduced by distribution of EU ETS allowances (or equivalent), as discussed on page 38. If tax credits were only applied during operation, no funding is required until CO_2 is actually being abated, which may increase the acceptability of the model. However, capital financing must also be addressed, particularly in the scale-up phase.

The traded price of a tax credit would likely be less than 100% of its value, unless the purchasing party had a particular interest in the success of the ICC project (e.g. project partners). It is suggested that the traded price would settle somewhere between 75% and 100% of the credit value. The ‘HMRC buyback guarantee’ is a guarantee by the government to purchase the tax credit at some proportion of its value (e.g. 75%) if it cannot be sold to another party at an acceptable price; in essence this becomes a cash payment. This provides a price floor for the credit value and some revenue certainty to ICC emitters or investors in the case that the tax credit trading market is not sufficiently liquid. It should be noted that while the subsidy has a fixed limit from a government perspective (100% credit value), the drawback is</td></tr>
</table>

that the ICC emitter will likely not receive all this, so some subsidy may not be used for its intended purpose.	
Acceptability to industry	**Acceptability to government**
• If credits are of sufficient depth, longevity and certainty, they provide strong incentive to emitters and certainty to investors. This mitigates the carbon leakage risk. The buyback rate (price floor) would need to be sufficiently high to minimise risk of losses by ICC operators. • Tax credits do not account for operational cost uncertainties, but may account for CO_2 price changes, partially or fully. • Mechanism is relatively simple and transparent for industry.	• Cost to government is moderate; efficiency and low-cost project selection are incentivised, and CO_2 price could be transferred to the emitter. However, costs are not passed to consumers and some emitters may be overcompensated under a fixed tax credit. • Policy track record of tax credits is strong[40] as they are widely used to support renewable energy investment (although usually as supplementary revenue), including 45Q, but the tradeable element remains unproven. • Implementation may be relatively quick; ongoing administrative complexity would depend on the chosen system, but would likely be relatively complex as transactions and contracts require ongoing government involvement. • The political acceptability of tax credits is thought to be reasonable, especially a fixed tax credit, as majority of risk is borne by private sector.

[40] Tax credit programs for CCS by US DoE: 8 entities have received $2 bn in tax credits since 2009 https://hub.globalccsinstitute.com/publications/strategic-analysis-global-status-carbon-capture-storage-report-3/56-taxation-incentives
UK Oil and gas field allowances for development of marginal oil fields (Delloitte taxation guide)
Enhanced Capital Allowances: Tax reductions for efficient plant machinery in the UK

Product taxes based on CO_2 intensity

Product taxes based on CO_2 intensity

Revenue model

Product taxes at point of sale based on CO_2 intensity relative to product benchmark. Potential to redistribute taxes, in the form of tax credits, to EIIs with ICC exporting products, to support competitiveness.

Risk management

- Advanced projection of tax levels and product benchmarks, with contract.
- Financial support e.g. additional tax credits or border arrangements for export

Funding source options

- Industrial consumers (and potentially fossil fuel consumers)
- Government contribution could be funded through general taxation or levies.

Capital options

- *Roll-out:* Emitter equity / debt + tax credits or loan guarantee
- *Scale-up:* may require grants.

Description and discussion

Product CO_2 taxes based on the carbon intensity (in tCO_2 / t. product), relative to a product benchmark, directly incentivises low carbon products. This has the advantage that it promotes production methods with lower emissions, or even product alternatives with lower embedded carbon. The tax level could also be index linked to the CO_2 price, so that when the CO_2 price is high, the taxes are lower, however this adds additional complexity.

An advantage is that if the tax is at the point of sale, it is applied regardless of the country of origin, so within the UK there is a level playing field for domestic and imported goods. However, UK manufacturers *with ICC* would still be at a disadvantage outside the UK, so this mechanism would require financial revenue support, for example additional tax credits, for competitively exposed industries on export. CO_2 taxes could also be applied to fossil fuels & this tax income redistributed to ICC to reduce the financial and competitiveness impact on industry. As product taxes raise the price of industrial products, the consumer acceptability of these tax mechanisms would have to be assessed, as well as addressing affordability concerns to protect vulnerable consumers.

Product carbon intensity benchmarks are required to assess the level of tax on each product; these could be based on the best available technology (BAT) or a product 'average' and could decrease over time (or the tax rate could increase). Due to the large number of industrial products, the definition of these benchmarks and associated tax trajectories would be a significant administrative undertaking and may be limited to products with the largest emissions associated. As there is no tradeable element to this mechanism, the government must administer any redistribution of money (through taxes) between low carbon and high carbon manufacturers, which has the disadvantage of continued government involvement and complexity.

Tax mechanisms are commonly used to alter markets and account for external costs to society such as health or environmental costs; examples include taxes on tobacco or sugary drinks. Therefore, they have some track record, albeit of limited applicability for industrial decarbonisation. The mechanism would be unlikely to spur the investment required in the scale-up phase due to the uncertainty and weaker revenue incentive.

Acceptability to industry

- This tax instrument primarily increases the cost of carbon intense products relative to low carbon ones. Even with redistribution of the collected taxes to ICC emitters, revenue strength is poor. Carbon leakage is partially, but not fully, addressed, as above.
- Operational cost uncertainties are not accounted for, and CO_2 price uncertainty is only incorporated if taxes are index linked to it.
- The mechanism may be complex for industry.

Acceptability to government

- Cost to government is low as ICC costs are primarily covered by industrial emitters / consumers and efficiency and low-cost project selection are incentivised.
- Policy track record of product tax instruments is reasonable, having altered market dynamics in the UK, however the nature of this instrument is unproven, particularly for such large capital investments.
- Mechanism is likely to be complex to implement and administer due to high number of products and market volatility, so application may be limited to few products.

Tradeable CCS certificates + obligation

<table>
<tr><th colspan="2">Tradeable CCS certificates + obligation (Element Energy & Vivid Economics, 2018)</th></tr>
<tr><td>Revenue model
• CCS certificates are awarded per tCO_2 abated and can be sold to other obligated emitters.
• Obligation on ‘emitters’ and/or fuel suppliers to present the required number of certificates.</td><td>Risk management
• Advanced projection of obligations.
• Certificate floor and ceiling prices.
• Free allocation or lower obligation to exposed industry.</td></tr>
<tr><td>Funding source options
• Obligated parties: all emitters and/or fuel suppliers.
• Potential government contribution in scale-up could be funded through general taxation or levies.</td><td>Capital options
• Roll-out: Emitter equity / debt (+ tax credits or loan guarantee).
• Scale-up: may require grants.</td></tr>
<tr><td colspan="2">Description and discussion

CCS certificates are awarded per tCO_2 abated relative to an industry benchmark. ‘Emitters’ and/or fuel suppliers are obligated by law to ensure a certain amount of CO_2 is captured and stored, with the obligations increasing over time to give a long-term decarbonisation trajectory and provide certainty to investors. The certificates may be used to meet the obligation or traded freely, so that parties with higher cost of CCS may choose to purchase cheaper certificates. The price of certificates is determined by the market, so is uncertain. However, the government may provide a buyout price, creating a floor price for certificate value; conversely, penalties for not meeting the obligation may create a price ceiling. The price floor and ceiling could be index linked to the CO_2 price, so that while CO_2 price is low, the floor price is higher, giving emitters more financial compensation certainty. Creating certificate markets and obligations is relatively complex with additional legal requirements.

This market mechanism should function well in the roll-out phase, where there is a degree of liquidity, but this would be lacking in the scale-up phase, where the certificate price would be highly uncertain and may not provide an investible incentive. It could therefore be supplemented by tax credits in the scale-up phase to support early projects. Alternatively, the certificate floor price could be raised for early projects, so that the mechanism will act similarly to CfDc.

Tradeable CCS certificates have been proposed as a market led solution, which allows reduced government involvement over time, both financially and in terms or risk allocation. It is similar to the EU ETS, so in a way acts as a UK top-up, but the obligation can be extended to additional firms if desired. One of the key advantages of this model is that the obligation to surrender certificates can be placed on whichever parties government deems most acceptable and able to bear the cost. For example, it could be placed on emitters, on fossil fuel suppliers or both; it is possible to begin the obligation with a narrow base, before extending coverage over time as the overall cost increases, as well as having different levels of obligation on different parties. An obligation on fuel suppliers addresses the industrial carbon leakage risk and reduces administrative complexity due to the smaller number of fuel suppliers. It also may have the benefit of incentivising fuel suppliers to use their infrastructure expertise to support the development of CCS infrastructure. However, this does not provide a direct obligation for industry to invest in ICC. The placement of the obligation will determine who ultimately funds the revenue; an obligation on fossil fuel suppliers will result in ICC costs partially being passed through to fossil fuel consumers e.g. of transport fuel and natural gas. However, as this consumer base is large, the proportional impact on price would be very small. This impact could be reduced further over time if necessary by additionally obligating emitters which are not trade-exposed, thereby passing some cost to industrial product consumers.

Creating certificate markets and obligations is complex on implementation, with additional legal requirements. The government could act as an intermediary in the purchase and sale of certificates, allowing the two prices to be different if necessary; this is less desirable in more mature phases where the</td></tr>
</table>

market should support itself. Alternatively, external intermediation may transform volatile market prices into long term fixed contracts i.e. the price risk is transferred to a third party such as a trader or bank, to provide certainty to investors.

The CCS certificate scheme allows price differentiation between CCS and other decarbonisation measures, analogous to the support for wind and solar generation during technology development. This differentiation could evolve into a single incentive in the future, as ICC costs reduce and the carbon price rises. One of the key questions remaining with this model would be the relationship with the EU ETS and associated CO_2 price. Over a long timeframe, if the CO_2 price increases and ICC is deployed, the number of CCS certificates available on the market increases and their price drops accordingly. However, the long timeframes for ICC deployment, and the relatively small numbers of projects likely over the next few decades, may prevent ideal market function. The government can intervene if necessary through the level of the floor and ceiling price as well as the level of obligation. For example, the floor price could be set so that CCS certificate floor + EU ETS combined gives the minimum subsidy required to avoid collapse of existing projects. The ceiling could be set such that CCS certificate ceiling + EU ETS provides no more than the subsidy required for the most expensive CCS projects. The level of obligation could be adjusted depending on factors such as the rate of ICC deployment vs decarbonisation targets, the EU ETS price and the current CCS certificate price. Whilst these mechanisms are useful to address market failures and provide the support and certainty required for early projects, they add complexity and negate some of the benefits of a free market mechanism. The option of creating a hybrid model through adding a CfD is explored in the Appendix section 8.3.

More information on the economic details of this mechanism can be found in "*Policy Mechanisms to support the large-scale deployment of Carbon Capture and Storage (CCS)*" (Element Energy & Vivid Economics, 2018). Alternatively, a similar CCS certificate obligation scheme could be used as a government revenue mechanism to fund other models.

Acceptability to industry	**Acceptability to government**
• Certificate price may be highly uncertain, resulting in a weaker incentive for industry and lower investibility. Price floor and ceiling may partially mitigate this. Carbon leakage risk is only addressed if exposed industry is not under the obligation or is given free certificates. • Mechanism does not incorporate operational cost uncertainties and doesn't account for CO_2 price changes, unless the price floor is index linked to the CO_2 price, or CO_2 certificate value is returned to government. • The mechanism is relatively simple and transparent for industry, compared with the product related models.	• Cost to government is low as costs are borne by emitters or fuel suppliers. Market mechanism incentivises efficiency of operation and lower cost projects. • Policy has a reasonable track record (e.g. Renewables Obligation, EU ETS) as well as providing a route to decreased government involvement over time. • While market creation may be relatively complex, the administrative burden on government may be low, assuming government does not act as intermediary in transactions.

Tradeable CO_2 credits + EPS

<table>
<tr><th colspan="2">Tradeable CO_2 credits + EPS</th></tr>
<tr><td>Revenue model
Tradeable CO_2 credits for products based on CO_2 intensity.
EPS must be met by surrender of credits, becoming stricter over time.</td><td>Risk management
Advanced projection of EPS.
Credit floor and ceiling prices.
Free allocation or higher benchmark for exposed industry
Loan guarantee.</td></tr>
<tr><td>Funding source options
Emitters (through credit purchase)
Industrial consumers through price increase
Potential government contribution in scale-up</td><td>Capital options
Roll-out: Emitter equity / debt + loan guarantee
Scale-up: may require grants.</td></tr>
<tr><td colspan="2">Description and discussion

CO_2 credits are awarded on product sales depending on their carbon intensity, relative to the industrial sector benchmark (e.g. in tCO_2/t.product). Sellers of industrial products are obliged by law to hold a level of credits annually to meet the Emissions Performance Standard (EPS), which increases over time with more stringent standards. The credits may be used to meet the obligation or traded freely, so that parties with higher decarbonisation costs may purchase cheaper certificates. Government may provide a buyout price, creating a floor price for credit value; conversely penalties for not meeting the obligation may create a price ceiling. The price floor and ceiling could be index linked to the CO_2 price, so that while CO_2 price is low, the floor price is higher, giving emitters more financial compensation certainty. Additional financial support may be required to address the carbon leakage risk. The EPS could be placed on industrial products such as cement or steel, or on the end-use such as buildings or vehicles, in terms of embedded carbon.

As with product CO_2 taxes, this has the advantage of directly incentivising low carbon products. Product carbon intensity benchmarks are required to assess the level of credit for each product; these could be based on the best available technology (BAT) or a product ‘average’ and could decrease over time. Due to the large number of industrial products, the definition of these benchmarks and associated EPS trajectories would be a significant administrative undertaking and may be limited to products with the largest emissions associated. The tradeable element allows the government involvement to be removed over time as the market transitions to an unsubsidised end-state. This provides the advantage of reducing the financial and administrative burden over time.

An EPS for CO_2 has been implemented in a number of jurisdictions, although not combined with tradeable certificates. It has successfully deterred investment e.g. in coal power plants but has not incentivised CCS investment or novel technologies. The scheme is also relatively similar to the ETS trading; the difference being that under these benchmarks, when a firm produces more product, but at the benchmark carbon intensity, they incur no additional liability. As product EPSs may raise the price of industrial products, the consumer acceptability of this mechanism should be assessed, as well as addressing affordability concerns to protect vulnerable consumers.</td></tr>
<tr><td>Acceptability to industry
Credit price may be highly uncertain, resulting in a weaker incentive for industry and lower investibility. Price floor and ceiling may partially mitigate this.
If EPS is solely on industrial products, carbon leakage risk is high. Mitigation would require a financial contribution from exchequer or fuel suppliers, or border adjustments.
The mechanism does not account for ICC operational cost uncertainties and doesn’t account for CO_2 price changes, unless the price floor is index linked to the CO_2 price or CO_2 allowances are returned to government.
Mechanism may be complex for industry.</td><td>Acceptability to government
Cost to government is low as costs are borne by emitters. Market mechanism incentivises efficiency of operation and lower cost projects.
EPSs have been used effectively, but primarily as a deterrent rather than incentivising large investments, so have little track record.
The mechanism is likely to be complex to implement and administer due to the large number of products requiring benchmark trajectories and the creation of the CO_2 credit market.
Mechanism may be effective in roll-out but would struggle to provide the required incentive certainty in scale-up.</td></tr>
</table>

Low carbon market creation

<table>
<tr><th colspan="2">Low carbon market creation</th></tr>
<tr><td>Revenue model

Creation of low-carbon market through certification, public procurement and end-use regulations, allowing a price premium for low carbon goods.</td><td>Risk management

• Long term regulation projections
• Public procurement contracts for early projects
• Potentially guarantee on minimum price premium in scale-up phase.</td></tr>
<tr><td>Funding source options

Industrial product consumers under the regulations. Potential government contribution to protect exposed industry on export.</td><td>Capital options

• Roll-out: Emitter equity / debt
• Scale-up: grants & loan guarantees likely to be required.</td></tr>
<tr><td colspan="2">Description and discussion

A long-term solution to decarbonising industry is to use market mechanisms to create a market demand for low carbon products. This would enable a price premium to be achieved and therefore cost pass-on to consumers. There are a number of ways to encourage development of this market, three of which are outlined:
1. Create standardised certification for low carbon products and raise awareness throughout the economy, including consumers of end-products, of the carbon intensity of goods. Positive perception may gradually create value, as suggested in the Cost Challenge Taskforce Report (2018).
2. Public procurement of low carbon products, directly or through contractors e.g. in construction
3. Regulation on end-products, such as buildings, infrastructure and vehicle manufacture, could include obligations to purchase a certain proportion of low carbon materials.
It should be noted that domestic end uses such as construction may be more desirable, as they are not competitively exposed in the same way as manufacturers exporting, for example vehicles. Zero carbon homes only addresses the energy performance once built; building regulations could additionally include the embedded carbon of a new build, either separately, or as a combined ‘total lifetime emissions’ limit.

These measures would be designed to create a guaranteed demand for low carbon goods, likely at a price premium. However, this demand and price premium is not present outside the UK, so firms with ICC would be less competitive abroad without financial support (e.g. a government contribution in £/t product on exports or tax credits to exposed industry).

The model is unlikely to provide the required certainty to incentivise investment in ICC in the scale-up phase, however, could work efficiently once there is sufficient low carbon product supply and demand in the market to allow for competition between suppliers and between purchasers. This mechanism could draw on aspects of other product related incentive models discussed. For example, product CO_2 taxes, and EPSs. To improve the strength of the revenue incentive, a price premium guarantee could be implemented similar to CfD_P, or tax credits could be provided for end-use e.g. buildings utilising low carbon materials. More work is required to assess the most effective instruments to create this low carbon market and understand the wider implications.</td></tr>
<tr><td>Acceptability to industry

• Strength of incentive (and investibility) of early projects is relatively uncertain before market develops sufficient supply and demand. Could be mitigated by direct public procurement contracts early on.
• Carbon leakage is not entirely addressed, as a price premium can only be created in the UK.
• As this is a market-based mechanism, once there is sufficient supply and demand, the uncertainties in opex and CO_2 price are inherently accounted for.
• Mechanism should be relatively transparent and simple for industry as they are selling their product in a competitive market as usual.</td><td>Acceptability to government

• Cost to government is relatively low (export compensation only) as majority of cost is borne by consumers (increased prices). Market mechanism incentivises efficiency of operation and lower cost project selection, once there is sufficient supply and demand for competition (likely only effective in the roll-out phase).
• Little track record, although public procurement and end-use regulation are common practise.
• It is likely to be complex to implement if applied to a large number of end-products, although public procurement targets may support early projects relatively quickly. Once implemented, the market should take over and the administrative burden should reduce.</td></tr>
</table>

6 Results and discussion

6.1 Outcomes of business model evaluation

Once the business models were developed, they were evaluated using the selection criteria outlined in section 5.1, to understand their acceptability from the perspectives of industry and government. The results are summarised below in Table 6-1.

Table 6-1 Summary of business model evaluation results. S: more applicable in scale-up phase. R: more applicable in roll-out phase.

	Step 1: acceptability to industry						Step 2: acceptability to government						
Business model	Capital availability	Revenue strength	Competitiveness	Opex uncertainty	CO_2 price	Simplicity	Cost: Efficiency	Cost: pass on	Track record	Implementation	Administration	CCS Phases	Sector applicability
CfD_C - CO_2 abatement													
CfD_P - product price premium													
Cost plus open book												S	
RAB (Hydrogen only)													
Tradeable tax credits linked to CO_2 price + capital tax credits													
Product CO_2 taxes linked to CO_2 price, with tax credits												R	
Tradeable CCS certificates + obligation + price floor & ceiling												R	
Product EPS + tradeable CO_2 credits + price floor & ceiling												R	
Low carbon market: public procurement & end-use regulation												R	

Market led mechanisms, such as the final four models evaluated, are generally the most cost-effective for government, as they promote efficiency in project selection and operation. They also enable cost-pass on to consumers or other parties (e.g. through product price increases or obligations on fossil fuel suppliers), thereby reducing the level of subsidy needed from the exchequer. However, as a result, they often don't provide such a strong and certain revenue incentive for industry. These mechanisms may perform effectively in the roll-out phase, once the market is established, but may not, alone, incentivise investment in early projects. A brief summary of the performance of each model is given below, with further detail found in section 5.2.

CfD_C CO_2 abatement

The CfD_C model performs relatively well on both sets of criteria. With long term contracts and carefully calculated strike prices, the mechanism provides a strong and certain revenue incentive, making it investible for industry. The policy track record is reasonably strong, cost to government is reasonable and it is a comparatively simple framework for industry and government. For this reason, CfD_C is **shortlisted as a promising business model** which provides a good balance between the requirements of the private and public sectors. The key weakness of the model is that it does not directly allow cost pass-on to consumers or other parties. Work could be done to understand whether this mechanism could be combined with CCS certificates, to obligate fuel suppliers to subsidise the model. It should be noted that if the CO_2 price rises, the cost to government falls, so in a world with a high international CO_2 pricing the government support could be removed, as with many of the mechanisms.

CfD_P product price

The CfD_P model is similar in nature to CfD_C and therefore has similar performance. However, some ratings are lower due to the additional complexity of providing benchmarks and strike prices for such a wide range of industrial products. As this model performs less well than CfD_C, it is **eliminated from the shortlist**. However, this concept of a guaranteed product price premium could be utilised in the early stages of the 'low carbon market creation' to provide additional certainty of revenue to investors.

Cost plus open book

The cost plus open book model performs very well on acceptability to industry, as the private sector is insulated from the majority of risks and the public sector absorbs these. Therefore, this low risk model with guaranteed returns provides a strong incentive to industry. A similar model has been used for Quest, Canada, with staged grant payments from government combined with emissions pricing incentives. However, the model performs poorly on its 'acceptability to government' as it would be relatively high cost and administratively complex due to the need to assess all capture plants annually. Therefore, it is suggested that this model still has the **potential to be used in the scale-up phase**, where a strong incentive is needed to incentivise industry, and there are few capture plants, thereby reducing complexity and cost.

Regulated Asset Base

The RAB model performs very well on acceptability to industry as all costs could be recovered from consumers in the hydrogen for heat market[41]. The model also performs reasonably well on acceptability to government, as it has low cost to government and a strong policy track record in the energy industry. For these reasons, it is **shortlisted as a promising business model**. The simplicity of implementation and administration would need to be further understood and additional incentives for efficiency may be required.

[41] It is not currently feasible for other industries to pass costs on in the same way, although this regulated model could be used with the exchequer as a proxy for the consumer base (acting in a similar manner to cost plus, but with additional regulation to encourage cost reductions).

Tradeable tax credits for CCS linked to CO_2 price + capital tax credits

The model performs reasonably well on 'acceptability to industry', providing the tax credits are tradeable and of sufficient depth and certainty. The mechanism also performs reasonably on 'acceptability to government', with the key uncertainties being the limited track record of the tradeable element and the potential administrative complexity. This model is **shortlisted as a promising business model**, with a more detailed cost-benefit analysis required to understand the implications and to assess the effectiveness of tax credit trading.

Box 1: Tax credits and why they need to be tradeable

The annual tax liability of many firms is insufficient to cover the cost of ICC. The estimated cost of ICC over a 15 year operational lifetime for a typical cement plant may be £716 m. This equates to an average of £48 m annually, including capital financing. For Breedon group, which operates two cement plants, around 80 quarries, and other production facilities, the annual pre-tax profit in 2016 was less than £47 m[A]. Hence, the corporation tax liability of the firm, is considerably less than the annual cost of ICC, and the firm would therefore not be able to realise the full value of a tax credit incentive. However, if the tax credits were tradeable, the firm may be able to sell any unused tax credit value on to another party, thereby realising the remaining value. In the 2016/17 tax year, UK corporation tax raised £56 bn for the UK government[B]. This would be sufficient to pay for over 1000 ICC plants of typical scale, even if tax credits were covering the full costs.

Reference A: https://www.breedongroup.com/images/uploads/articles/FULL-YEAR_2016_RESULTS_FINAL.pdf
Reference B: https://www.ft.com/content/ca3e5bd2-2a7e-11e7-9ec8-168383da43b7

Product CO_2 taxes linked to CO_2 price, with tax credits

Product CO_2 taxes perform poorly on acceptability to both industry and government, primarily due to the weakness of the revenue model and the large complexity of the required product taxes. For these reasons, the mechanism has been **eliminated from the shortlist**. However, a similar tax mechanism could be assessed for use as an additional element in the 'low carbon market creation' if required.

Tradeable CCS certificates + obligation + price floor & ceiling

CCS certificates perform reasonably well on acceptability to both industry and government and has been **shortlisted as a promising business model**. The key advantage is the low cost, as efficiency is incentivised, and costs can be passed on to a broader range of obligated parties through sale of certificates, for example to fossil fuel suppliers. As this is a market mechanism, government involvement could be gradually removed, financially, administratively and in risk ownership. However, the uncertain certificate price may not form sufficient strength of incentive to spur initial investment in the scale-up phase; a high price floor (similar to a CfD_C) or tax credits may be needed until the market matures. Additionally, if the certificate market is not liquid enough, government intervention may be required to stabilise it, and consideration should be given to how the CCS certificate price would/should interact with the EU ETS CO_2 price and how this could be controlled (see page 49).

Product EPS + tradeable CO_2 credits + price floor & ceiling

This model is relatively similar in concept to CCS certificates, with the obligations and credits related to the product. As a result, the evaluation shows similar performance, but with some lower ratings due to the likely complexity of defining benchmarks and trajectories for so many products in addition to creating the CO_2 certificate market. As a result, the model has been **eliminated from the shortlist**. However, the advantages of low cost and a defined decarbonisation trajectory may encourage use of elements of this model in the ‘low carbon market creation’, where EPSs will likely have a role to play.

Low carbon market: public procurement & end-use regulation

This market led model performs reasonably across both sets of criteria. The key strength is the low cost to government and the ability to remove government involvement over time to reach an independent and unsubsidised end state. For these reasons, the model has been **shortlisted as a promising business model**, although more research would be needed to further assess the most effective instruments to create this market. The key disadvantage of this model is the uncertainty over the revenue incentive in early years when there is insufficient low carbon product supply and demand to create a functioning competitive market. Therefore, it is likely that this model would only be applicable in the roll-out phase, and would require support from other mechanisms in the scale-up phase.

The strengths and weaknesses of each of the six promising business models are depicted in Figure 6-1 for acceptability to industry, and Figure 6-2 for acceptability to government. It can clearly be seen that the two mechanisms led by the market, ‘CCS certificates’ and ‘creation of a low carbon market’, have the weakest revenue strength due to inherent uncertainty, but perform correspondingly well on the cost to government. Hence a balance must be achieved between these two conflicting requirements, and this balance will shift over time as the market matures and becomes more able to take on the costs and risks of ICC.

Figure 6-1 Depiction of the 'acceptability to industry' evaluation for each of the 6 promising business models

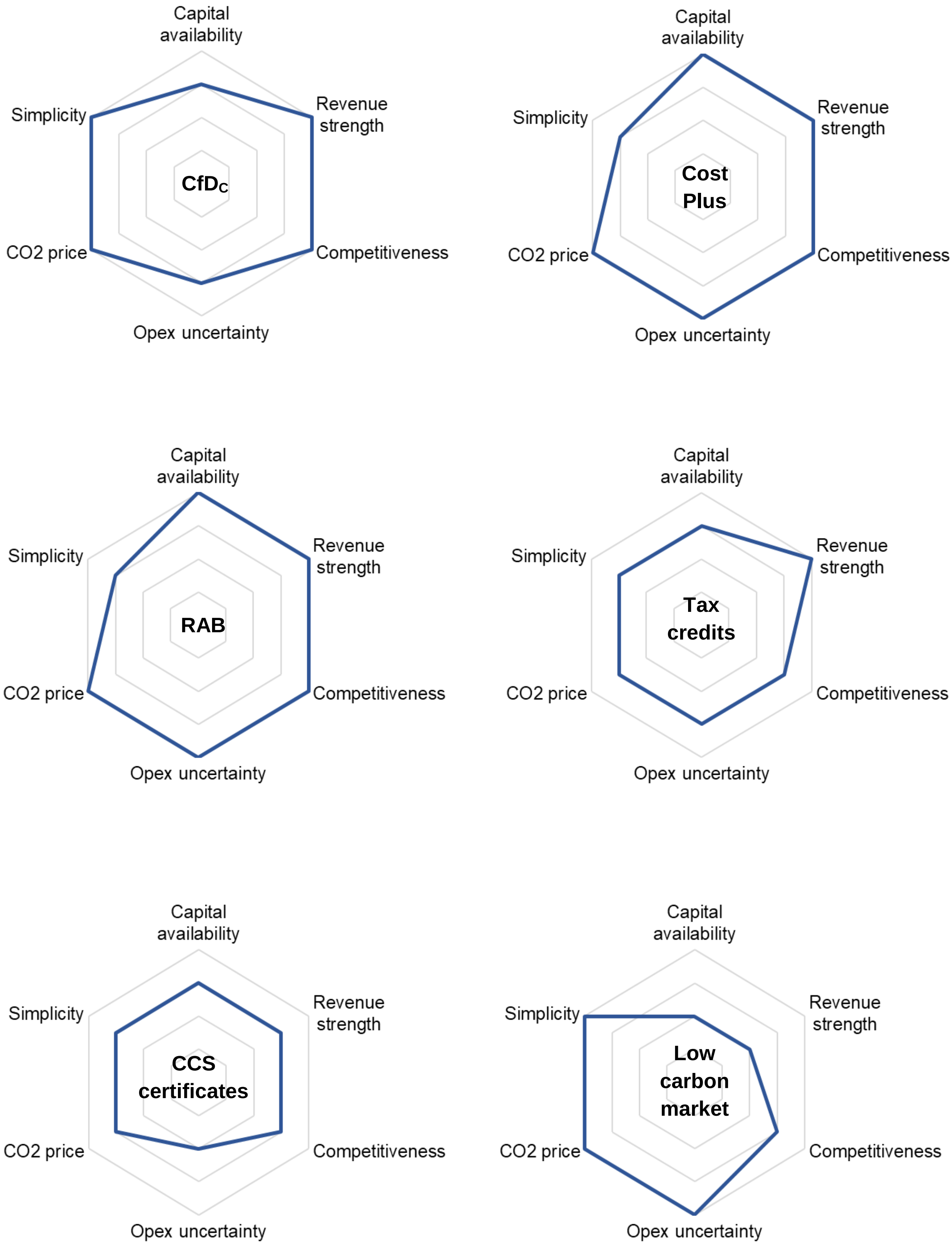
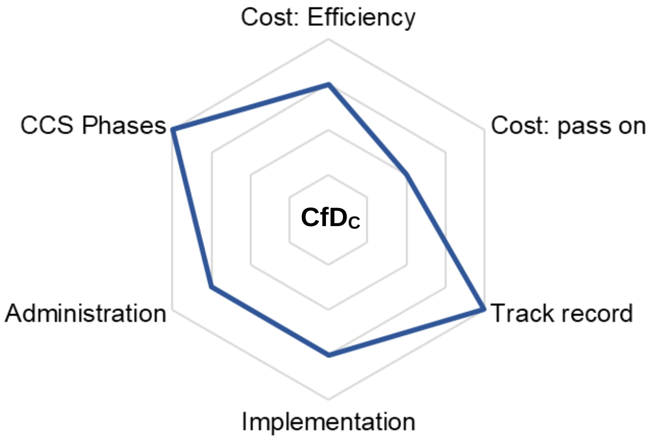
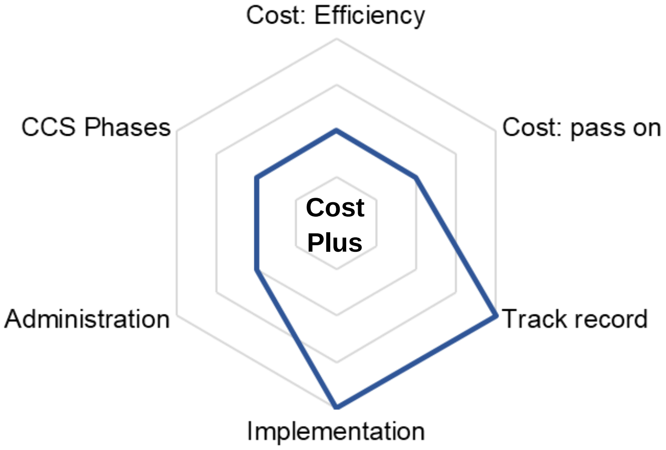
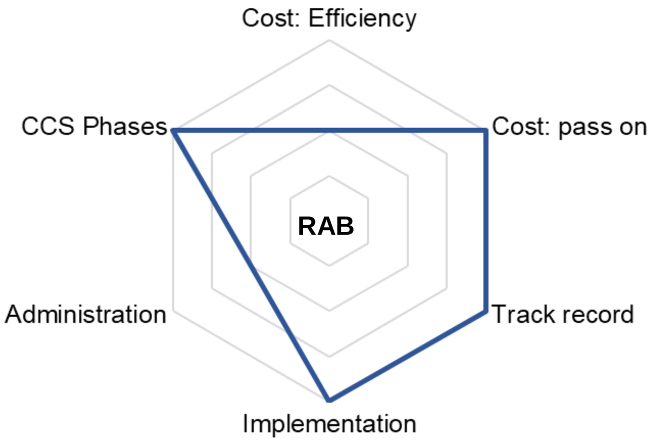
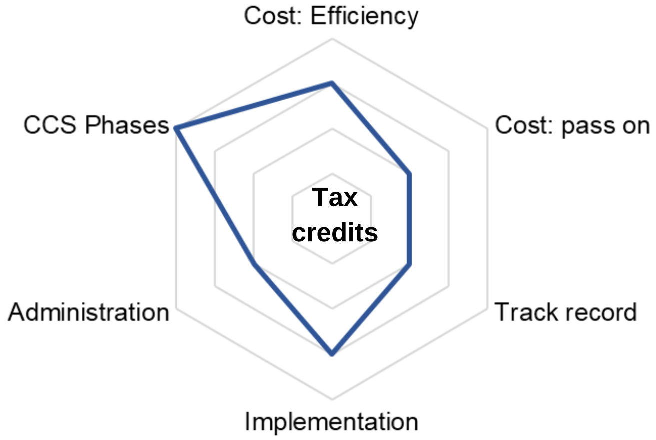


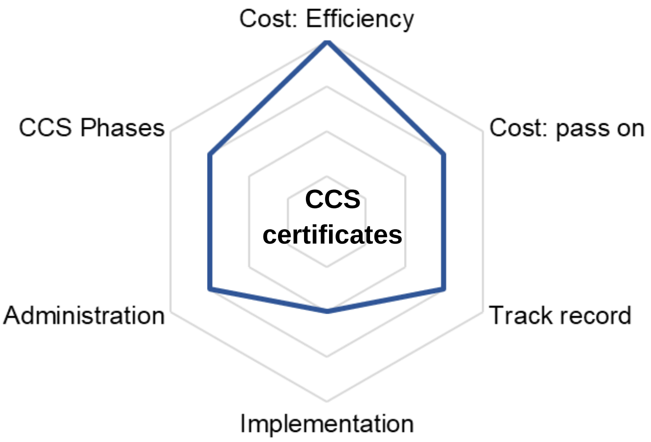
Figure 6-2 Depiction of the 'acceptability to government' evaluation for each of the 6 promising business models

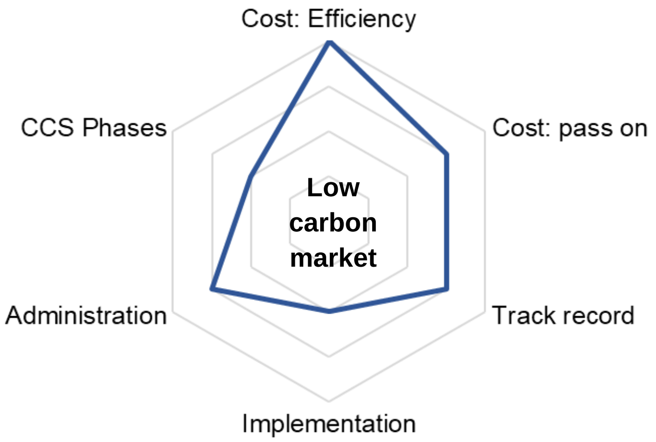












6.2 Further discussion of business model requirements

Industrial subsectors

The industrial subsectors are diverse, with differing processes, locations, scales and product markets, as described in section 3.1. The risks and challenges to ICC deployment in these subsectors are broadly similar, but with three key differences relevant to ICC market development, as outlined in section 3.3. These differences have an impact on the requirements and options of business models.

High purity CO_2 sites, such as ammonia, hydrogen and some other chemical sites have the lowest cost of ICC as the capital investment is low, but they may also be of small scale. It should be noted that some high purity CO_2 sites already capture CO_2 for utilisation (see page 60). Once T&S infrastructure is available, these sites can connect with lower ICC incentives. In particular, any capital support such as grants and loan guarantees, may not be required by these sectors, so could be removed. Additionally, fixed subsidies, such as blanket tax credits, may exclude pure CO_2 subsectors.

Impact on production costs (%) is dictated by factors including LCoA, carbon intensity of product and value of product and ranges from 3% - 70% across the energy intensive sectors analysed. Where the relative impact is low, a proportion of ICC costs *may* be borne by the emitter over time, provided the profit margins are sufficient to allow this. Additionally, low cost projects (in £/tCO_2) may have a significant contribution to their costs offset by the carbon price avoidance in the future. Again, the offered incentives could be adjusted to account for these factors.

The **hydrogen production subsector has some key distinctions and opportunities**, with three of the key advantages outlined:

1. As discussed, hydrogen for domestic heat does not compete internationally, so **costs can be passed to consumers** without risk of carbon leakage. This enables a broader range of business model options, including a RAB model, where costs are recovered through energy bills.
2. Many hydrogen plants may have capture technology **fitted during construction**, rather than retrofit, allowing a more cost-effective application. Additionally, once T&S infrastructure is in place, new hydrogen production facilities can choose to locate nearby to allow connection to this existing infrastructure. For new plants, regulation may dictate that 'capture' technology *must* be fitted and the plant *must* be located near existing or planned T&S infrastructure.
3. Hydrogen produced through SMR creates a pure CO_2 stream. As a result, complex capture technology is not required, and the **capital costs are lower**. Moreover, a large quantity of CO_2 is produced per tonne of hydrogen, improving the relative cost of capture against paying a carbon price. As above, the subsidies may no longer be required.

While the monopolistic market of hydrogen for heat opens up the potential for a Regulated Asset Base and passing costs onto consumers, this is not the only model which can effectively incentivise ICC for hydrogen. All other mechanisms considered here could also be applied and adapted for hydrogen, and the government contribution could be lowered. For example, the CfD_C strike price may be set lower, so that the costs are partially passed on to gas consumers, but a government contribution is used to reduce the impact on gas prices and protect consumers.

Furthermore, some subsectors can be **supported by regulations more effectively**. For example, new building regulations or regulations on infrastructure construction, where low carbon materials are used and sold domestically. In contrast, for other manufacturing sectors where the end product is sold internationally, such as vehicle manufacture, regulations around use of low carbon materials may put the manufacturers at a competitive disadvantage, resulting in carbon leakage.

CCS market maturity phases

The characteristics and requirements of the CCS market maturity phases were discussed in section 3.2 and the ratings for how applicable the models are in the scale-up and roll-out phases were given in section 6.1. In summary, the scale-up phase requires significant government involvement, both in terms of risk ownership and financial contribution, to create a strong and certain revenue model capable of incentivising industrial investment. The aim is that the business model should allow this support to be gradually removed over time as the market takes over and costs are passed to consumers.

Models such as cost plus perform well in the scale-up phase due to revenue certainty, but this is unlikely to be the most cost-effective solution for government in the roll-out phase. Market led mechanisms, such as the final four evaluated, are likely to allow reduced government involvement over time and drive cost reductions in the roll-out phase most successfully. These are considered to primarily apply to the roll-out phase, requiring supporting mechanisms in the scale-up phase.

Four mechanisms can be considered to apply reasonably effectively to both CCS market phases: CfD_C, CfD_P and tax credits could gradually reduce the incentive offered, at the same time as driving cost reductions, whilst also accounting for the CO_2 price avoidance. RAB passes costs to consumers so applies directly to both phases.

Using the same business model for both CCS market phases has benefits, including allowing the model to be tested and improved during scale-up. However, it may be necessary to make significant changes to the model, or even change the fundamental mechanism over time, to drive a cost-effective decarbonisation pathway in industry.

CO_2 utilisation (CCU)

The commercial market for bulk supply of liquefied CO_2 is well established globally, for use in various industrial sectors including chemicals, food & drink, healthcare, horticulture and other CO_2 utilisation (CCU) applications. The global market is around 80-100 $MtCO_2$/yr, of which approximately 60 $MtCO_2$/yr is used for CO_2-enhanced oil recovery (EOR), primarily in North America.[42] A number of specialist industrial gas suppliers dominate the global market on a commercial basis including Linde (BOC in the UK), Messers, Air Liquide, Air Products and Praxair. The main source of CO_2 currently is ammonia production. There are five major sites in the UK capturing CO_2 for merchant supply to the food and drink market: Manchester (Cargill/BOC, <0.1 $MtCO_2$/yr), Ince-in-Makerfield (CF Fertilisers, <0.6$MtCO_2$/yr), Billingham (CF Fertilisers, <0.8 $MtCO_2$/yr), Wilton (Praxair Bioethanol, 0.25 $MtCO_2$/yr) and Ipswich[43].

It should be noted that not all CCU applications sequester the CO_2 permanently. For many, the CO_2 is released into the atmosphere within weeks, thereby only delaying emissions for a limited period. For example, the CO_2 used for production of carbonated drinks, will be released into the environment when the drink is consumed. However, concrete curing, or concrete produced using CO_2 as an ingredient, may produce a product stable over a long timescale, so can be considered more permanent sequestration of the bound CO_2. As a result, only applications which result in sequestration over a long time period can be considered to contribute to climate goals, and incentives should be designed accordingly.

[42] The United States National GHG Inventory (2017) reports that 59.3 $MtCO_2$/yr was utilised for EOR in 2016, of which 13 $MtCO_2$/yr was captured from anthropogenic process streams.
[43] https://www.bbc.com/news/business-44613652 and emissions from UK ETS national allocation plan

Whilst CO_2 utilisation is not presently considered a primary driver for ICC in the UK due to the limited demand volumes currently, it could provide an additional revenue source and business models could be adapted to incorporate or promote this. For example, the section 45Q tax credit in the US contains different incentive rates for utilisation and storage: any new CO_2 producing industry that commences construction before 2024 is eligible for tax credits for up to 12 years up to \$35/tCO_2 if the carbon dioxide is utilised, or up to \$50 if it is permanently stored. If contracts for sale of CO_2 can be negotiated with UK ICC projects, the level of ICC incentive offered by government may be lowered accordingly. However, some of the additional revenue from sale of the CO_2 may be retained by the emitter, to increase their returns and provide an incentive to sell the CO_2 for utilisation where there is a demand (provided this complies with State Aid legislation). As an illustrative example, if a CfD_C is set at £90/tCO_2, but the CO_2 is sold for £30/tCO_2, the effective strike price may be reduced to £65/tCO_2.

Any direct government ICC incentive model (e.g. CfD_P, Cost plus, RAB, tax credits) could be adapted to reduce the subsidy, and therefore the cost to government, for ICCU. Conversely, in the early stages of new CCU technology development, models could be adapted to provide higher ICCU incentives than ICCS, if ICCU applications were particularly promising as a cost-effective decarbonisation pathway. However, market mechanisms where the value of ICC is not determined by government (e.g. low carbon market) would not easily allow price differentiation between ICCU and ICCS. For the CCS certificates + obligation model, the number of certificates generated per tCO_2 could be altered to differentiate between ICCS, permanent ICCU and temporary ICCU. For all models, separate incentives could be given to **CCU** applications which permanently sequester CO_2; this may support the development of new CCU technologies by reducing production costs. Further analysis on the expansion of the utilisation market and incorporation of utilisation into the ICC business models is recommended.

Industrial clusters

Clusters may enable the economies of scale required to drive such large scale T&S investments. Some models may allow additional benefits to clusters. For example, a model which can provide one **single incentive contract** to a cluster of emitters may reduce complexity for government, allowing negotiation on a cluster basis, rather than a site basis. Product related mechanisms, such as 'CfD_P' and 'EPS + CO_2 credits', would require separate contracts, agreements or regulations for each product type, so the benefits of clusters administratively would be minimal. However, for CfD_C, a single strike price could be negotiated with a cluster and for cost plus, one combined contract could be used, although individual transactions may still require assessment. CCS certificates could be traded as a cluster as easily as for individual sites and a fixed tax credit could also be given to a cluster. Thought would have to be given to the terms of the contracts as new firms wish to join the cluster over time. The terms of the business model could also be written to promote particular clusters. For example, there could be additional incentives given to sites which can connect to existing infrastructure or sites in a strategic location.

Specificity to ICC

Policies may directly incentivise industrial carbon capture, or they may promote decarbonisation of industry through any method. The product related mechanisms are often more general, promoting low carbon products regardless of the method used to decarbonise. For example, industry could invest in energy efficiency measures, fuel switching or new processes to reduce the embedded carbon in their products. In addition, mechanisms focussed on the end use, such as regulations on new building embedded carbon, may lead to use of different building materials, such as wood, rather than cement. The advantage of having a mechanism which incentivises decarbonisation through any route, is that industry is free to choose the most cost-effective decarbonisation pathway for its individual site and processes. However, due to the high capital investment associated with ICC, industry may be deterred from investing initially when lower capital options are available in the short-term, even if ICC could be the most cost-effective pathway to reach deep decarbonisation in the longer term. Additionally, the economics of CCS improve with higher volumes of CO_2, both in terms of a greater number of capture plants for a T&S network and earlier investment in CCS. For this reason, it may be preferable to limit the incentive to ICC as the decarbonisation route, to spur early capital investment and realise these financial and climate benefits. Many of the models assessed allow policy design to dictate whether they are specific to ICC or more generally applicable.

Benchmarking and market reference prices

A poorly-designed instrument could encourage carbon-intensive emitters to increase their share of production due to increased revenue available from CO_2 abatement. This problem is easily avoided by paying only for the CO_2 that is stored below the emissions of a benchmark carbon-efficient production technology. This is particularly important for the decision making around new industrial installations (plants), whereby the methodology should ensure that processes with higher emissions to produce the same product do not become more economic under the subsidy scheme. The definition of industry benchmarks (standards) and market reference prices (e.g. for CO_2) is important in many of the models evaluated.

The EU ETS already uses benchmarking to determine the level of free allocation that each installation within each sector will receive[44]. Product benchmarks are based on the average GHG performance of the 10% best performing installations in the EU producing that product[45]. A similar concept can be used in the ICC business models; the 'CO_2 abated' could be defined as the difference between the emissions released by the ICC plant, and the EU ETS industry benchmark (calculated from the benchmark tCO_2/t product multiplied by production quantities). Any incentive payments would then only be paid on this abated CO_2. This mechanism incentivises low emissions technologies and high capture performance to maximise returns for the ICC emitter. The benchmark *could* be reduced over time to drive decarbonisation and cost reductions. For existing installations, consideration may be given to raising the benchmark (e.g. to installation current emissions) if it would not be cost-effective to install new, lower emissions technology before the end of technology lifetime. Equally, for smaller or more niche subsectors without current benchmarks, the benchmark could also be the current level of emissions from each plant or average subsector emissions (both per unit output); the abated CO_2 is then the reduction below this current value. Similar benchmarks, in tCO_2/t product, can be used in the product related mechanisms e.g. to define the taxes each product should be subject to or the number of CO_2 certificates it should receive.

While the UK is under the EU ETS, the market reference CO_2 price would likely be an average (mean or median £/tCO_2) of the EU ETS auction prices over the timeframe for the subsidy payment calculation (e.g. month / year). This timeframe should be sufficiently long to allow stability (and prevent market manipulation), which would not be achieved by a single spot price.

Allocation of construction and performance risks

The models also differ in their allocation of construction and performance risks, which may be a key consideration in model selection. In the roll-out phase, the private sector is expected to take these risks in four of the promising models: CfD_C, Tradeable tax credits, Tradeable CCS certificates and Low carbon market. In Cost Plus, the government accepts the majority of the construction and performance risks and in RAB they are indirectly held by the energy consumers through impact on future energy bills. However, in the scale-up phase, it is likely that the government would have to accept at least partial liability for these risks in all models, through mechanisms such as loan

[44] For more information on benchmarking see https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf
[45] An alternative to this method, which may be simpler where there are not many installations, is using the emissions level from the best commercially available technology (BAT) for that subsector

guarantees and pain-gain sharing mechanisms. It is also worth noting that some additional operational risk sharing may occur under index linking of incentives e.g. strike prices index linked to fuel prices; this may be required in both CCS market phases for factors outside the control of the private ICC developer.

Hybrid models

Whilst this study outlines a range of discrete business models and highlights which of those models have promise, hybrid models could also be considered, utilising aspects from more than one of the models assessed. A few examples of potential combinations are outlined:

CCS certificates can be combined with CfD_C, by putting the CfD on CCS certificate price (similar to a price floor) or by using the CCS obligation to recover funds for the CfD mechanism. The benefit here is that there is greater certainty over revenues for the industrial emitter than in the original CCS certificates mechanism, but the cost to government can be reduced by extending the obligation to fossil fuel suppliers. In the roll-out phase, the CfD may then be removed as the market matures. For more detail on this hybrid model, see Appendix section 8.3.

CfD_C can benefit from elements of the cost plus mechanism during the scale-up phase, to further strengthen the incentive. Instruments to enable this include indexing the strike price to fuel prices or the CPI, as well as additional risk sharing around realised costs[46]. Again, these instruments could be removed once the private sector is more able to bear these risks.

RAB and cost plus are very similar. Cost plus could be made more efficient through subjecting projects to similar regulation and ensuring there are sufficient incentives to drive cost reductions[46]. For subsectors other than hydrogen, the exchequer would be a proxy for the ‘consumer’.

Tax credits can be used to support other measures in the short term. For example, tax credits can reduce the burden of the initial capital outlay in mechanisms such as CCS certificates and low carbon market creation.

Low carbon market creation can utilise elements of other product mechanisms. For example, the regulations would likely include EPSs for end-uses or primary products. A CfD_P could be used to create certainty over the minimum product price premium in the scale-up phase. Product CO_2 taxes could be used to spread the cost to consumers of goods with high embedded carbon. More research is required to understand the effectiveness and wider implications of these options.

Wider impacts and unintended consequences

It will be important to consider the wider implications of business models on all parties involved, as well as the broader economy. Consideration should also be given to potential unintended consequences of the models, and protection from these should be added. For example, product related mechanisms may incentivise other decarbonisation measures over ICC, thereby delaying the deployment of ICC and reducing its potential. A poorly-designed instrument could encourage carbon-intensive emitters to increase their share of production, to the detriment of the total quantity of emissions released. The range of incentives or regulations in place will have an impact on the attractiveness of the UK as a location for industrial operations, so care should be taken to protect or improve the appeal, for example increased attractiveness as a location for hydrogen production due to ICC support and T&S availability. The impact of any policies on consumers should be considered and efforts made to maintain affordability, particularly of consumer heating bills. Similarly, the

[46] For example pain-gain sharing mechanisms or cap and collar mechanisms.

purchaser of the industrial products may be impacted by any cost increases, particularly if this purchaser sells their final goods internationally. Additionally, end-use regulations may lead to ‘switching’ of materials rather than decarbonisation of the original materials. For example, in buildings, cement may be replaced by wood; although wood has a lower embedded carbon, it is less energy efficient during the building’s lifetime, so may lead to an increase in overall CO_2 emissions. As demonstrated, there will be many repercussions on the economy that are removed from the parties directly involved in the business model, so economic analysis is required to fully understand the benefits and potential risks.

6.3 Conclusions and recommendations

There are a number of mechanisms available to support the deployment of industrial carbon capture and realise the associated benefits and opportunities. Each of the revenue models requires support from a suite of risk management instruments to ensure risks and challenges are addressed where possible. The key to a successful mechanism is balancing the private and public sector requirements and allowing this balance to change as the market matures to ensure the most cost-effective decarbonisation pathway is followed.

Promising business models

Six models have shown promise in addressing the key challenges currently hindering the deployment of ICC and creating the required value proposition. Three of these models, all of which incentivise CO_2 abatement, are broadly applicable:

- **CfD_C on CO_2 price:** can create a strong and certain revenue stream, whilst protecting government from overcompensating the emitter if the market CO_2 price rises.
- **Tradeable tax credits** linked to CO_2 price + capital tax credits: also has the potential to create certainty of revenue through reduced tax liability, but the required tradeable nature is largely unproven.
- **Tradeable CCS certificates** + obligation + price floor & ceiling: a more market based mechanism which has the benefit of a clear pathway to reduced government involvement over time.

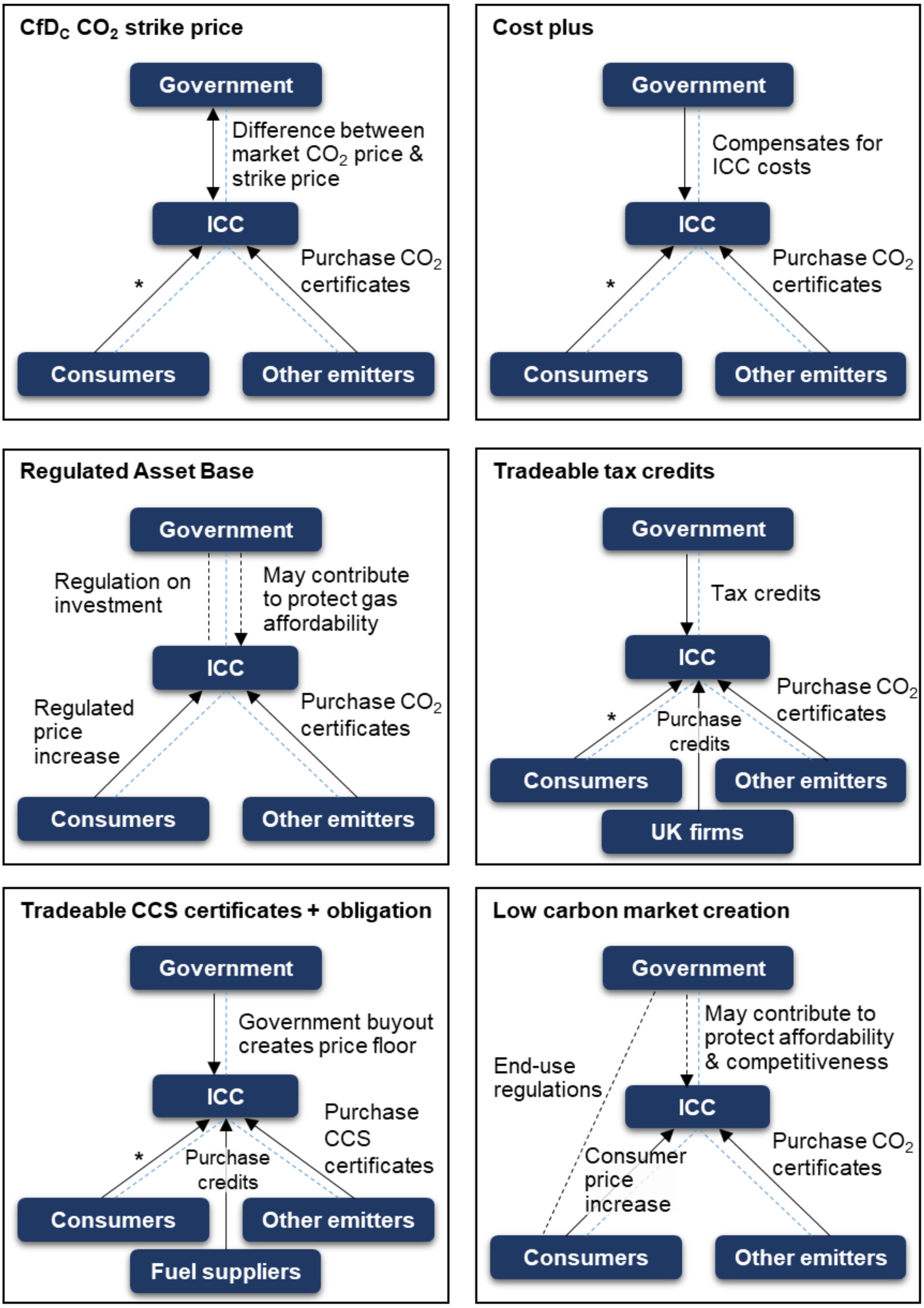
The other three promising models have limited applicability or require further research:

- **Cost plus** is a promising model for the scale-up phase due to low risk for the private sector but may not drive the desired cost reductions in the roll-out phase.
- **RAB** performs well on both analyses due to its certainty of cost recovery and low cost to government but is likely to only be directly applicable to hydrogen.
- **Low carbon market** creation has potential, with many mechanisms proposed to support the market development, and the advantage of directly incentivising low carbon products. However, the concept requires further research to better understand the instruments required for success.

Although the models proposed are distinct, they share many common themes and elements could be combined into hybrid models to further reduce risks and strengthen the proposition. Models can be tailored to meet the requirements of industrial subsectors and the CCS market maturity phases. They can also be adapted to incentivise and account for CO_2 utilisation as well as to promote cluster development. Supporting regulations may be key in driving a cost-effective decarbonisation pathway and meeting climate goals. For ICC to reach its full potential in futureproofing industry and growing the UK economy, it is crucial for appropriate policies to be put in place soon to address the challenges and drive early deployment.

Figure 6-3 shows a schematic of the six business models, with arrows representing the flow of money into the ICC project. The asterisk (*) represents consumer purchase of industrial goods, where the product price should be no higher than that of industrial plants without ICC.

Figure 6-3 A schematic representing the six promising UK ICC business models. (*) Purchase of goods where price is no higher than from industrial sites without ICC.



Recommendations for further work

This study has presented a high-level evaluation of potential ICC business models and highlighted six promising models for the UK. Additional studies or research should be completed to develop the promising models further and understand the implications of each for industry, consumers and the government. Some suggestions for further work are given below.

- Investigation into the **legislative requirements and implementation timeline** associated with each business model, as well as the requirement for a **delivery body or regulatory body**. If projects are to be deployed in the 2020s, policies must minimise complexity of implementation. The potential award process should also be considered further in this work.

- Further research on **market creation** for low carbon products to develop the concept and requirements. The work should seek to understand the potential contribution of additional mechanisms such as price premium guarantees, EPSs or tax credits, as well as evaluate the economic repercussions.

- **Cost-benefit analysis of various options**, including their implications on the wider economy and potential unintended consequences. This should include economic analysis on the impacts of these policies and business models on the attractiveness of the UK as an industrial location. Particular attention should be paid to policies which are not specific to CCS, such as policies which incentivise low carbon products; an understanding should be developed of the likely methods industry may utilise to decarbonise, and the alternative options available to consumers.

- **Further quantitative analysis on the selected business models.** Examples include reviewing the profits and tax liabilities of UK industries to assess the feasibility of tax credits; impact of low-carbon market creation on product prices such as impact of using green cement on building costs and housing prices; pricing mechanism of CCS certificates.

- More detailed study into the degree to which the six most promising business models are likely to match the requirements from European Commission regulation on **State Aid**, once the level of subsidy and award process are further developed.

- **Further engagement with UK clusters and industries** to identify which models would be most effective and acceptable for the UK clusters. Any remaining industrial concerns or barriers should then be addressed before policy finalisation. Detailed research into **how mechanisms could be applied to industrial clusters** and used to promote cluster development. This would include the potential for single cluster contracts, and the flexibility of the mechanisms and contracts to cluster growth over time.

- **Engagement with broader stakeholders and the general public** on the political and public acceptability of the promising policies. In particular, the acceptability of direct ICC grants, and the affordability of models which pass costs on to consumers. Work should also be completed to enhance public awareness of the benefits of ICC, as well as of the embedded carbon in industrial products.

- Analysis on the potential development of the **CO_2 utilisation market** and incorporation of CO_2 utilisation into the ICC business models is recommended. This should include consultation with the current CO_2 market players globally to identify opportunities to integrate or adapt their models to the developing ICC market.

- Work around the most effective way to account for the **CO_2 price uncertainty** considering the CO_2 pricing mechanism(s) the UK government intends to implement in the short-term.

- Analysis on the **funding source** should be completed to understand the feasibility and 'optimal' combination of funding sources for each model. This should include investigation into the political and public acceptability of allocating costs across certain groups, as well as analysis on the financial impact on the affected groups. The option of passing costs on to polluters, thereby reducing subsidies, through additional allocation of tradeable certificates to ICC projects (e.g. EU ETS certificates) should be explored, including consideration of NER 400.

- Potential for **evaluation of hybrid models**, including those outlined in section 6.2. An understanding should be developed as to which elements can complement each other most effectively to strengthen the proposition to the public and private sectors.

- Research on **integration of the ICC business model with the T&S business model**. It is crucial for the part-chain business models to build a robust CCS chain and to allocate the risks and benefits appropriately to each party.

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8 Appendix

8.1 Cashflow assumptions for risk quantification

The cashflow model for risk quantification required development of a number of assumptions around the technical capture parameters and the financial arrangements. For risks which are not sector specific, a typical cement plant was chosen as a representative industrial site due to its relatively 'central' characteristics in terms of magnitude of emissions (0.54 $MtCO_2$/yr), CO_2 stream purity (24%) and proportion of CO_2 available for capture (99%). The required CO_2 purity leaving capture site is 95% and the required output pressure for CO_2 is 10 MPa to maintain the dense phase of CO_2. Central assumptions of key capture parameters across 6 energy intensive sector archetypes are shown in Table 8-1. Product sale prices are included for use in estimating the % impact of ICC implementation on production price.

Table 8-1 Summary of capture assumptions across 6 energy intensive sector archetypes

Reference case assumptions (industrial sector archetypes)							Source
	Cement	**Iron/Steel**	**Refineries**	**Ammonia**	**Chemicals**	**Hydrogen**	
Direct emissions of typical plant ($MtCO_2$/yr)	0.54	6.8	0.76	0.43	0.24	0.35	Source 1[47]
CO_2 stream purity (%) Central assumption	24%	30%	10%	95%	11%	95%	Source 1
Capture site potential (%): proportion of flue gases practically captured	99%	60%	90%	99%	99%	99%	Source 1
Carbon intensity of product (tCO_2/t product)	0.52	1.9	0.24	1.75	0.79 (variable)	10	Source 2[48], source 3[49]
Product sale price (£/t product)	60	450[50]	715	241[51]	700[52] (variable)	1245 (uncertain)	Source 2, Source 4[53] or footnotes

The reference capex for the typical cement plant ICC is £120 m and opex is £5.8 m /yr excluding fuel and T&S fees, based on first generation amine capture technology (Element Energy, 2014). First generation amines were chosen as they are a mature capture technology, available for deployment in the 2020s. It should be noted that other technologies, such as calcium looping, could reduce the costs considerably. The incentives provided to the emitter in the reference case cashflow are based on the model proposed in the recent Teesside Collective study (Pöyry and Teesside Collective, 2017). The capital financing is 50% grant funding and 50% emitter equity,

[47] Source 1 *Demonstrating CO_2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A Techno-economic Study*, Element Energy, DECC & BIS, 2014
[48] Source 2: Industrial sector roadmaps, DECC and BIS 2015, https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050
[49] Source 3 *Industrial energy use and carbon emissions reduction in the chemicals sector: A UK perspective,* Applied Energy, 2017
[50] https://www2.deloitte.com/content/dam/Deloitte/ru/Documents/manufacturing/overview-of-steel-iron-market-2017-eng.pdf and (Element Energy, IEAGHG, 2018)
[51] Agribusiness Intelligence market report 2018
[52] Chemicals sector is diverse: ethylene estimated at 748 EUR/t https://www.sciencedirect.com/science/article/pii/S136403211600229X 2017
[53] (Element Energy, IEAGHG, 2018)

which is later repaid through operational incentives; the repayment is split into enhanced repayments over the first 3 years of operation and then residual repayments for the remaining operational period to provide an incentive for continued operation. T&S fees are £18 /tCO_2, split equally between fixed capacity fees and a variable usage component. The reference case business model assumes that the financial impact of most risks is borne by government in the scale-up phase and the emitter is protected. The capture operational period is 2025-2040 for this scale-up project. A social discount rate of 3.5% has been applied to all cumulative costs. Fuel cost projections are from the HMT Green Book[54] and CO_2 price projections use a central case of the Future Energy Scenarios 2018[55] central UK total carbon price project, with low and high sensitives from the BEIS 2016/17 short-term traded carbon value projections[56]. Contingent equity of 5% and a Debt Coverage Ratio (DCR) of 1.2 would also be expected for the project to be financeable for investors. These have not been included in the illustrative cashflow for clarity and as they are not directly incurred costs. The majority of the risks were quantified using this cashflow analysis and the impact of the risks assessed using the key metrics described in Table 8-2.

Table 8-2 Key metrics used to compare the impact of the risks quantified, along with the reference case values

Key comparison metrics[57]	Ref. case	Description
Total emission savings (Mt CO_2)	**6.0**	Net emissions savings (emissions captured – emissions from capture plant energy use)
Project costs (exc. EU ETS) (£m)	£650	Total cost of ICC through lifetime of project, including capex, opex, decommissioning, fuel, T&S fees, returns on loans / equity investment
Emitter benefit w. CC relative to base case (£m)	£17	Emitter return over project lifetime relative to 'no ICC' case, paying EU ETS. Includes ROI of emitter equity and other incentives / market mechanisms.
Required incentives (£m)	£469	Capital grants, capex repayments & opex support (directly or through incentives or market mechanisms).
Required incentives (undiscounted) (£m)	£542	As above but undiscounted
Project LCoA (£/tCO_2)	£137	Total project cost / total emissions savings
Government LCoA (£/tCO_2)	£99	Required incentives / total emissions savings

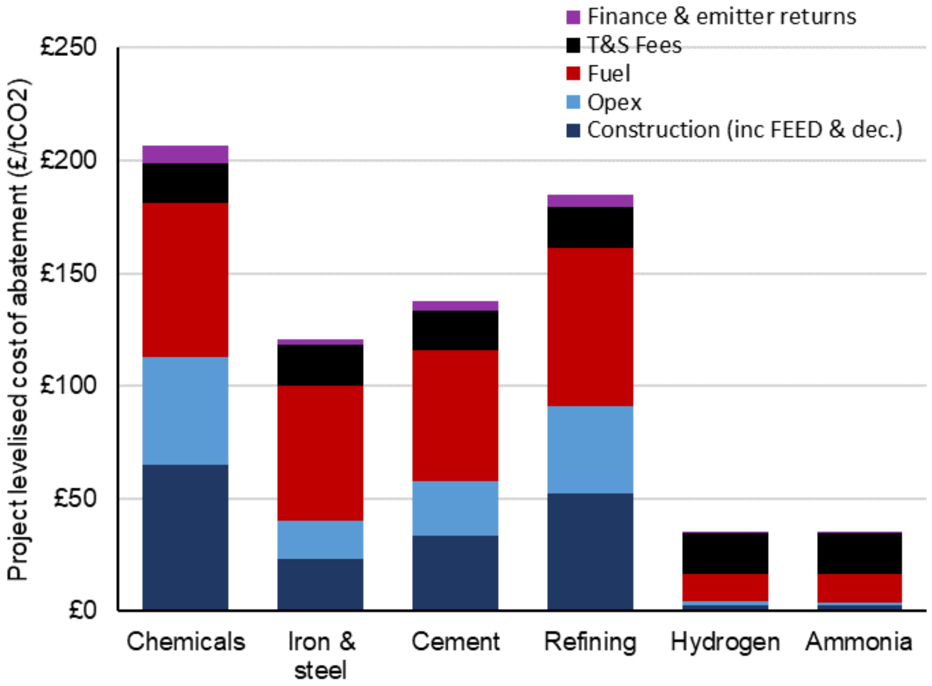
Sectoral Levelised Cost of Abatement

The estimated typical levelised cost of abatement (LCoA) in the short-term may be higher than that shown in Figure 3-1 for the first CCS projects in the UK, as they may use first generation amines for capture; Figure 8-1 shows this LCoA for 6 energy intensive industrial subsectors and the breakdown of cost elements, **including compression, financing and T&S costs** at £18/tCO_2 (Pöyry and Teesside Collective, 2017). As discussed above, the magnitude of these LCoAs is likely to drop with the development of the more efficient capture technologies which are not yet commercially available and also with the potential for industrial clusters to create economies of scale. In addition, the cost

[54] *The Green Book*, HM Treasury, Data tables, 2017
[55] http://fes.nationalgrid.com/fes-document/
[56] https://www.gov.uk/government/collections/energy-and-emissions-projections
[57] All metrics are discounted at the social discount rate of 3.5% unless specified otherwise.

to government would only be a proportion of this, depending on the incentive mechanism and the market CO_2 price.

Figure 8-1 Comparison of the levelised cost of abatement across industrial subsectors, *including the cost of compression, financing and T&S*.



8.2 Technical plant integration risks

Technical plant integration risks are understandably of concern to industrial plant owners, particularly where there could be an impact on operation of their production facilities or the quality of the products produced. Many of these risks are cross-sectoral, but some may have a higher likelihood or severity in some industrial subsectors. Any showstopper integration risks should be addressed and may require contractual consideration e.g. compensation for industrial plant downtime, particularly for early projects. However, the majority of the challenges will simply increase the cost of CCS where they are present, and many are expected to reduce significantly after the first projects, so their relevance for business models in the roll-out phase is reduced.

For large, **continuously operated** facilities the periods between major **overhauls can be very long** (~5 years for refinery crackers and up to 10 years for blast furnaces in the iron and steel sector). Where a capture plant can only be reasonably brought online in a major overhaul this can represent limited windows of opportunity for the development of capture plants and it may be challenging to synchronise ICC integration with plant downtime. There is also a risk of **technology lock-in**, where an ICC and process technology combination locks the plant into a high system cost solution over a long time period. The integration of a capture plant in an existing process may require **additional downtime** of the facility, beyond regular overhaul periods. This can lead to additional costs, for example lack of BAU revenue and the need to make other arrangements to ensure supply. The latter is especially relevant in the refining sector where a refinery sometimes supplies a specific area and alternative supply chains are not readily available[58].

Extending an industrial process with a capture plant **increases the complexity** and operational dependencies of the overall facility. Across the different industries, this increase in operational complexity is seen as a significant risk, especially for availability of assets. Where there are **multiple, disperse CO_2 vents** (e.g. in chemical and refining subsectors), a large duct network would be required, or multiple capture plants, both increasing complexity and cost, as well as requiring significant space. Different sectors have different levels of **familiarity and experience** with specific types of processes (e.g. gas separation, solids handling) employed in ICC technologies. This can potentially reduce or increase this barrier for specific technology-sector combinations, which are addressed in the sector specific barriers. Additionally, **logistical and HSE challenges** associated with amine storage and manipulation may elevate COMAH status for some sites which do not already work with the chemicals required for capture[58].

Site heterogeneity limits replicability of solutions, especially for the chemicals, oil refining and iron and steel sectors, where the actual layout and process design of different facilities within one subsector can vary significantly, limiting knowledge transfer and replicability of solutions across sites. **The location of sites** may also impact the availability of cooling water, or the restrictions around new industrial development, particularly relevant to UK cement sites[58]. The **size of some sites** may also be a challenge for early projects. For example, for iron and steel sites with emissions in the range 5-8 $MtCO_2$/year, early projects may not be able to capture 100% of the emissions until the capture technology is commercially mature and all risks have reduced.

The plant integration risks are considerably lower for **high purity CO_2 subsectors** (hydrogen and ammonia), as they don't require complex capture plants, thereby reducing the impact on the industrial operations. However, there may be multiple vents, including additional streams of low purity from gas combustion. These streams are unlikely to be captured in early ICC projects, but may be targeted later when emissions targets are more stringent.

[58] More detail can be found at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/312106/Element_Energy_DECC_BIS_ICCS_CCU_final_Report_Appendix.pdf

A summary of the key plant integration risks can be found in Table 8-3, along with their applicability across the industrial subsectors[58].

Table 8-3 Summary of key plant integration risks and their applicability across industrial subsectors

	Plant integration risk / barrier	Applicability
1	**Long overhaul periods** of assets can limit timeframes for ICC deployment.	Particularly important in refineries and iron & steel. Typical overhaul periods of blast furnace are more than 7 years and in refineries generally 5-7 years.
2	**Multiple disperse CO_2 vents**	Chemicals and refining sectors typically have the most vents. Chemicals typically have many furnaces and gas furnaces have dilute CO_2 streams.
3	**Location:** cooling water availability or new industrial development may be restricted.	This is a particular challenge in the UK cement sites but may also present a risk to some chemical sites.
4	Additional **operational downtime** or challenges synchronising with downtime	Additional downtime is a risk in all non-pure CO_2 subsectors, particularly where complex vents, ducting and capture technologies are required, or overhaul periods are long (see other risks).
5	Increased site and **operational complexity**	All sectors, with the exception of pure CO_2 subsectors, where complex capture plants are not required so there may be limited change.
6	**Site heterogeneity** limits replicability of solutions	Especially for the chemicals, oil refining and iron and steel sectors, the actual layout and process design of different facilities within one subsector can vary strongly.
7	**Space availability** for capture plant and ducting of large flue gas streams	This risk is very much site specific.
8	**Unfamiliarity with gas separation** / capture technologies e.g. amines.	Cement industry has limited experience with gas separation and CCS in general. Chemicals and refining industries are more familiar.
9	**Logistical and HSE challenges** associated with amine storage and manipulation; likely to elevate COMAH status for some sites.	This challenge is relevant to all subsectors, with the exception of pure CO_2 subsectors, but particularly relevant to Cement and Chemicals.
10	**Existing handling of ammonia**	Cement and refinery sites generally do not already handle ammonia, which can result in additional barriers to uptake for chilled ammonia capture technology.
11	**Technology lock-in** to a high system cost solution over a long time period	This concern depends on the capture – process technology combination. It is of particular concern in the cement, chemicals and iron & steel sectors.

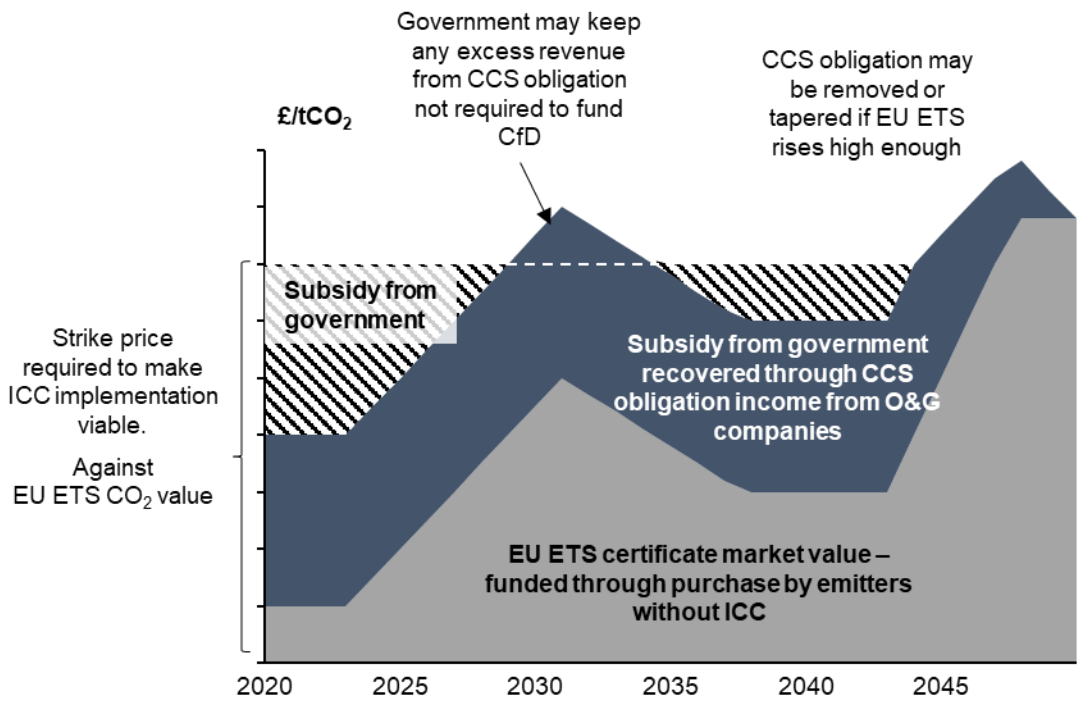
8.3 Hybrid business model example: CfD_C + CCS certificate obligations

Whilst this study outlines a range of discrete business models and highlights which of those models have promise, hybrid models could also be considered, utilising aspects from more than one of the models assessed. For example, **CCS certificates can be combined with CfD_C** and two potential options are outlined:

CfD_C model, with a CCS obligation used to contribute to the funding required:

The CfD_C model can be used, but with an additional CCS certificate obligation to reduce the direct government funding required. The CCS certificates do not need to be tradeable, if the aim is to keep the mechanism simple. Instead they may just be purchased from government to cover the obligation, at a value determined by government in £/tCO_2. The options for placement of the obligation are the same as those in the CCS certificates model described in the business model canvas, although here we have assumed the obligation is on fossil fuel suppliers. It should be noted that if the level of obligation on fossil fuel suppliers is set as a proportion of carbon in the fuel sold, this does not correlate with ICC deployment CO_2 volumes, so the proportion obligated would likely rise over time following the required ICC trajectory. A depiction of the model is given in Figure 8-2; the figure is solely illustrative, not based on economic modelling or price projections.

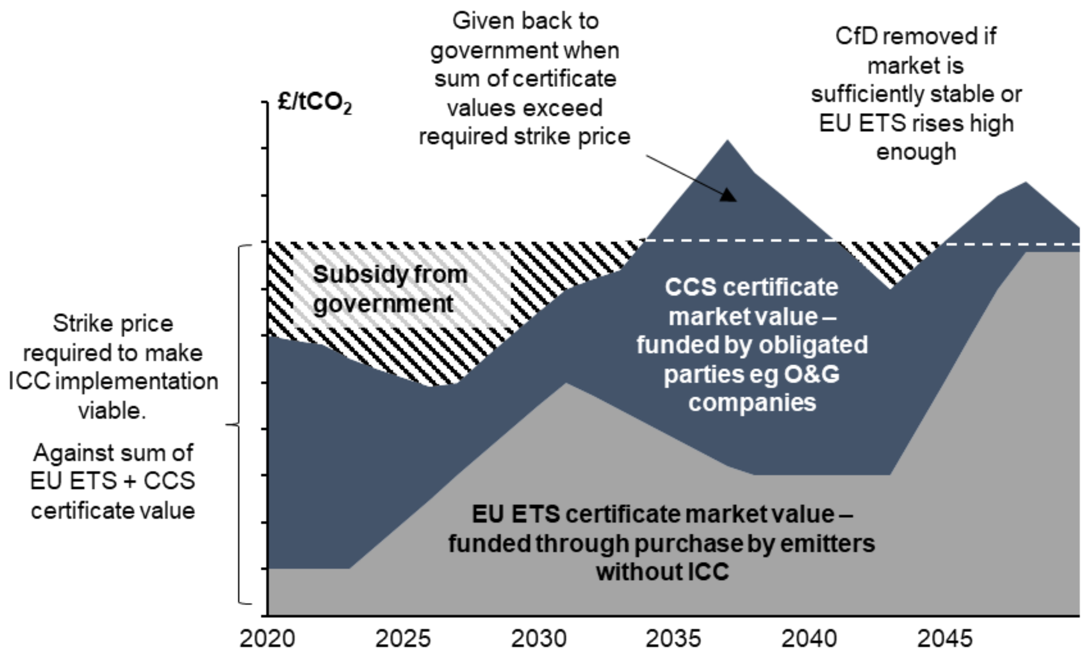
Figure 8-2 Illustrative depiction of the CfD_C model, with supporting CCS obligation



CCS certificates + obligation model, with a CfD to provide more certainty to ICC investors:

Alternatively, the CCS certificates + obligation model can be used, but with a CfD_C on the *sum of the EU ETS value + CCS certificate value*, particularly for the scale-up phase. The benefit here is that there is greater certainty over revenues for the industrial emitter than in the original CCS certificates mechanism. In the roll-out phase, the CfD may then be removed as the market matures. A depiction of the model is given in Figure 8-3; the figure is solely illustrative, not based on economic modelling or price projections.

Figure 8-3 Illustrative depiction of the CCS certificate obligation model, with supporting CfDC



8.4 Business model case study canvases

<table>
<tr><th colspan="3">Case Study: Quest CCS Project</th></tr>
<tr><td colspan="2">Summary

Operational industrial CCS project. Retrofit of Shell's ADIP-X™ CO_2 capture technology to CO_2-rich off-gas stream from 3 x steam methane reformer (SMR) plant manufacturing H_2 at the Scotford Oil Sands Upgrader, Alberta, Canada. CO_2 is transported 40km by pipeline for storage in a saline aquifer via 2-3 injection wells at up to 1.2 Mtpa for 10-25 years (up to 35% of the total CO_2 emissions from the Scotford Upgrader).

Quest operational since Spring 2015. Shell completed the Scotford Upgrader in 1999 plus two phased expansions by 2011. During the 2nd expansion, Shell (2007) publicly stated that "Implementation and use of CO_2 capture technologies depends on the establishment of appropriate government policy and supporting framework, as well as project economics".[59] Subsequently, around 2009 it made an application for Federal support for Quest under the Clean Energy Fund and to the Government of Alberta CCS Fund. Securing these sources in 2011 allowed for FID on project development in 2012, with the bulk of construction taking place during 2013-14.

Federal Government estimated the original cost at C$1.35 bn (US$ 1.28 bn), based on 5 year construction CAPEX spend plus 10 years of operation. Reported CAPEX under Alberta CCS Knowledge Sharing Program is C$790 m (US$600 m) with OPEX ranging C$30-35 m (US$23-27 m) per year.</td>
<td>Business Proposition

• Proving permanent CO_2 storage in deep saline aquifers (strategic interest of JV partners)
• Government of Alberta Climate Change Strategy
• Concerns about GHG intensity of Canadian syncrude (oil sand crude)
• Dependence of Albertan economy on syncrude export revenues</td></tr>
<tr><td>Ownership/Promotion

• Full chain promoter: Athabasca Oil Sands Project (AOSP), a 60:20:20 JV between Shell Canada, Marathon Oil and Chevron Canada (at the time of development).
• Developer/Operator: Shell Canada as operator for AOSP
• Owner: Canadian Natural acquired a 70% stake in AOSP in 2017 through purchase of all of Shell's and half of Marathon's equity interests; Shell acquired the other half of Marathons equity interests. Shell remains operator on behalf of AOSP.</td>
<td>Financing

• Grants (from Government):
  ○ Alberta Provincial: C$745 m (staged milestone payments over 15 years), with limitation of up to 75% of project costs.
  ○ Federal: C$120 m (Clean Energy Fund). [Total = C$865 m (US$822 m)]
• Equity: not reported
• Debt: not reported. Assumed to be zero
• Cash flow: Government contribution to total Project Spend during the operational period 2016-2026 is reported to be around 63-64% (excl. C$486 m offsets expected over the same period)</td>
<td>Revenue

• Double emission-pricing based revenue stream (under Alberta Specified Gas Emitters Regulation; now the Carbon Competitiveness Incentive Regulation):
  ○ Generation of offset by avoidance of CO_2 emissions.
  ○ Generation of offset through geological sequestration of CO_2.
• Range of C$20-30/t$CO_2$ <u>per</u> offset. Value estimated at around C$49 m per year.
• Possible future sale of CO_2 for EOR.</td></tr>
</table>

[59] Shell (2007). Shell Canada Upgrader (Scotford 2) EIA Public Disclosure document.

• Integrated project: "Quest" CCS asset is separate from other assets in the area (mines, upgrader, refinery, petrochemical plan).	• Allowable Returns on project costs capped at average Canada bond yield rate + 2%	
Obligations to customers • Obliged to operate plant to 2026 over the duration of the Government committed financing window	**Government role** • Joint finance from Federal & Provincial Gov't • Alberta Offset Credits significant source of revenue. Change of law clarified double crediting for CCS in Alberta	**Risk** • Performance risk held by JV • Any capture downtime or losses of CO_2 erodes income from offsets • Provincial grant financing tied to milestone payments according to plant performance.
Applicability to UK ICC • Integrated CCS project offers limited insights in the context of structuring a UK ICC "part-chain" business model. • Government grants more or less covered the entire CAPEX of the project, highlighting the need for private operators to be insulated against financial risks before agreeing to investment. • Carbon pricing with floor price (as is the case with the Alberta scheme) guarantees an operating revenue stream for at least 10 years, unlike EU emissions trading scheme which has seen significant price volatility through Phase III. Market Stability Reserve [MSR] could help stabilise EU Allowance prices moving forward. • Brexit means UK access to the Innovation Fund under EU ETS Phase IV could be limited, thus grant support likely to be limited to national & regional government. • Alberta Government grant structure offers lessons with respect to how ensure value for money and continued operation of the activity.		

Case Study: Abu Dhabi Al Reyadah/Emirates Steel CCS project

Summary

Operational 0.8 Mtpa industrial CO_2 capture plant at Emirates Steel mill at Mussafah, Abu Dhabi, UAE. The Emirates Steel site uses a steam methane reformer (SMR) to produce a syngas for use in a bauxite direct reduction (DRI) plant that converts iron ore to iron for steel making. The off-gas from the process consists of CO_2 and H_2O, which provides the source for CO_2 capture. Gas clean-up/separation is undertaken using amine-based system. The captured CO_2 is injected into Rumaitha and Bab oilfields in Abu Dhabi for the purpose of EOR. CO_2 substitutes natural gas that is widely used in Abu Dhabi for EOR purposes.

Worked started in 2012, and CO_2 capture plant and pipeline completed and commissioned in 2016.

CO_2 transported by 43 km by 8” onshore pipeline.

Total project cost of US$122 million.

Business Proposition

- Strategic gas demand and EOR. UAE/ADNOC uses large amount of natural gas for EOR, which it wishes to liberate for domestic supply
- EOR
- Emission reductions
- CCS technology leadership

Ownership/Promotion

- Downstream promoter: Al Reyadah is a 51:49 JV between Abu Dhabi National Oil Company (ADNOC) and Masdar (renewable energy arm of Mubadala Development, the Emirate’s strategic industrial investment fund)
- ADNOC has since acquired Masdar’s 49% holding in Al Reyadah (Jan 2018)
- Emirates Steel is a partner but does hold equity in the project
- EPC contract awarded to Dodsal Group for plant design and construction

Financing

- Equity: presumed to be 100% equity investment by JV partners
- Debt: no reported debt financing

Revenue

- Avoided natural gas use/purchase (and possibly imports)
- Crude oil sales

Obligations to customers

- Integrated project. CO_2 captured by Al Reyadah JV Company and supplied to ADNOC for EOR

Government role

- ADNOC is state-owned enterprise
- Masdar is a state-owned enterprise
- Emirates steel is state-owned enterprise

Risk

- High technical risk (large scale FOAK)
- Concerns over contamination of oilfields with CO_2

Applicability to UK ICC

- Limited relevance to UK ICC. Integrated onshore CCUS EOR project, promoted and developed by very well-capitalised state-owned enterprises
- Liberation of natural gas may have some limited relevance to developing EOR business model in UK (although use of natural gas for EOR in North Sea is quite small).

Case Study: Petra Nova CCS Project

Summary

Operational 1.4-1.6 Mtpa amine-based post-combustion CO_2 capture unit attached to slipstream from the 640 MW Unit 8 of WA Parish coal fired power plant, located near Houston, Texas, owned by NRG. Capture plant throughput equivalent to 240 MW coal power.

Included construction of 70 MW natural gas fired cogeneration plant, with about half of its output providing heat and electricity for the CO_2 capture unit. Elimination of the parasitic load on the primary coal plant avoided de-rating the WA Parish plant, and the use of combined cycle gas turbine unit increased overall capture energy/CO_2 efficiency.

CO_2 compressed and transported by 82 mile 12-16" CO_2 pipeline for use in EOR at West Ranch oilfield, Texas.

First conceived in 2009, construction started 2014 (with some delays due to offtake agreement issues) and completed and commissioned in late 2016.

Total project cost of around US$1.1 Bn. Built on time and within estimated budget.

Business Proposition

- Enhanced oil recovery. CO_2 use for EOR at the mature West Ranch oilfield, Texas.
- Fairly stable high demand for CO_2
- Revenues linked directly to oil sales. Integrated ownership structure allows NRG to realise benefits of $150-300 per tCO_2 from oil revenues vs. $15-35 per tCO_2 for a typical CO_2 sales arrangement

Ownership/Promotion

- Upstream promoter: NRG from 2009, based on political concerns about CO_2 emissions from coal combustion and the local EOR opportunities.
- 50:50 JV between NRG and JX Nippon Oil & Gas Exploration Corp (JV = Petra Nova Parish Holdings LLC ["Petra Nova"]; PNPH) 100% owns and operates CO_2 capture and cogeneration plant
- 50:50 JV between PNPH and Hilcorp Energy Co (JV = Texas Coastal Ventures LLC) 100% owns the pipeline and West Ranch oilfield
- Hilcorp Energy Co. operates the West Ranch oilfield
- CO_2 post combustion capture by amine plant designed and constructed by Mitsubishi Heavy Industry (KM CDR Process)

Financing

- Equity: $300 m each PNPH JV partner (US$600 m).
- Grant: US$190 m DOE grant ($167m from Clean Coal Power Initiative; $23m from another fund)
- Debt: JX Nippon involvement/interests opened up access to Japanese export credit line: $250 m loan from JBIC; $75 m from Mizuho insured by NEXI export credit agency. Loan tenor: approx. 10 years (maturity 2026). Interest rate: 1.5-1.75% above LIBOR. Payment: structured during construction and operation.

Revenue

- CO_2 for EOR. Commercial arrangement unknown since CO_2 capture and EOR operation largely held by same entity (PNPH) – see Business Proposition above
- Est. 3,000-15,000 bbpd increase in oil production through EOR.
- Reportedly needs an oil price >$50 to break even
- 45Q Tax Credit (possibly)[60]

Obligations to customers

- Similar to integrated project. PNPH revenues linked to oil sales from EOR

Government role

- Grant support as per above

Risk

- Technical risk: High. large scale FOAK

[60] The US Inland Revenue Service does not publish information about individual companies or taxpayers, and the recipients of 45Q are not publicly disclosed.

Case Study: Petra Nova CCS Project		
• Commercial situation with respect to Hilcorp Energy Co. unknown	• Grant meant need for Environmental Impact Statement to be prepared, giving an opportunity for stakeholder engagement and commitment to subsurface monitoring	• Commercial risk: Low. PNPH owns 50% equity West Ranch Oilfield; other possible large volume EOR off-takers present in the region. Limited number of parties involved, and chain ownership is integrated. Hilcorp largely insulated from technical risks.
Applicability to UK ICC • Upstream promoted, developed and financed. Very different business model to the midstream model in the CO_2 merchant market. Upstream promoter model is hard to envisage being relevant to UK ICC without significant downstream interests as was the case for NRG. It may be applicable in niche circumstances, however. • The interests of NRG in the West Ranch oilfield EOR operations shows that involvement of the CO_2 supplier in the downstream revenue generating asset may also be crucial to making business case for investment into CCS chain, at least for the initial infrastructure investment. • Limited applicability to UK ICC under a “part chain” model, since the flow of oil revenues to NRG were critical to supporting its investment. • Onshore EOR revenue model has limited relevance to UK.		

Case Study: Norway CCS project

Summary

Conceptual industrial CCS project. Ministry of Petroleum and Energy, working with Gassnova (state-owned CO_2 infrastructure company), launched a feasibility study for industrial CCS in Norway in 2016. The study proposed capture at 3 locations: [1] cement kiln, Norcem (Heidelberg), Brevik (400,000 tpa); [2] ammonia plant, Yara, Porsgrunn (already capturing and selling 200,000 tpa for food and beverage production [of 800,000 tpa total emissions]); [3] municipal waste incineration fired district heating plant, Fortum Oslo Varme, Klemetsrud, Oslo municipality (315,000 tpa). Captured CO_2 to be transported and aggregated/intermediately stored at Grenland industrial park, and shipped or piped to offshore storage location(s) (multiple sites being considered – primarily Smeaheia and Heimdal, with options for ship direct injection, floating injection/storage facility or subsea pipeline being considered).

Planning and investment costs (CAPEX) estimated range of NOK7.2-12.6 bn (US$880-1,550 million) depending on exact configuration (lower = 1 CO_2 source; upper = 3 CO_2 sources). O&M costs estimated in range NOK350-890 million per year (US$43-110 million). Further concept and feasibility studies carried out in 2017 reduced the options to the Norcem Brevik site with the added possibility of the Klemetsrud site; plans for the Yara site dropped due to limited technical learnings and "uncertainties concerning the plant". Equinor/Shell/Total leading T&S feasibility/FEED components.

FEED studies for capture at Brevik, alongside transport and storage FEED, are ongoing with final investment decision scheduled now scheduled for early 2020's.

Business Proposition

- Achieve knowledge that can be shared across countries and sectors.
- Provide a storage solution with sufficient capacity for economy of scale.
- Demonstrate that CCS is a safe and effective climate measure.
- Contribute to improvements of the market situation for CCS.

Ownership/Promotion

- Full chain promoter: Government via Gassnova
- Possible PPP: government has expressed wishes for CO_2 source operators to some extent invest/build CO_2 capture facilities. Storage developers could also be expected to make financial contribution

Financing

- Government support of NOK80 (2018) + NOK200 carried over from 2017 (total US$34 million) for Gassnova to sponsor FEED studies.
- Less than NOK360 m previously committed to Gassnova 2018 budget
- Equity contribution from private partners remains unclear, despite Government wishes.

Revenue

- Avoided Norway (EU-linked) emissions trading scheme compliance costs.
- Avoidance of possible new Norway CO_2 tax for onshore operations.

Obligations to customers

- None

Government role

- Promotor and lead developer
- Possibly financier. NPD has reported that the 2018 budget proposal would include the State's total costs and risks etc., however, this was not provided in the May 2018 budget revision
- May 2018 budget deferred FID until 2020/21.

Risk

- Technical risk. High (cement capture unproven)
- Political/financing: problems for Government funding of CCS were apparent in 2017. Situation has stabilised, but doubt remains over whether Government is willing to invest ~US$800 m finance need for the project

		• Multi-party structure creates complexities for managing commercial risks and limiting exposures of different parties across chain. • Government – via Gassnova – essentially will backstop most of the risks.

Applicability to UK ICC

- Conceptual project which is facing the same challenges as faced for UK development of CCS (first-mover risk and lack of incentives affecting willingness of private sector to finance projects; competitiveness concerns)
- Most likely it will be heavily reliant on significant government support to achieve successful deployment.
- Until it is built, few lessons can be drawn today, although parallels may be drawn.

Case Study: Lake Charles Methanol, industrial CCS in USA

Summary

Lake Charles Methanol is an Industrial CCS project in the advances stages of development, with construction starting this year (2018) and due to be operational in 2022, costing $3.8 billion. The CO2 source is refining (gasification to produce syngas and finally chemicals e.g. methanol and hydrogen) and the business model is built around EOR, chemical sales and investment tax credits (the Internal Revenue Code Section 48B, support from DOE and Treasury for clean fuels projects). The project is joining onto existing CO2 infrastructure along the Gulf Coast. Operations and management at the project will spend approximately $2 billion over the 30-year project life, which will primarily pay local workforces and purchase locally-procured materials and services. The US Department of Energy (DOE) announced it would be issuing a conditional loan guarantee of $2B, under the Advanced Fossil Energy Project solicitation, first project financed of the $8.5 bn program; the risk of default on loan repayment is borne by government, which will help the project developers obtain low-cost financing up to $2b. The applicants (i.e. the project developer) are charged a fee which, for a $2b guaranteed, amounts to $13m – just under 0.7% of the guaranteed value. The remaining $1.8B is expected to be financed via equity. Morgan Stanley led a process for raising equity for the project.

Business Proposition

- 1,500 new manufacturing and construction jobs
- Ultra-clean refining of waste petroleum coke into methanol and other valuable chemicals
- 4.5 million barrels per year of domestic oil production (EOR)

Ownership

- The LCM project has been developed by Lake Charles Methanol LLC, one of the leading developers of clean energy petroleum coke refineries in the US, which launched in 2015.

Financing

- Total capital investment (inc site construction) of $3.8 billion
- DOE conditional commitment of up to $2 bn loan guarantee, so $2 bn private debt expected.
- The remainder of the project financed with equity financing.

Revenue

- EOR: CO2 sold to Denbury Onshore (piped to oil fields for EOR)
- Chemical sales from new plant
- The equity investors will be able to claim a $130 million federal investment tax credit

Obligations

- Off-take contracts
- Contracts in place for their fuel supplies and operating management of the project.
- Fluor Corporation to engineer and build the facility under a lump sum, turn-key, date-certain construction contract

Government role

- DOE Conditional Commitment over the terms of a $2 bn loan from the Federal Financing Bank (U.S. Treasury) under the loan guarantee program
- Tax credits for equity investors (Section 48B)

Risk Management

- T&S risks are lower as utilising existing infrastructure and EOR
- Successful in getting an investment rating of Triple B- for the project from S&P, which includes the construction risk.

Applicability to UK ICC

- Advanced industrial CCS development with solid investible business model, including government support.
- Loan guarantee is a mechanism to improve investment terms which could be employed for UK ICC to reduce overall costs and make projects investible, particularly in the roll-out phase.
- Less applicable to UK as unlikely to be able to utilise EOR revenue and no current existing T&S infrastructure.

<table>
<tr><th colspan="3">Case Study: Sleipner</th></tr>
<tr><td colspan="2">Summary
[61][62]Sleipner is an industrial (natural gas processing) CO2 storage project in Norway capturing around 0.9 MtCO2/yr, operational since 1996. The CO2 capture is achieved using a conventional amine process (using MEA) and the CO2 Storage facility was the first in the world to inject CO2 into a dedicated geological storage setting, so does not rely on EOR revenue. Over 17 million tonnes has been injected since inception to date. The CO2 is monitored and there is no evidence of CO2 leakage. The Sleipner project has not addressed long-term liability issues, primarily due to the fact that being the first major CCS project, they had little to refer to when setting up parameters for the project.
Sleipner is a private sector demonstration project; the lead organisations running and sponsoring the project are Statoil and IEA. While the original project (Saline Aquifer CO2 storage) ended in 2002, project activities continued under the EU-funded CO2STORE project (2003-2006), and CO2ReMoVe (2006-onwards). In 1991, the Norwegian authorities introduced a CO2 emissions tax ($35/tCO2 in 1996) as an effort to reduce greenhouse gas emissions from Norwegian offshore oil and gas activities; this was one of the drivers of the project. The Norwegian CO2 taxes are applied differently to different industry sectors. The additional investments in order to compress and re-inject the removed CO2 amounted to approximately $100m (USD in 1996). Had this process not been adopted, the licensees of Sleipner would have had to pay CO2 taxes ($65/t in 2016). Injection currently costs $17 US/tCO2.</td>
<td>Business Proposition
• CO2 tax avoidance
• Natural gas production and reaching specification
• Private sector demonstration project driven by Norwegian emissions tax introduction</td></tr>
<tr><td>Ownership
• Petroleum JV; Statoil 58.35% and operator, ExxonMobil 17.24%, Lotos 15%, Total 9.41%</td>
<td>Financing
• $100m investment to compress and re-inject the removed CO2.
• Funded by the Petroleum JV as part of the field development and production activity.</td>
<td>Revenue
• CO_2 tax avoidance: CO_2 storage is an unremunerated cost, but emissions are taxed, so storing CO_2 avoids cost ($65/t in 2016).
• Sale of natural gas (max 2.5%)</td></tr>
<tr><td>Obligations
• T&S not separated from capture/petroleum activities, so no customer obligations
• Considerable MMV activity</td>
<td>Government role
• CO2 tax implementation. $65/t ($35 in 1996)
• Store originally approved as part of Petroleum Licence. Distinct CO2 storage approval in 2016.
• Increasing obligation to avoid new emissions.</td>
<td>Risk Management
• Project has not addressed long-term liability issues
• Single party so no cross-chain default risk</td></tr>
<tr><td colspan="3">Applicability to UK ICC
• Private investment in CCS infrastructure without relying on EOR. CO2 cost avoidance is the main driver for permanent CO2 storage.
• Not as relevant to cross-chain risks of part chain business model as single party.</td></tr>
</table>

[61] https://www.ice.org.uk/knowledge-and-resources/case-studies/sleipner-carbon-capture-storage-project
[62] https://sequestration.mit.edu/tools/projects/sleipner.html

<table>
<tr><th colspan="3">Case Study: Illinois Basin – Decatur Project (IBDP) & Illinois CCS Project (IL-ICCS)</th></tr>
<tr><td colspan="2">Summary
Operational industrial CCS project at Decatur, IL, USA, capturing 99% CO_2 fermentation off-gas stream produced at the Archer Daniels Midland (ADM) corn ethanol refinery. Purified using Alstom amine technology. CO_2 is stored onshore in the Mt. Simon Sandstone saline aquifer formation, Illinois Basin. CO_2 transport is via a 1.9 km pipeline. Project developed in multiple stages.
Phase I initial IBDP project implemented with US DOE and Illinois Department of Commerce and Economic Opportunity (DCOE) support under the umbrella of the Midwest Geological Sequestration Consortium (MGSC) – part of the US DOE Regional Sequestration Partnership Programme. Commenced injection in November 2011 and completed in November 2014 with almost 1 $MtCO_2$ injected.
Phase II IL-ICCS Project is an expansion of the IBDP project with the purpose of demonstrating industrial scale CCS. Continued injection commenced in April 2017 with plan to inject up to 5.5 $MtCO_2$ over 5 years (1 Mtpa) in accordance with its Class VI well/storage license.
Third pillar consists the Intelligent Monitoring System (IMS) project, sponsored by DOE and equity partners, with the aim of developing and validating software tools for advanced storage site monitoring.
Total project cost for IL-ICCS is US$208 m (IBDP reported to be in the region of US$84 m).</td><td>Business Proposition
• Test proof-of-concept
• Demonstrate industrial CCS at scale
• Demonstrate saline aquifer storage permitting and monitoring
• Longer-term strategy for potential EOR in Illinois Basin</td></tr>
<tr><td>Ownership/Promotion
• Full chain promoter: DOE through MGSC; ADM and partners
• Development partners: Cost share agreement between ADM, University of Illinois/Illinois Geological Survey, Schlumberger Carbon Services and Richland Community College for private investment (shares unknown)</td><td>Financing
• Federal and State Government grant:
  o Phase I (IBDP) = $66.7 m (DOE and DCOE)
  o Phase II (IL-ICCS) = $141.4 m (DOE under ARRA)
  o IMS = $3.1 m
• Equity: under cost share agreement:
  o Phase I (IBDP) = $18 m (unclear)
  o Phase II (IL-ICCS) = $66.5 m
  o IMS = $1.1 m</td><td>Revenue
• RD&D benefits (and possible tax benefits)
• 45Q Tax Credit (possibly)[63]</td></tr>
<tr><td>Obligations to customers
• None</td><td>Government role
• Majority funder</td><td>Risk
• Technical risks: High</td></tr>
</table>

[63] The US Inland Revenue Service does not publish information about individual companies or taxpayers, and the recipients of 45Q are not publicly disclosed.

		• Investment risk: Low (mostly government grant financed) • Regulatory: some permitting risk (first under Class VI rules) • Commercial: Low. Storage under stewardship of state. ADM only really supplying CO2 to research project.

Applicability to UK ICC

- Shows the benefits of phased development: starting as a smaller technology demonstration, and then expanding into a larger industrial-scale operation.
- Highlights the importance of government grants in supporting initial capital costs (around 66% of costs) in order to insulate private sector from investment risks. Highly likely that RD&D tax breaks also facilitated private sector investment.
- Illustrates the relevance of biorefineries as potential CO_2 capture demonstrations. These are growing in number in the UK.
- Onshore storage limits the overall replicability to UK situation.

<table>
<tr><th colspan="3">Case Study: China CO_2 Storage for EOR Project / Sinopec Qilu Petrochemical CCS Project</th></tr>
<tr><td colspan="2">Summary
Extension of pilot project. Chinese Government-approved major national programme since 2008: ‘CO_2 Storage for EOR’. Plans to extend existing CCSA
pilot project at Shengli oilfield, involving capture of 30-40,000 tpa CO_2 from Shengli Power Plant with road tankering since 2008, into major project. Project would involve capturing additional 0.5 Mtpa industrial CO_2 from Sinpoec Qilu Petrochemical plant (an existing coal/coke water slurry gasification unit at a fertiliser plant located in Zibo City, Shangdong Province) and a further 1 Mtpa CO_2 from Shengli coal-fired power plant. Transport would be via 74-80 km pipeline for increased use for EOR at Shengli Oilfield. Low oil price around 2014 put the project on hold.
Plans to be operational by 2018/19.</td><td>Business Proposition
• Enhance recovery from mature oilfields.
• Demonstrate commercial scale CCS with EOR.
• Improve energy security.</td></tr>
<tr><td>Ownership/Promotion
• Full chain promoter: Sinopec and Government</td><td>Financing
• Unknown. Presumed to be 100% equity of Sinopec</td><td>Revenue
• Oil sales</td></tr>
<tr><td>Obligations to customers
• None</td><td>Government role
• Sinopec is a state-owned enterprise</td><td>Risk
• Technical. Lowered due to pilot.
• Investment: economics contingent on higher oil prices.
• Commercial: Low. Single ownership. Sinopec is an arm of the Chinese government</td></tr>
<tr><td colspan="3">Applicability to UK ICC
• Limited. Onshore EOR by state-owned enterprises offers no real insights of relevance to UK industrial and economic situation.</td></tr>
</table>

Case Study: Rotterdam CCS project Porthos

Summary

Conceptual industrial CCS project: Port of Rotterdam Authority, state-owned Dutch natural gas distributer Gasunie and state-owned O&G enterprise EBN are studying infrastructure to transport CO_2 in Rotterdam's port area and store it in depleted gas fields offshore; there is also consideration of some CO_2 utilisation. Partners are currently talking with a number of companies in the chemical, industrial gas production and refineries sectors about the capture and supply of CO_2. Their ambition is to store 2 million tonnes of CO_2 per year from 2022 running up to 5 million tonnes per year by 2030.

Timeframe: FID planned to be taken early 2020, with start of operations by the end of 2022.

Financials: The CCS unit costs for this project are currently estimated to be be around €55-70/t CO_2, in which the costs of capturing/separating CO_2 has been averaged over several emitters. Current CO_2 prices are much lower, so government intervention is necessary to make the project worthwhile. The Netherlands are discussing introduction of a CO_2 tax on electricity at €18 per tonne in 2020 that should rise to €43 by 2030; a similar tax might be applied to industry in the future. Fossil fuels used in the industry are taxed, but at lower statutory rates than in the transport sector. CCS may contribute more than half of the targeted emissions reduction by the NL industry, i.e. over 7 Mtpa by 2030. The Dutch government intends to expand the current system which subsidises renewable technologies ("SDE") to support the deployment of CO_2 reduction technologies. This may lead to annual support of several billion euro per annum for the latter.

The main business proposition to CO_2 suppliers is an anticipated contribution from NL Government to the cost difference between purchasing EU emissions allowance rights (status quo) and paying for the costs of CCS for climate purposes only (through a Cost plus-like mechanism in start-up phase towards a CfD$_C$-lke mechanism later).

Business Proposition

- Anticipated contribution from NL Government to the cost difference between purchasing emission rights and paying for the costs of CCS (through a Cost plus-like mechanism)
- Economies of scale from multiple emitters
- Insulation from carbon pricing to secure industry
- Creation of T&S infrastructure which can encourage further industrial capture
- Industry commitment to "national climate agreement"

Ownership/Promotion

- PPP likely for capture
- (Semi)state investment in T&S infrastructure

Financing (capital)

- Private and public investment expected
- Government financial support / incentive required

Revenue

- Carbon price avoidance
- Additional government incentive, through Cost plus and later CfD-like mechanism

Obligations to customers

- Provision of ETS rights (i.e. customers off the hook for purchasing EUA certificates) and gurantees on liability for CO_2

Government role

- Expected to support the project both financially and through risk sharing

Risk Management

- Risk sharing with government. Cross-party risks high unless internalised through JV arrangement.

Applicability to UK ICC

- Industrial CCS from an industrial cluster, most likely for permanent geological storage, with public and private involvement.
- Decouplig of investment of (multiple) capture installations in industry, or power, over time, from investment in T&S backbone (by separate entity)
- Potential for revenues from EOR limited.

<table>
<tr><th colspan="3">Case Study: CCS Commercialisation Programme - White Rose (and Peterhead)</th></tr>
<tr><td colspan="2">Summary
[64][65]White Rose CCS project was a full-chain private sector CCS project established under the Commercialisation Programme and associated business model. It is based off a new coal-fired ultra-supercritical Oxy Power Plant (OPP) of up to 448 MWe (gross) and a Transport and Storage (T&S) network that will transfer the CO2 for permanent storage under the southern North Sea. Delivery of the project is through Capture Power Limited (CPL), an industrial consortium including National Grid (NGC), developing the T&S network. In addition to CPL and government, potential investors include Infrastructure UK, pension funds, European Commission and the EIB (in respect of the applicability of the products under the EFSI or Juncker Plan). The Juncker Plan could conceivably provide equity, mezzanine debt and loan guarantees that could facilitate a more effective risk allocation and/or improve liquid for the Project. CPL would be entitled to receive a grant from the Authority against certain Allowable Costs incurred during the construction and development of the Project. In line with the previous financing plans, the developer kept the grant amount at £450 million for the purposes of capital formation.
Contract for Difference CfD strike prices were likely to have been within the range forecast by the CCS Cost Reduction Task Force (CRTF); £150-200/MWh for both projects. Public funding for project development and FEED costs have so far been fundamental in moving projects forward prior to there being any binding contractual commitment to provide a CfD to a project.</td><td>Business Proposition
• Low-carbon electricity generation protected from CO2 price with long term contracts ensuring revenue via CfD.
• Demonstration / scale-UK project to commercialise CCS in the UK</td></tr>
<tr><td>Ownership
• Capture Power + National Grid (White Rose)
• Shell (Peterhead)
• Private ownership of capture facility</td><td>Financing
• 35% equity and grant funding, inc base equity, third party equity and DECC grant funding.
• 65% debt, inc ECA covered, multilateral debt and commercial debt.</td><td>Revenue
• Electricity Sales at CfD agreed strike price likely £150-200/MWh</td></tr>
<tr><td>Obligations
• CfD
• Supply and off-take contracts</td><td>Government role
• Backstops on some CCS risks e.g. CO2 storage risks
• CfD
• DECC grant funding</td><td>Risk Management
• HMG would have had to accept the majority of financial risks from CO2 stores.
• CfD; Supply and off-take contracts
• Insurance - limited term and capped in value.
• Diverse capital funding sources</td></tr>
<tr><td colspan="3">Applicability to UK ICC
• Directly applicable, with alterations based on the experience and learnings.</td></tr>
</table>

[64] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/531925/K17_Financing_Feasibility_Report_Final.pdf
[65] (CCSA, 2016) http://www.ccsassociation.org/press-centre/reports-and-publications/lessons-learned/

Case Study: CCS Commercialisation Programme - White Rose (and Peterhead)
• The full-chain private sector business model is thought unlikely to work in the future as CO2 storage is currently not investible and the likelihood and consequence of cross-chain default proved to be a major challenge to both debt and equity investors. • Contract for Difference model a key option for operational financing, particularly for power projects, but could be adapted for other industry.

Case Study: Teesside		
Summary Teesside Collective is a group of industrial companies, including chemicals, refining and hydrogen production, where CCS has been proposed to permanently store CO2 emissions. Many business models were considered, and in 2015, 2 options were proposed by Societe Generale[66]: emitter CFD model based on a strike price, linked to EU ETS; storage driven model based on T&S usage fee. More recently, Poyry and Teesside Collective[67] have proposed new financing terms for an industrial CCS support mechanism for an early project with considerable government support. This is a fixed-term contract between Government and the industrial company, to specifically support the development of CO2 capture at the industrial site. Under this model CO2 T&S infrastructure is developed separately by the Government, with a contract between T&S and emitter CO2 transfer. Government, through the CCS Delivery Company (CCSDC), provides partial upfront capital in the form of a grant, capex repayments with agreed returns, and opex payments. The on-going support costs are reduced by a proportion of the value from the CCS related carbon savings netted off from on-going support payments – the net support costs from Government therefore reduce in line with rising carbon prices. EII invests part of the capex upfront, and then receives repayment from Government with an agreed return on their investment. This payment stream from Government is shaped such that the majority of the original capital outlay is recovered by the EII in the first few years of operation.		**Business Proposition** • CO2 price avoidance. Mitigate the carbon leakage threat to industry; retention of industry in UK, job creation and attraction of industry. • Economies of scale of industrial cluster • Guaranteed returns for emitter, provided plant operates. • Demonstration / scale-UK project to commercialise CCS in the UK
Ownership • Capture plant owned and operated by emitter • T&S owned by government (directly or indirectly through CCSDC).	**Financing** • Government support of 50% capex, but repayment of the other 50% capex in shaped repayment. Potential cap to government support if capex unexpectedly high. Pre-FID costs covered by government. • 100% opex covered by government if properly incurred (open-book recovery).	**Revenue** • CO_2 price avoidance (split with government) • Guaranteed capex ROI of 8% over 3 years and 12% over project lifetime.
Obligations • Contract length of 15 years for repayments. • Contracts with T&S company including CO2 specs, ownership transfer, fees	**Government role (inc CCSDC)** • Government funding channelled through the CCSDC and must establish T&S company. • Government support of 50% capex directly, 50% through repayments (potential cap) and pre-FID. • 100% opex covered by government if properly incurred.	**Risk Management** • Risk of capture underperformance is shared between government and emitter contractually • Government carries the capital risk of the project • Warranties for capture plant. • Cross-chain risks high as multi-party
Applicability to UK ICC • Directly intended for use in first UK ICC project.		

[66] http://www.teessidecollective.co.uk/wp-content/uploads/2015/06/Teesside-Collective-Investment-Mechanism-Report.pdf
[67] http://www.teessidecollective.co.uk/wp-content/uploads/2017/02/0046_TVCA_ICCSBusinessModels_FinalReport_v200.pdf

<table>
<tr><th colspan="2">Case Study: HyNet North West[68]</th></tr>
<tr><td>

Summary

HyNet North West is an integrated low carbon hydrogen production, distribution and CCUS project across Liverpool, Manchester and parts of Cheshire, aiming to complete FID by 2022 and be operational by 2025. Hydrogen will be produced from natural gas and sent via a new pipeline to a range of industrial sites, for injection as a blend into the existing natural gas network and for use as a transport fuel. Proposal to re-use the Liverpool Bay oil and gas fields infrastructure, aligning with decommissioning, is an economic, practical and timely option for CCUS demonstration and reduces costs. Other benefits include that the project would be a FOAK hydrogen CCUS project, creation of hundreds of jobs, cost effective decarbonisation of industry creating confident investment.

Technical: Displaces 510MW of natural gas use at 10 industrial sites, plus 380MW in the distribution network, saving 1.14 million tonnes CO2 per annum at a total infrastructure cost of £920 million. Hydrogen production through auto-thermal reforming technology on 2 production lines, with 890 MW of hydrogen output capacity and 93% CO2 capture rate, costing £256 m per unit. 1.14 MtCO2pa captured from hydrogen plant and further 0.4MtCO2pa direct from industry, so 36 MtCO2 stored from Phase 1 Project over 25 years. Total opex is estimated at £85 m/yr, with electricity for CO2 compression to 10 bar at project initiation, rising to 60 bar at end, costs £26 m/yr and £10 m/yr for offshore T&S.

Funding: currently the equivalent of the RO, FIT or CfD doesn't exist for heat; RIIO2 Price Control mechanism for gas distribution is being consulted upon and there is a suggestion that the source of funds should be appropriately socialised across consumers and/or taxpayers, including support for the participating EII's. The most likely source of funds is via Cadent's Regulated Asset Base (RAB) under the forthcoming RIIO2 period from 2021-2026/29. The suggested model relies on Government support for industrial conversion (via the industrial strategy) and CO2 T&S infrastructure, and gas customers funding the hydrogen production and distribution, CO2 capture and part of the T&S through regulated networks, spread across local and national customers.

Coordination and risk: may pursue a framework similar to that recently used to fund the Thames Tideway Tunnel (TTT), which would bundle delivery and operation of activities together and fund them through RAB-financing; it would be important to maintain the practical risk separation of the hydrogen production, CO2 capture and distribution from CO2 T&S. Government will need to take on the key risks for CCUS chain failure, as this cannot be borne by the private sector.

"The contractual arrangements and ownership structure are driven from the funding model which Government chooses to adopt. For the initial projects (of which HyNet is one) use of the existing RABs to fund the complete chain is thought to be the best solution.

</td><td>

Business Proposition

- Demonstration / scale-up project to commercialise CCS in the UK
- Demonstration / scale-up for hydrogen in industry and grid blending
- CO2 price avoidance. Mitigate the carbon leakage threat to industry; retention of industry in UK, job creation and attraction of industry..
- Creation of T&S network with potential to expand and reduce costs for future capture sites.

</td></tr>
</table>

[68] (Cadent, 2018) https://hynet.co.uk/app/uploads/2018/05/14368_CADENT_PROJECT_REPORT_AMENDED_v22105.pdf

Case Study: HyNet North West[68]		
Innovation is a key element of the price control structure and there is potential to extend this to allow funding under RIIO-2 from April 2021. The advantage of this is that it avoids primary legislation and the use of Government money which are both very hard sells in the present climate. For the enduring regime the balance between support incentives and regulation is important to produce a model that works for private sector investors and requires minimum financial support from consumers or HMG.”		
Ownership • Hydrogen production and distribution and CO2 capture infrastructure potentially owned and operated by Cadent • The contractual arrangements and ownership structure will be driven from the funding model the government chooses to adopt.	**Financing** • £920 total infrastructure cost • RAB recovery of hydrogen production and distribution and CO2 capture. Potential for RAB funding of complete chain. • Government funding for EII conversion and T&S infrastructure is also an option.	**Revenue** • RAB gas customer bills both locally and nationally • Sale of hydrogen to EII’s, transport and domestic users
Obligations • Ofgem regulation and price control likely • The contractual arrangements and ownership structure will be driven from the funding model the government chooses to adopt.	**Government role** • Government regulation of RAB through Ofgem • Government will need to take on the key risks for CCUS chain failure • Potential government funding for EII conversion and T&S infrastructure	**Risk Management** • Hydrogen production plant is based on proven technology with multiple hydrogen customers reducing counterparty risk. • Multiple CO2 stores are available to minimise storage risk • Commercial segregation of hydrogen production and use from CCUS will minimise cross chain risk. Practical risk separation of the hydrogen production, CO2 capture and distribution from CO2 T&S • Government will need to take on the key risks for CCUS chain failure
Applicability to UK ICC • Directly applicable as a potential first UK ICCUS hydrogen project. • RAB with direct government funding for some elements, and government ownership of some risks.		

Case Study: Merchant CO_2 Market		
Summary Commercial market for bulk supply of liquefied CO_2 is well established globally, for use various in various industrial sectors including chemicals, food & drink, healthcare and other CO_2 utilisation (CCU) applications etc. Global market is around 80-100 million tonnes per annum (Mtpa), of which approx. 60 Mtpa is used for CO_2-enhanced oil recovery (EOR), primarily in North America.[69] A number of specialist industrial gas suppliers dominate the global market on a commercial basis including: Linde (BOC in the UK), Messers, Air Liquide, Air Products, Praxair etc.[70] Merchants utilise streams of CO_2 from their own operations, aggregate 3rd party sources and/or trade between themselves. Captured streams are typically high purity CO_2 by-product off-gases from industrial processes (e.g. steam reforming in ammonia/fertiliser production and petroleum refining etc; fermentation off-gases) or mined from geological reservoirs containing high concentration CO_2 gas. Supply per source may be in the order of 10,000 to 500,000+ per year. Merchants undertake treatment and sale as purified product in cylinders or bulk (tankered) product. High purity sources targeted due to lower treatment/purification costs. Limited examples of capturing more dilute CO_2 sources. In most cases merchants own the capture, transport and storage equipment (e.g. leasing of tanks). Market is characterised by a few major players, and a smaller number of sources supplying to a larger diversified customer base. This means merchants act as aggregators, balancers and price-setters in the market (oligopolistic). There are significant supply fluctuations driven by seasonal variation in primary product (ammonia) supply. In Europe, there is some transboundary shipment of CO_2 to balance supply and demand across different countries (e.g. Praxair operates a tanker fleet and landing facilities for ship borne CO_2 transport at Teesside and Tilbury).		**Business Proposition** • Add value to industrial by-product, presumably acquired at fairly low cost by merchants (e.g. £0 to <£30/tCO_2, untreated) • Mixed market with fairly growing demand for CO_2, albeit in fairly small individual quantities (e.g. 10-1000's tCO_2 per year per customer) • Generally low cost/high margin market
Ownership/Promotion • Midstream promoter/developer: largely vertically integrated supply chain; merchants own and operate the CO_2 gathering and purification (facilities at industrial sites), distribution (tanker fleet) and storage equipment (cylinders/tanks at customer properties).	**Financing** • Equity: most likely financed from merchants own capital. • Debt: unknown • CO_2 producers ("emitters") tend to not be involved in the gathering and treatment system themselves	**Revenue** • CO_2 sales, which can vary from US$30-300+ per t$CO_2$ depending on volume/specification (US$1000+/t$CO_2$ for small cylinder supplies). • Exact values unknown due to commercial nature of market.

[69] The United States National GHG Inventory (2017) reports that 59.3 Mtpa CO_2 was utilised for EOR in 2016, of which 13 Mtpa was captured from anthropogenic process streams.

[70] According to the BBC (https://www.bbc.com/news/business-44613652) there are five major sites in the UK capturing CO_2 for merchant supply: Manchester (Cargill/BOC), Ince-in-Makerfield (CF Fertilisers), Billingham (CF Fertilisers), Wilton (Praxair Bioethanol, 250 ktpa) and Ipswich (?). Plant capacities are unpublished, except Praxair. The UK's National GHG Inventory indicates no capture is carried out, highlighting the paucity of data in this respect.

Case Study: Merchant CO_2 Market

• Most merchants also offer customers technology solutions to capture CO_2 from other more dilute sources (e.g. ASCO/Messers capture equipment; Linde CO_2 amine capture technology)		
Obligations to customers • Uncertain due to commercial nature of contractual terms. • Multiple source/customer model allows balancing of supply and demand by merchants as midstream operators/brokers. • Most customers prefer to buy from merchants to avoid supply interruptions that could arise from bilateral arrangements.	**Government role** • None. • Current CO_2 supply shortage (June 2018) has led to GMB Union to call for Government intervention in the market to ensure food security.[71]	**Risk** • Technical risk: Low (proven technology). Some supply risks. Annual variation in supply due to seasonal nature of primary business from which CO_2 sourced (mainly fertiliser production). Excess supply during winter, shortfalls in summer months during fertiliser plant shutdowns. • Production strongly dependent on ammonia prices. • Commercial risk: Merchants hold all the risks since they are responsible for balancing supply-demand i.e. this removes cross-party default risks since the merchant acts as broker

Applicability to UK ICC

- Proven midstream promotion and development business model for industrial CO_2 capture and use. Emitters entirely insulated from technology, market and financing risks as this is all borne by the CO_2 merchant. For these reasons, the midstream promoter/developer model is relevant to UK ICC where emitters would prefer to be insulated from all risks, especially under a “part-chain” business model.
- Supply fluctuations (and shortages) highlight the dependence of production on the demand/supply of primary product from which CO_2 is extracted (e.g. ammonia)
- Market supply imbalances could possibly drive CO_2 merchants to invest into capture of more dilute industrial CO_2 sources to supplement existing supply sources.
- CCS could offer offers a means of enhancing market balancing by taking CO_2 during low demand periods (i.e. revenue during low demand, security of supply during high demand)
- Further economic analysis could help inform which levers could support CO_2 merchant’s motivations to invest in CO_2 capture (esp. under “part-chain” business model)
- Even at small-(demonstration) scale, establishing a midstream promoted, developed and financed industrial CO_2 capture project in UK could provide the basis for future expansion as per Decatur (see below). The current CO_2 supply shortage means it is probably a good time to discuss the possibility with industrial gas companies.

[71] http://www.gmb.org.uk/newsroom/co2-supply-chain

<table>
<tr><th colspan="3">Case Study: UK Nuclear industry[72]</th></tr>
<tr><td colspan="2">Summary
• Waste disposal: Plant operators submit decommissioning plans, including waste management, and set aside funds progressively. Government enters into a contract to take liability of certain waste under an agreed schedule, charging the nuclear operator for this transfer service at a fixed unit price, the ‘Waste Transfer Price’, which will include a significant risk premium and escalate with inflation. UK Nuclear Decommissioning Authority (NDA) carries the responsibility and cost for disposal of almost all the legacy and current nuclear power station spent fuel in the UK. The NDA determines the overall strategy and priorities for managing decommissioning. It owns interim stores at Sellafield and rail/shipping assets. A Geological Disposal Facility is planned. NDA has 200 staff and owns 17 sites across the UK
Business model options:
• RAB The RAB is a statement of the investors’ sunk funds in a utility, to which the duty to finance functions applies. It is a long-term contract between investors and customers, mediated through a regulator e.g. Ofgem, which is itself backed by statute (government). The RAB is remunerated from customers’ bills, not taxpayers. CAPEX contract could be divided into a series of steps and must ensure that the developer has sufficient incentives to be efficient. Charge to the system is re-evaluated periodically depending on costs; if the costs are higher than the market cost, consumers may pay or the actual price customers pay can be some combination of the rate of return allowed on the RAB and the market price for capacity. RAB: state promises via the regulator to ensure the legitimate and efficient functions are financed, and it therefore protects the nuclear developer from expropriation either by attempts to force down electricity prices, or from policy decisions.
• Hinkley-Style CfD: gives greater certainty and stability of revenues to electricity generators by reducing their exposure to volatile wholesale prices, in order to bring forward investment, whilst protecting consumers from paying for higher support costs when electricity prices are high. CfD provides a Strike Price for the developer (for Hinkley C this is £92.50/MWh) the developer is paid the difference between the Strike Price and the electricity market reference price for the duration of the contract. However, the strike price may look increasing at odds with the wholesale market price, and consumers are locked into higher unit charges.</td>
<td>Business Proposition
• Creation of reliable low carbon electricity at pre-agreed sale price or with a guarantee of returns
• Waste disposal liabilities not solely owned by nuclear facility, reducing risks.</td></tr>
<tr><td>Ownership
• Most nuclear developers are state owned, in whole or part, due to the safety, security and financing challenges.
• NDA is an executive non-departmental public body</td>
<td>Financing
• Large fixed capital cost and large decommissioning cost inc. waste disposal. NDA funded by government.
• CfD e.g. Hinkley 9% real cost of borrowing for 35 years.
• RAB private / state investment</td>
<td>Revenue
• Electricity sales and pricing
• Reduced CO2 payments over fossil fuels
• RAB: consumer pays for electricity based on costs.
• CfD: electricity revenue based on Strike Price</td></tr>
<tr><td>Obligations</td><td>Government role</td><td>Risk Management</td></tr>
</table>

[72] http://www.dieterhelm.co.uk/energy/energy/the-nuclear-rab-model/

Case Study: UK Nuclear industry[72]		
• RAB contract between investors, government and customers on electricity price and costs • CfD Strike Price contract via government for electricity price • Waste: liability contract between operator and government. NDA must eliminate site hazards and develop waste solutions.	• Government takes long term waste liability and potentially other risks contractually • Often owns nuclear developers • Financing guarantees and regulating operations	• Government takes long-term waste liability and most likely regulatory and policy risks • Allocate risks to those best able to manage them through fixed contractual arrangements and liability pension fund from revenues.
Applicability to UK ICC • RAB is effective way of solving 'time inconsistency' of sunk capital without guaranteed returns and investors treat the RAB as a very solid securitisable asset, improving investment terms. However, RAB could lead to inefficient operation and higher cost than alternatives. As RAB regulates / limits ROI it could deter investment in some cases. • CfD promotes efficient facility running and de-risks investment but strike price may not be cost effective long term for decarbonisation • Waste: paying government to take on liability is like paying T&S (or T&S needing gov liability). Government liability for storage would reduce one of the major ICCS barriers.		

Case Study: District heating Dunkirk, France		
Summary In Dunkirk, industrial waste heat is used to supply heat networks, with a system to record the amount of heat delivered at each node. In 1985, the agreement between the city of Dunkirk and the steelworks', now Arcelor-Mittal (AM), led to the installation of a 23 MW capture hood and construction of a heat network. The use of renewable energy (min of 50% DH heat from renewable and recovered sources) makes the heat network eligible to **reduced VAT rate and to the ADEME heat fund**. For AM, installing a hood at the exit of the sinter strands made it possible to recover process dust and thus was a solution to meeting **clean environmental requirements**. The Dunkirk area was the stronghold of powerful environmental associations which questioned the massive tax incentives offered to polluting industries to encourage them to set up local plants. AM therefore put efforts into **improving its relations with local stakeholders** from an environmental point of view and its participation in the heat network may be seen partly as a way of maintaining good relations with local people. AM did not invest in the first capture system: it was the concession holder that **invested, on behalf of the city council**, the owner of the network; AM paid for half of the investment of the second system. Other drivers include a carbon tax, sales of heat, council financial support and guaranteed demand for the heat provided it meets certain criteria (Classified networks: >50% renewable or recovered sources, guaranteed quantities supplied, reasonably cost-effective heat price).		**Business Proposition** • Improving relations with local stakeholders • Carbon tax avoidance • Meeting clean environment requirements
Ownership • Capture plant owned and operated by steelworks • Heat network indirectly owned by the city council	**Financing** • Initial capture facility publicly funded but run by the steelworks • Second capture facility 50% funded by the steelworks	**Revenue** • Waste heat sales with guaranteed demand • Carbon tax avoidance • Heat network received reduced VAT rate and ADEME heat fund. • Reduced environmental impact leading to improved local stakeholder relations
Obligations • Industry must guarantee certain quantities of heat supply to heat network and the heat network will guarantee demand for their waste heat.	**Government role** • Local government set up the heat network and financed the first capture facility • Heat network received reduced VAT rate and ADEME heat fund.	**Risk Management** • Contracts for heat supply and demand • Public investment in first capture facilities
Applicability to UK ICC • Industry being supported by local government to capture waste heat and sell it to a heat network, with environmental benefits. • Public capital funding and tax incentives to drive initial investment, along with environmental pressure from local stakeholders. • Heat has a value proposition for use in buildings, which CO_2 doesn't have in the same way (it must be created through CO_2 pricing).		

Case Study: Thames Tideway UK (TTT)

Summary

[73]London's combined sewerage system operates at capacity, with 39 million tonnes of sewage discharged to tidal River Thames in a typical year. Tideway's business as a regulated utility company is to design, build, commission and maintain the Thames Tideway Tunnel (TTT), a simple asset with a cost of £4.2bn, with construction between 2016 and 2023 and a 120 year design life. Thames Water serves the area as utility provider where TTT is being constructed. Bazalgette Tunnel Ltd, a special purpose investment vehicle funded by a number of institutional investors, has been awarded a regulated utility license.

Tideway is responsible for investing £3.1bn of an expected aggregate £4.2bn for the TTT project, with the £1.1bn balance provided by Thames Water. RPI-linked revenue collected from Thames Water's wastewater customers. Regulatory baseline cost of £3,144m. Fixed real WACC of c2.5% until 2030, assuming system acceptance by 2027, with partial protection against movements in the cost of debt. Support package provided by the UK Government as below. Financing: £1.3bn shareholder funds upfront; £1.0bn revolving credit facility; £0.7bn EIB RPI index-linked loan; £0.45bn forward start index-linked bonds.

Pain/gain sharing mechanism shared on a 50/50 basis, subject to adjustments for compensation events and liability caps. Delay damages provisions in place. Joint and several liability and step-in rights. At system acceptance, Tideway with transfer above-ground assets to Thames water; Tideway is responsible for deep tunnels and shafts.

Maintenance costs will be funded by customers through revenue provisions in the Licence, subject to 5 year price control process during operational period.

Business Proposition

- SPV long term infrastructure investment with commercial returns protected by legislation
- Government want to build critical infrastructure with low cost off balance sheet project

Ownership

- TTT owned by the special purpose vehicle (SPV), which acts as independent infrastructure provider holding regulated utility licence (by Ofwat).
- Tideway is owned by Allianz (34.26%), Amber (21.32%), Dalmore (33.76%) and DIF (10.66%), with many contractors.

Financing

- £4.2bn TTT project, of which £3.1bn Tideway sources and £1.1 bn Thames water.
- Fixed real WACC of c2.5% until 2030.
- £1.3bn shareholder funds upfront; £1.0bn revolving credit facility; £0.7bn EIB RPI index-linked loan; £0.45bn forward start index-linked bonds.

Revenue

- Customer revenue subject to price control from Ofwat
- Monthly fee directly from water customers. SPV charges Thames Water sufficient to recover its capital and operating costs. Return on capital is 2.497% to 2030. After 2030 Ofwat income is set based on WACC and regulated asset value in line with other regulated.

Obligations

- Price regulation by Ofwat

Government role

- 125-year licence to operate the tunnel.

Risk Management

- Tideway's commercial strategy has been designed to minimise risk to investors: Minimise reliance on any single

[73] https://www.tideway.london/media/2905/investor-presentation-26-jan-2017.pdf

Case Study: Thames Tideway UK (TTT)		
• Obligation to provide service to customers (operating asset)	• Government acts as insurer of last resort, giving cover above the amount the market is ready to provide. • Contingent Equity support from government in the event of cost overruns above the Threshold Outturn. • Compensation payment if government elects to discontinue project • £500m committed market disruption liquidity.	contractor; effective incentivisation aligned with Tideway's objectives • Pain/gain sharing mechanism shared on a 50/50 basis, subject to adjustments. • Government insurance, contingency and compensation. • Construction delivery risks with SPV. Strong incentives and penalties in the contractual arrangements (on construction time, quality and cost). Risks generally subcontracted. • Availability risk with SPV. SPV exposure to cost over run is capped and SPV not exposed to usage risk.

Applicability to UK ICC

- Government support package (insurer of last resort, contingent equity, compensation and disruption liquidity) can be used to minimise risk to both investors and the CO_2 emitters.
- Price regulation of the T&S infrastructure or similar contractual arrangements could be used to ensure fair T&S fees.
- Use of contractors, who are liable for infrastructure risks. Availability risk of T&S should be with T&S provider, but with potential caps on exposure to cost as with this SPV.