Enabling the Deployment of Industrial CCS Clusters

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ENABLING THE DEPLOYMENT OF INDUSTRIAL CCS CLUSTERS

Key Messages

- The aim of this study is to assess economic and business related issues with industrial carbon capture and storage (ICCS) clusters.
- The results of this study will be of interest to ICCS project developers and governments looking to support ICCS cluster development.
- ICCS is not yet commercially mature. Private investment is likely to occur if the following four key enablers are addressed:
    - Mitigate the risk of carbon 'leakage'[1]
    - Provide the emitters with margin certainty through appropriate subsidies
    - Decouple the business cases for capture and infrastructure
    - Share the key risks with government through guarantees
- The necessary level of government support is high. However, without ICCS, governments might need to rely on more expensive solutions to meet decarbonisation targets.
- ICCS plays an important role in supporting local industrial jobs and industrial markets.
- The study investigated four different ICCS cluster business models:
    - Public transport and storage (T&S) company
    - T&S as regulated assets (i.e. regulated fees for T&S access)
    - Anchor CCS project with third party access
    - CO_2 enhanced oil recovery (CO_2-EOR)
- The quantitative assessment shows that guarantees on loans, storage and CO_2 volumes are the key prerequisites for achieving investment.
- The expected costs for governments for an illustrative CCS cluster in Europe are between £29-53 per tonne of CO_2 abated. However, upward movements or regulation of the CO_2 price[2] and provision of grants can significantly reduce these costs.
- At least one of the business cluster models is relevant in each of the focus areas (North America, Europe, China and Australia).
- Recommendations for further work include a cost-benefit analysis for ICCS considering its wider benefits, a comparison of decarbonisation options across all sectors, the development of regional ICCS strategies and refinement of ICCS business models, and a further investigation of some of the key risk mitigation strategies.

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[1] Carbon leakage occurs when there is an increase in CO_2 emissions in one country or sector as a result of an emissions reduction by another country or sector. (Definition according to the Intergovernmental Panel on Climate Change (IPCC).)

[2] In general, the price of CO_2 can be either implemented as an emissions permit or a carbon tax. The illustrative calculations in this study assume a location of the ICCS cluster in Europe, thus the price of a permit in the EU emissions trading scheme (EU ETS) as the price of CO_2.

Background to the Study

It is widely considered that deployment of carbon capture and storage (CCS) for clusters of energy intensive industries (EIIs) will become vital for meeting long-term greenhouse gas (GHG) reduction targets, and is a cost effective way for doing so, according to organisations such as the International Energy Agency (IEA) and Intergovernmental Panel on Climate Change (IPCC). In addition, it will be important to develop the related finance mechanism quickly to prevent carbon leakage, i.e. businesses transferring operations to places with less stringent GHG emission standards. Recent evidence highlights there might be different needs and challenges in deployment of industrial clusters, compared to those involving power generation. IEAGHG's Technical Report 2015/03 "Carbon capture and storage cluster projects: review and future opportunities" reviews 12 CCS cluster projects and finds that the most successful clusters are currently based on CO_2-EOR in North America. This is to be expected as EOR provides a commercial benefit to investors in such activities.

Further requirements for ICCS clusters include: generating confidence for per-investment in CCS infrastructure, new methods to attract international investment and systematic development of CCS cluster business plans. Following on from the findings, the report recommends developing financial instruments and forms of contract for CCS clusters with the help of a leading financial institution. A report by the Zero Emissions Platform (ZEP) advocates creation of a market maker and flexible funding mechanism to enable market certainty and manageable risk for CO_2 transport and storage. Studies by Société Générale for the Teesside Collective and Deloitte for The Crown Estate provide first assessments of potential financial mechanisms and discuss the share of public and private sector investments. However, more information is necessary regarding the transferability of conclusions for CCS clusters based on power generation incentives, such as a UK Contract for Difference (CfD), to those involving multiple industry sectors, and especially EIIs.

Therefore, IEAGHG identifies a requirement to assess economic and business related issues of industry CCS (ICCS) clusters involving EIIs in more detail.

Scope of Work

In general, there are three separate areas of challenge, which a cluster model for CCS can address:

1. Incentivising CCS for industrial processes
2. Investment in transport and storage infrastructure
3. Commercial/contractual relationship between capture, transport and storage operators

To address these issues, the study first defines the technical and commercial risks and incentives associated with each main element of the general CCS chain, including:

1. High level analysis of commercial risks associated with capture, transportation and storage
2. Definition of the interface risks associated with each step of the CCS chain
3. Identification of the typology of entities best able to manage the different steps

The study then goes on to assess economic and business related issues with, and propose potential solutions to, the deployment of CCS clusters in EIIs. This includes the following tasks:

1. Explore the differences and commonalities of CCS clusters based on power generation and EIIs for four different CCS cluster models:
    1) Public transport and storage (T&S) company
    2) T&S as regulated assets
    3) Anchor CCS project with 3rd party access
    4) CO_2-EOR
2. Investigate the management of counterparty and default risk in the light of the more difficult/short-term credit profile of many EIIs compared to power generators
3. Develop investment mechanisms to overcome lack of commercial benefit of CCS to EIIs and different risk profiles of each element of the CCS chain
4. Assess the impact of risk allocation on the investment case
5. Evaluate different 3rd party access options
6. Propose commercial models for ownership (public or private) and operation of the different elements of the CCS chain in an industrial CCS cluster

The geographical scope of the study is international, with the results being applicable to but not solely focussing on UK industry CCS clusters. The main aim is to understand risks and solutions that are common and those that are different between regions. The assessment covers the following regions:

a. North America,
b. Europe,
c. China,
d. Australia.

IEAGHG commissioned Element Energy to undertake this study. Element Energy was supported by financing expert Richard Simon-Lewis (White Rose CCS Project, UK CCS Commercialisation Programme) and Angela Whelan (Ecofin, UK CCS Commercial Development Group). The study further benefitted from the input of several ICCS stakeholders.

Findings of the Study

Role of CCS in decarbonising industry

As countries look to decarbonise their economies in ways which are compatible with the Paris Agreement, one priority is to find solutions to curb emissions from industrial sources, which account for over one-quarter of global CO_2 emissions. Since the demand for industrial products is expected to at least double by 2050[3], such solutions also need to be quickly scalable. In this context, the potential of industrial Carbon Capture and Storage (ICCS) to rapidly achieve deep industrial decarbonisation while at the same time meeting global demand represents a unique value proposition, compared to other mitigation options.

[3] IEA, 2011, Technology Roadmap: Carbon Capture and Storage in Industrial Applications.

Although the economics of several North American CCS projects have been improved by the sales of the captured CO_2 for enhanced oil recovery, the specific circumstances of these projects limit their replicability on a global scale, meaning that other existing projects have understandably mainly relied on government support. To meet the 2050 decarbonisation targets, however, the ICCS sector must experience a step change in growth only attainable through significant public and private investment. Thanks to the intrinsic economies of scale, cluster projects are predicted to be the main way in which initial deployment will happen in regions where no infrastructure is already available, and it is therefore on these that this study focusses.

Current conditions are not conducive to attract private investment and several high level enablers must be appropriately addressed first: if this is done, substantial amounts of private capital can be unlocked and ICCS may then be deployed on a large scale over time. After successful completion of these first projects, future ones will likely be developed with reduced government intervention, ultimately resulting in commercial models fully driven by wider market mechanisms.

Key enablers to unlock private investment

Exploring the business environment surrounding ICCS reveals four enablers that must be simultaneously addressed to enable the creation of business models that are investable.

Addressing carbon leakage

One way to ensure that carbon pricing can lead to the intended results is for industries to be able to pass the emission charges on to consumers – in case the emission translates to a cost. However, industry is usually unable to do so if trading on international markets due to competitiveness. This is because at the carbon price levels required to independently stimulate investment in ICCS, there is a risk of inducing relocation of the production activities to less regulated countries – a phenomenon known as carbon leakage. International coordination on the price of CO_2 may well be the best option to address carbon leakage but, due to difficulties in its implementation, other options to address this geographical inconsistency must be considered. To date, trade-intensive sectors have usually been either exempted from carbon pricing schemes or provided with free allowances to emit. While the first solution at once negates the financial benefits arising from investment in decarbonisation measure, the second may still provide the right motivation so long as the allowances can be traded for a high enough price; however, both options fail to result in an increased cost to emitters and their customers, and therefore externalise the cost of decarbonisation, in contrast with the original policy purpose. Other options to address carbon leakage include national or regional border-adjustment measures as well as incentives to increase demand for green products, e.g. via public procurement and product standards. If these measures are implemented and a high enough carbon price is achieved, investment in ICCS could be justified from the avoided emission charges: this represents the first step towards the creation of commercial models that do not exclusively rely on *ad hoc* subsidies for ICCS.

Margin certainty through subsidies for industrial emitters

Even if the risk of carbon leakage is effectively addressed or modified, policy-induced carbon prices and taxes are expected to remain too low to provide a sufficient price signal for investment in ICCS, which our analysis suggests is in the range of £75-£110 per tonne of CO_2 for clusters like the ones modelled. Even if these expectations were to be exceeded, interviews with potential investors revealed that the investability of business cases that are overly reliant on the price of carbon is undermined by great political uncertainty, and for this reason, on market failure grounds, additional subsidies can be justified. It is expected that any subsidy provided should insulate the project revenues from volatility in the price of CO_2, as well as from the related increase in the price of fuel and electricity, since these add up to a sizeable portion of the cost of capture. As an alternative to direct subsidies, we find "Green Procurement" and product standards amongst the measures which may be able to trigger investment in ICCS, but the scope of these measures must be large enough to create a market with the right profit margins and able to offer attractive growth opportunities for prospective investors.

Decoupling the ICCS business chain

Fundamental differences between the capture, transport, and storage businesses mean that no single organisations may be willing to manage a full-chain project independently. Delinked part-chain projects allow all parties to focus on their core strengths and thus achieve maximum efficiency. Through extensive literature review and stakeholder engagement, this study has identified four different options for transport and storage infrastructure:

- <u>Government-owned transport and storage infrastructure:</u> The government establishes a public transport and storage (T&S) company to construct the infrastructure and lead the cluster project towards operational stability. At a later stage, this model can be liberalised through the privatisation of the T&S company;
- <u>Regulated infrastructure:</u> A Regulated Asset Base (RAB) model is used to enable fully privatised delivery of the project. In this option, an independent market regulator would need to be set up with government funding;
- <u>Existing infrastructure:</u> The simplest option presented is if the industrial cluster can latch on to existing infrastructure (which may either be government owned or regulated). This might be possible for future CCS projects in certain locations in North America where a relatively extensive CO_2 pipeline network and associated easements already exist (6,000 km of CO_2 pipelines vs 230 km in Europe[4]). Alternatively, industrial emitters could join an existing "anchor" CCS project, e.g. on power, provided the infrastructure was built oversized;
- <u>CO_2-EOR:</u> Only an option if active oil fields exist in the cluster region, this is the most common option for currently operating projects but might not be a long-term solution for large-scale deployment of ICCS clusters globally if the demand for fossil fuels decreases and/or their price is not sufficient to justify the purchase of captured CO_2.

Public-private risk sharing

Regardless of what commercial agreement is achieved for the construction and operation of the T&S infrastructure, several show-stopper risks – risks that would impede financial close – can only be mitigated through government intervention. Some of the options for government to de-risk the project are illustrated in Table 1.

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[4] IEAGHG, "CO_2 Pipeline Infrastructure", 2013/18, December, 2013

Table 1 Show-stopper risks and suitable government mitigation

Illustrative show-stopper risks	Suitable government mitigation
Uncapped liability from CO_2 leakage long after storage site decommissioning	**Back-stops or caps** on the long-term storage liability to enable a layered insurance approach, where the storage operator can get insurance coverage up to the capped amount.
Emitter default volume risk	**Volume guarantees** reduce the loss experienced by the T&S operator.
Storage failure after completion of development phase (risk for the emitter)	**Storage guarantees** to provide minimum payments to emitters in replacement of subsidy and carbon costs.
Storage failure after completion of development phase (risk for the T&S company)	**Grants** to cover the cost of storage development, potentially also of a back-up storage.
Risk of default on loan repayment makes project not bankable	**Loan guarantees** ensure project bankability despite the low creditworthiness of some of the project parties.
Emitter unable to reach FID due to insufficient capital	**Grants** to the emitters decrease the need for external financing and the expected shareholder equity contribution.

Private finance can be brought in if government helps in mitigating the above risks, often referred to as show-stoppers. In addition to these, many other risks affect the various parties of a part-chain project, and the cost of capital will be reduced by additional risk sharing with the public sector. This is not to say that no risk can be fully managed by the private sector participants: as an example, off-take agreements including *take-or-pay* and/or *ship-or-pay* clauses are expected to regulate the transfer of CO_2 across the network (from capture, through transport to injection and storage). Considering that government is ultimately paying for a large part of the project through subsidies, it is in its interest to achieve value for money, which can be achieved by further reducing the privately held risks. Other cases could include staged funding approaches that release funding when certain milestones are reached.

Government intervention and subsidies

Cost effectiveness of ICCS

This study draws attention to the fact that "*it may not be possible to decarbonise industrial sectors without CCS*"[5], and with a worked case study we also point out that subsidies in support of ICCS may in fact be cost-effective for society, when compared to subsidies to other low-carbon technologies such as offshore wind. If policy makers valued the cost of carbon emissions consistently with the cost of meeting the 2050 goals, rather than on the prevailing carbon market price, it could be seen that, without ICCS, governments might need to support more expensive measures in other sectors to compensate for the lower reduction in industrial emissions. However, the inability of current pricing mechanisms to

[5] IEA, 2013, Global Action to Advance Carbon Capture and Storage: A Focus on Industrial Applications. Annex to Tracking Clean Energy Progress 2013.

incorporate the full cost of carbon represents a market failure that needs to be addressed to fulfil the Paris Agreement. For example, governments could implement policies to strengthen the carbon price, and/or they could consider providing subsidies for ICCS and other cost-effective projects. Unless one of these options is pursued, governments may be faced with a higher bill for decarbonisation, or they might fail to meet the decarbonisation targets.

Local jobs

Among the multiple decarbonisation options that a government could incentivise, ICCS offers a unique value proposition: by capping carbon emission charges, and assuming that the CO_2 leakage risk is addressed, CCS directly improves the competitive position of industries that implement it, especially under an increasing carbon price. Thus, ICCS acts as a protection on the local jobs that may be otherwise displaced if industries go out of business, due to increasing financial pressure from escalating carbon costs.

Detailed assessment of the four business models

Model 1: Public T&S company

The key feature of Model 1 is that the T&S infrastructure is developed and operated by a public T&S company, tasked by the government with ensuring the CO_2 pipeline network is suitably oversized to be capable of hosting future cluster expansion. While it is possible that private sub-contractors will be employed for specific tasks and will be held accountable for them, the T&S Company has full ownership of the key T&S risks. Additionally, the T&S Company must decouple the business chain and coordinate the overall project delivery to reduce the industrial emitters' exposure to counterparty risks. The other key features and the money flows are summarised in Figure 1 below.

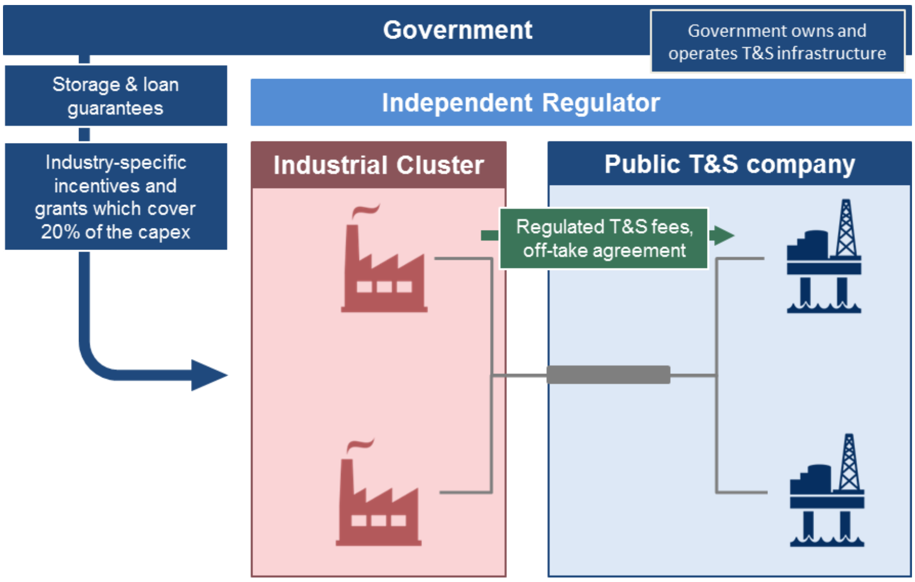

Figure 1 Public T&S company

Model 1 is expected to result in the lowest possible cost of capital for the T&S investment because the public T&S Company is expected to have lower profitability requirements than those of private companies that could participate in the regulated business discussed in Model 2 (7% hurdle rate, compared to 12% of the private counterpart). Further benefits arise because of public ownership, and crucially because of the government's unique position to implement a long-term strategy that from the start includes extended lifetimes of T&S assets. The modelling assumption used is that the assets will be used for 40 years, which greatly reduces the average T&S cost per tonne of CO_2 abated. Based on the reasons outlined above, Model 1 represents the least-cost option to develop new T&S infrastructure.

Model 2: T&S as regulated asset

In Model 2, see Figure 2, the transport and storage parts of the infrastructure are developed and operated by two separate companies through a regulated infrastructure model such as the regulated asset base (RAB). An independent regulator is set up, tasked with regulating the revenues of (and hence the fees charged by) the infrastructure companies and with ensuring that they do not abuse their monopolistic position. The regulator should also coordinate the project delivery from the pre-FID phase, and should also mandate that the CO_2 pipeline network be oversized (as in all models). Either government or the regulator on their behalf provide the support measures to decrease the overall level of privately held risk and guarantee regulated returns palatable to a wide range of infrastructure investors. One of the unique features of this model is the fact that half of the transport and storage revenues are provided by means of capacity payments – government subsidies that only depend on assets' availability and that reduce the need for utilisation revenues (and hence the fees paid by the emitters) – and that the transport and storage companies are supported by government grants.

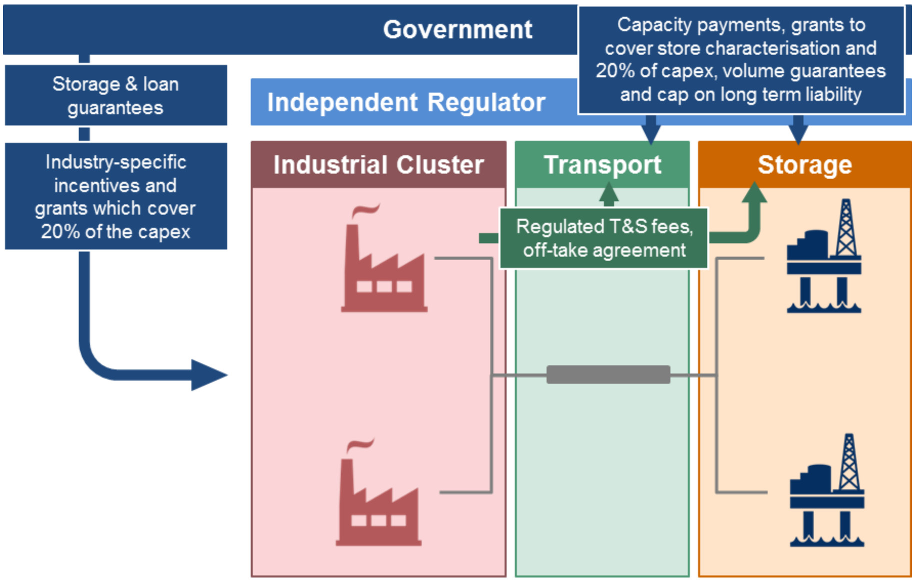

Figure 2 T&S as regulated asset

Model 3: Third party access to CCS anchor project

In Model 3, see Figure 3, the investment in the already existing transport infrastructure is treated as a sunk cost fully borne by the anchor CCS project (via relevant government subsidies which are not in scope of this study), and while the industrial emitters are required to pay for connection to the trunk pipeline, they are only charged transport fees at marginal cost. Since the cost of CO_2 compression for onshore transport is already included in the emitters' operational cost, the marginal transport cost is assumed to only be linked with the electricity cost for the booster compressor for offshore delivery – a cost of just £0.3/t. Although investment in additional compressors might be required in practice, the simplifying assumptions used here permit the evaluation of the maximum cost reduction that can be expected from the availability of pre-existing T&S infrastructure – in other words, this is the best-case scenario for third party access. As for the storage costs, it is assumed that a new site must be developed for the occasion and all corresponding costs are fully recharged to the industrial cluster. These costs are taken to be identical to those experienced in Model 1, since it is also assumed here that the T&S infrastructure is owned and operated by government, but it is possible that the development cost of additional storage sites that are adjacent to the ones used by the existing CCS project would be cheaper than is estimated here.

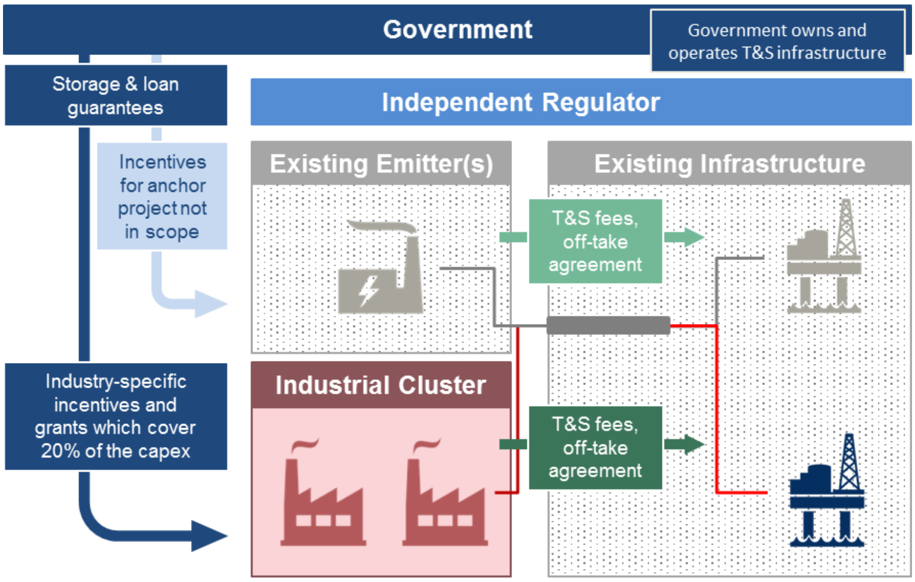

Figure 3 Third party access to CCS anchor project

Model 4: CO_2-EOR

In Model 4, see Figure 4, it is assumed that CO_2-enhanced oil recovery (EOR) operations in the industrial cluster's region can cost-effectively be connected through a new pipeline network to the industrial emitters. Crucially, this implies that the alternative CO_2 sources that are available to the EOR operator would cost more to them than purchasing the CO_2 at £20/t (minus the cost of transport, which is passed on to the emitters while allowing for a hurdle rate of 12% as in Model 2). Perhaps even more importantly, there is an underlying assumption that the market price of oil[6] is suitably high and extraction costs are suitably low to justify CO_2-EOR in the region, and that it is expected the oil price will remain high for the duration of the project. Finally, it is worth reflecting on the diverging incentives naturally occurring to the two parties: the emitters aim to store as much CO_2 as possible, whereas the EOR operator prefers to minimise the volume of CO_2 stored, since this represents an operational cost. Regulatory intervention might be required to align the EOR operator's tax incentives to ensure maximum carbon abatement, but any incentive or regulation around this would need consider factors beyond purpose of this study.

[6] If a different hydrocarbon is extracted, one could instead talk about enhanced hydrocarbon recovery.

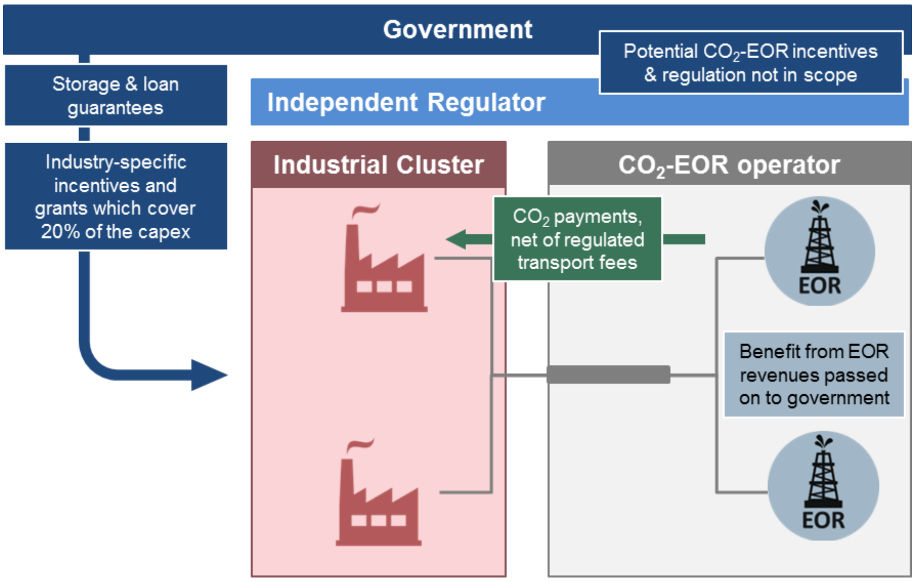

Figure 4 CO_2-EOR

The CO_2-EOR operator takes full responsibility for the construction and operation of the T&S infrastructure; no grants are provided towards the T&S capex, and the oversizing requirements set by the independent regulator are the same as in the previous models[7] – an assumption which is made for the sole purpose of allowing a transparent comparison between the four models. Although an assumption is made that all the captured CO_2 volumes are used for EOR, in practice this would greatly expose the EOR operator to the volume risk if the industrial cluster is their primary source of CO_2 – this is because any change in the industrial CO_2 flowrates might conflict with the EOR operator's commercial requirements.

Comparison of the four models

A detailed financial model was developed to compute cash flows and other relevant parameters for all project stakeholders, including government, for an illustrative cluster in that is assumed to be operational between 2025 and 2040. In addition to the operational subsidy, which is assumed to be complementary to the carbon cost avoidance, government is expected to de-risk the investment by providing:

- Storage guarantees to industrial emitters and volume guarantees to the private T&S operator, i.e. a guaranteed minimum payment from government to mitigate major incidents that might otherwise prevent investability[8];
- Loan guarantees that result in payments to the creditors if the ratio of the net operational income from CCS-related cash flows to the debt service – known as the Debt-Service Coverage Ratio (DSCR) – is below 1.0[9];

[7] Similarly, the profits allowed for the investment in the transport assets are the same as in Model 2.

[8] These guarantees would partially protect the shareholder margins in cases that cannot adequately be recharged through offtake agreements, such as in the event of counterparty default.

[9] A DSCR that is lower than 1.0 would imply that the debt cannot be serviced. Based on feedback from potential investors, the minimum DSCR that would be expected for regulated cash flows is around 1.15, whereas a value of 1.4-1.5 might be required for unregulated cash flows. The minimum emitters' DSCR in the four models is 1.3.

- Capital grants which, though not essential for achieving investability, decrease the project costs, reduce the need for third party financing and might in some cases be necessary to allow emitters to finance the project from their balance sheet. They are also needed for front-end engineering design (FEED) studies and storage appraisals.

Additionally, comprehensive off-take agreements are employed to protect each party from counterparty underperformance (this includes construction delays as well as operational issue – e.g. T&S unavailability leading to unexpected emissions). The importance of using a consistent template for these contracts cannot be understated: without this consistency, future third party access may be unnecessarily hindered. Keeping in mind that the first-of-a-kind project on which this study focusses should be developed with a view to encourage future third party access; all models assume that the pipeline network is oversized.

Figure 5 illustrates the key results from the comparison of the four business models[10]. While the capital and operational expenditure for CO_2 capture and compression are the same in all models, by influencing the cost of T&S greater cost effectiveness can be achieved. CO_2-EOR and existing CO_2 infrastructure may improve the project economics if these opportunities are available. For kick-starting a new industrial CCS cluster, establishing a public T&S Company is more cost-effective than asking a private operator to construct and operate the infrastructure. However, it should be noted that the overall cost variation between all models is small compared to the absolute value because T&S costs do not account for more than 30% of the overall cost, although this value could be much higher for smaller ICCS clusters.

Based on the results below for an illustrative cluster, government is expected to subsidise 57%-75% of the cost of abatement; however, if the carbon price required to meet the UK's 2050 target[11] is used in the modelling – based on Model 2 – the corresponding cost to government drops by 80% to £11/t, whereas it increases by 40% to £75/t if CO_2 emissions are not charged. Since subsidies pay for a large part of the cost of abatement in the business models assessed, it is in government's interest to decrease the total bill: one of the levers available to them is to decrease the cost of capital by providing grants. Higher shareholder equity contributions and high interest rate loans increase the cost of capital, whereas grants lower it as no return is expected on them

[10] Levelised costs and revenues use a social discount rate of 4%.

[11] UCL-TIAM modelling presented in Committee on Climate Change, 2012, The 2050 Target.

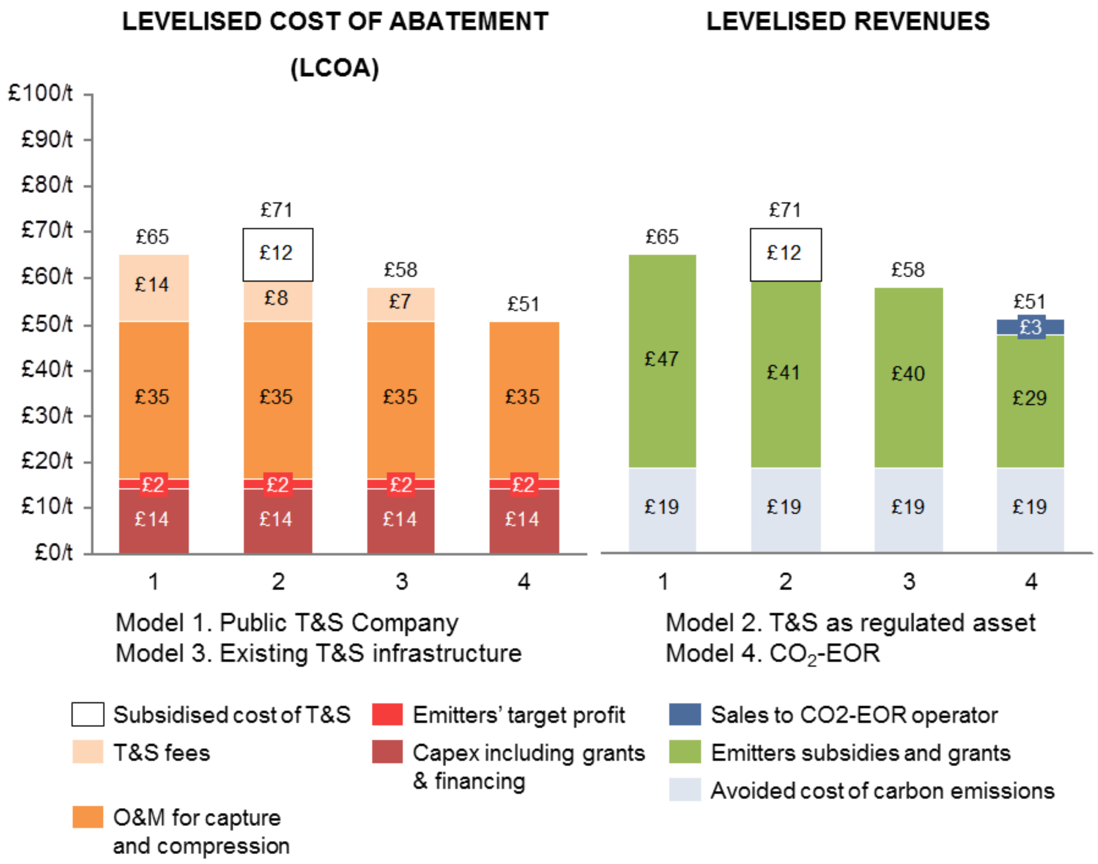

Figure 5 Comparison of levelised costs and revenues of abatement

Regional differences and applicability of business models

The business models presented in this study were reviewed by government representatives and other CCS stakeholders to confirm the applicability of the suggested features in the different regions. Based on their feedback as well as on publicly available information, it was determined that while not all models are viable everywhere, at least one of them is feasible in each country and, see Table 2, specific features of the various models can be combined to create the most relevant models for each region.

Table 2 Regional applicability of the four ICCS business models

Region	Applicability of the business models investigated
North America (USA and Canada)	• It is reasonable to expect that future industrial clusters will join the extensive CO_2 transport network (anchor CCS project). • In the short term, the captured CO_2 is likely to be used for EOR. • This suggests that a combination of Models 3 and 4 is likely to be viable in North America depending on the region. • In the US, it is possible that future operational subsidies will be provided in the form of tax incentives, for instance based on the Section 45Q tax credit.

Europe (specifically UK, Norway and the Netherlands)	• Model 1 broadly resembles the approach that is currently being pursued in Norway, and is not too dissimilar from what was recommended to the UK Government by the Oxburgh report[12]. • However, Model 2 might be preferable for national governments not intending to be directly involved in the T&S business. • Whereas the applicability of a CO_2-EOR model might be restricted given the limited availability of affordable CO_2-EOR operations, Model 3 could easily become relevant after the first CCS projects are developed. • Most of the European governments may choose to utilise a subsidy mechanism similar to the Contract for Difference, in which a minimum CO_2 price is agreed with emitters and the difference between the agreed price and EU ETS carbon price is paid.
China	• No specific incentives for CCS are available at present, but the Chinese central government is aiming at time of writing to establish a national cap and trade system, which might prove to be the first step towards the establishment of further incentives for CCS. • Several national companies exist in sectors such as oil and gas, utilities and infrastructure. However, the decentralisation of decision making around the CCS sector to provincial authorities means that it is not possible to determine whether Model 1 or 2 would be the preferred option in each province. • It is expected that a combination of CO_2-EOR-led (Model 4) and government-led (Model 1) options will be considered in China.
Australia	• CCS could be a way to reduce CO_2 emissions while addressing national energy security needs. • If CCS projects are developed in the power generation sector first, Model 3 is likely to become a candidate for future ICCS clusters. • Published literature suggests that government is more likely to take a regulatory role rather than investing in a public T&S company, hence Model 2 is more suitable than Model 1. • Although no specific incentives for CCS are available at present, options such as feed-in tariffs, CCS certificates or a Contract for Difference might be employed in the future.

Expert Review Comments

10 individuals from a variety of different organisations were invited to review the draft report, and 5 of them returned comments. Overall, the majority of reviewers commented that the report generally was strong and timely, with the main topics identified and clarified and the related risks and options correctly mentioned. However, there have also been several requests for clarification and most of them have been addressed by the contractor in the final version of the report. This includes the clarification that the study does not address the business model for the upstream parts/processes of ICCS clusters, as this was outside the scope for this work. Further, the authors added several clarifications regarding the assumptions for the models and more clear definitions of the financial terms used. More text was added highlighting the importance of a level playing field for ICCS in order to address the issue of carbon leakage and the potential effect of unabated emissions, especially from CO_2-EOR's incrementally produced oil, on LCOA and LR. It is assumed in the calculations of LCOA and LR that carbon leakage is addressed. At request of a reviewer, the authors also added more references to earlier work in the methodology section and appendix, however, at other points throughout the report decided not to include them individually, as there have been multiple inputs coming together, including stakeholder

[12] Oxburgh, 2016, Lowest Cost Decarbonisation for the UK: The Critical Role of CCS. Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary Advisory Group on Carbon Capture and Storage (CCS).

feedback. More details on gas storage have not been included, as this is outside the scope for this study. Questions regarding the illustrativeness of the examples used in this report can be alleviated by the fact that the data used has been verified by multiple stakeholder, so can be considered adequate. Finally, the question why 300km offshore storage was assumed can be answered with the decision to not provide a best case but more conservative estimation.

Conclusions

This study has highlighted that the industrial CCS sector is not yet commercially mature, and that private investment can occur only if four enablers are simultaneously addressed:

- The risk of carbon leakage is mitigated;
- Margin certainty is provided to the emitters via appropriate subsidies;
- The business cases for capture and infrastructure are decoupled;
- Government shares the key risks through guarantees to investors and project developers.

If any of the above is not addressed, ICCS projects may still be developed for demonstration purposes, but the underlying business cases cannot be fully commercial and are thus not replicable – a requirement to achieve large-scale deployment of ICCS. Although some governments might struggle to provide the extensive level of support required for the first commercial ICCS projects, this study reasoned that, without ICCS, governments might eventually have to rely on more expensive solutions to meet the 2050 decarbonisation targets. It was also argued that only by implementing CCS can local industrial jobs be retained and/or new industrial jobs be created in the long term, or else the escalation in manufacturing costs due to increasing carbon price may lead to disruption of the major industrial markets.

Four business models were presented which enable the industrial emitters to maintain their competitiveness, and through quantitative assessment of three key project risks it was demonstrated that guarantees on loans, storage, and CO_2 volumes are a prerequisite for achieving investability. The cost that government is expected to pay over the lifetime of the illustrative ICCS cluster in Europe was found to range between £29-£53 per tonne of CO_2 abated, but it was shown that two important levers can reduce greatly reduce this cost: upwards regulation of the price of CO_2, and the provision of grants.

In conclusion, it was determined that at least one model is relevant in each of the regions focus of this study (North America, Europe, China, and Australia), a finding that was validated through interviews with government officials and CCS stakeholders.

Recommendations

Based on the conclusions it is suggested that future work should/could focus on:

1) Assessment of alternative strategies to address carbon leakage: A number of alternative measures to mitigate the carbon leakage risk were discussed including mechanisms to create demand for green industrial products. Further assessment is required to examine these alternative strategies in more detail including the level of procurement/regulation required to justify investment in CCS and whether these alternative measures could mitigate some of the ICCS risks and challenges described in this report.

2) Strengthening the case for industrial CCS for individual states: Similar to all the other decarbonisation technologies, industrial CCS projects will require government support and subsidies. It is therefore vital to strengthen the case for industrial CCS for each region/state and justify any potential public support. This potential further work could assess the following:
    a. reviewing the alternative deep-decarbonisation options for all major carbon-intensive products;
    b. focussing on the value of CCS and carrying out a cost-benefit analysis for industrial CCS considering wider benefits of CCS including jobs and environmental benefits;
    c. defining the right units/metrics for comparing decarbonisation initiatives across sectors;
    d. defining further demonstration (technical and commercial) and education requirements to increase confidence of private investors and public; and
    e. consideration of potential international collaboration (both inter-governmental and public/private) to deliver archetypal/benchmark CCS projects on budget and on time.

3) Development of regional industrial CCS strategies: Further work is required to develop regional or national industrial CCS strategies including appropriate subsidy and risk-sharing mechanisms considering the key enablers and business models described in this report.

elementenergy

Enabling the deployment of industrial CCS clusters

Final Report

for

ieaghg

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Element Energy is a leading low carbon energy consultancy working in a range of sectors including carbon capture and storage, low carbon transport, low carbon buildings, renewable power generation, energy networks, and energy storage. Element Energy works with a broad range of private and public sector clients to address challenges across the low carbon energy sector, and provides insight and analysis across all parts of the CCS chain.

Element Energy was supported by two financing experts:

- Richard Simon-Lewis, who led the financing, structuring, and fund/capital raising for the White Rose CCS project – a commercial-scale full-chain CCS project, established as part of the UK Government's £1bn CCS Commercialisation Programme; and
- Angela Whelan (Chief Executive, Ecofin Research Foundation), who helped establish the UK CCS Commercial Development Group, which she led for the last three years.

Disclaimer

While the authors consider that the data and opinions contained in this report are sound, all parties must rely upon their own skill and judgement when using it. The authors do not make any representation or warranty, expressed or implied, as to the accuracy or completeness of the report. There is considerable uncertainty around the development of industrial carbon capture and the available data are extremely limited. The authors assume no liability for any loss or damage arising from decisions made on the basis of this report. The views and judgements expressed here are the opinions of the authors and do not reflect those of IEAGHG or any of the stakeholders consulted during the course of this project.

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EXECUTIVE SUMMARY

CCS is the key tool for rapid decarbonisation of industry

As countries look to decarbonise their economies in ways which are compatible with the Paris Agreement, one priority is to find solutions to curb emissions from industrial sources, which account for over one-quarter of global CO_2 emissions. Since the demand for industrial products is expected to at least double by 2050[1], such solutions also need to be quickly scalable. In this context, the potential of industrial Carbon Capture and Storage (ICCS) to rapidly achieve deep industrial decarbonisation while at the same time meeting global demand represents a unique value proposition.

Nearly all existing CCS projects have largely relied on government support. To meet 2050 decarbonisation targets, the scale of required investment in CCS to support the decarbonisation of industry suggests that significant amounts of private capital will need to be mobilised alongside government support. It is therefore vital to identify what conditions must be met to enable private investment in ICCS.

Projects where the CO_2 transport and storage infrastructure is shared by multiple neighbouring industrial emitters, as clusters, benefit from substantial economies of scale and are expected to represent the predominant format for commercial projects; however, it is not clear which business models might be feasible to enable the deployment of industrial CCS clusters in different regions.

Element Energy was commissioned by IEAGHG to examine the economic and commercial arrangements needed to enable the global deployment of industrial CCS clusters. Over a period of eight months, with significant input from stakeholders from industry, government and the investment community, the project has identified the key enablers to unlock private investment in ICCS and developed four business models, which are expected to work in various regions around the world including North America, Europe, Australia and China.

Four enablers to unlock private investment in industrial CCS

By exploring the business environment surrounding ICCS, this report points to four enablers that must be simultaneously addressed to enable the creation of investable business models.

1) Addressing carbon leakage

Before carbon pricing can lead to investment in CCS, industries must be able to pass emission charges on to consumers, which they are unable to do if trading in international markets. This is because at the carbon price levels required to independently stimulate investment in ICCS, asymmetrical regulation poses a large competitive disadvantage that might induce relocation of production activities to less regulated countries – a phenomenon known as carbon leakage. International coordination on the price of CO_2 may well be the best option to address carbon leakage but, due to difficulties in its implementation, other options to address geographical inconsistencies in regulation must be considered.

To date, trade-intensive sectors have been either exempted from carbon pricing schemes or provided with free allowances to emit. While the first solution at once negates the financial benefits arising from investment in decarbonisation measure, the second may still provide the right motivation so long as the allowances can be traded for a high enough price. However, both options fail to result in an increased cost to polluters and their customers, and therefore externalise the cost of decarbonisation, in contrast with the original policy purpose. Other options to address carbon leakage include national or regional border-adjustment measures as well as incentives to increase demand for green products, e.g. via public procurement and product standards. If these measures are implemented and a high enough carbon price is achieved, the

[1] *IEA, 2011, Technology Roadmap: Carbon Capture and Storage in Industrial Applications*.

avoided emission charges could be an important financial driver for industrial CCS: this represents the first step towards the creation of business models that do not exclusively rely on *ad hoc* subsidies for ICCS.

2) Margin certainty through subsidies for industrial emitters

Even if the risk of carbon leakage is addressed in a suitable manner, policy-induced carbon charges are expected to remain too low to provide a price signal that is sufficient to trigger investment in ICCS: for the illustrative industrial cluster assessed in this study a charge of £75-£110 per tonne of CO_2 was found to be required at a minimum. Interviews with potential investors revealed that even if these requirements were to be exceeded, the investability of business models that are overly reliant on the price of carbon is undermined by political uncertainty, and for this reason additional public subsidies must be provided. It is expected that any subsidy provided should insulate the project revenues from volatility in the price of CO_2, as well as from the increase in the price of fuel and electricity, since these add up to a sizeable portion of the cost of capture. As an alternative to direct subsidies, we find "Green Procurement" and product standards amongst the measures which may be able to trigger investment in ICCS, although the scope of these measures would need to be large enough to create a market with the right profit margins and able to offer attractive growth opportunities for prospective investors.

3) Decoupling the business chain

Fundamental differences between the capture, transport, and storage businesses mean that no single private company may be willing to manage a full-chain project involving multiple emitters independently. Delinked part-chain projects allow all parties to focus on their core strengths and thus achieve maximum efficiency. Through extensive literature review and stakeholder engagement, this study identified four different options for transport and storage infrastructure. Each of the business models discussed in this study investigates one of the below options.

- **Government-owned transport and storage infrastructure**: The government establishes a public transport and storage (T&S) company to construct the infrastructure and lead the cluster project towards operational stability. At a later stage, the T&S Company could be listed/spun-off to reduce the public stakes in the project. A Government could consider establishing two separate companies for transport and storage from the outset, which may be easier to privatise separately in view of their different risk profiles.

- **Regulated infrastructure**: A regulated infrastructure model (such as Regulated Asset Base) is used to enable fully privatised delivery of the project. In this option, an independent market regulator would first be set up, likely with government funding, and given responsibility for drafting the terms under which infrastructure investors would be guaranteed the agreed rate of return, and for regulating the fees and conditions for access to the infrastructure.

- **Existing infrastructure**: The simplest option presented is the case where the industrial cluster can latch on to existing infrastructure (which may either be government owned or regulated). This might be possible for future CCS projects in areas where a CO_2 pipeline network with spare capacity already exists. This is similar to what the Alberta Carbon Trunk Line will enable, albeit with a specific focus on enhanced oil recovery; alternatively, industrial emitters could join "anchor" CCS projects, e.g. on a power plant, developed in advance of the ICCS project with oversized infrastructure or where CO_2 shipping is possible.

- **CO_2-EOR**: Only an option if active oil fields exist in the cluster region, this is the most common option for currently operating projects, but it is not expected to provide a wide-scale solution for ICCS globally. This is because the capacity and location of suitable oil fields do not always match the need for CO_2 storage, and even when they do, the oil fields will eventually become depleted and their economic viability as CO_2 storage might be compromised if the price of fossil fuels decreases excessively. It should also be noted that this may not be a long-term solution considering the long-term decarbonisation ambition.

4) Public-private risk sharing

Regardless of what commercial agreement is achieved for the construction and operation of the T&S infrastructure, several show-stopper risks, which would impede financial close, can only be mitigated through government intervention. Some of the options for government to de-risk the project are illustrated in the table below.

Table 1: Illustrative show-stopper risks and required government mitigations.

Illustrative show-stopper risks	Suitable government mitigation
• Uncapped liability from CO_2 leakage long after storage site decommissioning	• **Back-stops** or caps on the long-term storage liability to enable a layered insurance approach, where the storage operator can get insurance coverage up to the capped amount.
• Emitter default • Volume risk	• **Volume guarantees** reduce the loss experienced by the T&S operator.
• Storage failure after completion of development phase	• **Storage guarantees** to provide minimum payments to emitters in replacement of subsidy and carbon costs.
• Risk of default on loan repayment makes project not bankable	• **Loan guarantees ensure** project bankability despite the low creditworthiness of some of the project parties.
• Storage failure after completion of development phase (risk for the T&S Company) • Emitter unable to reach FID due limited capital availability	• **Grants** to cover the cost of storage development, potentially also of a back-up storage. • **Grants** to the emitters decrease the need for external financing and the expected shareholder equity contribution.

Private finance can be brought in if the government helps in mitigating the above risks, often referred to as show-stoppers. In addition to these, many other risks affect the various parties of a part-chain project, and the cost of capital will be reduced by additional risk sharing with the public sector. This is not to say that no risk can be fully managed by the private sector participants: as an example, offtake agreements including *take-or-pay* and/or *ship-or-pay* clauses are expected to regulate the transfer of CO_2 across the network (from capture, through transport to injection and storage). Considering that government is ultimately paying for a large part of the project through subsidies, it is in its interest to achieve value for money, which can be achieved by further reducing the privately held risks.

Some of the show-stopper risks were assessed quantitatively to understand the impact of disruptive events on the project economics and on the cost to government. The results highlight that the unmitigated consequences of these events are such that the affected parties may be forced to declare bankruptcy – an eventuality that would in turn cause much greater losses to all remaining parties and much lower value for money to government. Recognising that excessive government guarantees may incentivise the wrong behaviours, this report argues that the right balance must be struck via negotiations between government and the project parties.

The case for government intervention

Subsidies to industrial CCS are a cost-effective decarbonisation tool

In this study, we draw attention to the fact that, for several industrial sectors, "*it may not be possible to decarbonise [them] without CCS*" [2], and with a worked case study we also point out that subsidies in support of ICCS may in fact be cost-effective for society, when compared to subsidies to other low-carbon technologies such as offshore wind. If policy makers valued the cost of carbon emissions consistently with the cost of meeting the 2050 goals, rather than on the prevailing carbon market price, it could be seen that, without ICCS, governments might need to

[2] *IEA, 2013, Global Action to Advance Carbon Capture and Storage: A Focus on Industrial Applications. Annex to Tracking Clean Energy Progress 2013.*

support more expensive measures in other sectors to compensate for the lower reduction in industrial emissions. However, the inability of current pricing mechanisms to incorporate the full cost of carbon represents a market failure that governments committed to the Paris Agreement should address. To do so, they should preferably implement policies to strengthen the carbon price, or alternatively they should consider providing subsidies for ICCS and other cost-effective projects. Unless one of these options is pursued, governments may be faced with a higher bill for decarbonisation, or they might fail to meet the decarbonisation targets.

CCS can stimulate local industrial activity and foster inward investment

Among the multiple decarbonisation options that a government could incentivise, ICCS offers a unique value proposition: by capping carbon emission charges, and assuming that the CO_2 leakage risk is addressed, CCS directly improves the competitive position of industries that implement it, especially under an increasing carbon price. Thus, ICCS acts as a protection on the local jobs that may be otherwise displaced if industries go out of business, due to increasing financial pressure from escalating carbon costs.

Key findings from analysis of the four business models

Table 2 shows the simplified diagrams and the key features of the four business models selected with the intention of exploring the different value propositions of the four options for decoupling the business chain. A detailed financial model was developed to compute cash flows and other relevant parameters for all project stakeholders, including government, for an illustrative cluster in that is assumed to be operational between 2025 and 2040.

In addition to the **operational subsidy**, which is assumed to be complementary to the carbon cost avoidance, government is expected to de-risk the investment by providing: **storage guarantees** to industrial emitters and **volume guarantees** to the private T&S operator (i.e. a guaranteed minimum payment from government to mitigate major incidents that might otherwise prevent investability[3]); **loan guarantees** that result in payments to the creditors in case of default on loan repayment; and **capital grants** which, though not essential for achieving investability, decrease the project costs, reduce the need for third party financing and might in some cases be necessary to allow emitters to finance the project from their balance sheet. Capital grants are also needed for front-end engineering design studies and storage appraisal.

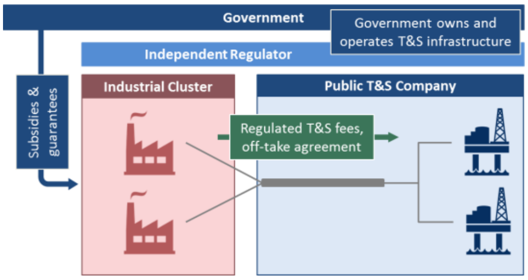
Additionally, comprehensive **offtake agreements** are employed to protect each party from counterparty underperformance (this includes construction delays as well as operational issue – e.g. T&S unavailability leading to unexpected emissions). The importance of using a **consistent template for these contracts** cannot be understated: without this consistency, future third party access may be unnecessarily hindered. Keeping in mind that the first-of-a-kind project on which this study focusses should be developed with a view to encourage future third-party access; all models assume that the pipeline network is oversized.

Figure 1 illustrates the key results from the comparison of the four business models[4]. While the capital and operational expenditure for CO_2 capture and compression are the same in all models, by influencing the cost of T&S greater cost effectiveness can be achieved. CO_2-EOR and existing CO_2 infrastructure may improve the project economics if these opportunities are available. For kick-starting a new industrial CCS cluster, establishing a public T&S Company is more cost-effective than asking a private operator to construct and operate the infrastructure. However, it should be noted that the overall cost variation between all models is small compared to the absolute value because T&S costs do not account for more than 30% of the overall cost, although this value could be much higher for smaller ICCS clusters.

[3] These guarantees would partially protect the shareholder margins in cases that cannot adequately be recharged through offtake agreements, such as in the event of counterparty default.
[4] Levelised costs and revenues use a social discount rate of 4%.

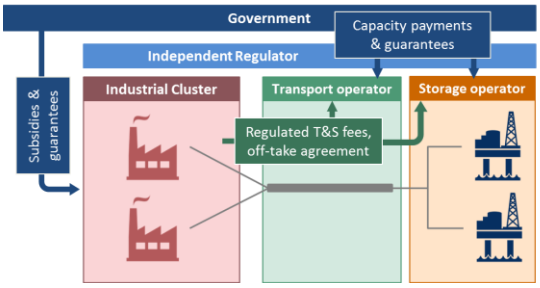
Table 2: Simplified diagrams and key features of the four business models.

Model 1: Public T&S Company



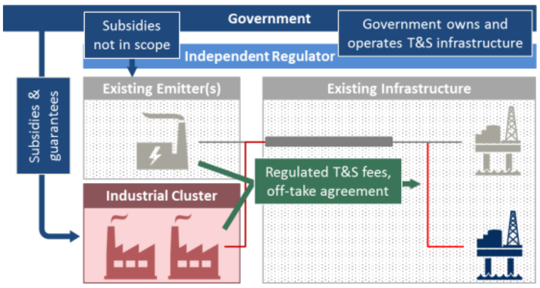
- Government fully funds T&S through a public T&S Company
- All T&S risks are held by the public T&S Company
- This results in the lowest possible cost of finance for T&S
- Least-cost option to develop new T&S infrastructure if politically acceptable

Model 2: T&S as regulated asset



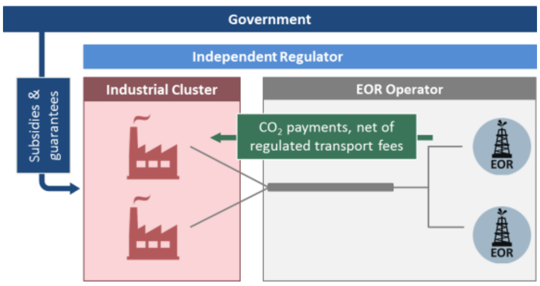
- The T&S infrastructure is operated through a regulated asset base model and allows higher returns for the T&S operator than in Model 1
- 50% of the T&S revenues originate from capacity payments, which act as a partial volume guarantee
- Assets regulation is likely to be a viable option in all region assessed in this study

Model 3: Third party access to existing CO_2 infrastructure



- Anchor CCS project absorbs all sunk costs, including that of oversizing the infrastructure
- Only marginal costs are recharged, including development of new storage site
- This model effectively simulates the best-case scenario for third party access
- Least cost solution for a project if the captured CO_2 is sent to dedicated permanent storage

Model 4: CO_2-EOR



- The entire volume of captured CO_2 is sold to an EOR operator at a price of £20 per tonne
- A regulatory framework and additional tax incentives might be needed to prevent the EOR operator from acting against the objectives of CCS by minimising the volume of injected CO_2
- CO_2-EOR related revenues reduce but do not eliminate the need for subsidies

Based on the results for an illustrative cluster, government is expected to subsidise 57%-75% of the cost of abatement; however, if the carbon price required to meet the UK's 2050 target[5] is used in the modelling – based on Model 2 – the corresponding cost to government drops by 80% to £11/t, whereas it increases by 40% to £75/t if CO_2 emissions are not charged. Since subsidies pay for a large part of the cost of abatement in the business models assessed, it is in government's interest to decrease the total bill: one of the levers available to them is to decrease the cost of capital by providing grants. Higher shareholder equity contributions and high interest rate loans increase the cost of capital, whereas grants lower it as no return is expected on them.

[5] UCL-TIAM modelling presented in *Committee on Climate Change, 2012, The 2050 Target.*

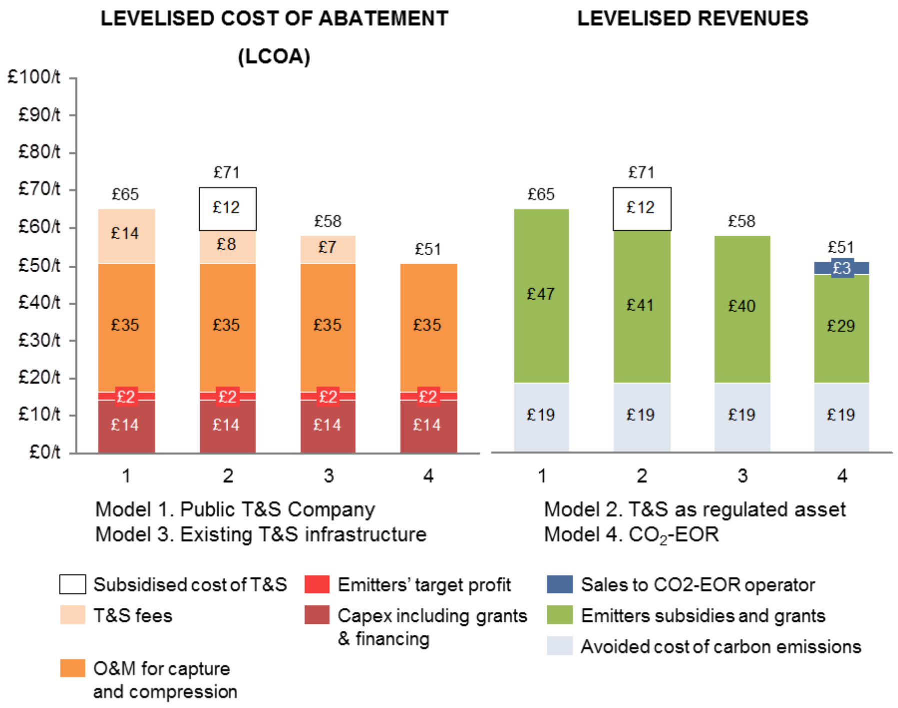


Figure 1: Breakdown of levelised costs and revenues "per tonne of CO_2 abated"

Business models can be adapted to suit national preferences

The business models presented in this study were reviewed by government representatives and other CCS stakeholders to confirm the applicability of the suggested features in the different regions. Based on their feedback as well as on publicly available information, it was determined that while not all models are viable everywhere, at least one of them is feasible in each country and, as is summarised in Table 3, specific features of the various models can be combined to create the most relevant models for each region.

Table 3: Regional applicability of the four business models

Region	Applicability of the business models investigated
North America (USA and Canada)	• It is reasonable to expect that, wherever possible, future industrial clusters may join the extensive CO_2 transport network and in the short term, the captured CO_2 is likely to be used for EOR. This suggests that a combination of Models 3 and 4 would be the preferred option in North America depending on the region. • In the US, it is possible that future operational subsidies will be provided in the form of tax incentives, for instance based on the Section 45Q tax credit.
Europe (specifically UK, Norway and the Netherlands)	• Model 1 broadly resembles the approach that is currently being pursued in Norway, and is not too dissimilar from what was recommended to the UK Government by the Oxburgh report[6]; however, Model 2 might be preferable for national governments not intending to be directly involved in the T&S business. • Whereas the applicability of a CO_2-EOR model might be restricted given the limited availability of affordable CO_2-EOR operations, Model 3 could easily become relevant after the first anchor CCS projects are developed. • Most of the European governments may choose to utilise a subsidy mechanism similar to the Contract for Difference, in which a minimum CO_2 price is agreed with emitters and the difference between the agreed price and EU ETS carbon price is paid.

[6] Oxburgh, 2016, *Lowest Cost Decarbonisation for the UK: The Critical Role of CCS. Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary Advisory Group on Carbon Capture and Storage* (CCS).

China	•	No specific incentives for CCS are available at present, but the Chinese central government is aiming at time of writing to establish a national cap and trade system, which might prove to be the first step towards the establishment of further incentives for CCS.
	•	Several national companies exist in sectors such as oil and gas, utilities and infrastructure. However, the decentralisation of decision making around the CCS sector to provincial authorities means that it is not possible to determine whether Model 1 or 2 would be the preferred option in each province.
	•	It is expected that a combination of CO_2-EOR-led (Model 4) and government-led (Model 1) options will be considered in China.
Australia	•	CCS could be a way to reduce CO_2 emissions while addressing national energy security needs.
	•	If CCS projects are developed in the power generation sector first, Model 3 is likely to become a candidate for future ICCS clusters.
	•	Published literature suggests that government is more likely to take a regulatory role rather than investing in a public T&S Company, hence Model 2 is more suitable than Model 1.
	•	Although no specific incentives for CCS are available at present, options such as feed-in tariffs, CCS certificates or a Contract for Difference could become relevant in the future.

Recommendations for further work

1) **Assessment of alternative strategies to address carbon leakage:** A number of alternative measures to mitigate the carbon leakage risk were discussed including mechanisms to create demand for green industrial products. Further assessment is required to examine these alternative strategies in more detail including the level of procurement/regulation required to justify investment in CCS and whether these alternative measures could mitigate some of the ICCS risks and challenges described in this report.

2) **Strengthening the case for industrial CCS for individual states**: Similar to all the other decarbonisation technologies, industrial CCS projects will require government support and subsidies. It is therefore vital to strengthen the case for industrial CCS for each region/state and justify any potential public support. This potential further work could assess the following:
    - **reviewing the alternative deep-decarbonisation options** for all major carbon-intensive products, also considering possible low-carbon alternative products and their potential to substitute carbon-intensive products in global and national markets;
    - **focussing on the value of CCS and carrying out a cost-benefit analysis for industrial CCS** considering wider benefits of CCS including jobs and environmental benefits using existing economic appraisal CBA guidelines of government;
    - **defining the right units/metrics** for comparing decarbonisation initiatives across sectors, and thus consistently explore their true cost-effectiveness (e.g. incentives for the power sector based on £/tCO_2 rather than £/MWh might better demonstrate the cost-effectiveness of ICCS projects);
    - **defining further demonstration** (technical and commercial) **and education requirements** to increase confidence of private investors and public (for instance, further benchmark CCS projects might be needed in iron&steel, chemicals, oil refining and cements sectors to increase investor and public confidence); and
    - **consideration of potential international collaboration** (both inter-governmental and public/private) to deliver archetypal/benchmark CCS projects on budget and on time.

3) **Development of regional industrial CCS strategies**: This study identified the key enablers for the deployment of industrial CCS clusters globally and high-level business models that are expected to be feasible in different regions. Further work is required to develop regional or national industrial CCS strategies including appropriate subsidy and risk-sharing mechanisms considering the key enablers and business models described in this report.

Contents

1. INTRODUCTION

1.1 Context and project objectives

Industrial processes are responsible for over one-quarter of global CO_2 emissions, and their absolute contribution is expected to nearly double by 2050[7]. If the goals set in November 2015 with the Paris Agreement are to be achieved, drastic reduction of industrial emissions is therefore a must, rather than a choice. Several technology roadmaps have highlighted that, without CCS, industrial decarbonisation in line with these goals may not be possible[8]: it is in this context that the unique value proposition of industrial Carbon Capture and Storage (ICCS) becomes clear, and for this reason IEA forecasts that CCS could reduce annual industrial CO_2 emissions by 4 Gt in 2050. IEA also forecasts that between 25% and 40% of the global production of steel, cement and chemicals must be equipped with CCS by 2050[7]; however, this is in stark contrast with the present situation: only one large-scale CCS project on iron and steel production is currently operational, but none have been developed on cement manufacturing, as illustrated in Figure 2 (a full list of projects can be found in Appendix A.1). Similarly, IEA estimates that around 120 $GtCO_2$ would need to be stored until 2050 globally that would require significant level of storage exploration and appraisal activities over the next decades.

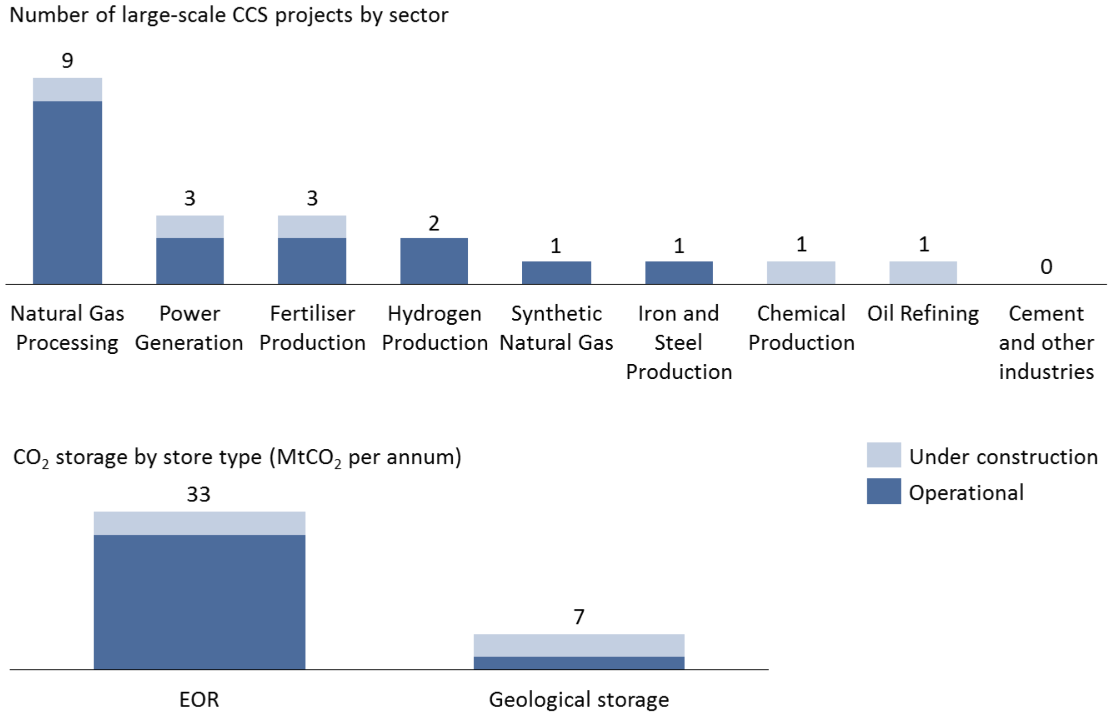


Figure 2: Large scale CCS projects are needed in each industrial sector to complete the demonstration phase, but at present only a few are operational or under construction.

Based on this, it is argued that two preliminary phases, characterised by high but progressively decreasing government intervention, must be completed before large scale deployment can happen:

- The **demonstration and scale-up phase**, still ongoing, during which great focus is expected on projects that demonstrate the technical and cost performance of full-chain projects in each industrial sector. This phase requires substantial investment in R&D,

[7] *IEA, 2011, Technology Roadmap: Carbon Capture and Storage in Industrial Applications*.
[8] See for instance the *Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050* published in 2015 by the UK Department for Business, Innovation & Skills and the Department of Energy & Climate Change.

storage exploration/appraisal and the creation of flagship projects delivered on-time and on-budget, the learnings of which should be shared to inform and educate project developers, governments, and investors. Projects developed in this phase should begin to consider the business models and market mechanisms that will later be necessary, but the absence of any commercial justification demands a very high degree of government involvement.

- Next, the commercial maturity of CCS will need to be established in each industrial sector through the delivery of multiple successful projects based on **investable business models** and repeatable contracts that investors trust and understand. This phase would stimulate private investors' participation – fundamental in attaining the growth trajectory set out by IEA – and gradually reduce the level of government support. Although a sufficiently high carbon price may eventually provide the right financial motivation for investment in ICCS, government intervention will still be required in the first part of this phase to guarantee the project revenues and to mitigate some of the intrinsic risks that necessarily affect any new CCS cluster project.

When the above phases are complete and CCS infrastructure is available all regions, **large scale deployment** is then expected to be driven primarily by market mechanisms.

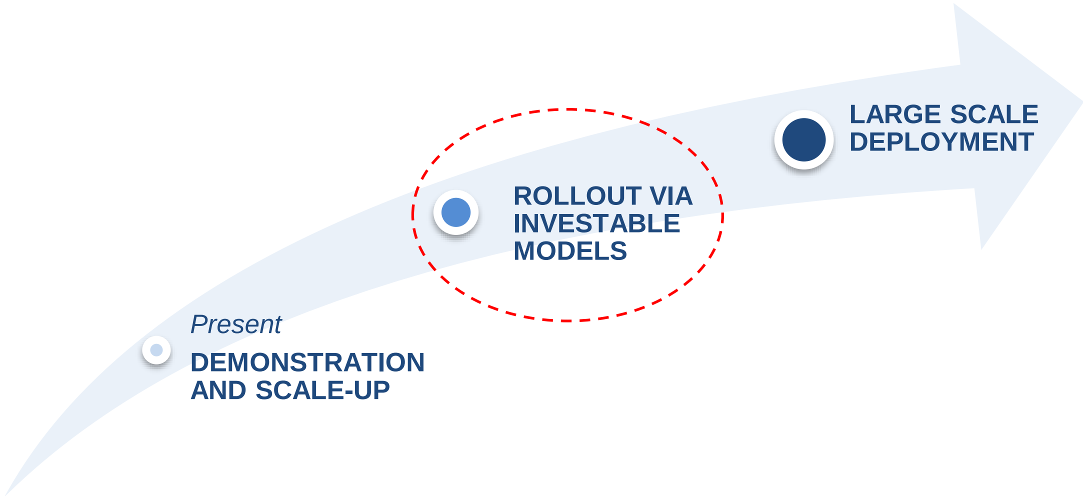


Figure 3: This study focusses on the investable business models for ICCS that are required to bridge the gap between the current demonstration phase and future large scale deployment.

1.2 Project scope and methodology

Over a period of eight months, with significant input from stakeholders from industry, government, and the investment community (see Acknowledgments list on the inside cover) and drawing from the extensive literature published on the subject (see References in the Appendix), the project has identified the key enablers to unlock private investment in ICCS. Although ICCS can be delivered in point-to-point projects, with single emitters linking up with newly developed or pre-existing infrastructure, projects where the CO_2 transport and storage infrastructure is shared by multiple neighbouring industrial emitters – also known as industrial clusters[9] – benefit from substantial economies of scale and are expected to represent the predominant format for commercial projects. This is especially so, since the infrastructure costs only marginally depend on the volumes of CO_2 transported and stored[10]. Additionally, by combining multiple emission

[9] The Global CCS Institute defines industrial clusters as "a geographic concentration of interconnected businesses, suppliers, and associated institutions in a particular field […] For CCS, the idea of clusters takes advantage of the fact that around the world, many emissions-intensive facilities (both industrial and power) are located in tight geographical clusters", from GCCSI, 2016, *Understanding Industrial CCS Hubs and Clusters.*
[10] For instance, Pale Blue Dot, 2015, *Industrial CCS on Teesside – The Business Case* found that, for the Teesside industrial cluster, "trebling the infrastructure capacity only requires an additional 8% of support".

sources, cluster projects decrease the reliance of the transport and storage operator(s) on each of the individual emitters, thus decreasing the counterparty risk, and can also provide volumes of CO_2 that – for these reasons, cluster projects are expected to represent the predominant format for commercial projects.

With reference to the preliminary assessment of the development status of ICCS presented above, this study focusses on the second of the phases shown in Figure 3, and aims to shed light on how investable business models can help to bridge the gap between the current demonstration phase and future large-scale deployment. Towards this aim, four business models, expected to work in various regions around the world including North America, Europe, Australia and China, were developed to evaluate the economics of illustrative projects developed in the early stages of the second phase, the investability of which will be shown to be closely interlinked with the available level of government support.

Report structure

The report is structured as follows:

- **Chapter 2** discusses four high level enablers that must be simultaneously addressed to unlock substantial amounts of private capital, a step required for the large-scale deployment of ICCS. As part of this, required government support measures are set out and, with the assumption that these will be made available during the rollout phase, these are assumed to be part of all business models developed.
- **Chapter 3** presents the main reasons for governments to provide support in addressing the challenges introduced in the previous chapter. Although this study does not provide individual governments with specific policy recommendations, no discussion around the industrial applications of CCS can be complete without a reflection on the perspective of government, often asked to support the projects.
- **Chapter 4** presents four business models for an illustrative cluster designed to include a variety of industrial sectors and plant sizes. The models developed allow industrial emitters with CCS to be competitive in their markets under stable regulatory conditions. The results from detailed financial modelling are presented, including the breakdown of levelised costs and revenues as well as cash flows for all project stakeholders (including government). In conclusion of the chapter, quantitative assessment of three project risks sheds insight on the implications of the guarantees that government is expected to provide in support of all models
- **Chapter 5** offers a comparative discussion of the four models introduced in the previous chapter and, after reviewing some of the main levers available to government to improve the project economics, assesses the viability of the key features of the four models in the aforementioned regions.
- **Chapter 6** provides a summary of the key findings from this study and puts forward recommendations for further work.

2. ENABLERS TO UNLOCK PRIVATE INVESTMENT

2.1 Addressing carbon leakage

Around 40 countries already put a price on carbon, either through a tax or via an Emissions Trading System (ETS), and up to 60 more are planning or considering either instrument[11]. This is an encouraging testimony to the growing awareness that action to combat climate change is urgently required, and that putting a price on carbon emissions can incentivise the uptake of many decarbonisation measures.

Carbon leakage undermines industrial decarbonisation

In industry, a high carbon price would provide a strong financial reason for reducing emissions through investment in the most appropriate decarbonisation measures. ICCS is often the only solution capable of achieving the deep reductions needed to meet the 2050 target. However, unless there is a way for industries that operate in international markets to pass a significant part of the emission charges on to consumers, asymmetrical carbon pricing will result in a competitive disadvantage that may encourage cross-border relocation – a phenomenon known as **carbon leakage**. If industrial activities relocated in regions where primary energy has a higher carbon footprint, there would be a global increase in emissions, an eventuality that, combined with the prospect of industrial jobs losses in areas with stronger regulation, has meant that trade-intensive sectors are generally exempted from bearing the full cost of their emissions. This has been achieved either via direct provision of “free allowances” to emitters operating in cap-and-trade programs such as the EU ETS and Ontario’s equivalent, or by excluding them from national carbon pricing schemes altogether, as is the case for the Norwegian carbon tax.

It is not the aim of this study to review the level of carbon leakage risk for the different industrial sectors, but it is assumed that, at the levels of carbon pricing required to trigger investment in ICCS, carbon leakage will present a substantial challenge to industrial decarbonisation unless it is addressed effectively.

Alternative options to address carbon leakage

As it was mentioned above, policies to address carbon leakage must consider the trade intensity of affected sectors, with trade-intensive sectors being exposed to greater competition from less regulated regions. While the allocation of free allowances addresses this issue, by preventing any increase in the sales price of carbon intensive products, it fails to fully internalise the carbon externality and to accordingly influence consumer demand and private sector investment. Thus, lower-carbon products that may be competitive at a higher sales price will not be able to penetrate existing markets for a longer period, thus delaying industrial decarbonisation. Alternative options to address carbon leakage in a way that fully levels the playing field for international markets while internalising the carbon externality would require one of the following options:

- International coordination on carbon price, which might not be feasible or realistic in the near-term;
- National or regional border-adjustment measures[12];
- Incentives or public procurement/regulation to create demand for green products;

If these measures are implemented, the avoidance of emission charges can become an important driver to enable private investment in ICCS

[11] *World Bank, 2016, State and Trends of Carbon Pricing*.
[12] Such measures were proposed to the European Parliament to address carbon leakage for several industries, most noticeably cement. The European Parliament rejected this measure in February 2017.

2.2 Margin certainty through subsidies for industrial emitters

Under the assumption that the risk of carbon leakage is addressed in a way that does not exempt carbon intensive industries from carbon pricing, decarbonisation measures such as ICCS will be incentivised. By reducing the volume of CO_2 emissions released to the atmosphere, the cost of the unused emission allowances can be avoided (if emitters are charged for their emissions either through a tax or otherwise) or monetised (if they receive free allowances that can be sold if unused). For simplicity, we shall refer to this source of revenue as **carbon cost avoidance**, regardless of which solution is found to address the risk of carbon leakage. However, an important difference exists between the two alternative options because, if industrials are charged for their emissions, they will inevitably have to pass part of this cost of on to consumers. Demand for carbon intensive products will then shrink in response to increasing sales prices – the higher the price elasticity of demand, the greater the shrinkage. In the base case assessment of each business model, the implications of the potential demand reduction are ignored, but this assumption is later reviewed in Section 4.7, where its financial implications are quantified. Next, the Case Study Box below presents an illustrative example of the impact of carbon pricing on cement manufacturing – an example that outlines why subsidies are required to achieve a solid business case for industrial emitters. An illustrative comparison with other sectors is provided at the end of this discussion to show that similar conclusions apply to most industrial sectors.

Case Study Box: Impact of carbon pricing on cement in Europe

Figure 4 shows three cost projections for a cement manufacturer that is charged for its carbon emissions (with the underlying assumption that the risk of carbon leakage is addressed in a compatible way): the indexed cost increase due to carbon pricing, based on a recent EU ETS carbon price projection and shown by the dashed line, illustrates that, by 2040, cement manufacturing costs may increase by roughly a third without CCS.

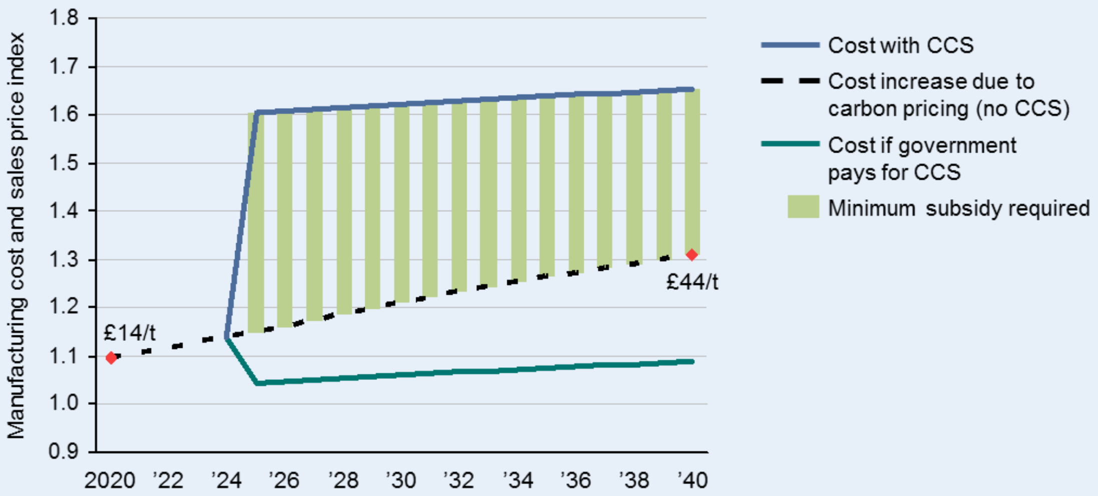


Figure 4: A worked example of the impact of carbon pricing and CCS on cement.

Based on our modelling, if a cement manufacturer were to invest in CCS without any government support (dark blue line in the chart), overall manufacturing costs would increase by more than 50% plus the carbon charges on the residual emissions that cannot be abated[13]. Due to the large gap between the two cost projections, a cement manufacturer **cannot justify**

[13] The discounted cost of CCS, inclusive of capital and operational expenses as well as a competitive rate of return and based on the first business model's results in (Section 4.3), is about £70 per tonne of CO_2 abated. In undiscounted terms, CCS on cement would be fully justified by a carbon price of £116/t. Cost savings that may be achieved in in future decades are beyond the scope of this case study.

investment in CCS purely on the basis of carbon cost avoidance. If instead government strategically decided to pay for the entire cost of CCS while letting the manufacturer reap its benefits (green line in Figure 4), a substantial advantage could be gained by emitters with CCS compared to their competitors that would not benefit from the same carbon cost avoidance. Thus, regions that pursued this strategy would be able to attract inward investment, provided the CO_2 network is oversized and capable of hosting third party access. Although this study does not focus on the legal viability of these options but merely presents the economic impact, several interviewed stakeholders highlighted that this approach overly rewards the emitters and thus conflicts with international trade rules and results in poor value for money for government.

The fourth option, which is assumed to be effected as a basis of all models presented in this study, results in **cost-neutrality of CCS** and could be achieved if government provided a subsidy, the minimum value of which is represented by the green area above, to complement the benefits from carbon cost avoidance and ensure that the emitters do not pay for CCS more than they would otherwise for their emissions. In the current status of EU ETS, industrial emitters may return their free allowances and receive the full subsidy instead – this would correspond to the same level of overall subsidy – represented by the green area above.

Impact on other industrial sectors

Although the analysis above focussed primarily on cement manufacturing, more general conclusions around the (lack of) financial motivation for investment on industrial CO_2 capture can be drawn. Six factors affect the motivation for investment in CCS:

1. A higher **carbon price** or tax provides a bigger incentive for carbon abatement;
2. Greater **carbon intensity** of a product implies that carbon pricing has a bigger relative impact on the manufacturing cost;
3. A lower **cost per tonne of CO_2 captured** improves the case for CCS;
4. CCS' benefits are greater if the **portion of easily capturable CO_2** is high;
5. If the ratio of the **carbon emissions embedded in the CCS process** to those captured is high, the abatement potential and hence CCS' benefits are more limited;
6. A high **manufacturing cost** per tonne of product means that carbon pricing and CCS have a lower overall impact (a more gradual increase) on the manufacturing cost.

Of these, the first three determine whether CCS is a more convenient option than emitting, whereas the last three determine the relative impact of carbon pricing and/or CCS on the overall production costs and hence on the emitter's competitiveness. To understand whether an industry is exposed to carbon leakage, all the above factors as well as the sector's trade intensity must be evaluated organically.

Figure 5 extends the analysis presented earlier to the steel and ammonia industries[14], the slopes of which can be understood considering the factors discussed above. By comparing these sectors with cement, it is seen that:

- **Steel** has higher carbon intensity but, since it is also substantially costlier to produce, the manufacturing cost increases only by 18% with CCS. Additionally, a lower portion of the emitted CO_2 can be easily captured on steel[15]; hence a smaller capture plant will be

[14] Although the term "ammonia plant" or "industry" is used in this report, ammonia is often produced as part of fertiliser manufacturing.
[15] It is estimated that CCS can be used to capture about 60% of the direct emissions from steel and 67% of those from ammonia manufacturing based on practical constraints. Future technologies are likely to improve on this aspect.

required on a "per tonne of product" basis and higher charges will be levied on the remaining emissions;

- The high purity of the CO_2 stream produced with **ammonia**, combined with the fact that only about two thirds of the total emissions can be easily captured, means that CCS has a relatively low impact on production costs (+16%).

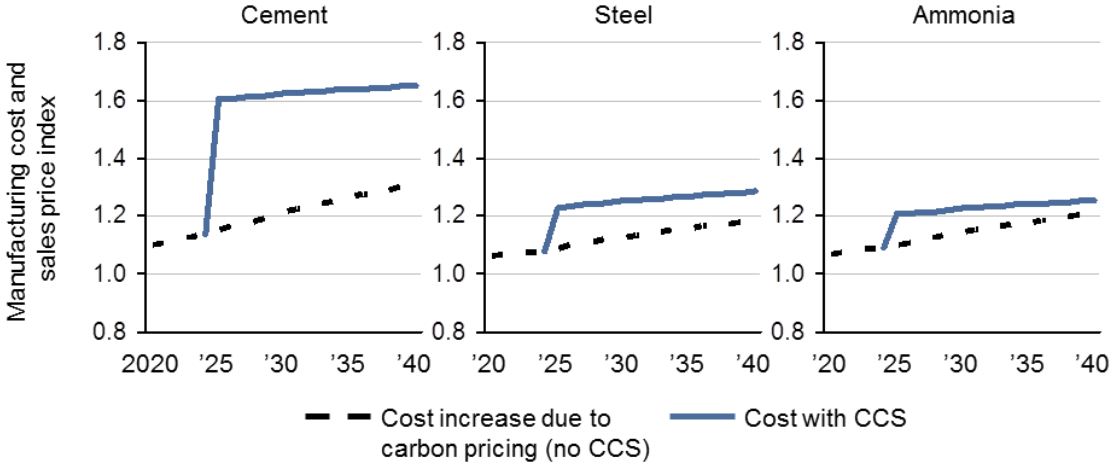


Figure 5: Comparative impact of carbon pricing on three industries.

It should be noted that any projection on future carbon prices carries with it a high degree of uncertainty. Similarly, the cost of CCS may reduce over time through technological improvements, and revenues from the sales of CO_2 to any CO_2-utiliser (e.g. CO_2-EOR) may reduce the amount of subsidies needed[16]. However, it should be noted that, CO_2 utilisation technologies also require additional investments and the business model for a given CCU technology should be viable separately so the revenues of CCU may not be used to pay for CCS.

Determining the right subsidy

Although the above assumptions about the future price of CO_2 may be considered conservative, few published projections of the future of various carbon pricing instruments achieve a price sufficient to justify investment in CCS for cement within the next two decades in Europe. Even if the performance of current carbon pricing schemes were to exceed expectations, interviews with potential investors in ICCS revealed that high political uncertainty undermines the creditworthiness of any revenues which are highly dependent on the price of carbon. Business models overly reliant on savings from reductions in carbon emissions are therefore deemed not investable, and in absence of commercial markets able to sustain a high carbon price[17], additional revenues must be found. In this study, it is assumed that such revenues originate from government subsidies, which can be provided by a combination of capital and ongoing support. To increase the creditworthiness of ICCS related cash flows, it is expected that any subsidy provided should insulate the project revenues from volatility in the price of CO_2, as well as from the increase in the price of fuels and electricity, since these add up to a sizeable portion of the cost of capture. Also, depending on national preferences and existing policies, the subsidy could be delivered through different vehicles; a detailed description of the additional subsidy requirements is provided in Section 4.1, whereas relevant mechanisms for the regions that are the focus of this study are presented in Chapter 5.3. In alternative to the provision of direct

[16] Or else the emission charges would not be avoided. Carbon Capture and Utilisation (CCU) options help the economic case for CO_2 capture if they allow the emitters to claim benefits for the avoided emissions (i.e. reduced carbon charges plus any carbon abatement subsidy). Should such benefits not be claimable, as might be the case for CCU options that do not lead to permanent CO_2 storage, the business case for capture would instead be hurt, unless the CO_2 purchase price were higher than the missed benefits.

[17] Alternative commercial markets for CO_2 could exist if CO_2-EOR operations or other CO_2 utilisation activity leading to permanent storage were available in the region where the industrial emitter operates.

subsidies, among the measures which may able to trigger investment in ICCS we find "Green Procurement" and product standards, but the scope of these measures must be large enough to create a market with the right profit margins and able to offer attractive growth opportunities for prospective investors.

2.3 Decoupling the business chain

The previous section outlined ways to ensure that industrial emitters can be financially motivated to invest in CO_2 capture. Even when this motivation is present, fundamental differences in the risk profiles of the capture, transport, and storage businesses pose a challenge to any organisation aiming to deliver a point-to-point full-chain project independently. In a cluster setting, the presence of multiple emitters with diverging priorities adds further complexity to the project: for these reasons, feedback from CCS stakeholders consistently points in the direction of part-chain projects as the most efficient and possibly only way to deliver an ICCS cluster project.

Government is the only party capable of handling project-on-project risks

In a part-chain configuration, each party can focus on their core strengths and has limited responsibilities, but important issues around how best to manage the project-on-project risks remain. It would be possible to imagine that O&G companies with exhausted fields could be keen to make them storage-ready and thus delay the decommissioning costs while generating further revenue from such fields, if a market for CO_2 storage existed – for instance one in which industries or power sector alike could bid for this service. However, a "Chicken and Egg" problem arises: no emitter would invest in capture without guarantees that the captured CO_2 is going to be stored (or else no benefits could be claimed), and at the same time no private storage developer is willing to invest in storage without having the certainty that the CO_2 volumes will be there. Unless the CCS infrastructure is already existing, an option discussed below, government intervention is required to address these project-on-project risks.

Government could officially declare its intention of developing a CCS project and take ownership of the infrastructure development through a public transport and storage (T&S) Company appropriately supported by private sub-contractors. By doing so, emitters could have increased certainty that their investment in CO_2 capture (probably motivated by subsidies, as outlined in the previous section) will not be stranded. Alternatively, government could fund an independent market regulator tasked with coordinating the delivery of the various aspects of the project, and financially capable of reimbursing the project parties should the project not be successful. A regulated infrastructure model such as Regulated Asset Base (RAB), in which the regulator holds a substantial share of the construction risks as well as some of the "show-stopper" risks defined in the next section, could then be used to enable private companies to develop and operated the T&S infrastructure.

Independent regulation is required to prevent a monopolistic behaviour which may penalise present and future emitters

Both cases presented above successfully address the concerns of investors in the various segments of the CCS business, but certain aspects of the projects warrant further regulation:

- T&S is likely to be a natural monopoly at local level; hence the T&S operator may not have any incentive to operate the assets efficiently and could charge unreasonable fees to the emitters. Thus, the T&S fees must be approved by an independent regulator, which may need to adjust such fees periodically (e.g. every 5 years, as is often stipulated in RAB models) to reflect changes in the cluster and allow a fair rate of return to the T&S Company;
- Without a centralised strategy, the T&S Company may prefer not to over-size the infrastructure. However, unless the infrastructure of early projects is oversized, future

economies of scale may not be maximised, leading to a greater cost of carbon abatement for society. An independent regulator could assess the regional requirements and ensure that these are accounted for in the development plans of the T&S Company;

- Finally, emitters that may choose to join the cluster in the future could be unable to do so unless the T&S Company has an obligation to transport and store their CO_2, provided capacity is available (which is linked to the point above) and they pay a fair fee. Again, an independent regulator is required to impose an obligation on the T&S Company to allow third party access.

If government intervenes to mitigate the key risks and an independent organisation is responsible for regulating the above, a commercial framework with regulated rates of return can be achieved. Interviews with prospective financers confirm that this option would be of interest to a wide range of infrastructure investors, and justify our focus in this study on this type of business model. At the same time, it must be recognised that the regulated cash flows arising from these models might not always be appealing to companies that might be prime candidates to become a storage developer and/or operator: for instance, oil and gas companies accustomed to handling geological risks typically expect a high rate of return. Considering that the main source of revenue for the project is likely to be government funding, this might be politically unacceptable.

Four options for decoupling capture and infrastructure investment

Building on the above reflections, four broad options for decoupling investment in the T&S infrastructure from that in capture were defined and will form the basis for the business models analysed in this study:

- **Government-owned transport and storage infrastructure**: The government establishes a public transport and storage (T&S) company to construct the infrastructure and lead the cluster project towards operational stability. At a later stage, the T&S Company could be listed/spun-off to reduce the public stakes in the project. A Government could consider establishing two separate companies for transport and storage from the outset, which may be easier to privatise separately in view of their different risk profiles. Even if this model is pursued, an independent regulator is expected to be required;
- **Regulated infrastructure**: A regulated infrastructure model is used to enable fully privatised delivery of the project. In this option, an independent market regulator would first be set up, likely with government funding, and given responsibility for drafting the terms under which infrastructure investors would be guaranteed the agreed rate of return, and for regulating the fees and conditions for access to the infrastructure;
- **Existing infrastructure**: The simplest option presented is if the industrial cluster can latch on to existing infrastructure (which may either be government owned or regulated). This might be possible for future CCS projects in areas where a CO_2 pipeline network with spare capacity already exists. This is similar to what the Alberta Carbon Trunk Line will enable, albeit with a specific focus on EOR; alternatively, industrial emitters could join “anchor” CCS projects, e.g. on power, developed in advance of the ICCS project with oversized infrastructure or CO_2 shipping is possible;
- **CO_2-EOR**: Only an option if active oil fields exist in the cluster region, this is the most common option for currently operating projects (see Table 6 in the Appendix), but it is not expected to provide a wide-scale solution for ICCS globally. This is because the capacity and location of suitable oil fields does not always match the need for CO_2 storage, and even when it does, the oil fields will eventually become depleted and their economic viability as CO_2 storage might be compromised if the price of fossil fuels decreases excessively.

Although some of these options are not mutually exclusive, this study looks at them individually to better assess the merits and limitations of each feature. In practice, hybrid solutions will likely be selected wherever existing infrastructure and/or CO_2-EOR operations are locally available.

2.4 Public-private risk sharing

Through extensive review of publicly available literature, several risks were found to affect ICCS clusters throughout the various project phases and across the entire value chain.

Table 4 presents a shortlist of the most frequently mentioned risks, accompanied by a selection of possible mitigation strategies for each of them. All the risk mitigations requiring government intervention are presented in boldface to highlight the substantial level of government input that is necessary for successful mitigation of most of the key risks. This study argues that **effective management of the key project risks requires public-private risk sharing**, and without it, it is not expected that private initiative alone will lead to the successful deployment of ICCS clusters.

Table 4: Key risks affecting industrial CCS clusters and illustrative mitigation strategies. Measures requiring government intervention are highlighted in bold.

	Project phase	Risk description	Suitable mitigation strategies
CAPTURE	Development	First mover disadvantage	• **Allowed rate of return accounts for this** • **Capital grants**
		Marginal cost of capture varies within individual factories	• **Subsidy adjusted to reflect this** • **Performance standards could mandate minimum capture levels**
		High variability in cost of capture across industries	• **Subsidy tailored to each industry**
	Development / Construction	Novelty / first of a kind project	• **Government provides risk back-stops and guarantees** • Reputable stakeholders are involved
	Construction	Long overhaul time can affect BAU operations	• Target minimal impact on BAU in project delivery • Financial compensation for disruption to BAU
	Construction / Operations	Confidentiality of industrial data	• Confidentiality agreements
	Operations	Impossibility to pass cost of CO_2 emissions or CCS on to consumers without causing carbon leakage	• **Subsidy make CCS cost neutral compared to avoided emissions cost considering uncertainty of regulation** • **International coordination on carbon pricing or border adjustment tax for carbon intensive products**
		Demand for industrial products decreases as the sales price increase	• **Subsidy includes minimum payments linked with baseline production volumes**
		Natural monopolies occurring in T&S leading to excessive fees for emitters	• T&S fees regulated to allow a fair return
		Complexity for emitters compared to BAU	• **Allowed rate of return accounts for this**

Table 4 (continued)

	Project phase	Risk description	Suitable mitigation strategies
TRANSPORT	Development / Construction Operations	Sub-optimal network sizing due to missed coordination	• **Government bears cost of oversizing via grants (if private T&S Company) or via public company**
		Volume risk due to operating regime of emitters	• Offtake agreement (send-or-pay) • Capacity payments
		General transport liabilities	• Insurance
STORAGE	Development	Storage failure after completion of development phase	• **Storage guarantees to emitters** • **Loan guarantees to lenders** • **Early back-up storage could be developed via government funds** • **Increased return of return to account for this**
	Development / Construction	Novelty / first of a kind project	• Same mitigation as for equivalent capture risk
	Operations	Volume risk due to operating regime of emitters	• Same mitigation as for equivalent transport risk
	Post-operations	Uncapped liability from CO_2 leakage long after storage site decommissioning	• Public T&S Company bears the risk • Government provides back-stops to cap the liability, allowing layered insurance approach • Create central fund that bears long-term liability to which all store operators must contribute
CROSS-CHAIN	Construction	Deliverability risk / timing issue between parties	• Offtake agreement regulating the operations start date
	Operations	Counterparty risk / cross-chain default	• Government guarantees minimum payments to emitters, transport, storage and lenders in case of cross-chain default
POLITICAL AND MARKET CONDITIONS	Development	No incentive mechanism currently exists	• **Government develops new policy ahead of project FID**
	Development / Construction	No strong commitment from public sector, policy changes and permissions not granted	• **Government develops new policy ahead of project FID** • **Public T&S Company shows government commitment**
		Delays due to lack of public knowledge and acceptance	• Education and consultation of wider public
	Operations	Uncertainty about future CO_2 prices	• **Subsidy is complementary to carbon cost avoidance**
		Changes to carbon pricing policies for specific industries	• **Government develops new policy ahead of project FID**

Government support is required to address show-stopper risks

Poor mitigation of certain risks affecting ICCS clusters can result in expectations for greater rates of return and more expensive financing. Among these we find operational risks that may be addressable via bilateral agreements such as supplier guarantees (e.g. to protect emitters in case of underperformance of the capture plant), and offtake agreements (which regulate the transfer of the CO_2 liability across the network). Should incidents of this type occur, the emitters would be exposed to increased carbon cost and reduced subsidies, but through the above agreements the liability can be correctly transferred to the responsible party. Government intervention to mitigate the impact of these risks is primarily useful to reduce the cost of capital, and thus of the overall project[18]. Other risks, referred to as **show-stopper risks**, are not currently acceptable for the private sector: project developers, potential investors, and insurance companies alike consider these too big to price, and would rather not invest in projects where these risks are not suitably mitigated. Government has an important role to play in mitigating the show-stopper risks, some of the main ones of which are shown in the table below together with suggested government intervention measures. If these measures are implemented, the private sector can achieve an acceptable level of risk, and in response to this it is expected that private investment in ICCS can be achieved.

Table 5: Illustrative show-stopper risks and required government mitigations.

Illustrative show-stopper risks	Suitable government mitigation
• Uncapped liability from CO_2 leakage long after storage site decommissioning	• **Back-stops** or caps on the long-term storage liability to enable a layered insurance approach, where the storage operator can get insurance coverage up to the capped amount.
• Emitter default • Volume risk	• **Volume guarantees** reduce the loss experienced by the T&S operator.
• Storage failure after completion of development phase (risk for the emitters)	• **Storage guarantees** to provide minimum payments in replacement of subsidy and carbon cost avoidance.
• Risk of default on loan repayment makes project not bankable	• **Loan guarantees ensure** project bankability despite the low creditworthiness of some of the project parties (see Case Study Box on page 18).
• Storage failure after completion of development phase (risk for the T&S Company) • Emitter unable to reach FID due limited capital availability[19]	• **Grants** to cover the cost of storage development, potentially also of a back-up storage. • **Grants** to the emitters decrease the need for external financing and the expected shareholder equity contribution.

In this chapter, four enablers were presented which must be addressed to allow private investment in industrial CCS cluster. For all of them, it was argued that government has an important role to play in:

- Devising new policies to address carbon leakage;
- Providing subsidies that insulate the project revenues from the carbon pricing;
- Developing the transport and storage assets or funding an independent regulator;
- Provide suitable support in mitigating show-stopper risks.

Building on these findings, the next chapter addresses the question of whether governments have the right motivation to offer the recommended level of support.

[18] Government could have a vested interested in reducing the privately held risks further as a means of increasing value for money, as they are ultimately paying for large part of the project. For instance, by reducing the risk to which investors are exposed, low cost loans can become available and bring with them the substantial cost-reductions discussed on page 40.
[19] Lenders may only fund a certain percentage of the capex (e.g. 60%), and the remaining portion may still be too large for industrials to fund from their balance sheet. If government is determined to make project happen, it is in their interest to ensure that FID can be achieved.

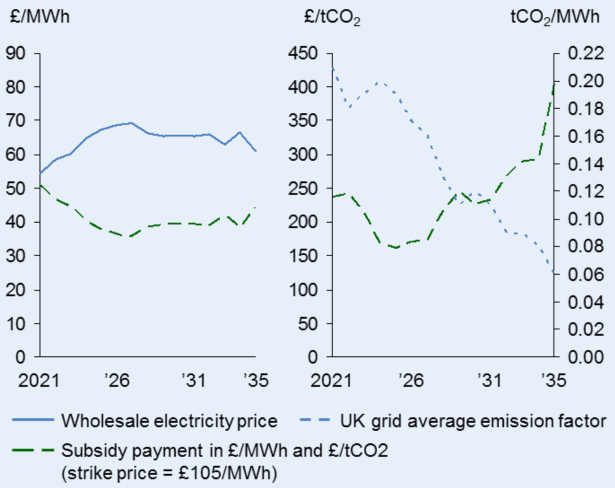
3. THE CASE FOR GOVERNMENT SUBSIDIES

Subsidies to industrial CCS are a cost-effective decarbonisation tool

Previous studies have shown that, for a number of industrial sectors, "*it may not be possible to decarbonise them without CCS*"[20], and in this study we draw attention to the fact that subsidies in support for ICCS may in fact be very cost-effective for society, when compared to subsidies to other low-carbon technologies, and should hence be supported. Taking offshore wind as an example (see Case Study Box below), the **subsidised cost of abatement for offshore wind can be well over £200/t – more than four times as high as that of the ICCS cluster modelled in this study** (which varies between £29/t-£53/t, see Figure 31 in Chapter 5).

Case Study Box: The Cost of Subsidies to Offshore Wind

- Subsidies to renewable energy operators in the UK are typically administered via a Contract for Difference (CfD) mechanism, whereby a subsidy payment equal to the difference between a pre-agreed "strike price" and the market price of electricity is paid for each unit of renewable electricity fed to the grid (and then recharged to consumers – see end of this chapter).
- The *Budget Notice of the Second CfD Allocation Round* set the Administrative Strike Price for offshore wind in 2021/22 to £105/MWh (it should be noted that the actual cost of offshore wind might be well below that).
- Assuming a £105/MWh strike price, during the lifetime of an illustrative UK offshore wind project operating from 2021 for 15 years, the subsidy payment is expected to range between £36-£51/MWh, based on official projections which predict the wholesale price of electricity will oscillate between £54 and £69/MWh.



- However, the CO_2 abatement potential of renewable electricity generation reduces in line with the average grid carbon intensity.
- Since an 80% decrease in the UK grid's carbon intensity is expected by 2035, the subsidy payment "per tonne of CO_2 abated" will increase over time, hitting £400/t in 2035[21].
- This represents an **average subsidised cost of £237/tCO$_2$ abated"**[21].

[20] IEA, 2013, *Global Action to Advance Carbon Capture and Storage*: A Focus on Industrial Applications. Annex to Tracking Clean Energy Progress 2013.

[21] Discounted using a 4% rate. In undiscounted terms, the subsidy payment in 2035 would be over £700/tCO$_2$, and the average government cost would be of £338/tCO$_2$. Even assuming that the grid's carbon

The cost-effectiveness of ICCS could only be fully appreciated by policy makers if they valued the cost of carbon emissions consistently with the cost of meeting the 2050 decarbonisation goals, rather than based on the prevailing carbon price. As an example, a study that looked at what is required for meeting the 2050 goals in the UK[22] found that the average cost of decarbonisation between 2025 and 2040[23] will likely average around £150/t (see green lines in the figure below). Conversely, a carbon price of £75/t-£110/t is sufficient to pay, without subsidies, for the full chain cost of the CCS cluster in the business models discussed in this study[24], meaning that, without ICCS, government might need to support more expensive measures in other sectors. However, current carbon pricing mechanisms are not projected to achieve a sufficient value in the required timescale: by 2050, a price of less than €90/t may be achieved by the EU ETS (see red lines in the figure below) and, in the same timeframe, the price of carbon might remain below $100 in the USA and not above C$50 in Canada[25]. The inability of current pricing mechanisms to incorporate the full cost of carbon (or in other words to fully internalise the carbon externality) represents a market failure that governments committed to the Paris Agreement and looking to achieve best value for money should address. To do so, they should preferably implement policies to strengthen the carbon price, or in alternative consider providing subsidies for ICCS and other cost-effective projects. Unless one of these options is pursued, society may be faced with a higher bill for decarbonisation, or worse we might fail to meet the decarbonisation targets.

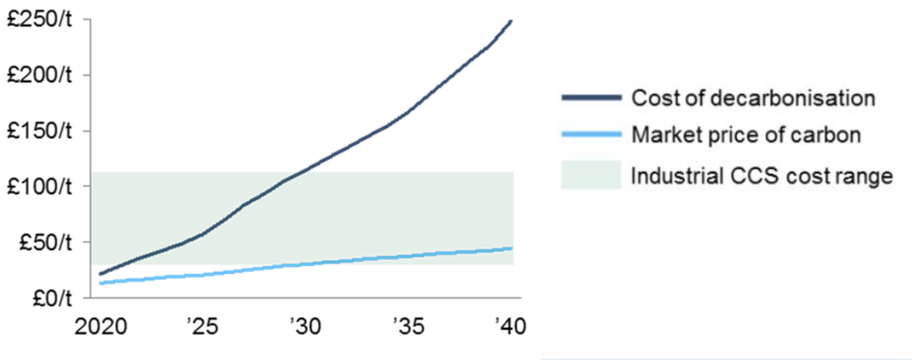


Figure 6: ICCS is a cost-effective decarbonisation option.

CCS can stimulate local industrial activity and foster inward investment

Among the multiple decarbonisation options that a government could support, ICCS has a unique value proposition: by reducing the carbon cost of existing industrial processes, **ICCS has the potential to improve the long-term competitive position of local industries under an increasing carbon price**. In Section 2.1 it was pointed out that, due to the way the risk of carbon leakage is being addressed, most industries currently bear little or no costs for their carbon emissions, but in this report it is assumed that this will change. Figure 7 illustrates the trade-off between environmental benefit and protection of local industrial jobs that would occur if policies

intensity remained at 2021 levels throughout the project lifetime, the government cost would only decrease to £143/t.

[22] UCL-TIAM modelling in *Committee on Climate Change, 2012, The 2050 target*. A price of C$250 in 2030 was found to be necessary in Canada by *Mark Jaccard et al., 2016, Is Win-Win Possible? Can Canada's Government Achieve Its Paris Commitment and Get Re-Elected?*

[23] These dates are chosen because a project able to achieve financial close by 2020 at the latest would likely not be conclude commissioning until 2025. 15 years is used as a representative timescale for an ICCS project capable of delivering reasonable value for money.

[24] The blue line in Figure 6 shows the cost CCS on cement – other emitters with a lower cost of capture bring the cluster average down to the range mentioned above.

[25] EU ETS prices based on *EU 2016 Reference Scenario*. For the projected CO_2 price in the USA see *Synapse Energy Economics, Spring 2016 National Carbon Dioxide Price Forecast*; the proposed plan for a Canadian carbon tax can be found online, e.g. see www.bloomberg.com/view/articles/2016-10-06/canada-sets-the-trend-on-climate (retrieved on 10/02/17).

other than free emission-allowances allocation (or exclusion from the carbon pricing system) were pursued to prevent carbon leakage. As the price of carbon increases, without ICCS it is possible that disruptive innovation will result in high market penetration of alternative low-carbon products[26]. Although new jobs will be created in the nascent industries, these may not arise in the same areas that are affected by the disruption of industrial markets in the first place. Instead, if ICCS is implemented early, **local industrial jobs and skills can be preserved** and if the CCS infrastructure is built with sufficient additional capacity, **inward investment can be fostered** – this might be considered of great importance by governments concerned with ensuring a **socially fair transition** to a lower-carbon economy.

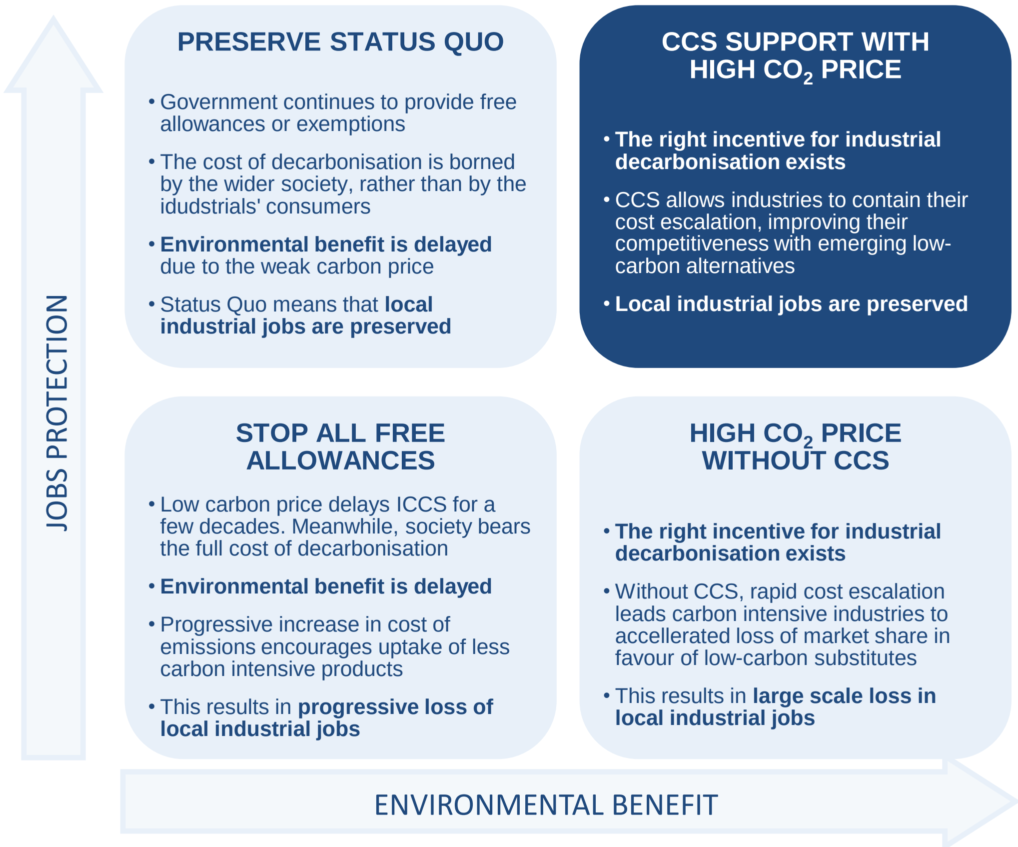


Figure 7: Not all policy options can decarbonise industry and protect local industrial jobs.

In conclusion, it should be noted that **the cost of subsidies does not need to be covered by taxpayers**, as there are various ways to create the funding budget. Taking the UK CfD subsidy for renewable energy as an example, a levy is imposed on all electricity suppliers via an obligation, the cost of which is then passed on to consumers. If the risk of carbon leakage is addressed as discussed in the previous chapter, this mechanism can be replicated for industrial CCS, meaning that consumers of carbon-intensive products will be asked pay for their embedded emissions. Alternative mechanisms that can be introduced to fund the subsidy budget include performance standards or obligations on different parties. Feedback from potential investors suggests that mechanisms that ultimately pass the subsidy cost to the consumer base responsible for the specific source of carbon pollution are generally considered more sustainable and creditworthy. If government provides subsidies and takes up a significant share of the key project risks, this study confirms that investable business models can be devised, and these would attract substantial amounts of private investment. Based on the assumptions set out up to here, four business models were selected and are presented next.

[26] See IEA, 2009, *Cement Technology Roadmap* for a review of possible low-carbon substitutes to cement.

4. DETAILED BUSINESS MODELS ASSESSMENT

4.1 Common features of all business models

This chapter investigates the merits and limitations of four models that are based on the four options for decoupling investment in capture from that in infrastructure proposed in Section 2.3. At the core of each model is the same illustrative cluster, composed of five industrial emitters: a steel plant, a refinery, a cement plant, an ammonia plant and a hydrogen plant.

Industrial CCS subsidy mechanisms

The industrial cluster is assumed to operate in a cap-and-trade system where the carbon price follows the trajectory defined in the EU 2016 Reference Scenario[27]. An emitter subsidy is assumed to be provided which, based on the requirements set out in Section 2.2, is centred on three simple criteria:

- **Cost neutrality**: emitters should not be worse off because of CCS, but they should also not be overly rewarded, to ensure value for money for the taxpayer is achieved;
- **Competitive reward for the risk taken**: investors should be allowed a rate of return that is comparable to that which they would seek for other capex programmes;
- **Continued commitment for capture**: the emitters should have a strong, long-term incentive to capture operations, and not to quit the project as soon as the target return on investment is achieved.

An important ramification of the first criterion is that profit margins need to be insulated from changes in the price of carbon and of other commodities, and hence the subsidy needs to not only complement the revenues from carbon cost avoidance, but also allow a pass-through of increased commodity costs. By a similar argument, if the sales volumes were to decrease over time (possibly because of the increased sales price[28]), the reduced margins may be insufficient to justify the economic viability of the project[29], and this suggests that a **mechanism to link the minimum subsidy value to the baseline level of emissions** is required.

The first two criteria imply that if the carbon cost avoidance is at any time insufficient to cover the cost of CCS, and to also provide the expected rate of return, the subsidy payment should at least bridge the gap. To achieve this outcome, a **CO_2 price guarantee** is negotiated between government and each emitter, and the subsidy payment for each tonne of CO_2 abated is equal to the difference between such a CO_2 price guarantee and the prevailing carbon price (which may be determined by any carbon pricing mechanism)[30]. Finally, the third criterion establishes that the emitters' profits should be fairly distributed over time; however alternative subsidy mechanisms are possible if this criterion is dropped. Of relevance are subsidies that provide front-loaded revenues, able to generate a quicker payback period – which may need to be as short as 3-5 years to comply with typical corporate requirements on industrial capex projects – at the expense of reduced long-term commitment from the industrial emitters. Excessive front-loading might in fact greatly reduce the motivation for industrial emitters to continue the CCS operations beyond the time required to achieve their targeted rate of return. Ultimately, it is likely that a compromise will need to be reached between government and industry over the level of front-loading, so that

[27] The models are equally applicable if the carbon price originated from a tax.

[28] On page 35, this risk is assessed quantitatively, whereas the reader should refer to Section 2.1 for the discussion of the prospects of increased sales price, should the risk of carbon leakage be addressed without recurring to free allocation of emission allowances.

[29] If the sales volumes decreased, less CO_2 would be abated in absolute terms, leading to decreased revenues from both subsidy and cost avoidance. Costs do not scale down as much as revenues because they are in part fixed, thus leading to decreased margins insufficient to meet the initial hurdle rates.

[30] This is similar to the concept of *strike price* employed in the UK Contracts for Difference.

the commercial requirements can be fulfilled and, via sufficient additional profits achievable after the payback period, long-term commitment towards carbon abatement is preserved.

The central role of offtake agreements

The contract at the core of each business model is an offtake agreement[31], which ensures that unplanned whole systems costs are correctly reallocated to the responsible party, examples of which are presented in Section 4.7. Feedback from interviewed CCS stakeholders highlighted the importance of a consistent template for offtake agreements between different parties; without this consistency, future cluster developments (i.e. third-party access) would be hindered. The offtake agreement regulates:

- The **transfer of CO_2 ownership** (and liability), accompanying the physical transfer of the CO_2 volumes across four stages: capture and compression, transport, injection, storage;
- The **commissioning timeline**, to protect each party from construction delays and operational incidents affecting the other side;
- Acceptable **thresholds** for changes to the volumes of captured CO_2 (*ship-or-pay*) and for allowable infrastructure unavailability (*take-or-pay*);
- An **obligation** on the T&S Company to ensure that third party access is guaranteed if sufficient capacity is available.

Government support measures

In Section 2.4 it was highlighted that some of the project risks cannot be fully managed by the private sector. To ensure that the business models are investable, the following government support measures are also included in all models:

- **Storage guarantees** to industrial emitters and **volume guarantees** to the private T&S operator, a guaranteed minimum payment from government to mitigate major incidents that might otherwise prevent investability[32];
- **Loan guarantees** that result in payments to the creditors in case of default on loan repayment[33] (see Case Study Box below);
- **Capital grants** which, though not essential for achieving investability (and hence possibly only available to first-of-a-kind projects) decrease the project costs, reduce the need for third party financing and might in some cases be necessary to allow emitters to finance the project from their balance sheet[34].

Additionally, as part of the regulated infrastructure framework used in Model 2, the private storage operator requires additional protections against storage failure and CO_2 leakage risks. The appropriate mitigations for addressing the former depend on the exact storage site characteristics – for sites that are well known in advance of the project (e.g. depleted oil & gas fields) the volume guarantees discussed above might be sufficient, but for less well-known sites **the storage developer might request financial support to cover the cost of storage characterisation**

[31] Also known as *purchase and sale guarantee*.
[32] These guarantees would partially protect the shareholder margins in cases that cannot adequately be recharged through offtake agreements, such as in the event of counterparty default.
[33] Another parameter of great importance for lenders is the Debt-Service Coverage Ratio (DSCR), the ratio of the net operational income from CCS-related cash flows to the debt service. If lower than 1.0, the debt cannot be serviced. Based on feedback from potential investors, the minimum DSCR that would be expected for regulated cash flows is around 1.15, whereas a value of 1.4-1.5 might be required for unregulated cash flows – the minimum emitters' DSCR in the four models assessed is 1.3.
[34] The impact of grants on the overall project costs is investigated through sensitivity analysis in the next chapter.

and development[35]. As for the risk of CO_2 leakage from the decommissioned store, it is suggested that government should **cap the storage operator's liability**, a measure that might be sufficient to enable them to purchase an insurance policy on the remaining liability (an approach known as "layered insurance"). In Section 4.7, quantitative assessment of three key project risks sheds light on the extent to which the risk mitigations discussed above may provide financial relief to the project participants, and clearly shows the need for their provision.

Case Study Box: The $2B Loan Guarantee for the Lake Charles Methanol Project

About the project. The Lake Charles Methanol Plant, expected to become operational in 2019 and cost $3.8B in total, will produce methanol and other chemicals from petroleum coke (petcoke, a by-product of oil refining). The project aims to reduce greenhouse gas emissions by 36% compared to typical methanol facilities by capturing nearly 80% of the CO_2 produced, which will then be used for EOR.

The loan guarantee. In December 2016, the US Department of Energy (DOE) announced it would be issuing a conditional loan guarantee of $2B on the Lake Charles Methanol Project[36]. The guaranteed was requested in response to the Advanced Fossil Energy Project solicitation, issued in late 2013 by the Loan Programs Office and seeking to help "finance projects and facilities located in the United States that employ innovative and advanced fossil energy technologies that avoid, reduce, or sequester anthropogenic emission of greenhouse gases". This solicitation was part of the Climate Action Plan devised by the Obama Administration, and aimed "to ensure [the USA] develop all [their] abundant energy resources responsibly and sustainably".

What are the costs? Under the Advanced Fossil Energy Project solicitation, 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 guarantee will help the project developers obtain low-cost financing up to $2b, whereas the remaining $1.8B is expected to be financed via equity. Under the conditions set by the guarantee, the risk of default on loan repayment is borne by government, responsible to repay the creditors should the project fail to deliver. However, no additional cost to the government exists if the project is successful.

4.2 Modelling methodology and techno-economic assumptions

The cluster archetype, shown in Figure 8, was designed based on representative medium-size plants from industrial sectors that might be expected to participate in early ICCS clusters[37]. The storage site was assumed to be located offshore at 300km from the coast. A trunk pipeline, oversized by a factor of two, connects the storage site to the shoreline compressors and extends 50km inland. The emitters are expected to bear the costs of connecting to the trunk pipeline through 20km long feeder pipelines, and are also responsible for delivering high-purity CO_2 at the supercritical pressure of 100bar. The store operator is instead responsible for further compression to 150bar at the shoreline hub.

[35] And potentially also covering the characterisation and partial development of back-up storage that can be promptly be made ready for use should the initial storage site fail.
[36] All information and quotes retrieved on 15/01/2017 on the official DOE website: energy.gov/articles/energy-department-offers-conditional-commitment-first-advanced-fossil-energy-loan-guarantee, energy.gov/lpo/services/solicitations/advanced-fossil-energy-projects-solicitation, and energy.gov/articles/department-energy-releases-8-billion-solicitation-advanced-fossil-energy-projects.
[37] Their participation in early ICCS clusters is deemed likely either because they are large contributors to regional carbon emissions (steel, refineries, cement) or because of their low cost of capture because of the high CO_2 concentration in their exhaust streams (ammonia, hydrogen).

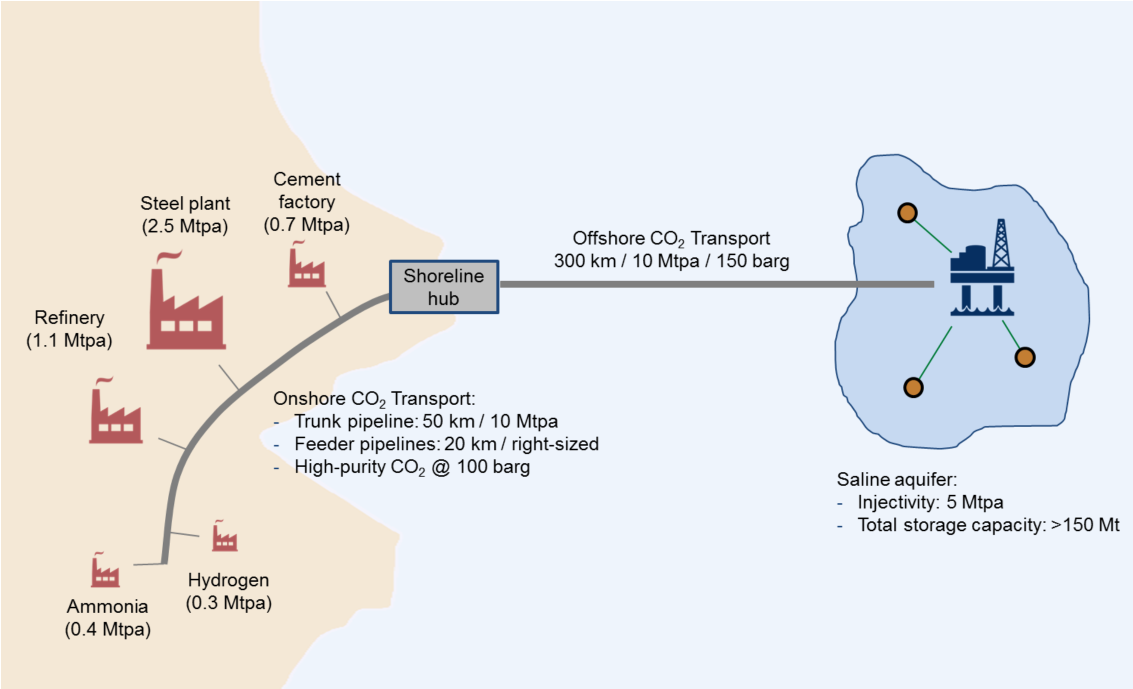


Figure 8: Industrial cluster archetype.

As for the project timeline, the pre-FID (final investment decision) phase is assumed to start in 2018 and, after reaching FID three years later, all parties begin construction in 2022. Operations start in 2025 and last 15 years, and the capture plants are decommissioned in 2040 after having led to the emission-avoidance of 61 Mt of CO_2. The useful life of the T&S assets is assumed to be 40 years in the models where the T&S Company is public[38], whereas their decommissioning also happens in 2040 in the other models. The storage site must be monitored for 20 years post-decommissioning, after which any remaining liability is transferred to government or to the relevant authority.

A simple capex financing model was included where each emitter receives a government grant (20% of capex) and two low-cost[39] loans with maturity of 10 years and 15 years respectively (30% of capex, each). Shareholders equity contributions of 20% of capex complete the funding. The financial model is then used to compute the cash flows required to achieve predefined hurdle rates for each project participant (12% for the private parties[40] and 7% for the public T&S Company). To account for the time discounted value of future cash flows, a social discount rate of 4% is used throughout this study.

Incentives for abatement, not for capture

Subsidies to the industrial emitters should reward them for carbon abatement – i.e. for the net reduction in emissions to the atmosphere per unit of output – rather than merely for capture. To this end, the true abatement potential of CCS must be evaluated by subtracting the emissions occurring because of heat and electricity usage for the capture and compression[41] from the total captured volumes: based on this approach, the abatement potential as a fraction of the captured

[38] The underlying assumption is that additional emitters later join the cluster, but this is not directly modelled in this study.
[39] The interest rates are assumed to be 3% and 2.5% respectively – a low cost of finance that is only possible thanks to the extensive support from government.
[40] For the emitters, this hurdle rate results in returns of investment (ROI) between 17-25% – with the higher value applicable for purer emitters – by the end of the project, and in a payback period of 10 years. All values should be intended as before tax – the legislation around which varies considerably across the regions focus of this study and is beyond purpose of this study.
[41] The impact of electricity requirements for transport and storage was found to be negligible and hence not included.

volumes was found to range from around 78% to 93%, with the highest values representative of the high CO_2 concentration streams (Ammonia and Hydrogen). Additionally, the true abatement potential of CCS depends not just on the net reduction in emissions of the individual factory, but also on the relevant market benchmark for the specific industrial product, or else the subsidy might end up rewarding dirtier factories more than cleaner ones. To this aim, one must first determine a product's carbon intensity, which is a function of all energy inputs (electricity, heat and raw fuels) and all production outputs (for a typical steel manufacturer, this includes steel and iron in their different final shapes). Crucially, benchmarking must be performed against the relevant counterfactual, represented by the market-average carbon intensity of products equivalent to that which is "decarbonised" through CCS. Assessment of the correct carbon intensity and definition of the correct benchmarks are beyond purpose of this study. Instead, it is here assumed that the emitters' carbon intensity is equal to the benchmark performance before CCS is added. With this assumption, the volume of carbon abated becomes equivalent to that of carbon captured minus all direct and indirect emissions from CO_2 capture and compression.

4.3 Model 1: Public T&S Company

Business model overview

The key feature of Model 1 is that the T&S infrastructure is developed and operated by a public T&S Company, tasked by the government with ensuring the CO_2 pipeline network is suitably oversized to be capable of hosting future cluster expansion. While it is possible that private sub-contractors will be employed for specific tasks and will be held accountable for them, the T&S Company has full ownership of the key T&S risks introduced in Section 2.4. Additionally, the T&S Company must decouple the business chain and coordinate the overall project delivery to reduce the industrial emitters' exposure to counterparty risks. The other key features and the money flows are summarised in the diagram below.

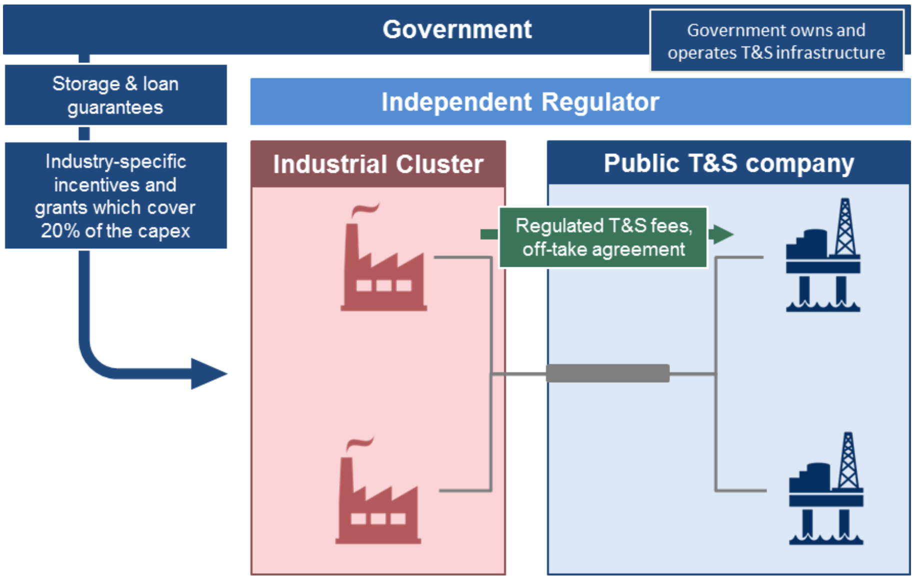


Figure 9: Summary diagram for Model 1.

Model 1 is expected to result in the lowest possible cost of capital for the T&S investment because the public T&S Company is expected to have lower profitability requirements than those of private companies that could participate in the regulated business discussed in Model 2 (7% hurdle rate, compared to 12% of the private counterpart). Further benefits arise because of public ownership, and crucially because of the government's unique position to implement a long-term strategy that from the start includes extended lifetimes of T&S assets. The modelling assumption used is that the assets will be used for 40 years, which greatly reduces the average T&S cost per tonne of CO_2 abated. Based on the reasons outlined above, Model 1 represents the least-cost option to develop new T&S infrastructure.

Costs, revenues, and cash flows

The key results for the first business case are shown in Figure 10, where a detailed breakdown of emitters' costs and revenues is provided. The total project costs for each emitter were obtained by summing the discounted costs experienced by the emitters – illustrated in the cash flows in Figure 11 – with any additional payments from government to the private T&S operator (grants and capacity payments, both zero in this model since the T&S Company is public). The total project costs were subsequently divided by the total volume of abated emissions to obtain a **levelised cost of abatement (LCOA)**[42] of £65/t on average.

[42] This measure allows like-for-like comparison of different decarbonisation measures in a similar fashion to how the levelised cost of electricity (LCOE) is used to compare different electricity generation options.

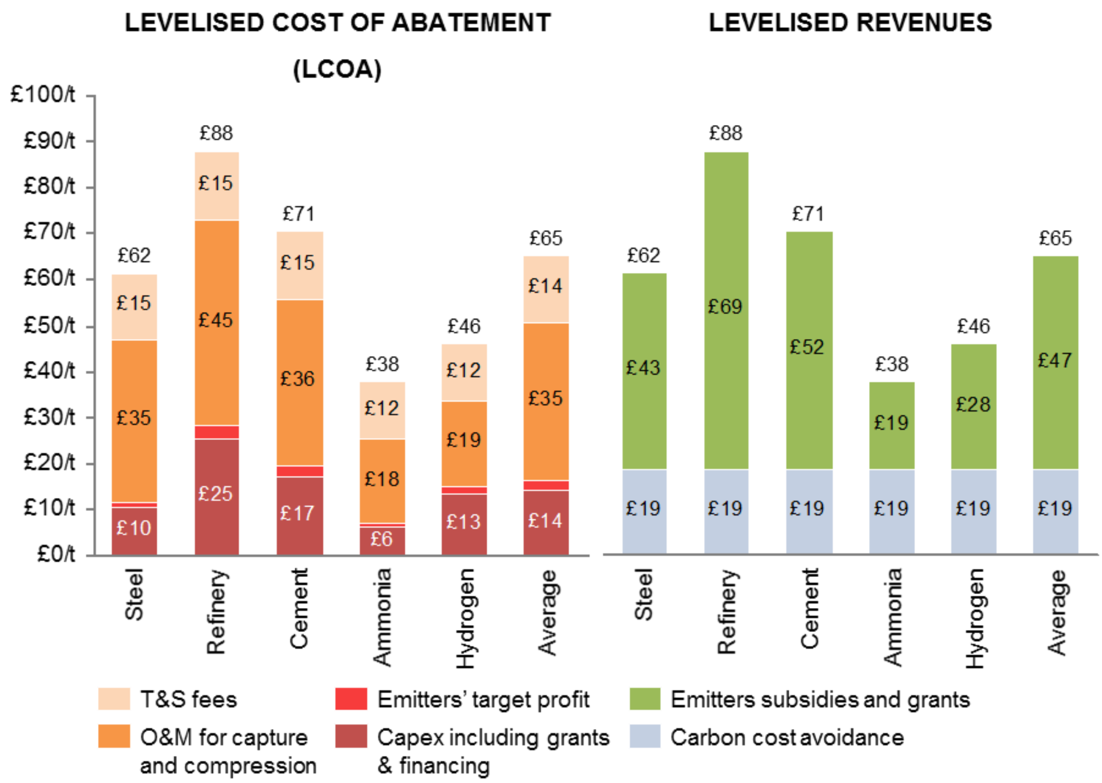


Figure 10: Breakdown of costs and revenues for Model 1.

Without exception, the operational costs of CO_2 capture and compression provide the largest contribution to the LCOA[43]; based on our assumptions, this is driven by the large heat requirements for amine regeneration and the electricity costs for CO_2 compression. Significant variations in capex instead occur because of differences in the exhaust streams' CO_2 concentration and on economies of scale. Finally, it is interesting to note that Ammonia & Hydrogen experience a lower T&S cost "per tonne abated" although the T&S fees[44] "per tonne of CO_2 captured" are the same for all emitters. This is because more CO_2 is abated for each tonne captured in their processes than for other emitters.

On the revenues side, it is important to note that the carbon cost avoidance provides the same revenue to all emitters because they are all assumed to pay the same price for any carbon emissions – the £19/t value thus corresponds to the discounted average price of carbon throughout the operational period. The remainder of the project revenues[45] make up the **government cost of abatement**, the value of which is highly dependent on the prevailing carbon price. Under the assumptions used, government is only expected to pay £47 for the abatement of tonne of CO_2, instead of the total LCOA of £65/t, hence it is on this value that any assessment of value for money should be conducted.

Figure 11 illustrates the emitters' cash flows which provide the basis for the levelised costs and revenues discussed above. The cash flows highlight the main features of the capex financing model: the bulk of the capex is paid via two loans tranches covering 30% of the capex requirement each, with a maturity of 10 and 15 years respectively; the remainder is equally split between a

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[43] On average, compression represents 44% of the O&M costs, but is as high as 78% for the Ammonia plant, for which the capture costs are minimal. It is worth pointing out that the compression technology is more mature and closer to thermodynamic limits; hence only limited cost reductions are to be expected to arise from further improvements in CO_2 compression.

[44] Considering that the government subsidy depends on the T&S fees, the government might prefer to provide the T&S service for free and reduce the CO_2 price guarantee.

[45] That is, except for CO_2 sales for CO_2-EOR or for another utilisation purpose.

grant and shareholder equity (20% of capex each)[46]. Since both loans are assumed to offer low interest rates thanks to the extensive government guarantees, they reduce the net present value (NPV) of the capex investment[47]. Similarly, grants help to reduce both the LCOA and the overall cost to government since no returns are expected on them (the impact of different capex financing options is further explored on page 40).

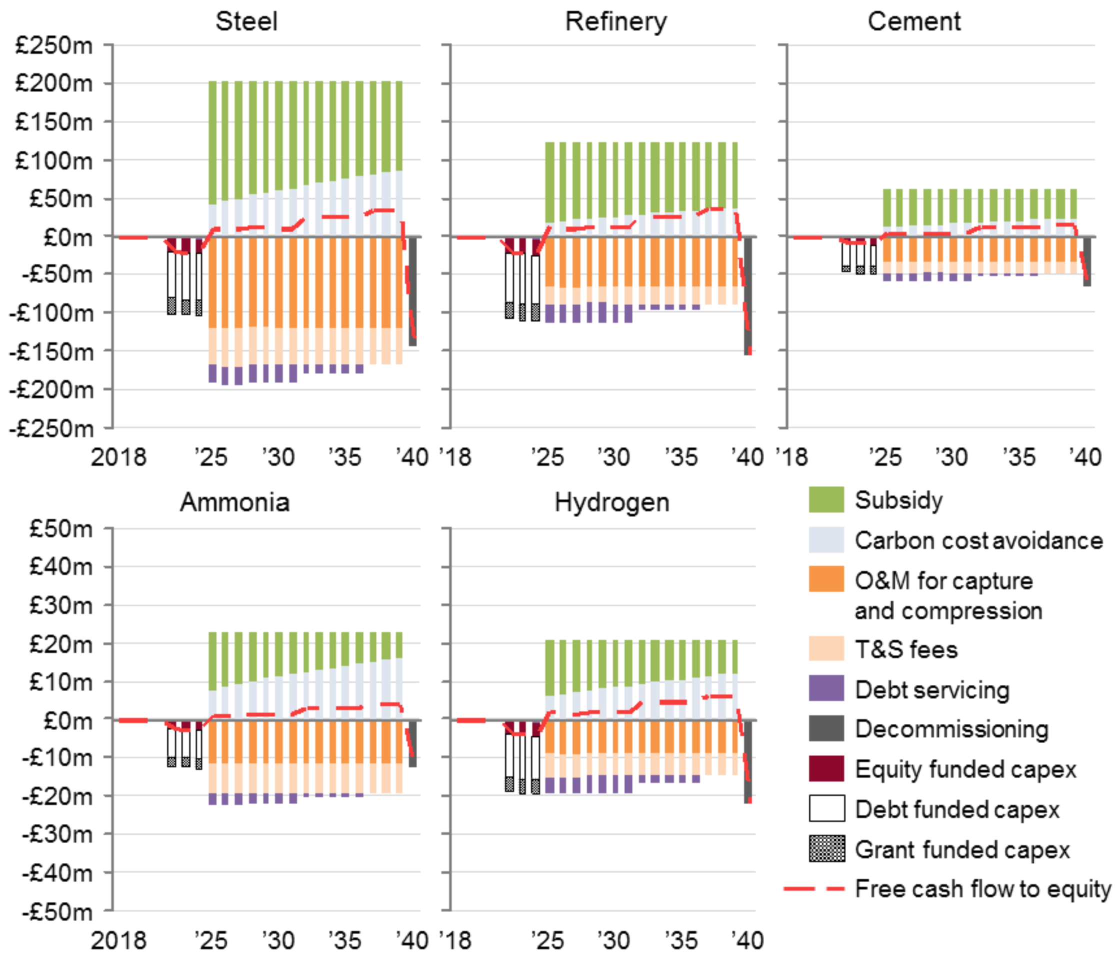

Figure 11: Emitter cash flows in Model 1.

The cash flow for the T&S Company shown in Figure 12 was obtained based on the transport and storage fees (£20 per tonne of CO_2 captured, split roughly equally between the two[48]) that the T&S Company must charge to achieve the target hurdle rate of 7%. Although the initial industrial cluster is not expected to continue operations past 2039, strategic government decisions mean that the public T&S Company can expect similar cash flows for the remaining 25 years. The long-term profits also justify the near-zero cash flows incurred by the public T&S Company while the first tranche of the loan is being serviced, a period throughout which government may have to provide additional equity. Differently from the private emitters and the private T&S operator in

[46] Although the loans and grants are shown on the costs side of these cash flows, these represent a revenue stream that the emitters use to pay for the capex. An alternative representation of the emitters' cash flows would include the total capex as a cost, as well as grants and loans as revenues.

[47] The shorter-term loan, supposedly offered by a commercial bank, carries an interest of 3.0%. The longer-term loan, considered representative of the advantageous conditions that multilateral organisations may be able to provide under the right conditions, has a rate of 2.5%. Both rates are lower than the emitters' hurdle rate (12%) and the social discount rate (4%), therefore lowering the capex NPV.

[48] The difference between the T&S fee value presented here and the T&S impact on the levelised cost of abatement is attributable to the difference between capture and abatement potential, as well as to the effects of discounting.

Model 2, the T&S Company does not require grants, as all its equity is effectively government funded.

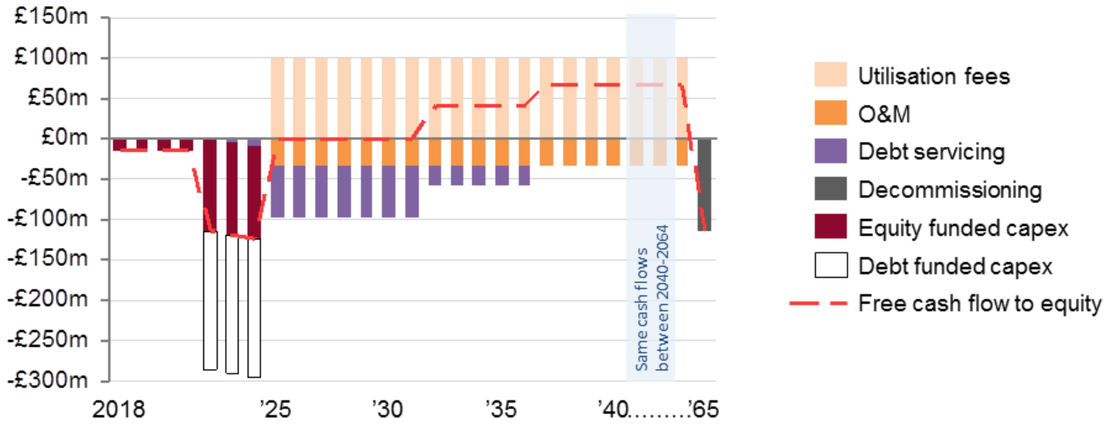

Figure 12: T&S cash flow in Model 1 (excludes 20-year monitoring period[49]).

Government perspective

The government cost of abatement was previously introduced as the discounted sum of the government costs over the total volume of abated emissions, and Figure 13 shows these costs – which in Model 1 are limited to grants and operational subsidies to the emitters – together with the additional equity transfer between government and the public T&S Company. Government's cumulative discounted cost amounts to £2.5B in NPV terms, but if the profits from the T&S Company (£0.3B NPV) are not offset from the total cost, the resulting discounted cost of abatement is £2.8b, which marries up to the £47/t figure presented earlier for a total CO_2 abatement volume of 60.5 Mt of CO_2.

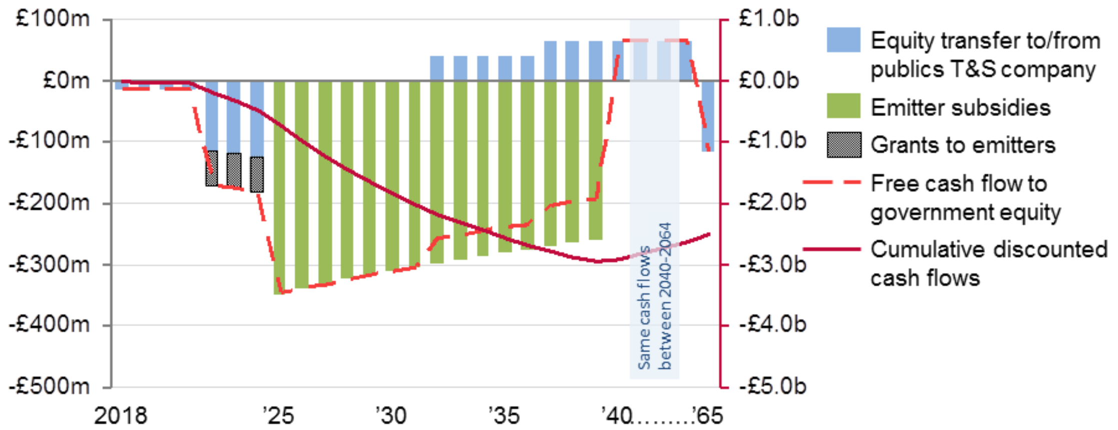

Figure 13: Government cash flow in Model 1.

[49] The monitoring costs are very small compared to the cash flows shown here, and their discounted impact is even smaller as they happen far in the future. For this reason, they are not shown here.

4.4 Model 2: Regulated T&S infrastructure

Business model overview

In Model 2, the transport and storage parts of the infrastructure are developed and operated by two separate companies[50] through a regulated infrastructure model such as the regulated asset base (RAB). An independent regulator is set up, tasked with regulating the revenues of (and hence the fees charged by) the infrastructure companies and with ensuring that they do not abuse their monopolistic position. The regulator should also coordinate the project delivery from the pre-FID phase, and should also mandate that the CO_2 pipeline network be oversized (as in all models). Either government or the regulator on their behalf provide the support measures discussed in Section 4.1 to decrease the overall level of privately held risk and guarantee regulated returns palatable to a wide range of infrastructure investors. The key features and the money flows for this model are summarised below: one of the unique features of this model is the fact that half of the transport and storage revenues are provided by means of capacity payments – government subsidies that only depend on assets' availability and that reduce the need for utilisation revenues (and hence the fees paid by the emitters) – and that the transport and storage companies are supported by government grants.

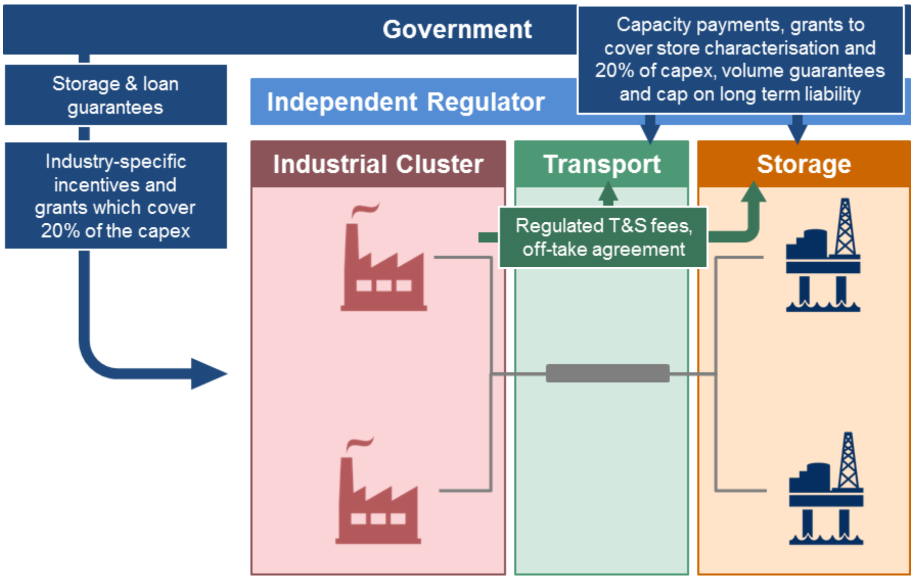

Figure 14: Summary diagram for Model 2.

Costs, revenues, and cash flows

The breakdown of levelised costs and revenues[51] shown in Figure 16 is largely similar to that presented in Figure 10 for Model 1, and in particular the capture and compression costs as well as the carbon cost avoidance are the same in all models. This is unsurprising considering that the industrial cluster and the capture plants' capex financing assumptions are the same in all models, hence any difference between the models can be imputed to the infrastructure side. Although the T&S fees only account for £8/t out of the £71/t of the average LCOA, if the government grants and subsidies in support of construction and operation of the T&S infrastructure are included, the total LCOA percentage imputable to T&S is seen to rise to £20/t, a 40% increase compared to Model 1. The first reason for such an increase is that the private T&S companies target a higher hurdle (12% instead of 7%), and this alone would increase the T&S fees by over 30%; furthermore, the fact that the private companies only account in their business case for cash flows up to and including the 15th year operations (25 years less than the public T&S Company is assumed to do) also implies a 30% increase in the fees. If it were not for

[50] In certain cases, a single company may be able to take responsibility for both.
[51] For all definitions, the reader is referred to Section 4.3 – *Model 1: Public T&S Company*.

the fact that grants provided cover 20% of the construction capex as well as 100% of the storage pre-FID expenditure, the overall cost of T&S would rise even further.

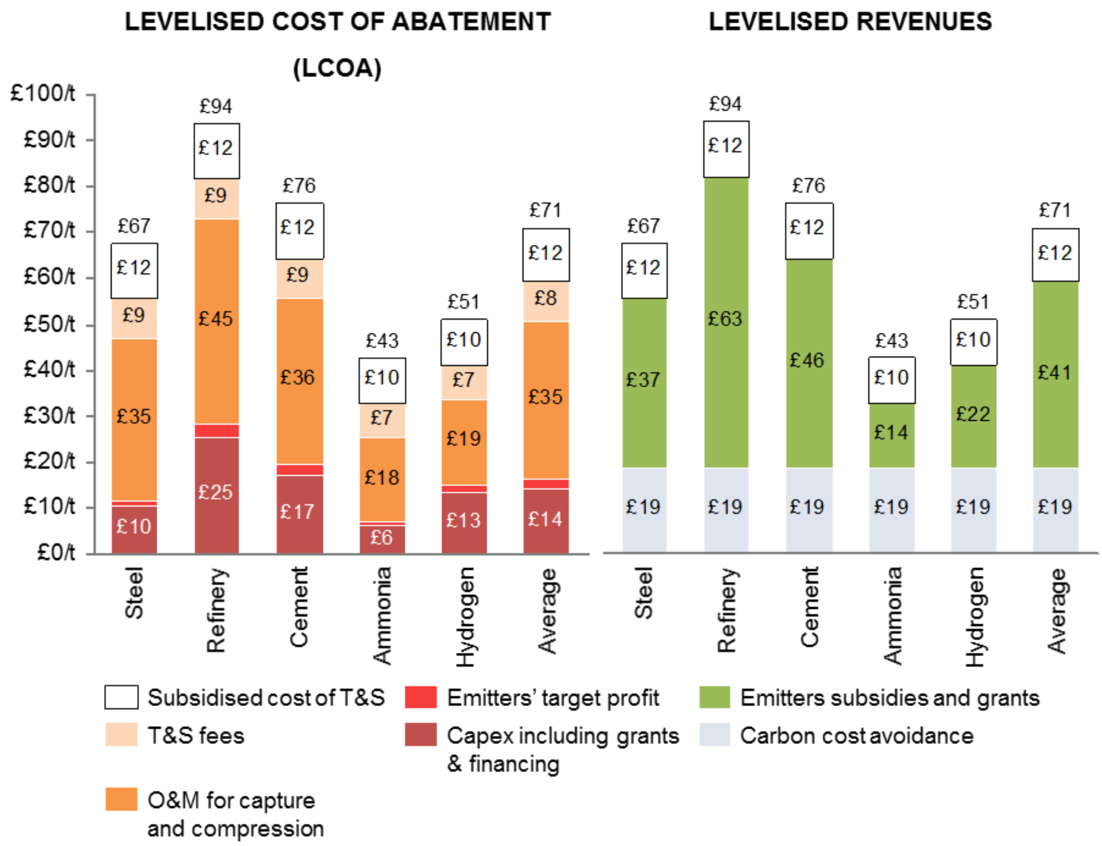

Figure 15: Breakdown of costs and revenues for Model 2.

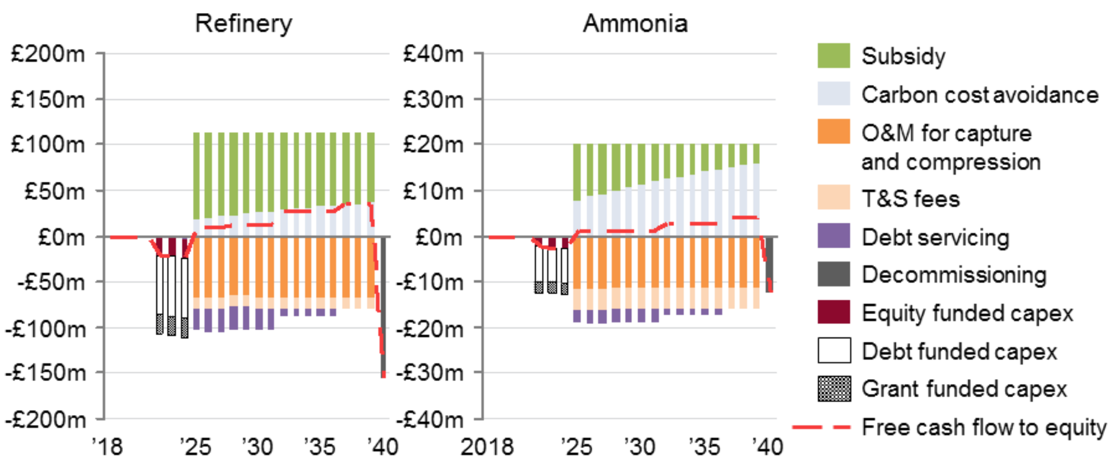

Figure 16: Emitter cash flows in Model 2.

Considering the similarity between the emitters' cash flows (both among themselves and across the different models), only two of them are shown in Figure 16: that of the Refinery and that of the Ammonia plant, requiring respectively the greatest and the least amount of government support. By comparing the emitters' revenues in the first two models, it can be seen that the carbon cost avoidance now represents a higher proportion of the total, a circumstance that is only possible because of the separate subsidies to T&S. The government cost of abatement is £53/t, an increase of 13% that supports the conclusion that the public T&S Company can provide the greatest value for money under the financial assumptions used here.

The most prominent feature of the T&S cash flows for Model 2, shown in Figure 17, is that capacity payments represent 50% of the respective revenues. Since these payments are independent of actual CO_2 volumes, they act as a partial guarantee for the infrastructure operators, whose revenues are therefore less dependent on the emitters' performance. Additionally, the storage cash flow shows that the storage characterisation is funded by government grants – an important risk mitigation strategy that was included in the model to comply with the public-private risk sharing requirements outlined earlier[52]. In conclusion, it should be noted that under the regulated asset base model it is probable that the T&S fees (£6.2/t for transport and £5.5/t for storage in undiscounted terms) would be periodically adjusted to reflect changes in cost, e.g. from the addition of new emitters, and to maintain a fair remuneration for the T&S operators. This may result in smoother cash flows than those shown below and may therefore also impact on the emitters' cash flows, although any cost changes are expected to be met by an equivalent adjustment to the emitters' subsidy[53].

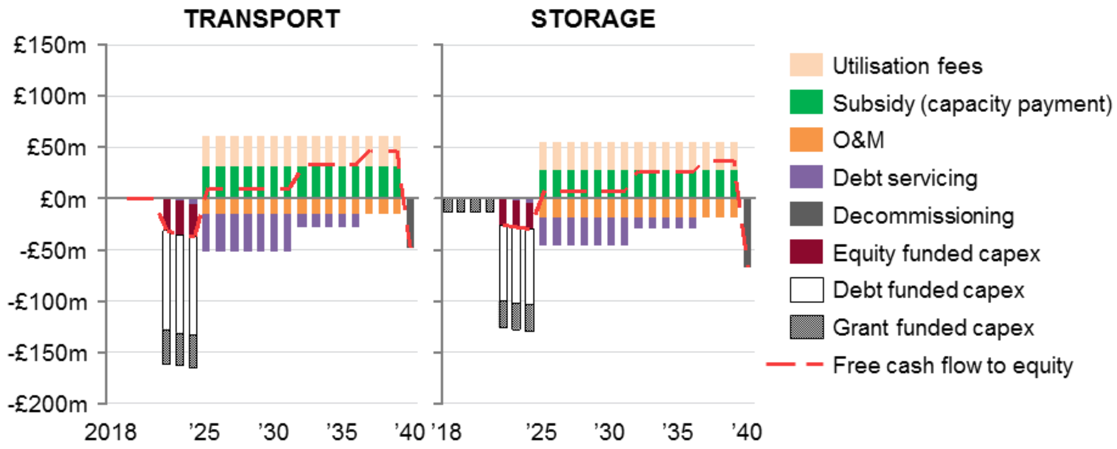

Figure 17: T&S cash flow in Model 2 (excludes 20-year monitoring period).

Government perspective

The government cost of abatement of £53/t, in which the emitter subsidies form the largest part, directly matches up with the total discounted cost of £3.2B shown in Figure 18 since any profits from the T&S operations remain with shareholders of the private regulated businesses.

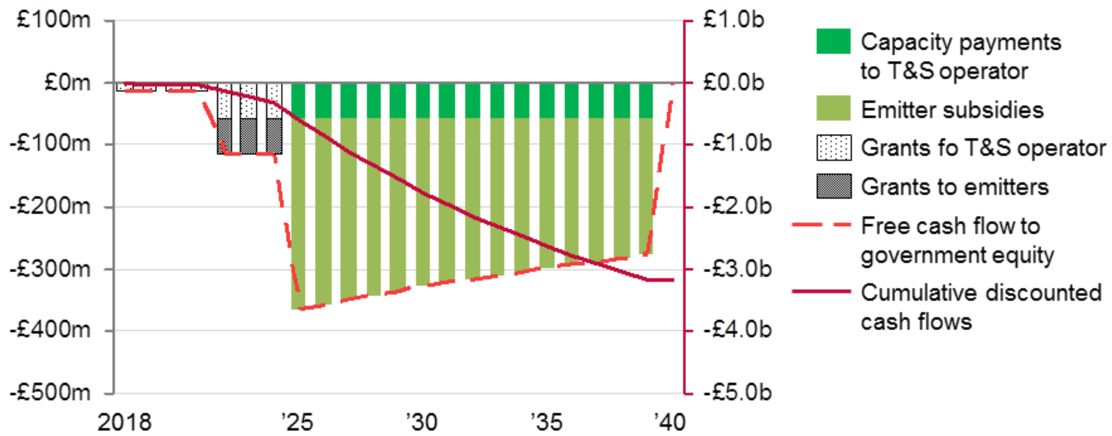

Figure 18: Government cash flow in Model 2.

[52] Alternative risk mitigation strategies are possible, for which the reader is referred to in Section 2.4.
[53] Or else the subsidy would fail to be cost-neutral, a requirement set out at the beginning of this chapter.

4.5 Model 3: Third party access to existing infrastructure

Business model overview

In Model 3, summarised in Figure 19, the investment in the already existing transport infrastructure is treated as a sunk cost fully borne by the anchor CCS project (via relevant government subsidies which are not in scope of this study), and while the industrial emitters are required to pay for connection to the trunk pipeline, they are only charged transport fees at marginal cost. Since the cost of CO_2 compression for onshore transport is already included in the emitters' operational cost, the marginal transport cost is assumed to only be linked with the electricity cost for the booster compressor for offshore delivery – a cost of just £0.3/t. Although investment in additional compressors might be required in practice, the simplifying assumptions used here permit the evaluation of the maximum cost reduction that can be expected from the availability of pre-existing T&S infrastructure – in other words, this is the best-case scenario for third party access. As for the storage costs, it is assumed that a new site must be developed for the occasion and all corresponding costs are fully recharged to the industrial cluster. These costs are taken to be identical to those experienced in Model 1, since it is also assumed here that the T&S infrastructure is owned and operated by government, but it is possible that the development cost of additional storage sites that are adjacent to the ones used by the existing CCS project would be cheaper than is estimated here.

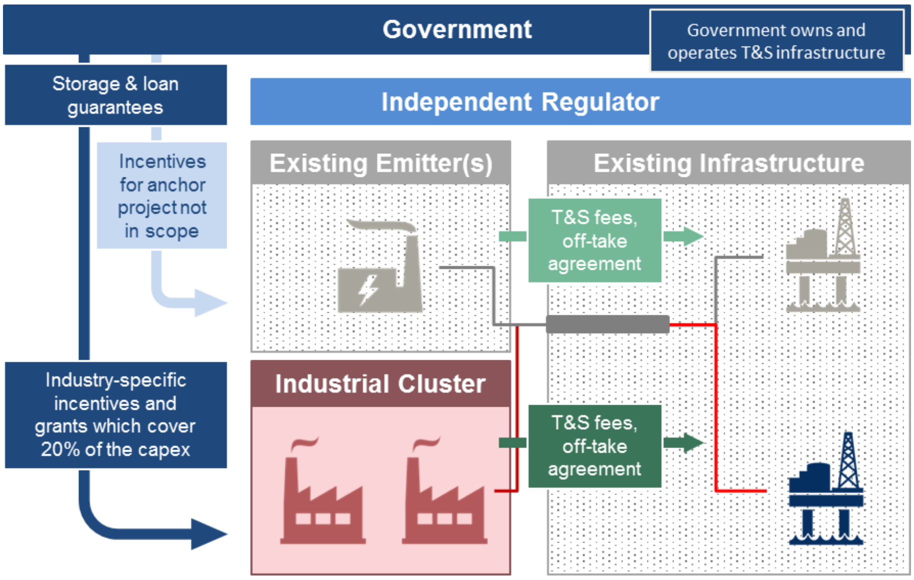

Figure 19: Summary diagram for Model 3.

Costs, revenues, and cash flows

The breakdown of levelised costs and revenues[54] shown in Figure 16 is largely similar to that presented in the previous models; in particular, the capture and compression costs as well as the carbon cost avoidance are the same in all models. Since only marginal costs are recharged for transport, the impact of the T&S fees on the average LCOA is reduced to £7/t, almost entirely attributable to storage. Thanks to the large reduction in the cost of T&S, the government cost of abatement is reduced to £40/t – the lowest level achievable unless additional revenues can be provided by the sales of CO_2 for utilisation purposes that lead to permanent geological storage (including CO_2-EOR). An interesting insight that can be drawn from looking at the Ammonia plant's cash flow shown in Figure 21 is that, in the later years of operation, CCS can be almost fully financed by the cost savings related to the avoided emissions (which pay for 60% of its revenues

[54] For all definitions, the reader is referred to the discussion of the first business model.

in total) – under more ambitious carbon pricing scenarios Ammonia could possibly join an existing CCS project with virtually no need for government subsidies.

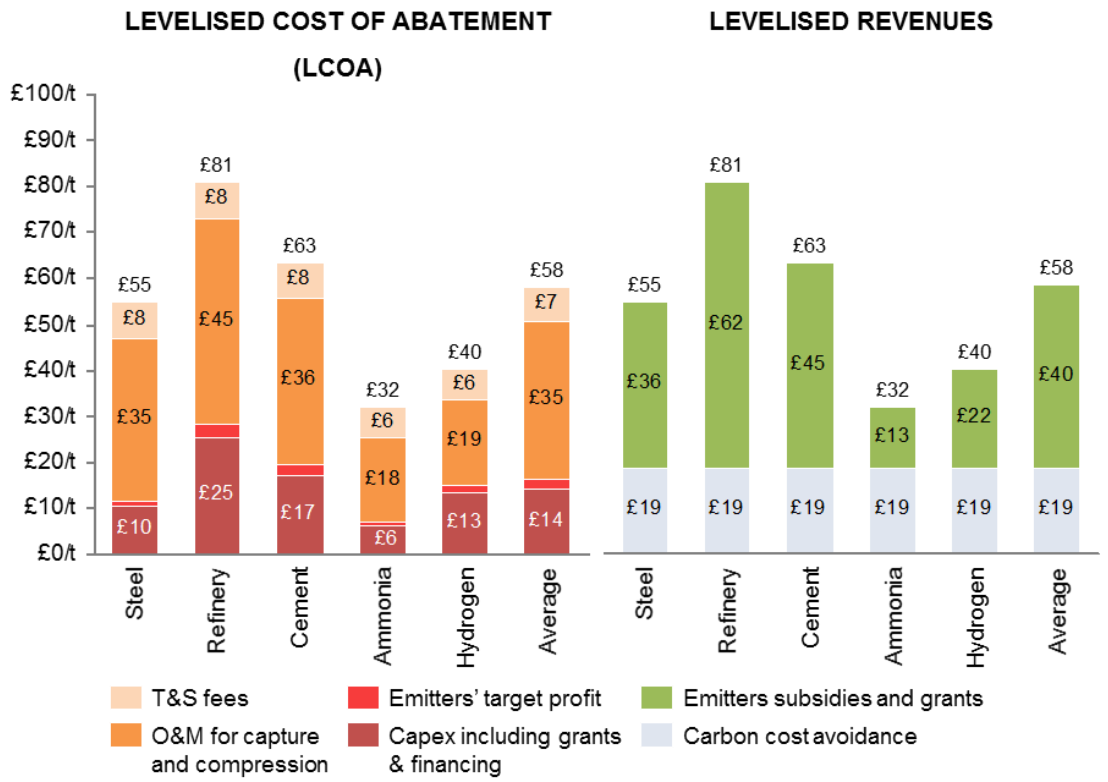

Figure 20: Breakdown of costs and revenues for Model 3.

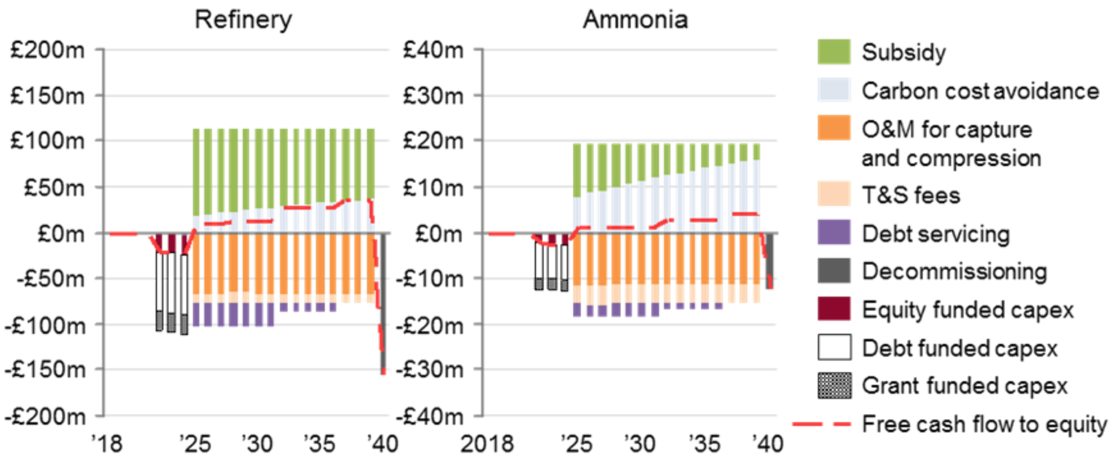

Figure 21: Emitter cash flows in Model 3.

Based on the assumptions outlined earlier, the combined T&S cash flow for Model 3 almost exactly matches the storage cash flow. This is because the marginal cost of transport results in a small transport fee of £0.3/t – almost negligible compared to the £10/t storage fee. It is also worth noting that, if the infrastructure to which the industrial cluster latches onto were operated under a regulated asset base model, and should the financial assumptions outlined for Model 2 stand, the storage fee would increase by 60% because of the greater profitability requirements of the private storage company, and because of the shorter timescale over which they would expect to achieve the targeted returns.

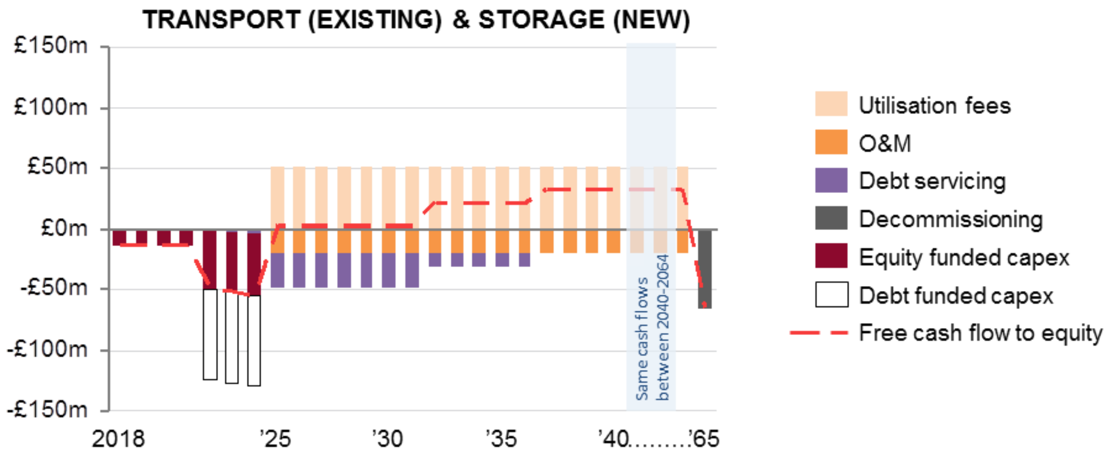

Figure 22: T&S cash flow in Model 3 (excludes 20-year monitoring period).

As is the case for Model 1, government benefits from the profits achieved by the public T&S Company, and by the end of the project should expect to have contributed just over £2B in NPV terms. Following on from the discussion in the previous paragraph, if the infrastructure were operated through a regulated asset base model the government cost of abatement would increase by 10% to about £44/t.

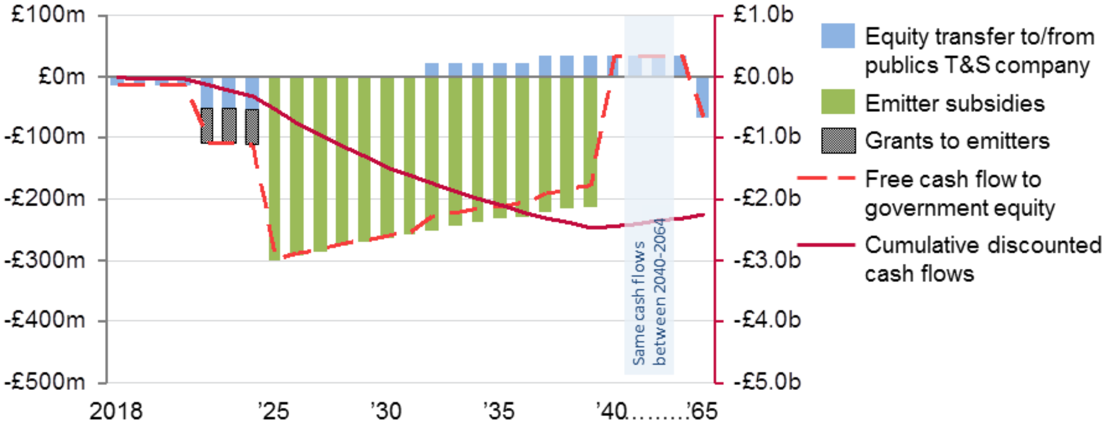

Figure 23: Government cash flow in Model 3.

4.6 Model 4: CO_2-EOR

Business model overview

In Model 4 it is assumed that CO_2-enhanced oil recovery (EOR) operations in the industrial cluster's region can cost-effectively be connected through a new pipeline network to the industrial emitters. Crucially, this implies that the alternative CO_2 sources that are available to the EOR operator would cost more to them than purchasing the CO_2 at £20/t (minus the cost of transport, which is passed on to the emitters while allowing for a hurdle rate of 12% as in Model 2). Perhaps even more importantly, there is an underlying assumption that the market price of oil[55] is suitably high to justify CO_2-EOR in the region, and that it is expected it will remain high for the duration of the project. Finally, it is worth reflecting on the diverging incentives naturally occurring to the two parties: the emitters aim to store as much CO_2 as possible, whereas the EOR operator prefers to minimise the volume of CO_2 stored, since this represents an operational cost. Regulatory intervention might be required to align the EOR operator's tax incentives to ensure maximum carbon abatement, but any incentive or regulation around this would need consider factors beyond purpose of this study[56].

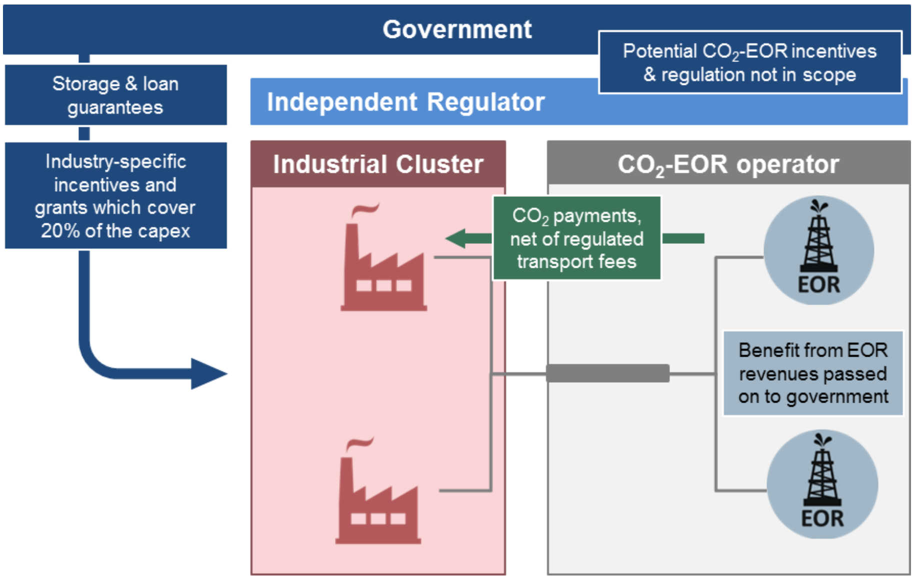

Figure 24: Summary diagram for Model 4.

The CO_2-EOR operator takes full responsibility for the construction and operation of the T&S infrastructure; no grants are provided towards the T&S capex, and the oversizing requirements set by the independent regulator are the same as in the previous models[57] – an assumption which is made for the sole purpose of allowing a transparent comparison between the four models. Although an assumption is made that all the captured CO_2 volumes are used for EOR, in practice this would greatly expose the EOR operator to the volume risk if the industrial cluster is their primary source of CO_2 – this is because any change in the industrial CO_2 flowrates might conflict with the EOR operator's commercial requirements.

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[55] If a different hydrocarbon is extracted, one could instead talk about enhanced hydrocarbon recovery.

[56] Additional concerns could be made around the limited timeframe available to owners of oil & gas fields for deciding to extend a field's lifetime and do CO_2-EOR. This present a strong regional limitation to the availability of such fields to CCS projects: final investment decision for the cluster project will likely need to be achieved 5-10 years before the end of the normal extraction operations, or else any CO_2-EOR opportunity might be missed.

[57] Similarly, the profits allowed for the investment in the transport assets are the same as in Model 2.

Costs, revenues, and cash flows

As in the previous models, the carbon cost avoidance provides a levelised revenue of £19/t that covers almost 40% of the £51/t LCOA. Conversely, T&S does not feature among the costs and in fact features as a revenue – that from the CO_2 sales. Although CO_2 is purchased for £20/t, the transport fees resulting from the unsubsidised investment offset over £15/t from this value, meaning that the levelised revenue ascribable to EOR is of £3/t. Considering that no T&S costs are charged to the emitters, this represents a net reduction in the LCOA and in the government cost of abatement of £20/t and £24/t respectively, compared to Model 2[58].

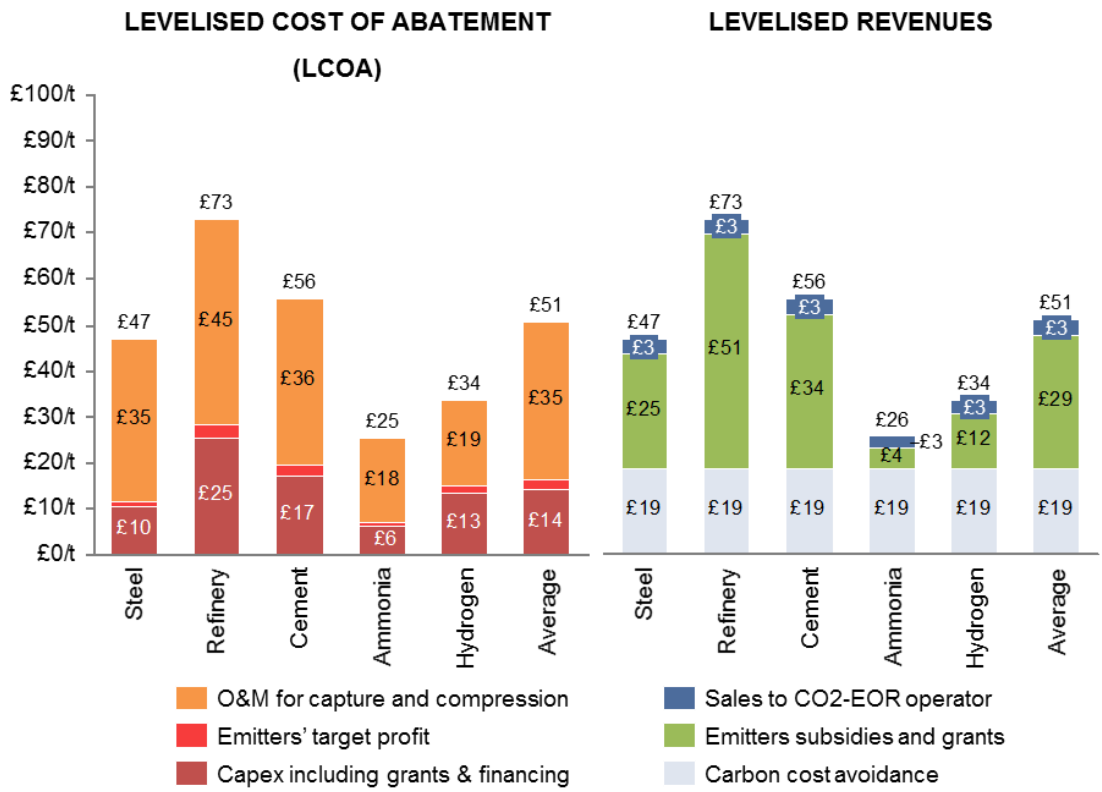

Figure 25: Breakdown of costs and revenues for Model 4.

Thanks to the large reduction in the cost of abatement, the cash flows of the Ammonia plant, illustrated in Figure 26, lead to a 14% rate of return which exceeds the profit targets – this is caused by the increased cash flows throughout the last 5 years of the project. It is insightful to note that any other measure that can decrease the cost directly borne by the emitters can lead to increased emitter profit, so long as the price of carbon achieves a suitably high value at some point during the project's lifetime. As an example, if government decided to offer free access to the T&S infrastructure, a lower CO_2 price guarantee would need to be established to back-up the subsidy, hence making it easier for the prevailing price of carbon to cross the lowered threshold.

Government perspective

As it was mentioned earlier, the subsidy required by the emitters in Model 4 is reduced by £24/t in NPV terms, because the T&S costs are fully borne by the CO_2-EOR operator. The additional CO_2 payments further offset the need for government subsidies up the point beyond which the profitability of the lowest-cost-of-capture emitters increases instead. Thanks to this, government can now expect to spend less than £2B in NPV terms. Certain governments might also include the additional tax revenues (or oil revenues if state-owned oil companies exist) in their assessment to justify the subsidies required for CCS operations.

[58] Model 2 is used as comparison as it is the only other case in which T&S is not owned by government.

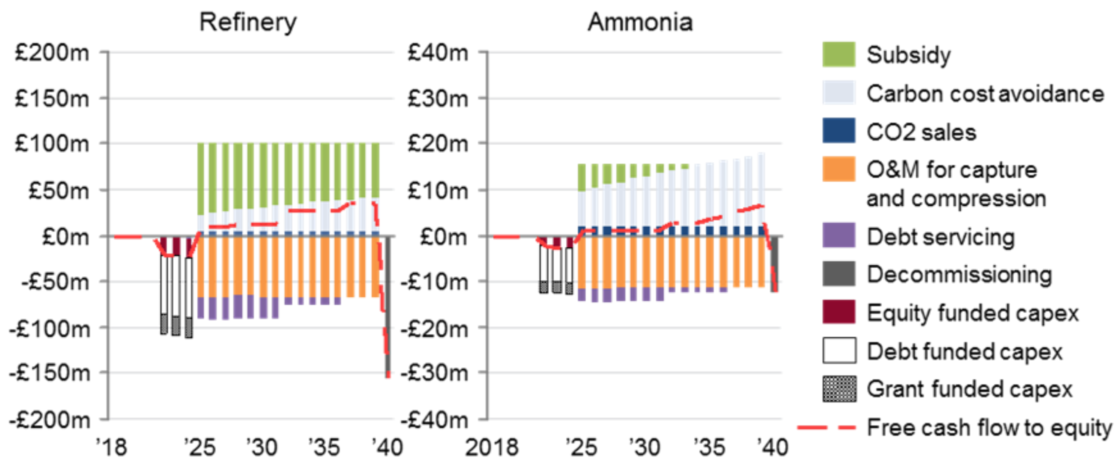

Figure 26: Emitter cash flows in Model 4.

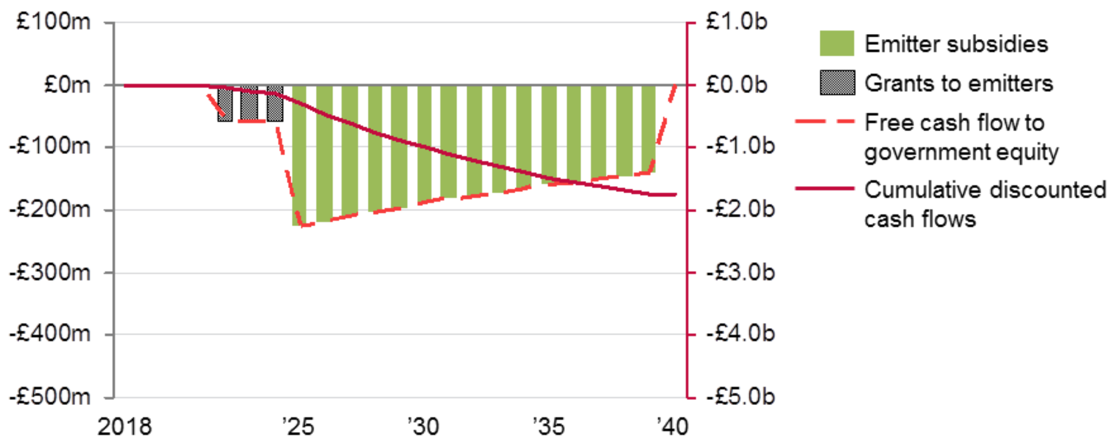

Figure 27: Government cash flow in Model 4.

4.7 Quantitative risk assessment

At the beginning of this chapter, a set of three required government guarantees was introduced: storage guarantees to the emitters, volume guarantees to the T&S operators, and loan guarantees to the lenders. These measures do not interfere with the project cash flows unless disruptive events occur, and they are therefore merely held in stand-by in the base case modelling presented up to this point. This section investigates what happens when some of the key project risks materialise, with the aim of revealing the indispensable role of government guarantees. Through the quantification of the financial risk to which the various project parties are exposed, it should become clear why investors and shareholders alike would most certainly choose to not be part of an ICCS cluster project without these guarantees, as the daunting prospect of cross-chain default looms over any business case not suitably protected against the risks discussed next.

To quantify the maximum financial loss[59] that may by suffered by the project parties under the three investigated scenarios, the assessment is initially conducted on models stripped of offtake agreements[60] and of all government guarantees, the role of which is then evaluated by considering the change in the government cost of abatement if guarantees covering 100% of the

59 The loss expressed in net present value (NPV) terms, using the same social discount rate of 4% to represents the cost to government should they ultimately bear all losses. If this was not the case, the different parties would actualise their individual losses using discount rates comparable to their commercial rate of return.

60 The effect of the offtake agreements is merely to redistribute the loss among the project participants, rather than to contain it.

project losses are offered. In any real project, a thorough negotiation process will be required to determine which risks are covered by guarantees and the extent to which government should absorb the project losses, but for greater clarity, the analysis below presents two extreme cases in which the losses are born by either the project companies or by government.

Illustrative risk 1: storage failure in Model 1

Should a storage site be deemed unsuitable for permanent CO_2 storage after completion of the construction works (which is very unlikely), the storage developer (the public T&S Company in Model 1) will incur additional costs for the development of a new store[61] as well as missing out on the asset utilisation fees throughout the unplanned delay period, which is here assumed to last 3 years. Net of the avoided costs, the T&S Company experiences a NPV loss of £330m whereas the unplanned emissions cost the industrials £260m[62] – the resulting cash flows are shown below.

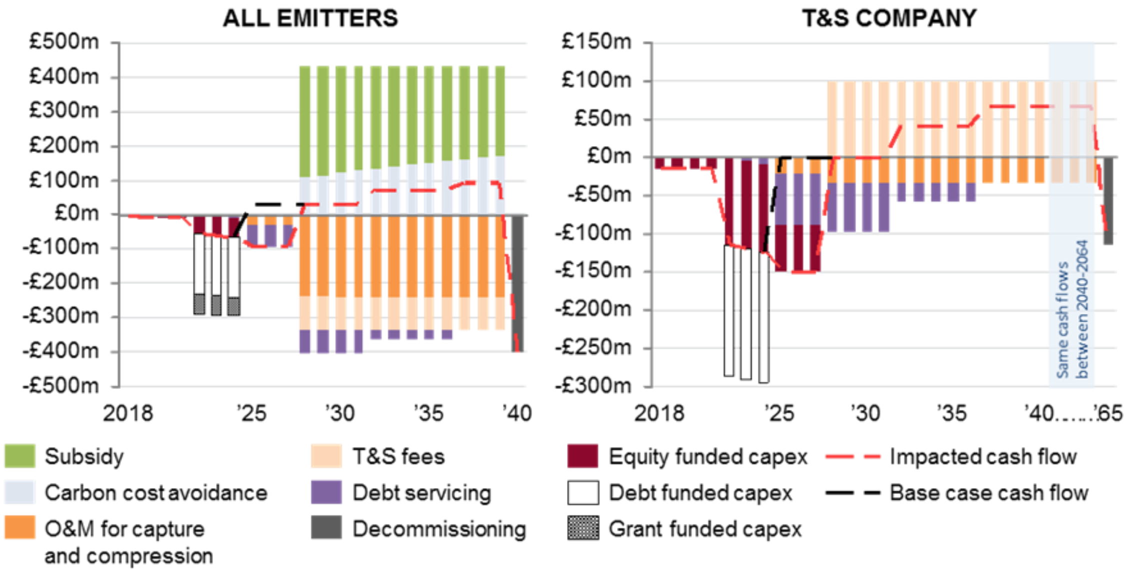

Figure 28: Emitter and T&S cash flows in the event of storage failure.

Assuming government offers the guarantees discussed earlier and absorbs the entire costs shown above, their share of the cost of abatement can increase by up to £8.5/t, or 18% more than the original business case, because of a 20% reduction in the volume of CO_2 abated. Although no subsidies are paid out during the 3-year delay, the loan guarantees mean that government is responsible for paying up to £290m to the project lenders (equally split between lenders to emitters and to the T&S Company), as well as up to £115m and £185m respectively to the emitters' shareholders and to the T&S Company to reimburse them for the lost cash flows, as stipulated by the storage and volume guarantees[63].

Without suitable loan guarantees, the emitters and the T&S Company might default on the loans, and prospective lenders will either price this risk accordingly or not invest in the project if they consider the risk too high to price. Instead, the equity losses experienced by the project parties in the absence of storage and volume guarantees would be such that they would never be able to break even on the original investment, hence they would increase the hurdle rates to ensure that

[61] It is here assumed for simplicity that the capex for the second store development is 50% that of the first, since it is possible that part of the existing assets will be reusable (e.g. the offshore platform, if one is used).
[62] Since no CO_2 can be captured due to storage unavailability, the emitters do not benefit from subsidies and cost avoidance, and the T&S Company does not receive any utilisation fee. At the same time, the variable costs can be assumed to be zero, whereas not all the fixed costs can be avoided as they may be tied up in existing contracts (e.g. with suppliers) – the modelling assumes the residual costs to amount to 50% of the fixed costs.
[63] The term "up to" is used here because all guarantees may only cover a portion of the liability. Hence the value indicated represent the maximum cost to government.

a reasonable profit can be made also in the eventuality that this risk materialises. Finally, the magnitude of the losses described above is such that some parties may be led to bankruptcy, an eventuality (explored in the third risk assessment below) that would cause much greater than the ones anticipated here to all remaining parties. Because of these reasons, it is understandable why the prospects of unmitigated losses might prevent investment in ICCS in the first place. In conclusion, it is suggested that the storage failure risk might alternatively be mitigated through the development of back-up storage simultaneously to the main one, a solution which would initially increase the capital investment in T&S but could be cost-effective as it greatly shortens the delay before CCS operations can start.

Illustrative risk 2: decreased consumer demand in Model 1

In Section 2.1 it was mentioned that future policies to address the risk of carbon leakage may enable industrial emitters to pass part of the emission charges on to consumers, which means that the price of industrial products would increase together with that of CO_2 whether an emitter implements CCS or not. Because of the increase in the sales price, demand for carbon intensive products may decrease – a phenomenon known as **price elasticity of demand**. Following a simplified approach, this illustrative case study assumes that demand for all the industrial products decreases by 2% per year[64]. Thus, the industrial emissions decrease over time, as shown on the revenue side of the emitter cash flows in Figure 29, leading to underutilisation of the T&S assets.

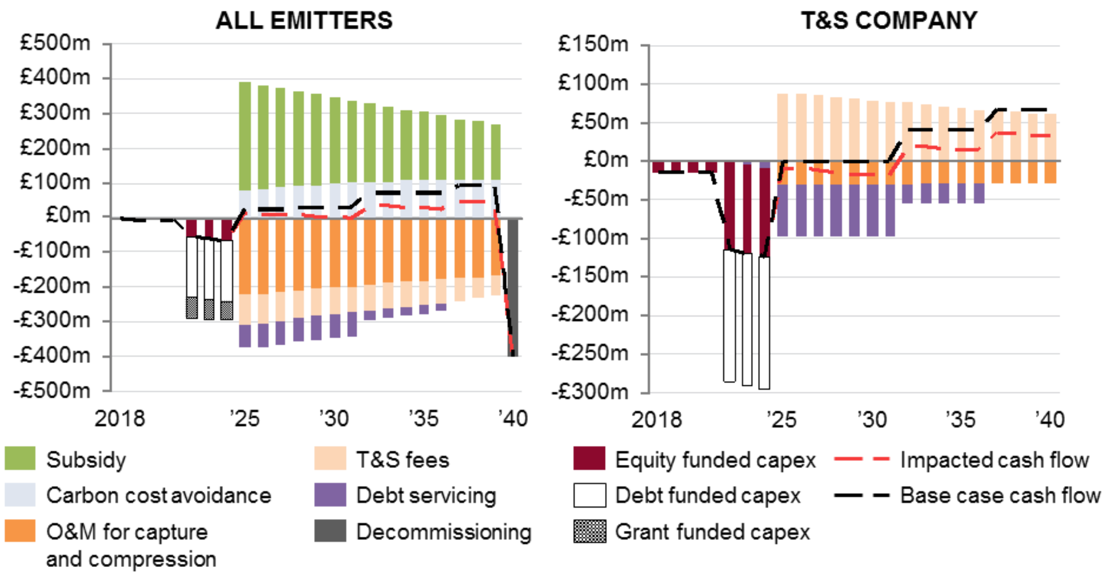

Figure 29: Project cash flows if consumer demand decreases over time.

Due to the missed revenues and net of the reduced operation costs, the emitters' and T&S Company's profits decrease by £290m and £350m respectively and, if government absorbs all these costs, government's cost of abatement increases by over £17/t, 37% more than in the original business case in response to a 24% reduction in the volume of CO_2 abated. In this case, the loan guarantees would transfer up to £65m of the T&S debt servicing costs (corresponding to the portion of the loan at risk of default between 20205-2032) to government. Conversely, the remaining T&S loss of £285m may need to be compensated as stipulated by the volume guarantees, whereas the emitters' loss of £290m would be reimbursable because of the subsidy support mechanism introduced in Section 4.1. Once again, the substantial magnitude of the potential losses would cause the affected party to reconsider investment in CCS unless suitable guarantees are available. In addition to confirming the importance of loan and volume guarantees, this case study highlights the **need for a subsidy support mechanism providing minimum payments if the production volumes decrease below baseline**, in the absence of which the

[64] Although this corresponds to a different price elasticity of demand for all emitters, this assumption is used here for the sake of simplicity, rather than exactness.

emitters would be forced to negotiate a higher CO_2 price guarantee to better protect their profit margins.

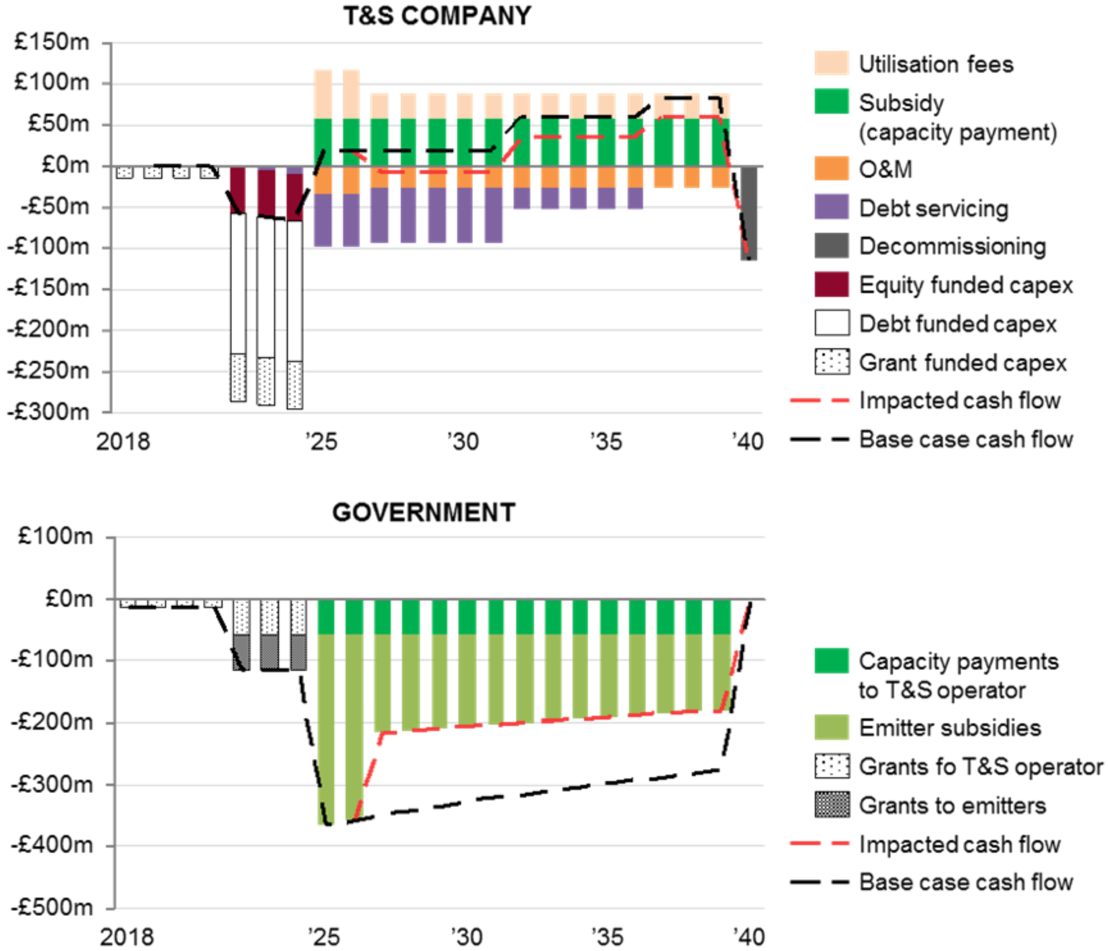

Figure 30: T&S cash flow in the event of emitter's default.

Illustrative risk 3: industrial emitter's default in Model 2

In the third and final case study, the largest emitter (the steel plant) is assumed to go bankrupt after the second year of operation because of excessive non-rechargeable costs arising from the CCS operations. Both the private T&S Company (Model 2 is used for this case study) and government suffer from the loss of emitter. The former receives lower utilisation fees in response to the halving of the captured CO_2 volumes (but the abatement reduction is limited to 43%[65]), whereas the latter is committed to the payment of capacity-based subsidies to the former despite the reduction in carbon abatement. The steel plant's shareholders lose £270m in future profits since the CCS operations only last two years, and they may be unable to service the remaining portion of the loans, which add up to a further £100m. At the same time, the T&S Company's profits decrease by £240m, and may be unable to service £20m of their debt in the years between 2027 and 2031 (this corresponds to the magnitude of the negative cash flows in those years, as illustrated in Figure 30). If government is liable for the above losses because of the loan and volume guarantees offered, their share of the cost of abatement may increase by up to £33/t.

Model 2 was selected for this case study to highlight that, thanks to the fact that **capacity payments act as a partial volume guarantee**, the private T&S Company' exposure to the counterparty default is partly mitigated. Finally, it is worth highlighting that although the other emitters are not affected in this case study, the T&S fees may be readjusted as is likely to be

[65] The steel plant captures half of the industrial cluster's emissions, but abates a smaller percentage since, for reasons discussed on page 19, its abatement potential is lower than the cluster average.

stipulated under the regulated asset base agreement. If this happens, the T&S Company's loss would be in part redistributed to the emitters.

Without government guarantees, all models are at risk of default

The three case studies discussed above point at the need for suitable guarantees in protection of shareholder's profit margins and loan repayments. At best, without these guarantees investors might request substantially higher returns to counterbalance the increased risk exposure. At worse, the investability of the business models presented in the previous chapter would be irreversibly compromised.

In conclusion, since government pays for any increase in the cost of abatement – the revenue from carbon cost avoidance is fixed – it is in their interest to ensure that ICCS projects can provide value for money, which may only be achieved if the private parties do not demand very high rates of return. Although the guarantees described would successfully reduce the expected rates of return, it is recognised that the emitters and the T&S Company may be perversely incentivised to take unnecessary risks unless they also share the consequences. For this reason, the right balance must be struck via negotiations to achieve a fair allocation of responsibility to all parties.

5. GOVERNMENT PERSPECTIVE

In Chapter 3 the case for government intervention in support of industrial CCS projects was brought forward, and the previous chapter explored four models that, also thanks to government support, present an investable business case capable of rewarding all parties while committing them to long-term carbon abatement. Having looked at each of the models individually, this final chapter aims to provide a comparative review to determine whether any of the models analysed might be preferable to different governments, either from a "value for money" perspective or because of specific geographical characteristics and national preferences.

5.1 Value for money

To transparently compare the merits of the different business models (or of other decarbonisation measures), government should assess value for money based on the (discounted) price that they must pay per tonne of CO_2 abated. This was introduced earlier as the government cost of abatement, a measure that accounts for all subsidies (capital and operational) paid by government to any project party. Comparing the four business models, Figure 31 shows that the government cost of abatement ranges from £29/t (Model 4) to £53/t (Model 2), which is in all cases well below the average cost that government may need to pay to achieve the 2050 decarbonisation targets, and lower than the cost of offshore wind subsidies parties (see Case Study Box on page 18).

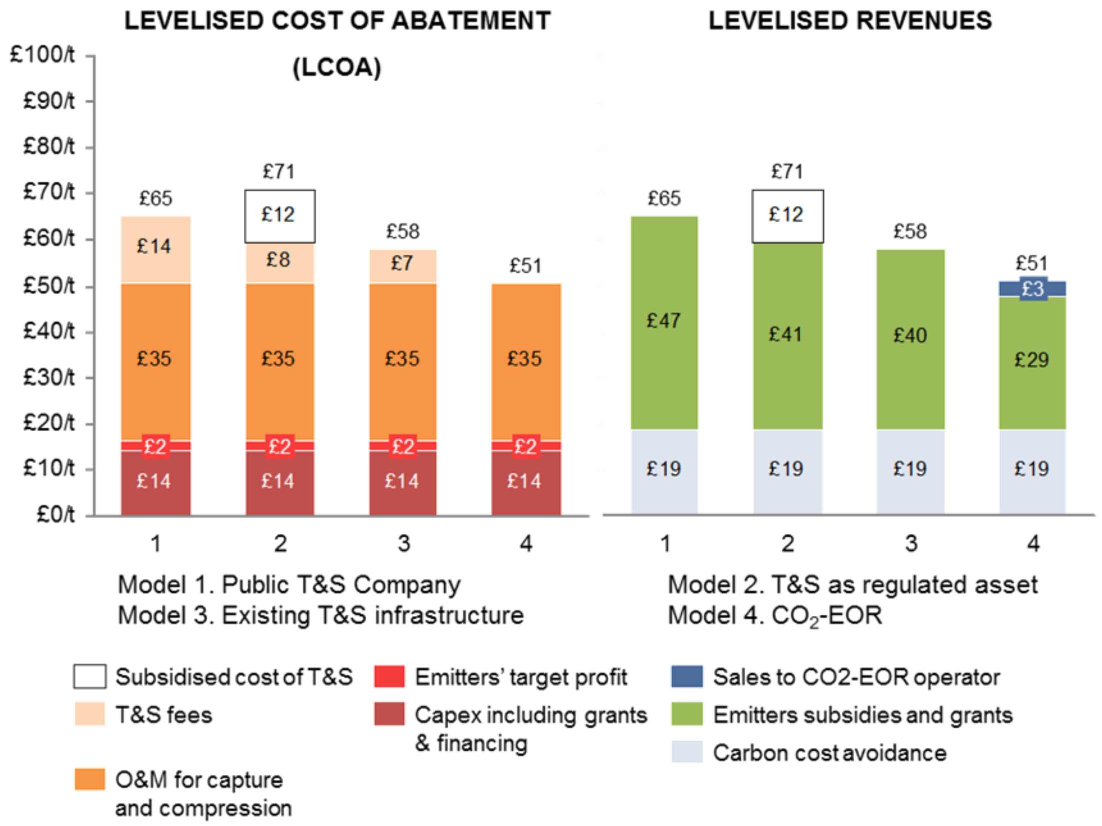

Figure 31: Comparison of levelised costs and revenues across the four models.

Greater cost effectiveness is achieved by models that can reduce the cost of T&S, since the capital and operational expenditures for CO_2 capture and compression are the same in all models[66]. The three key findings from this comparison are that:

[66] This is so by design, since the same industrial cluster is modelled in all cases.

1. CO_2-EOR can greatly reduce the cost to government, although even by using the generous assumptions set out in Section 4.6 it is by itself unable to fully erase the need for subsidies, which still cover almost 60% of the levelised cost of abatement (LCOA). However, this does not account for the emissions arising from the use of the recovered oil, nor does it account for the corresponding tax revenues;
2. If no CO_2-EOR is possible, third party access to existing CCS infrastructure offers the lowest cost solution;
3. Thanks to the public T&S Company's lower profitability requirements and its ability to strategically account for future profit (beyond the 15 years of subsidised operation for the initial cluster), it is more cost-effective to establish a public T&S Company than tasking a private one with construction and operation of the infrastructure. While this may not be considered a viable option by certain governments, business models where the initially public T&S Company is later privatised could be conceived, and this might improve the project's political acceptability.

Based on these considerations, it is expected that regions where CO_2-EOR is available will rely on this additional revenue stream, but it should not be forgotten that value of this proposition is highly dependent on the market price of oil[67], which adds a substantial risk to the business case's long-term stability. Additionally, sensitivity analysis around the price paid by the EOR operator for the captured CO_2 reveals that, if they only offered to store CO_2 "for free" (and charge the same transport fees as in Model 4), government would not be paying significantly less than if they established a public T&S Company (Model 1), thus making it difficult to justify the additional risks posed by the oil's price long-term volatility.

For any region without EOR opportunities, the second point supports the argument that the infrastructure of initial CCS projects should be suitably oversized, or else it will not be possible to achieve the economies of scale required to greatly reduce the average cost of abatement of future CCS projects. Finally, it is worth noting that, since T&S never accounts for more than 30% of the overall cost, the cost variation between all models is small compared to the absolute magnitude, which suggests that possibly larger cost reductions can be achieved by impacting on the cost of capture and compression.

5.2 Government levers to decrease the cost of abatement

Under the assumptions set out in the previous chapter, government funds provide much of the project revenues in all models. Despite this, government can greatly reduce both the overall cost of abatement and the magnitude of the subsidies by acting on two levers:

- By implementing policies to increase the price of carbon – and after having addressed the risk of carbon leakage – government can ensure that most of the project cost is passed on to consumers[68], rather than paid for via subsidies;
- By offering sufficient guarantees, the financing conditions can be improved and the average cost of capital be lowered. Similarly, grants further lower the cost of capital and hence reduce the project's cost.

Policies to increase the carbon price greatly reduce government cost and may provide a great opportunity for investors in industrial CCS

Figure 31 previously showed that the carbon cost avoidance always provides levelised revenues of £19 per tonne of CO_2 abated, but this revenue is highly dependent on the underlying carbon price, which was set to match available projections on the price of the EU ETS allowances. By implementing policies that increase the carbon price to a level consistent with that required in the

[67] And on the price of any other hydrocarbon that may be extracted as part of the tertiary recovery.
[68] This assumes that a solution to carbon leakage is implemented, as discussed in Section 2.1.

UK to meet the 2050 target (see page 13), most of the project revenues could be provided by cost avoidance, thus decreasing the government cost of abatement by nearly 80% (to £11/t, using Model 2) compared to the base case. Conversely, Figure 32 shows that if no carbon cost was charged to the emitters, the government cost of abatement would increase by 40% (to £75/t). To improve any[69] decarbonisation project's value for money, government should therefore implement policies that increase the price of carbon (e.g. a carbon price floor or tax). In addition to reducing government's cost of abatement, a high carbon price also offers a substantial opportunity to all emitters: as shown below, their cash flows increase above the level guaranteed by the subsidy as soon as the price of carbon surpasses the CO_2 price guarantee[70] and, in this example, the emitters generate a rate of return of 28%, much higher than their 12%

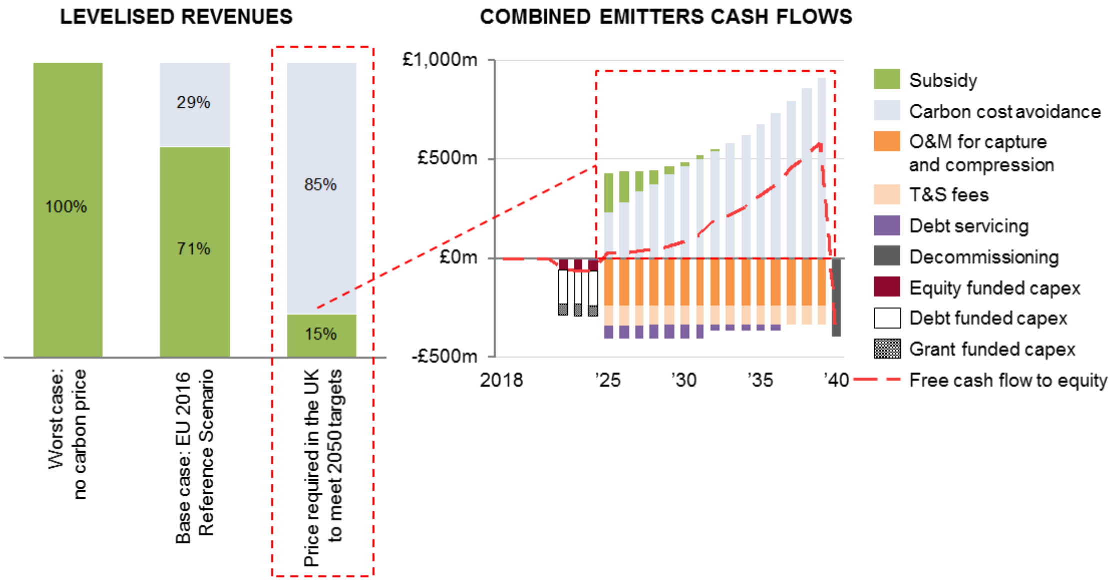

Figure 32: A high carbon price decreases the cost to government and offers a great opportunity to the industrial emitters.

Grants and loans can halve the cost of the investment

The second lever available to government to reduce the cost of abatement is to actively reduce the cost of capital, which can be done by increasing grant funding and by ensuring that third party financers are not exposed to excessive risks. As an example, if the entire capture plants capex (£880m) were funded via grants, the corresponding levelised cost would be equal to £15/t for a CCS project active for 15 years and which avoids the emissions of 60 Mt of CO_2[71] – this is shown on the right-hand side of both charts in Figure 33. Two scenarios are discussed here:

1. In the first one, loans are available to contribute up to 60% of the capex and their interest rate (4%) is equivalent to the social discount rate;
2. In the second one, no loans are available and shareholder equity funds the portion of capex that is not funded via grants.

In the first scenario, as the grant funding percentage decreases from 100% to 40%, the levelised capex does not change since the loan's interest is offset by the effect of discounting. Conversely,

[69] Carbon pricing incentivise all decarbonisation measures, not just ICCS.
[70] The function of the CO_2 price guarantee is explained on page 16.
[71] The assumptions used in these case study only partly match those of the business models discussed previously, hence the results do not match exactly. While the capture capex, the abatement potential, and the emitters' hurdle rates are the same, the loan interest rates and the project timing have been changed for simplicity. Interest rates above the social discount rate will increase the levelised capture capex, whereas cheaper loans will decrease it. The social discount rate is 4% as in the rest of the study.

since a hurdle rate of 12% is assumed on the shareholders' equity, the levelised capex increases rapidly: compared to the case where 100% grant funding is provided, if no grants are available the levelised capex increases by 65% in the first scenario and more than trebles in the second. Since the difference between the two scenarios is imputable to the difference between the loan's interest rate and the shareholders' hurdle rate, government should primarily ensure that debt can be made available to the industrial emitters, which entails the provision of sufficient loan guarantees. Finally, government should offer grants to the greatest extent possible if its primary aim is to further reduce the cost of the project.

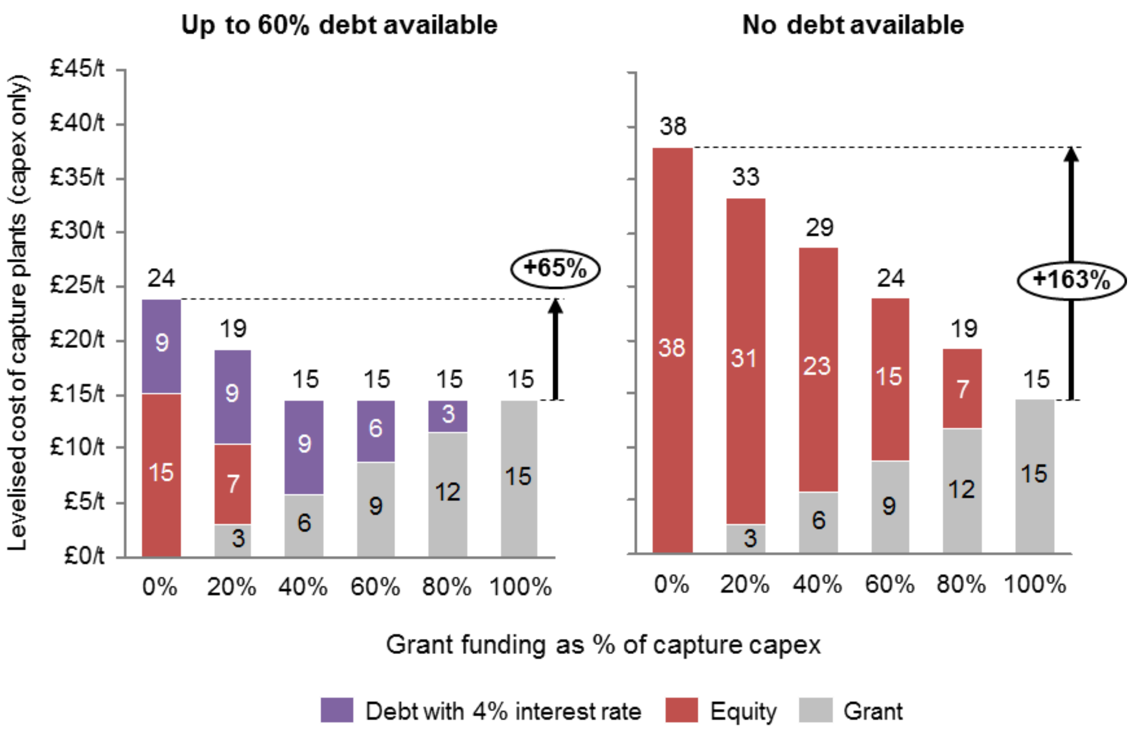

Figure 33: The levelised cost of abatement decreases with grant funding.

It is worth highlighting that the reception of public funds such as grant is often accompanied by additional project requirements such as for additional reporting, and may also include additional such as knowledge transfers which would not be otherwise required for the project execution. These additional requirements would add further cost to the project, but are not explicitly assessed in this study as no model was found to be fully viable with public funding, and hence or models would be similarly affected by the additional requirements.

5.3 Regional considerations

Despite regional differences, the selected business models can be adapted to suit national preferences in all regions of interest

The business models presented in this study were reviewed by government representatives and/or other CCS stakeholders from Europe, North America, China, and Australia[72]. Based on their feedback and on publicly available information[73], it was determined that while not all models are viable everywhere, at least one of them is feasible in each country and, additionally, specific features of the various models can be combined to create the most relevant models for each region. This section provides a brief review of the geographical and regulatory features – including

[72] A complete list of the interviewees is included in the acknowledgments section. Even though the USA and Canada share some similarities (especially in relation to the availability of onshore EOR), the regulatory differences between the two countries warrant a separate review.
[73] All policy information was obtained from IEA's policy database: www.iea.org/policiesandmeasures/.

any available financial support mechanisms – that may influence the development of future ICCS projects in the regions listed above.

USA

With 8 large-scale projects[74] in operation and 4 in other stages of development, the USA host the largest number of large-scale CCS projects globally, and 11 of these projects are linked with CO_2-EOR. In the USA, CO_2-EOR has historically been justified by the availability of cheap CO_2 from natural reservoirs, which resulted to date in the creation of a 4500-mile-long CO_2 transport infrastructure[75]. This suggests that CCS in the USA is primarily (financially) motivated by EOR, although the Federal Government has in the past provided funds to support CCS projects. Additional revenues are available through the CCS Tax Credit known as *Section 45Q*, which offers $20 for each tonne of CO_2 deposited in secure geological storage, or $10/t if the CO_2 is used for EOR. Additional state-level incentives for CCS (capital and operational) are detailed by the Centre for Climate and Energy Solutions[76], and worthy of note is the recent provision of a conditional loan guarantee of up to $2 billion by the U.S. Department of Energy to Lake Charles Methanol, LLC to be used for the construction of a large methanol production facility which, if successfully completed, will be the World's first one to employ CCS[77].

Amongst the federal policies that might be relevant to CCS[78] we highlight: *Climate Action Plan*, *Clean Power Plan*, *Final Carbon Pollution Standards for New, Modified and Reconstructed Power Plants*, *Clean Coal Power Initiative Program* (which contributed up to $190m to the funding of the Petra Nova project). Additionally, CCS could help the USA deliver their Nationally Determined Contribution to the Paris Agreement, which includes an economy-wide target to reduce greenhouse gas (GHG) emissions by 26-28% below 2005 levels in 2025.

Based on the above, it is reasonable to expect that, early industrial clusters may join the extensive CO_2 transport network and that the captured CO_2 will be used for EOR. The direct state ownership of the T&S business is unlikely to be a viable option in the USA. The most relevant business model for the USA would therefore need to be adapted from features of model 2 (regulated CO_2 infrastructure), model 3 (access to existing infrastructure) and model 4 (CO_2-EOR).

Canada

Out of the 5 large-scale projects that operate or are currently under development in Canada, 4 destine the captured CO_2 to EOR, for which an extensive pipeline network exists. To this extent, Canada is not dissimilar from the USA, and it is reasonable to expect that future industrial clusters may join such CO_2-EOR network. In order to understand whether CCS could be part of the national decarbonisation strategy, it is important to consider that Canada ranks third in the World for its proven oil reserves[79], most of which are in the province of Alberta, and holds large reserves of natural gas and coal. Canada's *CO_2 Capture & Storage Technology Roadmap*[80] states that:

> *"It is imperative that Canada aggressively pursue CCS R&D to take advantage of current Canadian strengths and to capitalize on domestic and international opportunities. […] inherent CCS opportunities exist in Canada, which, in combination, set Canada apart from many other parts of the world. These include the nation's current position as a country with:*
>
> - *Vast fossil fuel resources, particularly oil sands and coal;*
> - *Internationally competitive industry producers and exporters of fossil fuels;*

[74] As defined by the Global CCS Institute: www.globalccsinstitute.com/projects/large-scale-ccs-projects.
[75] *DOE NETL, 21 April 2015, A Review of the CO_2 Pipeline Infrastructure in the U.S., DOE/NETL-2014/1681.*
[76] https://www.c2es.org/us-states-regions/policy-maps/ccs-financial-incentives.
[77] https://www.energy.gov/articles/energy-department-offers-conditional-commitment-first-advanced-fossil-energy-loan-guarantee, accessed on 15/02/2017. The captured CO_2 will be used for EOR.
[78] And by extension to ICCS, since even where these policies may only provide a direct incentive for power-sector CCS, ICCS could be facilitated by such developments.
[79] U.S. Energy Information Administration, International Energy Statistics, accessed on 25/02/2017.
[80] *CCSTRM, 2008, Canada's CO_2 Capture & Storage Technology Roadmap*.

- *Enormous potential for geological storage of CO2 in various regions across the country;*
- *Existing, leading-edge knowledge and expertise in CCS applications."*

The above confirms the clear strategic interest in CCS, which Canada may pursue as an important option to achieve its Nationally Determined Contribution to the Paris Agreement, which targets an economy-wide reduction in GHG emissions of 30% below 2005 levels by 2030. The most obvious sectors in which ICCS could be advanced are natural gas processing and oil refining – the largest contributors to CO_2 emissions in Canada.

From a policy point of view, it is significant that all Canadian provinces are expected to adopt a carbon price plan by 2018[81] (as an example, a carbon levy of C$20/t is charged on all fuels in Alberta since 1 January 2017); as a result, the combination of carbon cost avoidance with the revenues from CO_2-EOR may sufficiently incentivise high-CO_2-purity emitters (e.g. hydrogen and ammonia) to latch on to the existing infrastructure. Although these revenues would likely not be sufficient for other higher-cost-of-capture emitters, both federal and provincial governments have previously contributed to the capital and operational costs of CCS projects (e.g. C$745m to the Quest Project, and $495m to the ACTL – Alberta Carbon Trunk Line Project[82]).

Conclusions like the ones for the USA can be drawn based on this assessment: early ICCS projects are likely to be developed part-chain, latching on to the existing CO_2 transport network (which is being extended through the ACTL project), and their CO_2 may be used for EOR. The most relevant business model for Canada are therefore a combination of models 2 (regulated assets, rather than public ownership), 3 (access to existing infrastructure) and 4 (CO_2-EOR).

Europe

In addition to the 2 operational CO_2 storage projects in Norway, only a few CCS projects are in earlier development phases in the North Sea region (and specifically in Norway, the Netherlands, and the UK). Due to the higher cost of tertiary oil extraction when offshore, CO_2-EOR is not considered to be of priority for European ICCS projects; instead, financial motivation for ICCS projects will need to be provided by policy interventions that may need to be implemented to meet the collective EU target to reduce greenhouse gas emissions by at least 40% by 2030 compared to 1990 levels, as stated in the Nationally Determined Contribution to the Paris Agreement. The EU ETS is expected to form the basis of future policies, but since the price EU ETS emission allowances is not expected to independently justify investment in ICCS (see Section 2.2), additional funding mechanisms will need to be relied upon. A subsidy mechanism of great interest for ICCS is that used by the UK government to subsidise renewable energy projects: the Contract for Difference (CfD). If a similar format were to be used for future ICCS subsidies, a "strike price" would need to be negotiated between government and the emitters, and the difference between the strike price and the value of one EU ETS emission allowance would be paid for every tonne of CO_2 abated (if the carbon leakage risk is addressed). Alternatively, industrial emitters could return their free emission allowances and receive the subsidy in full. However, the question remains of how best to fund the budget for such a subsidy, for which a few suggestions were given in Chapter 3.

It is not possible to determine *a priori* whether the CCS infrastructure will be developed via a publicly owned T&S Company or through a regulated asset model, but both Model 1 and Model 2 may be viable in different countries, depending on national preferences[83]. Additionally, Model 3

[81] http://www.cbc.ca/news/politics/canada-trudeau-climate-change-1.3788825 accessed on 10/1/2017.
[82] http://www.energy.alberta.ca/CCS/3822.asp accessed on 1/03/2017.
[83] It is worth highlighting that Model 1 broadly resembles the approach that is currently being pursued in by the Norwegian Government for the Oslo cluster, and is not too dissimilar from what was recommended to the UK Government by the "Oxburgh report": *Lowest Cost Decarbonisation for the UK: The Critical Role of CCS. Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary Advisory Group on Carbon Capture and Storage.*

is not relevant for the first regional projects but may unlock great economies of scale for future projects, especially considering the geographical distribution of industrial clusters and storage sites in Europe; this suggests that future projects should ideally develop organically as additions to the initial, largely oversized, infrastructure. To achieve this, a strong, broad-based strategic vision for CCS in Europe would need to be achieved in advance of the first large-scale European CCS project[84].

China

Until recently, the major policy focus in China was associated with supporting strong growth and development, but several policies have recently signalled a change of direction in favour of actions that more strongly contrast climate change. Among these is China's First Nationally Determined Contribution to the Paris Agreement, which includes the objective to achieve the peaking of CO_2 emissions around 2030, whereas other relevant – though not CCS specific – policies have been set out as part of *The Thirteenth Five-year Plan* and of *China's Policies and Actions on Climate Change*. In addition to these strategic policies, a national ETS expected to commence in 2017, following the success of 7 provincial schemes[85].

ADB's recent CCS Roadmap suggests several relevant subsidies including payment of fixed subsidy per tonne of CO_2 capture and stored; tax credits for CO_2-EOR operations; capital grants; carbon tax and CO_2 emission caps[86].

Out of the 8 CCS projects currently under development, 5 include EOR, thus suggesting the applicability of Model 4. Additionally, the existence of several national companies in sectors such as oil and gas, utilities, and infrastructure, suggests that T&S could be delivered by a public company (Model 1). However, decisions around future CCS projects are likely to be made by provincial authorities, rather than by the central government, meaning that it is not possible to generalise whether this approach may be preferred to that offered by regulated-asset models (Model 2).

Australia

Australia's first Nationally Determined Contribution to the Paris Agreement includes a commitment to reduce greenhouse gas emissions by 26-28% below 2005 levels by 2030. This, combined with the fact that energy security is a national priority and that the country is a large supplier of coal, suggests that CCS could be developed first on the power sector. Future ICCS projects could then rely on Model 3 to latch on to the then-existing infrastructure, provided sufficient financial incentives exist.

After the cancellation of the first Australian ETS in 2014, the main policy mechanism in support of decarbonisation projects is the Emission Reduction Fund, through which "*the Australian Government purchases Australian Carbon Credit Units generated by emissions avoidance and offset projects*"[87]. However, a recent working paper in support of a CCS roadmap for Australia suggested that options such as feed-in tariffs, CCS certificates or a Contract for Difference might be employed to support CCS in the future[88].

Published literature and stakeholder feedback suggest that government is not likely to invest in a public T&S Company, hence Model 2 is likely to be more suitable than Model 1.

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[84] For instance, see the roadmap for the development of ICCS clusters in Europe suggested by *Bellona Europa, 2017, Manufacturing Our Future: Industries, European Regions, and Climate Action.*
[85] Retrieved on 25/2/2016 at http://ets-china.org/news/china-announced-the-13th-five-year-plan-on-energy-saving-and-emissions-reduction-2/.
[86] Asian Development Bank, 2015, Roadmap for Carbon Capture and Storage Demonstration and Deployment in the People's Republic of China
[87] http://www.aph.gov.au/, accessed on 25/2/2016.
[88] *The University of Queensland, 2017, Working Paper 2: Financial Incentives for the Acceleration of CCS Projects*, retrieved on 25/2/2016 at http://www.co2crc.com.au/publication-category/reports/.

6. CONCLUSIONS AND RECOMMENDATIONS

This study has highlighted that the industrial CCS sector is not yet commercially mature, and that private investment can occur only if four enablers are simultaneously addressed:

- The risk of carbon leakage is mitigated;
- Margin certainty is provided to the emitters via appropriate subsidies;
- The business cases for capture and infrastructure are decoupled;
- Government shares the key risks through guarantees to investors and project developers.

If any of the above is not addressed, ICCS projects may still be developed for demonstration purposes, but the underlying business cases cannot be fully commercial and are thus not replicable – a requirement to achieve large-scale deployment of ICCS. Although some governments might struggle to provide the extensive level of support required the first commercial ICCS projects, this study reasoned that, without ICCS, governments might eventually have to rely on more expensive solutions to meet the 2050 decarbonisation targets. It was also argued that only by implementing CCS can local industrial jobs be protected in the long term, or else the escalation in manufacturing costs due to increasing carbon price may lead to disruption of the major industrial markets.

Four business models were presented which enable the industrial emitters to maintain their competitiveness, and through quantitative assessment of three key project risks it was demonstrated that guarantees on loans, storage, and CO_2 volumes are a prerequisite for achieving investability. The cost that government is expected to pay over the lifetime of the illustrative ICCS cluster in Europe was found to range between £29-£53 per tonne of CO_2 abated, but it was shown that two important levers can reduce greatly reduce this cost: upwards regulation of the price of CO_2, and the provision of grants.

In conclusion, it was determined that at least one model is relevant in each of the regions focus of this study (North America, Europe, China, and Australia), a finding that was validated through interviews with government officials and CCS stakeholders.

Based on these conclusions it is suggested that future work should focus on the following:

4) **Assessment of alternative strategies to address carbon leakage:** A number of alternative measures to mitigate the carbon leakage risk were discussed including incentives or public procurement/regulation to create demand for green products. Further assessment is required to examine these alternative strategies in more detail including the level of procurement/regulation required to justify investment in CCS and whether these alternative measures could mitigate some of the ICCS risks and challenges described in this report.

5) **Strengthening the case for industrial CCS for individual states**: Similar to all the other decarbonisation technologies, industrial CCS projects will require government support and subsidies. It is therefore vital to strengthen the case for industrial CCS for each region/state and justify any potential public support. This potential further work could assess the following:
   - **reviewing the alternative deep-decarbonisation options** for all major carbon-intensive products, also considering possible low-carbon alternative products and their potential to substitute carbon-intensive products in global and national markets;
   - **focussing on the value of CCS and carrying out a cost-benefit analysis for industrial CCS** considering wider benefits of CCS including jobs and environmental benefits using existing economic appraisal CBA guidelines of government;
   - **defining the right units/metrics** for comparing decarbonisation initiatives across sectors, and thus consistently explore their true cost-effectiveness (e.g. incentives for the power sector based on £/tCO_2 rather than £/MWh might better demonstrate the cost-effectiveness of ICCS projects);

- **defining further demonstration** (technical and commercial) **and education requirements** to increase confidence of private investors and public (for instance, further benchmark CCS projects might be needed in iron&steel, chemicals, oil refining and cements sectors to increase investor and public confidence); and
- **consideration of potential international collaboration** (both inter-governmental and public/private) to deliver archetypal/benchmark CCS projects on budget and on time.

6) **Development of regional industrial CCS strategies**: This study identified the key enablers for the deployment of industrial CCS clusters globally and high-level business models that are expected to be feasible in different regions. Further work is required to develop regional or national industrial CCS strategies considering the key enablers and business models described in this report.

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APPENDIX

A.1. List of large scale CCS projects

Table 6: Large scale CCS projects in operation or in execution phase with expected start date by the end of 2017, based on Global CCS Institute's public database[89].

Phase	Industry	Location	Project name	Capture capacity (Mtpa)	Primary storage type
OPERATE	Fertiliser Production	United States	Coffeyville Gasification Plant	1	EOR
			Enid Fertilizer CO_2-EOR Project	0.7	EOR
	Hydrogen Production	Canada	Quest	1	Dedicated
		United States	Air Products Steam Methane Reformer EOR Project	1	EOR
	Iron and Steel Production	United Arab Emirates	Abu Dhabi CCS Project (Phase 1 being Emirates Steel Industries (ESI) CCS Project)	0.8	EOR
	Natural Gas Processing	Brazil	Petrobras Santos Basin Pre-Salt Oil Field CCS Project	1	EOR
		Norway	Sleipner CO_2 Storage Project	0.9	Dedicated
			Snøhvit CO_2 Storage Project	0.7	Dedicated
		Saudi Arabia	Uthmaniyah CO_2-EOR Demonstration Project	0.8	EOR
		United States	Century Plant	8.4	EOR
			Lost Cabin Gas Plant	0.9	EOR
			Shute Creek Gas Processing Facility	7	EOR
			Val Verde Natural Gas Plants	1.3	EOR
	Power Generation	Canada	Boundary Dam Carbon Capture and Storage Project	1	EOR
		United States	Petra Nova Carbon Capture Project	1.4	EOR
	Synthetic Natural Gas	Canada	Great Plains Synfuels Plant and Weyburn-Midale Project	3	EOR
EXECUTE	Chemical Production	United States	Illinois Industrial Carbon Capture and Storage Project	1	Dedicated
	Fertiliser Production	Canada	Alberta Carbon Trunk Line ("ACTL") with Agrium CO_2 Stream	0.3 – 0.6	EOR
	Natural Gas Processing	Australia	Gorgon Carbon Dioxide Injection Project	3.4 – 4.0	Dedicated
	Oil Refining	Canada	Alberta Carbon Trunk Line ("ACTL") with North West Sturgeon Refinery CO_2 Stream	1.2 – 1.4	EOR
	Power Generation	United States	Kemper County Energy Facility	3	EOR

[89] https://www.globalccsinstitute.com/projects/large-scale-ccs-projects retrieved on 14/02/17.

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