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IEAGHG Technical Report 2024-01

The Role of Indices in Assessing the Maturity of CCUS Technologies and their Readiness for Deployment

February 2024

IEA GREENHOUSE GAS R&D PROGRAMME

Acknowledgements & Citations

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This report describes work undertaken by Foresight Transitions Ltd on behalf of IEAGHG. The principal researchers were: Niall Mac Dowell, Mark Workman, Piera Patrizio, and Mai Bui.

To ensure the quality and technical integrity of the research undertaken by IEAGHG, each study is managed by an appointed IEAGHG manager. Furthermore, this report was reviewed by a panel of independent technical experts before its release.

The IEAGHG manager for this report was Keith Burnard. The expert reviewers for this report were: Mark Ackiewicz (and colleagues) – USDOE, Gerdi Breembroek (and colleagues) - Netherlands Enterprise Agency, Sara Budinis – IEA, Arthur Lee – Chevron, Ryozo Tanaka – RITE, Treasure Ubador (and colleagues) – DESNZ, and Hans Jørgen Vinje – Gassnova.

Further information can be obtained by contacting IEAGHG at: ***Email:*** *mail@ieaghg.org* ***Phone:*** *+44 (0)1242 802911* ***Address:*** *IEAGHG, Pure Offices, Hatherley Lane, Cheltenham, GL51 6SH, UK*

About IEAGHG

Leading the way to net zero with advanced CCS research. *We pioneer technology to accelerate project development & deployment.*

We are at the forefront of cutting-edge carbon, capture and storage (CCS) research. We advance technology that reduces carbon emissions and accelerates the deployment of CCS projects by improving processes, reducing costs, and overcoming barriers. Our authoritative research is peer-reviewed and widely used by governments and industry worldwide. As CCS technology specialists, we regularly input to organisations such as the IPCC and UNFCCC, contributing to the global net-zero transition.

About the IEA

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate is twofold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy. The IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics.

A REVIEW OF THE ROLE OF INDICES IN ASSESSING THE MATURITY OF CCUS TECHNOLOGIES AND THEIR READINESS FOR DEPLOYMENT

This study was undertaken on behalf of IEAGHG by Foresight Transitions Ltd. While a technology may be technically mature, it has become increasingly clear that the technology may not necessarily be considered commercially 'bankable' by investors. In this study, the potential for an index or indices to provide that confidence was explored. The findings from the study will be of interest to the broader energy community but, in particular, should benefit technology developers, CCUS end users, investors and policymakers.

Key Messages

1. Analysis and modelling have highlighted the essential role of carbon capture, utilisation and storage (CCUS) in the portfolio of technologies for cost-effectively achieving net zero. However, the window to achieve net-zero and remain within a 1.5°C carbon budget is shrinking rapidly and effective deployment of CCUS must accelerate.
2. In its recent 'Tracking Clean Energy Progress Report 2023', where the International Energy Agency (IEA) assessed the progress of technologies to fulfil their potential on the path to net zero by 2050, *CO_2 capture and utilisation* was assessed as 'More efforts needed' and *CO_2 transport and storage* as 'Not on track'.
3. While CCUS technologies and their associated value chains are already technically mature and extensively deployed in certain industrial contexts, their 'commercial readiness' for deployment in a number of other industrial sectors, and the policy and regulatory frameworks required for them to be considered a 'bankable' asset by investors, are less well characterised and understood.
4. The main barriers identified to CCUS being considered a bankable asset were related to commercial, policy and regulatory risk. Unless these risks were addressed effectively, it was likely that broader deployment at scale would be problematic.
5. Means were considered to address these risks and to chart a path to bankability. The value of using an index, in much the same way that the technology readiness level (TRL) index is used for technology development, was explored as the focus of this study, i.e., to examine whether an index to assess the commercial maturity of CCUS technology would be of practical value. Insights were sought regarding the role that commercial readiness indices might play in providing the relevant market signals for CCUS to be considered a bankable asset.
6. Indices are already applied in many spheres. Over 45 indices relevant to commercial, policy, regulatory and societal readiness were mapped and, of these, 38 were critically reviewed. Analysis found that the indices reviewed could be adapted to cover all aspects likely to be relevant to the establishment and upscaling of CCUS.
7. In addition to reviewing the value of indices online, consultations via interviews and workshops were undertaken with specialists drawn from across the CCUS project developer community – project developers, policymakers, finance specialists, regulators, the environmental NGO community and representatives of civil society. Views were taken on which aspects of commercial readiness were important to the various stakeholders, as well as the stakeholders' views on their perceived value of a bespoke index.

8. Due to the substantial complexity already facing stakeholders in addressing commercial, policy and regulatory risk, consensus from the consultations found the perceived benefits of applying ‘commercial readiness’ indices to CCUS to be limited. CCUS specialists felt the investment in resources that would enable the wide range of audiences to understand new CCUS-relevant indices would be a distraction.
9. Consultees also stressed that they viewed metrics[1] as more important and more useful than indices to specific stakeholders. Metrics in existence, for example, credit ratings, CO_2 capture efficiency and geological pore space were already used extensively. The relevant communities and audiences understood these long-established metrics; they are ubiquitous and have widespread application and acceptance.
10. To overcome commercial barriers, views contended that, rather than developing indices, there was a need for a strengthening of relationships between stakeholders integral to the scaling of the sector. This would enhance stakeholder capacity, knowledge transfer, shared awareness of risks, uncertainty and complexity. For effective strengthening of relationships, CCUS projects would need to be constructed and operated via long-term government CCUS implementation plans, i.e., firm and stable policies in place.
11. Moreover, the generation of a generic index or generic indices to provide insights to the broader commercial factors which need to be considered for CCUS bankability was considered a distraction by the majority of CCUS specialists. While a generic index such as the Commercial Readiness Index, as created and used by the Australian Renewable Energy Agency (ARENA), was not considered a priority, metrics were seen as having an important role in identifying aspects of CCUS commercial readiness and deployability.
12. It was felt that the main drawback of the application of indices in this context was the time and resource that would be expended generating the capacity to understand them across a broad range of audiences.
13. Barriers to bankability and widespread deployment of CCUS, as cited by specialists, ranged from affordability, lack of institutional knowledge, lack of policy champions, inadequate knowledge sharing and the need for the appropriate policy design. There was, however, a lack of agreement as to which of these specific barriers were a priority to be addressed.
14. A set of important considerations regarding the process of CCUS policy design were raised by stakeholders, notably:
    a. There was a need for an overarching vision and narrative as to the role of CCUS in addressing net zero;
    b. Societal engagement mechanisms play an integral role to CCUS policy design processes; and that
    c. CCUS policy needs to account for the varying levels of risk appetite of industrial stakeholders, sectors and investors that were looking to adopt CCUS.

[1] The study makes the distinction between ***indices*** which are generic, composite assessments of parameters made by specialists and translated into indices and ***metrics*** which are associated with specific aspects of CCUS development, e.g., geological storage capacity, weighted average cost of capital, etc., which do not need assessment by specialists to be translated into a generic variable and are already widely used across the CCUS sector.

Background to the Study

Analysis and modelling from a number of international bodies, including respected bodies such as the IPCC and the IEA[2], have highlighted the strategic and long-term importance of a portfolio of technologies for cost-effectively achieving net zero. Within this portfolio, CCUS is recognised as an essential technology: it enables mitigation for a number of industrial sectors; acts as an enabler for the production of low-carbon hydrogen;[3] and is a core component of carbon dioxide reduction (CDR) technologies that extract CO_2 directly from the atmosphere. With the 1.5°C carbon budget being consumed rapidly, the need for swift deployment of these technologies is increasingly important. Despite the need for an accelerated deployment of CCUS technologies and the technological advancements that were being made, the deployment of CCUS was far from aligned with the needs of a net zero transition to 2050.[4]

Some CCUS technologies and their associated value chains were already technically mature and extensively deployed in industrial contexts, e.g., in gas sweetening and industrial gases. Their broader commercial readiness for deployment – how CCUS will be deployed in several other industrial sectors, and the policy and regulatory frameworks required in order to be considered 'bankable' by investors – however, is less well characterised and understood. With this in mind, the potential to use an index, in much the same way that the technology readiness level (TRL) index is used for technology development, was considered.

An index to assess a technology's capacity to be adopted commercially, which is relevant to the wide range of stakeholders involved in stages of technology and commercial development, could be highly beneficial. If effective, it could better enable the risks and uncertainties to be identified by the relevant agents and, therefore, where relevant policy interventions could be applied to address those risks and uncertainties.

TRLs have tended to be applied to address the challenges associated with technological development and have been where the energy innovation community have focused their assessments of CCUS technology's potential for commercialisation and scalability. They have allowed benchmarking, risk management and funding decisions, enabling consistent, uniform discussions of technical maturity across different sectors. However, when a technology has reached TRL 9, i.e., when it has been proven in an operational environment, it does not immediately or necessarily mean that it is commercially viable. At this stage, barriers to deployment may include operational matters, such as the degree of system modification needed for the technology to be successfully integrated, or it may include market or commercial factors, e.g., affordability, disruptive competition, public acceptance, environmental and regulatory considerations. Given the complexity of an index for this application, consideration of indices relevant to the commercial readiness of CCUS is at a relatively early stage.[5]

Scope of Work

The aim of the study is to explore the potential for an index or indices to provide the confidence for CCUS technologies to be considered mature and commercially `bankable' by investors in pursuit of realising net zero. It seeks to explore the underappreciated commercial challenges of

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[2] IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector, Flagship Report, May 2021.
[3] IEA, Special Report on Carbon Capture Utilisation and Storage: CCUS in clean Energy Transitions, September 2020.
[4] IEA, Tracking Clean Energy Progress 2023: Assessing Critical Energy Technologies for Global Clean Energy Transitions, Flagship Report, July 2023.
[5] IEA 2020. Energy Technology Perspectives 2020. International Energy Agency February 2020 pp400

scaling up CCUS infrastructure, e.g., system modification, public acceptance, environmental and regulatory considerations, and the role that an index might play in providing the relevant market signal to the investor community as to the market status of CCUS and whether the risks of deployment in a particular case are sufficiently manageable.

In the study a distinction is made between ***indices***, which are generic, composite assessments of parameters made by specialists, and ***metrics***, which are quantitative measurements associated with specific aspects of CCUS development, e.g., CO_2 capture efficiency and geological storage capacity. Metrics are already widely used across the CCUS sector.

Methodology

A meta-study[6] was undertaken to gain a greater understanding of the meaning of commercial readiness, i.e., what it takes for a technology to move beyond TRL 9 and become a recognised commodity. The analysis covered technology diffusion, energy transitions, infrastructure and the CCUS literature.

A non-exhaustive critical review was carried out of indices used by other economic and technology sectors exploring how they address scaling, bankability, commercial readiness and market penetration, and how they might be applied to CCUS.

Interviews and workshops were undertaken with 26 specialists drawn from across the CCUS project developer community – project developers, policymakers, finance specialists, regulators, the environmental NGO community and representatives of civil society – to assess which aspects of commercial readiness and bankability were important to different stakeholders within the CCUS diffusion ecosystem. The relevance of indices and metrics more broadly was then evaluated.

During the study, the deployment and scaling of CCUS technologies was framed as a complex problem rather than a complicated one.[7] This systematic approach was considered important as complexity will likely increase as multiple sectors of the economy simultaneously co-evolve with steadily progressing decarbonisation policies required to meet the net zero transition.[8]

Finally, it was acknowledged that CCUS is a family of technologies - encompassing capture, transport, utilisation, and storage which cuts across a number of economic sectors. Where relevant, the study investigated the specific requirements of commercial readiness for CCUS technologies around three specified value chains:

1. Synfuels sector, particularly those around direct air capture (DAC);
2. Bioenergy carbon capture and storage (BECCS) power plant; and
3. Steel and cement production.

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[6] A meta-study is a statistical analysis that combines the results of multiple scientific studies that address the same question.

[7] The study frames complex problems as consisting of interdependent drivers – political, economic, regulatory, cultural – for which a change in any one dimension has non-linear and unpredictable impacts on the other, as opposed to complicated ones, which are comprised of discrete components which have linear and predicable impacts on each other.

[8] Foxon, T.J., 2011. A coevolutionary framework for analysing a transition to a sustainable low carbon economy. *Ecological economics*, *70*(12), pp.2258-2267.

Findings of the Study

What is the meaning of *commercial readiness* for CCUS?

In 2022, around 44 Mt CO_2 were captured globally,[9] which is projected to reach 1.2 Gt CO_2 per annum in the energy sector by 2030[10]. and 6.2 Gt by 2050[11] if net zero is to be achieved Substantial and timely CCUS sector development is constrained by a number of issues: Not only are CCUS projects burdened with the conventional risks associated with new technology and systems integration, but they are further challenged by the following factors:

- CCUS is a large-scale capital-intensive infrastructure investment which is subject to system of system[12] infrastructure challenges. It also requires the establishment of new CO_2 transport and storage infrastructure.
- It is a distinct infrastructure asset class with an associated risk profile, see Figure 1. It has, for example, an upfront cost of oversized infrastructure and the need to address long term liability for stored CO_2.

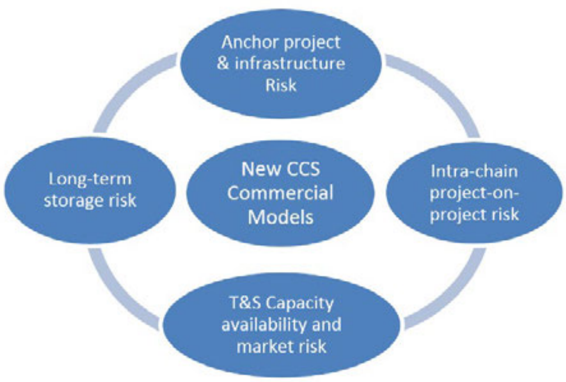

Figure 1: Carbon Capture and Storage - Specific Risks

- CCUS requires the establishment of distinct business models which must be underpinned by the establishment and stability of long-term policy and regulation.
- It requires cross-sectoral collaboration with stakeholders that are culturally distinct and that are not used to working together, as well as integrating technologies with which they lack familiarity.
- It is an infrastructure sector which will invariably open up a whole set of issues relating to the regulatory landscape, to cultures and to sector practices. Consequently, the technical development of the CCUS systems and their associated value chains will need to co-evolve with socio-political aspects, to create the appropriate enabling economic environment for CCUS to be deployed at scale.
- As a function of the limited deployment of CCUS technologies, there is a lack of granular empirical data as to how technology costs will reduce with deployment. Until there are sufficient numbers of CCUS projects, across a number of economic sectors, in different geographical jurisdictions, the ability to generate modelling outputs which will reliably inform time sensitive CCUS policy will be problematic.

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[9] GCCSI, Global Status of CCS 2023: Scaling up through 2030, November 2023.
[10] IEA, Credible Pathways to 1.5°C: Four pillars for Action in the 2020s, April 2023.
[11] IEA, Energy Technology Perspectives 2023, January 2023.
[12] Systems of Systems = Large-scale systems, the components of which are complex systems themselves.

These factors need to be overcome for CCUS to be considered a widely deployed commercial product. When competing with the substantial amount of investment in other net-zero technology value chains, which are less capital intensive, less complex and less risky, CCUS is often de-prioritised. With deployment of the full portfolio of technologies needed to reach net zero, this will need to change. The non-technical nature of the barriers to the establishment of CCUS in the marketplace mapped by the literature review was reflected in the specialist interviews and workshops.

The role of indices in assessing commercial readiness

The technology readiness level (TRL) index is a type of measurement system used to assess the maturity level of a particular technology. It provides a useful and easily interpretable snapshot for the assessment of risk and uncertainty associated with an individual technology in the context of a specific application. The TRL index should be applied in the following way:

- As an assessment of the risk and uncertainty that an individual technology has in the context of its application to the system to which it is being applied.
- As a useful mechanism by which to communicate a common understanding of risk and uncertainty assessment for individual technologies across multiple stakeholders within the timely and cost-effective execution of a specific technology programme.
- In turn, the index allows a common framework to understand the processes for maturing technology within a specific technology programme.
- As a programme management tool, the TRL index allows responsibility for technology development to be assigned to a stakeholder within a specific programme, i.e., a department will accomplish TRL `x’ within the specified `y’ timeframe.

TRLs, however, have often been mis-characterised and misapplied in the innovation literature in that they do not have complete transferability, nor do they anticipate how any specific technology might be applied generically across industrial sectors and/or decarbonisation programmes.[13]

As part of the meta-study, over 45 readiness indices were mapped and 38 critically reviewed. They tended to be qualitative, sector specific and ordinal. The indices reviewed covered all aspects likely to be relevant in CCUS establishment and scaling and could be easily adapted to do so.

The study made the distinction between ***indices*** such as those used in the ARENA’s Commercial Readiness Index, e.g., stakeholder, regulatory, and finance readiness, which are assessed by specialists and translated into indices, and ***metrics***, which are associated with specific aspects of CCUS development, e.g., CO_2 capture efficiency and levelised cost of electricity. Indices are often derived from multiple metrics.

Expert Review Comments

Comments from a review of the draft report were fed back to the authors and all were addressed prior to submission of the final study report.

It was generally considered that the study gave a thorough review of indices, with some interesting high-level analysis, and provided a valuable insight into the complexity of indices to assess the commercial readiness of CCUS. Given that, reviewers’ opinions regarding the

[13] NDA (2014), Guide to Technology Readiness Levels for the NDA Estate and its Supply Chain, Issue 2, 6 November 2014.

application of an index to assess the commercial readiness of CCUS were mixed. While some felt that an index might be of value to assess the commercial maturity of the technology, the majority leant towards the view that it could/would be a distraction. The use of metrics to provide an indication of a technology's maturity was favoured, particularly given metrics were already widely used and well understood.

Given most felt that using indices would be a distraction, a reviewer asked what would need to change for stakeholders to change their mind. For example, if complexity was the issue, the reviewer asked if there might be a case for exploring simplistic indices that could still give insights. While this may be worth exploring, it is more likely that simplistic indices would actually be the same as the metrics widely used in the CCUS community at present.

One reviewer thought that exploring some of the more relevant indices in greater detail might reveal more insights, while another speculated that developing an objective index for CCUS could prove a challenge as a significant contribution to risk would be subjective, e.g., a company's desire to invest in a CCUS project would depend to a large extent on that company's own risk appetite.

Conclusions and Recommendations

The ultimate purpose of this study was to gain an insight regarding the potential for a commercial readiness index to provide the relevant market signals as to the commercial `bankability' of CCUS.

There was consensus that the main barriers to CCUS bankability and widespread deployment lay presently in the domain of commercial, policy and regulatory risk. Specific examples included affordability, lack of institutional knowledge, lack of policy champions, inadequate knowledge sharing and the need for appropriate policy design. There was, however, a lack of agreement as to which of these specific barriers were a priority to be addressed.

Over 45 indices relevant to commercial, policy, regulatory and societal readiness were mapped, with 38 critically reviewed. The indices reviewed covered all aspects likely to be relevant to the upscaling and establishing of CCUS or could easily be adapted to be so. However, with the substantial complexity already facing stakeholders in addressing commercial, policy and regulatory risk, the perceived benefits of the application of an index to assess commercial maturity in the CCUS sector were found to be limited.

Applying indices to highlight the broader commercial factors that need to be considered for CCUS bankability was considered a distraction by the majority of CCUS specialists. A major drawback to the development and application of an index or indices was felt to be the valuable time and resource that would be spent generating the capacity to understand them across the broad range of audiences.

However, while the application of indices was not considered a priority, metrics were seen as having an important role in identifying aspects of CCUS commercial readiness and deployability. Metrics important to specific stakeholders within the CCUS ecosystem were already in existence e.g., credit ratings, weighted average cost of capital and reservoir capacity. These were considered more useful than indices. Metrics were long-established and the relevant communities and audiences understood them; they had widespread application and acceptance.

Rather than the development of an index to overcome commercial barriers, there was a consensus on a need for a strengthening of relationships between stakeholders integral to the scaling of the sector. Such stakeholders include:

- Public and societal actors
- Government and policy
- Finance, investors and legal entities
- Project developers
- Supply chain actors

Stronger relationships would enhance stakeholder capacity, knowledge transfer, shared awareness of risks, uncertainty and complexity, as well as generating secondary benefits at a project-programme level.

Suggestions for further Work

It was suggested that future work might focus on the following:

- Determine what a national CCUS implementation plan would look like for a selection of geographical jurisdictions, which may identify spillover effects.
- Explore how institutional knowledge is established and best disseminated at a project-to-project level.
- Investigate how greater institutional knowledge can be generated across a broader stakeholder group and how societal stakeholders can be integrated into the design of CCUS regulation and policy.
- Consider how to improve net zero decision support analysis to enable better generation of time sensitive CCUS innovation requirements into policy.

FORESIGHT TRANSITIONS

The Role of Indices in assessing the maturity of Carbon Capture and Utilisation Technologies and Readiness for Deployment

Foresight Transitions Ltd

Deep Uncertainty Research at Foresight Transitions

Set up in 2017, Foresight Transitions offers a unique level of research to assist decision-making under deep uncertainty across technology transitions, resource systems, and environmental and climate change issues. We provide bespoke analysis based on fundamental research around financial modelling, user perceptions and experiences, technological development, and regulatory and policy risks in possible futures, accommodating for deep uncertainty.

Project Team

Prof Niall Mac Dowell is a Professor in Energy Systems Engineering at Imperial College London. He is a Chartered Engineer, a Fellow of both the IChemE and the Royal Society of Chemistry. His research is focused on understanding the transition to a low carbon economy, and has published more than 150 peer-reviewed scientific papers at the molecular, unit operation, integrated process, and system scales in this context.

Dr Mark Workman is the Director of Foresight Transitions Ltd and an Affiliate Researcher at Imperial College London where he undertakes research on resource systems, energy transitions, environmental and climate change, violent conflict and the processes of decision making under uncertainty.

Dr Piera Patrizio is a Research Associate in the Centre for Environmental Policy (CEP) at Imperial College London. Her works investigates key sustainability trade-offs associated Carbon Dioxide Removal (CDR) technologies with a special focus on BECCS value chains. While at CEP, Piera has led several studies on the cost, mitigation potential and ecosystems impacts associated with CCS and BECCS deployment in the power and transport sectors and in fossil intensive industries.

Dr Mai Bui is a Research Associate in the Centre for Environmental Policy at Imperial College London. She has first-hand experience in designing pilot plant test campaigns and dynamic operation of pilot plants, including CSIRO's pilot plant (AGL Loy Yang power station, Australia) and the CO_2 capture facility at TCM (Mongstad, Norway). Mai has expertise in developing chemical process modelling tools and surrogate models to simulate absorption-based CO_2 capture plants in the context of power/industry and GGR applications.

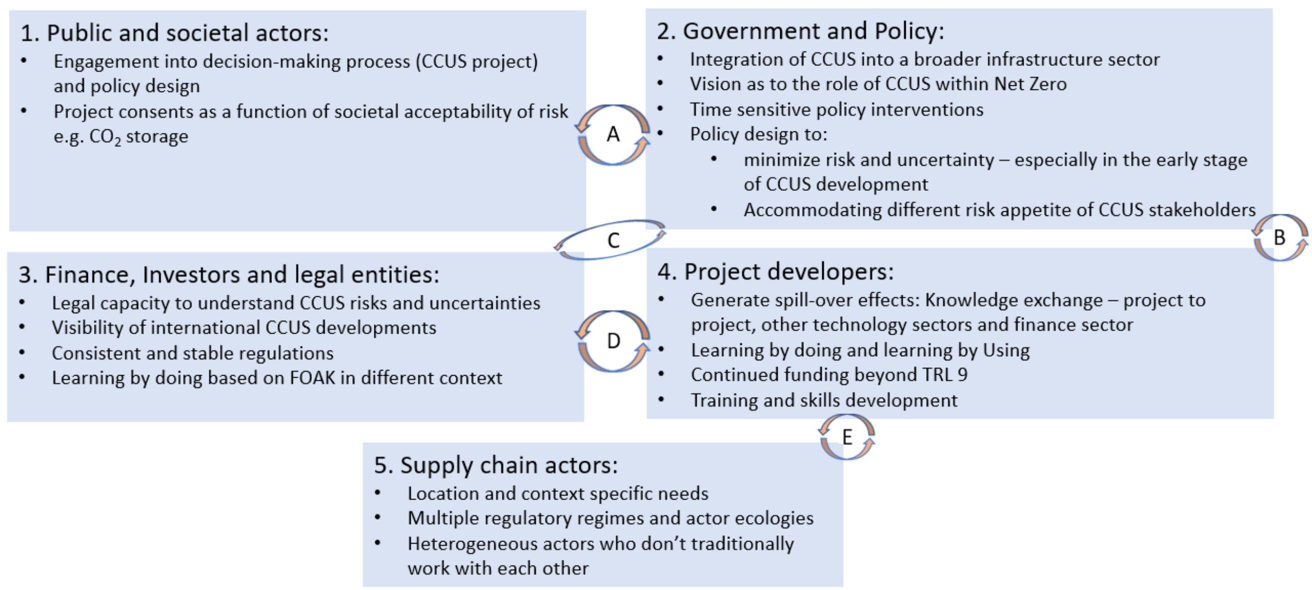
Key Messages

This study ***sought to explore the underappreciated commercial dimensions of scaling up CCUS infrastructure e.g. public acceptance, environmental and regulatory considerations etc - and the role of indices in effectively communicating these to the CCUS community***. This was undertaken via a literature review, interviews and workshops with 26 specialists from the CCUS project developer community, policy makers, finance specialists, regulators and civil society representatives.

The key findings of the study are as follows:

- The main barriers identified to CCUS being considered bankable are related to commercial, policy and regulatory risk. Without these being addressed, deployment at scale will be problematic.
- Over 45 indices relevant to commercial, policy, regulatory and societal readiness have been mapped and 38 critically reviewed. The indices that have been reviewed cover all aspects likely to be relevant in CCUS establishment and scaling and could be easily adapted to be so.
- ***The perceived benefits of the application of commercial and public goods indices in the CCUS sector was limited.*** This was attributed to the substantial complexity already facing actors in addressing commercial, policy and regulatory risk. CCUS specialists considered the investment in additional resources to enable the wide range of audiences to understand new CCUS relevant indices would be a distraction.
- Metrics[1] which are important to specific stakeholders within the CCUS ecosystem are already in existence e.g., credit ratings, weighted average cost of capital, and reservoir characterization etc. These were considered more useful than indices. The relevant communities and audiences understand these long-established metrics, they are ubiquitous and have widespread application and acceptance.
- ***Rather than the development of indices, to overcome commercial barriers there is a need for a strengthening of relationships between actors integral to the scaling of the sector*** - see figure KM1. This will enhance actor capacity, knowledge transfer, shared awareness of risks, uncertainty and complexity as well as generate secondary benefits at a project-programme level. For that to happen effectively CCUS projects need to be constructed and operated via long term government CCUS implementation plans.

Figure KM1: Actor roles, requirements and relationships identified as salient to CCUS sector scaling. Relationships A to E need strengthening to enhance knowledge transfer and shared perspectives of risks and uncertainty - see figure 3.5.



[1] The study makes the distinction between ***indices*** which are generic, composite assessments of parameters made by specialists and translated into indices and ***metrics*** which are associated with specific aspects of CCUS development, e.g., geological storage capacity, weighted average cost of capital, etc., which do not need assessment by specialists to be translated into a generic variable and are already widely used across the CCUS sector

Summary

Background to the Study

Analysis and modelling from a number of international bodies have highlighted the strategic and long-term importance of a portfolio of technologies for cost-effectively achieving net zero[2]. Within this portfolio, Carbon Capture Utilisation and Storage (CCUS) is a keystone technology not only enabling mitigation for a number of industrial sectors which underpin national economies but also acting as an enabler for the establishment of the hydrogen[3] and CO_2 removal sector[4]. With the 1.5°C carbon budget being consumed rapidly, the need for the rapid deployment of these technologies, especially CCUS, is increasingly important. Despite the need for an accelerated deployment of CCUS technologies and the technological advancements[5] that are being made, actual CCUS deployment is far from aligned with the needs of a net zero transition to 2050.

Many CCUS technologies and their associated value chains are already technically mature with their various elements extensively deployed in other industrial contexts, e.g., gas sweetening, industrial gases, etc. Their broader commercial readiness for deployment - how CCUS portfolios will be retrofitted into a number of existing industrial sectors, infrastructure networks, and the policy and regulatory frameworks required in order to be considered `bankable' by investors - however, is less well characterised and understood.

The ability to assess a technology's capacity to scale based on indices, which are relevant to the wide range of stakeholders involved in stages of technology and commercial development, is important. It better enables the risks and uncertainties to be identified by the relevant agents in innovation ecosystems and therefore where the relevant policy interventions can be applied to address those risks and uncertainties. It also potentially allows the adjustment of interventions to address unintended consequences or better align technology commercialisation for the realisation of other global public goods beyond net zero such as the United Nations (UN) Sustainable Development Goals (SDGs).

Of the two broad dimensions associated with technological diffusion[6], technology readiness levels (TRL) have tended to be applied and where the energy innovation community have focused their assessments of CCUS technology's potential for commercialisation and scalability. It has allowed benchmarking, risk management and funding decisions, enabling consistent, uniform discussions of technical maturity across different sectors. However, when a technology has reached TRL 9, it does not necessarily mean that it is commercially viable. At this stage, commercial factors, which include affordability, disruptive competition, public acceptance, environmental and regulatory considerations remain important barriers to deployment.

The importance of broader indices relevant to commercial readiness has only just started to be incorporated in CCUS assessments[7]. This mimics' the proliferation of other indices which seek to accommodate broader readiness that have been generated from other economic and technology sectors.

Scope of Work

The aim of the study is to explore the role of indices in providing sufficient confidence to consider CCUS technologies to be a mature and commercially `bankable' option by investors in pursuit of realising net zero.

It is noteworthy that the study makes the distinction between ***indices*** which are generic, composite assessments of parameters made by specialists and translated into indices and ***metrics*** which are associated

[2] IEA 2021. Net Zero by 2050. A roadmap for the Global Energy Sector. Flagship Report dated May 2021
[3] Biggins., F et al., Green hydrogen investments: Investigating the option to wait. Energy 241 (2022) 122842
[4] Minx, J. C., et al. (2018). Environmental Research Letters, 13 (6), 063001.
[5] Bui., M. et al 2018 Carbon capture and storage (CCS): the way forward (Review Article) Energy Environ. Sci., 2018, 11, 1062-1176 DOI: 10.1039/C7EE02342A
[6] Bloomberg New Energy Finance. 2010 Crossing the Valley of Death: Solutions to the next generation clean energy project financing gap dated 21th June 2010.
[7] IEA 2020. Energy Technology Perspectives 2020. International Energy Agency February 2020 pp400

with specific aspects of CCUS development, e.g., geological storage capacity, weighted average cost of capital, etc., which do not need assessment by specialists and are already widely used across the CCUS sector.

The intention of the work is to assess whether the provision of a broader suite of indices beyond TRL might assist in providing the relevant market signal to the investor community and beyond as to whether the risks of establishing and scaling a CCUS sector are sufficiently manageable by the private sector. The primary audience for the report is supra-national policy makers such as those at the IEAGHG, IEA and GCCSI.

Approach

The study approach sought greater understanding as to the meaning of commercial readiness for CCUS technologies by undertaking a meta study of the technology diffusion, energy transitions, infrastructure and CCUS literature.

A non-exhaustive critical review of indices which are used by other economic and technology sectors was then undertaken assessing how they might be applied to inform aspects of CCUS scaling and bankability in commercial readiness.

Interviews and workshops were also undertaken with 26 specialists from across the CCUS project developer community, policy makers, finance specialists, regulators and civil society representatives - to assess which aspects of commercial readiness and bankability are important to different actors/stakeholders within the CCUS diffusion ecosystem. Evaluation of the relevance of indices and metrics more broadly is then undertaken including their role in addressing the SDGs.

During the study, the deployment and scaling of CCUS technologies was framed as a complex problem rather than a complicated one[8]. This systemic approach allowed the generation of deeper insights as to what is required for the realisation of CCUS bankability and deployment[9]. This was considered important as complexity will likely increase as multiple sectors of the economy simultaneously co-evolve with the ratchetting up of decarbonisation policy required to meet the net zero transition[10]. It also allows research and expertise in systems and other networked infrastructures to be applied e.g., how capital investment operates as a critical enabler of different pathways for energy transitions[11,12].

Finally, it was acknowledged that CCUS is a family of technologies - encompassing capture, transport, utilisation, and storage which cuts across a number of economic sectors. Where relevant, the study investigated the specific requirements of commercial readiness for CCUS technologies around three specified value chains: (1) Synfuel sector particularly those around DAC; (2) Bioenergy Carbon Capture and Storage Power Plant; and (3) Steel and Cement production.

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[8] The study frames complex problems as `*consisting of interdependent drivers such as political, economic, regulatory, cultural which are reflexive in that a change in any one dimension has non-linear and unpredictable impacts on others etc.'* as opposed to complicated ones which are `*comprised of discrete components which have linear and predicable impacts on each other.'*

[9] Workman M, Darch G, Dooley K, et al., 2021, Climate policy decision making in contexts of deep uncertainty-from optimisation to robustness, Environmental Science and Policy, Vol:120, ISSN:1462-9011, Pages:127-137

[10] Foxon, T.J., 2011. A coevolutionary framework for analysing a transition to a sustainable low carbon economy. *Ecological economics*, *70*(12), pp.2258-2267.

[11] Bolton, R. and Foxon, T.J., 2015. A socio-technical perspective on low carbon investment challenges–insights for UK energy policy. *Environmental Innovation and Societal Transitions*, *14*, pp.165-181.

[12] Barazza, E. and Strachan, N., 2020. The co-evolution of climate policy and investments in electricity markets: Simulating agent dynamics in UK, German and Italian electricity sectors. *Energy Research & Social Science*, *65*, p.101458.

Findings of the Study

What is the Meaning of Commercial Readiness for CCUS?

CCUS technologies are required globally at a multi $GtCO_2$ pa scale by 2050, and markets for CCUS products are projected to reach $550 billion by 2040 [13]. At present ~40 $MtCO_2$ is captured and markets for CCUS products are <$1B pa[13]. Substantial and timely CCUS sector development is inhibited by a number of issues: Not only are CCS projects burdened with the conventional risks associated with new technology and systems integration, but they are further challenged by the following additional factors:

- It is a large-scale capital-intensive infrastructure investment which is subject to ***system of system[14] infrastructure economics[15], path dependency and potential for lock-out***. It also requires the establishment of new CO_2 transport and storage infrastructure[16].
- It is a ***distinct infrastructure asset class*** with CCUS specific dimensions such as upfront cost of oversized infrastructure, long term liability for stored CO_2 and cross-chain, or project-on-project risks amongst others - see figure E1 - thereby increasing its investment risk profile.
- Requires the establishment of ***distinct business models*** which can only be underpinned by the establishment and stability of long-term policy and regulation.
- Requires ***cross-sectoral collaboration*** with actors that are culturally distinct and that are not used to working together as well as integrating technologies with which they lack familiarity.
- It is an infrastructure sector which will have to be retrofitted into existing communities and networks, which at scale, will invariably open up a whole set of intricate, subtle and complex issues - such as a fragmented regulatory landscape, cultures and sector practices. Consequently, ***the technical development of CCUS systems and their associated value chains will need to be co-evolved with socio-political aspects***, to create the appropriate enabling economic environment for CCUS to diffuse and scale.
- As a function of the limited deployment of CCUS technologies ***there is a lack of granular empirical data as to how technology costs will reduce with deployment***. Until there are sufficient numbers of CCUS projects, across a number of economic sectors, in different geographical jurisdictions the ability to generate modelling outputs which will reliably inform time sensitive CCUS policy will be problematic.

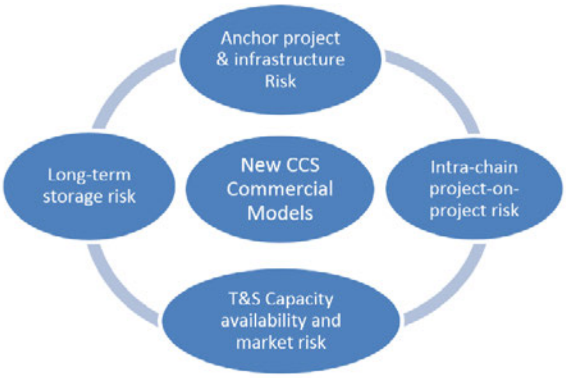

Figure E1: Carbon Capture and Storage **-** Specific Risks

These factors need to be overcome for CCUS to be considered commercially scalable. When competing with the substantial amount of investment in other net zero technology value chains which are less capital intensive, less complex and less risky - CCUS is therefore often de-prioritised especially with the larger capital requirements that financial bodies now have to carry[17]. The non-technical nature of the barriers to the establishment and scaling of a CCUS sector mapped by the literature review was reflected in the specialist interviews and workshops.

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[13] Nature 29th March 2022. The race to upcycle CO_2 into fuels, concrete and more - Companies are scrambling to turn the greenhouse gas into useful products — but will that slow climate change?

[14] Oughton, E.J. et al 2018 - Infrastructure as a Complex Adaptive System. Hindawi Complexity Volume 2018, Article ID 3427826, 11 pages https://doi.org/10.1155/2018/3427826

[15] Hall., J. et al 2014 - Assessing the Long-Term Performance of Cross-Sectoral Strategies for National Infrastructure. J. Infrastruct. Syst., 2014, 20(3): 04014014

[16] Hackett, L. Industria Mundum, 2018. Commercialisation of CCS. Conference Presentation at Calabria, Italy dated June 2018

[17] Bank for International Settlements - accessed 22nd March 2022: https://www.bis.org/publ/bcbsca.htm Basel II: Revised international capital framework

The role of indices in assessing commercial readiness

Technology Readiness Level (TRL) measures how ready equipment is for use now in a broader system. It is a useful and easily interpretable snap-shot index for the assessment of risk and uncertainty associated with an individual technology in the context of a specific application in the present. TRL should be applied in the following way:

- It is an assessment of the risk and uncertainty that an individual technology has ***and*** the context of its application to the system to which it is being applied.
- It is a **useful** mechanism by which to communicate a ***common understanding*** of ***risk*** and ***uncertainty*** assessment for individual technologies across multiple stakeholders within the timely and cost-effective execution of a specific technology programme.
- In turn it allows a ***common framework*** to understand the processes for maturing technology ***within a specific technology programme.***
- As a programme management tool, TRL ***allows responsibility for technology development to be assigned to an actor*** within a specific programme i.e. a department will realise TRL `x' within the specified `y' timeframe.

Scale through the nested hierarchy of transformational change		Examples of Readiness Levels
Systemic: Economy Wide	***Societal Capacity***	• Societal Readiness Levels by the Innovation Fund Denmark, 2018. • How to Assess Market Readiness for an Innovative Solution by Hjorth and Brem, 2016 • End User Readiness Level by Luscinus, 2020.
Increasing in scale and decreasing in extent of bounding	***Governance, Regulatory and Finance***	• Legal-Social-Technology Readiness Levels by Bruno et al., 2020 • Green bonds shades of green by CICERO 2020
	Sector System Innovation	• Service innovation Readiness Level by Yen et al., 2012 • Transformation Readiness Level by Gudergan et al., 2015 • Aspects of Innovation by Energy Systems Catapult, 2020
	Sector Business Model	• Small Medium Enterprise readiness for Manufacturing 4.0 by Chonsawat & Sopadag, 2020 • Small Medium Enterprise readiness to implement service design by Teso and Walters (2016) • Nanotechnology Commercialisation Readiness Scale by Duret et al., 2012 • Change Readiness Levels - Change Readiness by Combe, M., 2014 • Business Transformation Readiness Assessment by TOGAF, 2011
	System and Service Readiness	• System of Systems Technology Readiness Level Assessment by W. Majumdar, 2009 • Advancement Degree of Difficulty (AD2) by Bilbro, (2008) • Manufacturing Readiness Level by the Automotive Council (2011) • System Readiness Assessment by Austin et al., 2015 • Carbon Capture and Storage Readiness Index by Global Carbon Capture & Storage Institute 2018
Atomistic: Bounded	***Technology Readiness Level***	• Technology Readiness Level by Department of Energy 2006 • Expansion of the Technology Readiness Levels Perspective by IEA 2020

Figure E2: Summary of mapping of the non-systemic meta-study of indices to assess components of Commercial readiness

It has, however, been ***mis-characterised*** and ***misapplied*** in the innovation literature in that it does not have complete transferability or an anticipatory dimension as to how any specific technology might be applied generically across industrial sectors and/or decarbonisation programmes[18].

[18] NDA 2014 - Guide to Technology Readiness Levels for the NDA Estate and its Supply Chain dated 6th November 2014 505/02 Issue 2

As part of the meta study, over 45 additional readiness indices have been mapped and 38 critically reviewed. These have tended to be qualitative, sector specific and ordinal. The indices that have been reviewed cover all aspects likely to be relevant in CCUS establishment and scaling and could be easily adapted to do so. Figure E2 - above - shows a stylised typology.

The study makes the distinction between ***indices*** such as those used in the Australian Renewable Energy Associations Commercial Readiness Indices e.g. Stakeholder, Regulatory, Finance Readiness etc which are assessed by specialists and translated into these indices and ***metrics*** which are associated with specific aspects of CCUS development e.g. geological storage capacity, weighted average cost of capital, levelised cost of electricity, etc., which do not need assessment by specialists to be translated into an index. Furthermore, indices are often comprised of multiple metrics.

The role of indices in assessing CCUS commercial readiness - Conclusions

The ultimate purpose of this research was to seek insight as to the role of commercial readiness indices in providing the relevant market signals as to the commercial `bankability' of CCUS in realising net zero.

It is within this context that the following study findings are made:

1. ***The generation of generic indices to provide insight to broader commercial factors which need to be considered for CCUS bankability is considered a distraction by the majority of CCUS specialists.*** Though generic indices such as Commercial Readiness Indices as used by the Australian Renewable Energy Agency were not considered a priority - metrics were seen as having an important role in identifying aspects of CCUS commercial readiness and deploy-ability. It was largely considered that the metrics which are important to specific stakeholders within the CCUS ecosystem are already in existence e.g., credit ratings, weighted average cost of capital, geological storage capacity and reservoir characterization etc. The relevant communities and audiences understand these long-established metrics, they are ubiquitous and have widespread application and acceptance.

   The main justification to negate the need for the application of new indices was that much time and resource would be expended generating capacity to understand them across the broad range of audiences.

2. ***There was consensus that the main barriers to the establishment, bankability and widespread deployment of CCUS presently lies in the domain of commercial, policy and regulatory risk.*** A number of barriers were cited by specialists ranging from affordability, a lack of institutional knowledge, lack of policy champions, inadequate knowledge sharing and the need for the appropriate policy design. There was, however, a lack of agreement as to which of these specific barriers were a priority to be addressed.

3. ***A set of important considerations regarding the process of CCUS policy design were raised by stakeholders. The following are salient:***

   (1) There is a need for an overarching vision and narrative as to the role of CCUS in addressing net zero;

   (2) broad based inclusive societal engagement mechanisms play an integral role to CCUS policy design processes; and that

   (3) CCUS policy needs to account for the varying levels of risk appetite of industrial actors and sectors looking to adopt CCUS and investors. For example, the US 45Q tax credit has a 12-year time limit which seems well suited for Oil & Gas industry but unsuitable for other sectors such as steel/cement. Similarly, different financial institutions each vary in their risk appetites.

Contents

1. Project Context

1.1 Introduction

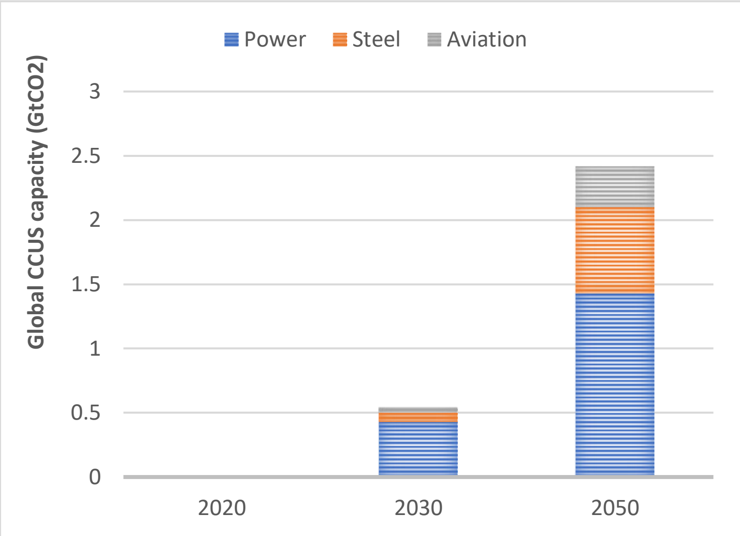
Carbon Capture and Storage (CCUS) is a keystone technology to address deep decarbonisation for a number of industrial sectors which underpin national economies. It is also an enabler for the establishment of the hydrogen[19] and CO_2 removal sector[20]. Despite clarity on the role of CCUS technologies in meeting climate change targets, and the technological advancements[21] that are being made, actual CCUS deployment is far from aligned with the needs of a net zero transition to 2050.

1.2 Scale of CCUS Needed, Market Potential, Sentiment & Maturity Indices

The establishment, development and scaling of CCUS technologies is required at a global $GtCO_2$ pa scale. As CCUS represent a broad range of technologies[22] which require integration into the power sector, energy intensive industries such as steel and cement, the production of sustainable fuels, the hydrogen economy as well as underpin elements of the carbon removal sector - the technology in all its configurations - will pervade every aspect of modern economies.

The scale of CCUS deployment anticipated to meet net zero means[23] that from early 2020 increasingly large volumes of secure CO_2 storage capacity will be required which will be accessed through an extensive and interconnected network of transportation networks - including pipelines, shipping, and road transport - by clusters of CO_2 sources. The latest simulations of CCUS capacity requirement in $GtCO_2$ for the power, steel and sustainable aviation fuel production sector can be found in figure 1.1, below[24].

Figure 1.1: IEA $GtCO_2$ simulations for CCUS deployment for the global power, steel and sustainable aviation fuel sectors



As a function of the transition to the net zero economy, research by Lux suggested that more than 80 firms are working on new approaches to using CO_2. The market for these products amounts to less than US$1 billion today but it is anticipated to grow to $70 billion by 2030 and could reach $550 billion by 2040. This initial activity is being driven by a combination of factors including but not limited to reductions in the cost of renewable energy, various carbon pricing mechanisms and the efficiency of the underlying technologies.

Though the actual ability for these products to lock CO_2 on the timescales to be relevant to realise Paris climate goals is open to question[25] it does represent an uptick in

[19] Biggins., F et al., Green hydrogen investments: Investigating the option to wait. Energy 241 (2022) 122842
[20] Minx, J. C., et al. (2018). Environmental Research Letters, 13 (6), 063001.
[21] Bui., M. et al 2018 Carbon capture and storage (CCS): the way forward (Review Article) Energy Environ. Sci., 2018, 11, 1062-1176 DOI: 10.1039/C7EE02342A
[22] Zimmermann 2016 - Assessing Early-Stage CO2 utilization Technologies—Comparing Apples and Oranges
[23] IEA (2021). Net Zero by 2050, A roadmap for the global energy sector
[24] IEA (2021). Net Zero by 2050, A roadmap for the global energy sector; Perez-Fortez et al (2016). Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment. Applied Energy 718-732; and Jarvis and Samsatli (2018). Technologies and infrastructures underpinning future CO2 value chains: A comprehensive review and comparative analysis. Renewable and Sustainable Energy Reviews 46-68.
[25] Nature 29th March 2022. The race to upcycle CO_2 into fuels, concrete and more - Companies are scrambling to turn the greenhouse gas into useful products — but will that slow climate change?

CCUS interest which will sustain bridging revenues and generate spill-over effects across value chains and likely result in more permanent CO_2 storage (>1000 years)[26].

Though interest in CCUS technologies in meeting organisations net zero goals is increasing. Sentiment is mixed as demonstrated by recent research undertaken by Decarbconnect[27]. This identified the varied willingness of executives, mainly based in North America and Europe, from the energy intensive sectors (Cement, Glass, Chemicals, Steel) to engage in CCUS development - see Box 1. CCUS limited economic viability and perceived risk makes the willingness to invest very limited - with only 25% considering CCUS very or the most economically viable technology to realise net zero - figure 1.1. They cite operational issues, finance, and space considerations and even the need for a better skills base to be generated. Only 12% of the sample considering there to be sufficient certainty or manageable risk to engage with CCUS - see figure 1.2.

As reflected in the survey, many CCUS technologies and their associated value chains have realised technological maturity. Their broader commercial readiness for deployment - how CCUS portfolios will be retrofitted into a number of existing industrial sectors, infrastructure networks, and the policy and regulatory frameworks required in order to be considered `bankable' by investors and industrial sectors, however, is less well characterised and understood.

Indices are generic, composite assessments of parameters made by specialists using expert judgment as to a technology's technological and commercial readiness. The ability to assess a technology's capacity to scale based on indices, which are relevant to the range of stakeholders involved in stages of technology and commercial development, is important. It better enables the risks and uncertainties to be identified by the relevant agents in innovation ecosystems and therefore where the relevant policy interventions can be applied to address those risks and uncertainties. It also potentially allows the adjustment of interventions to address unintended consequences or better align technology commercialisation for the realisation of other global public goods beyond net zero such as the United Nations (UN) Sustainable Development Goals (SDGs).

Box 1: Decarbconnext survey of executives and specialists including those from energy intensive industries as to their perceptions regarding the role of CCUS investment in their net zero plans and their willingness to invest in the technology and associated value chain.

Salient Findings relevant to this study:

- 65% of respondents citing CCUS as critical or a key part of their plans to reach their 2030/2050 decarbonisation goals.
- Some concerns remain – operational issues, finance and space considerations for example – and there is clearly still some reticence in the market, but over a third of respondents are conducting their own research/pilots so there is a tangible commitment to exploring the potential of CCUS.

Figure 1.1: Which decarbonisation solution do you feel is most economically viable for your business?

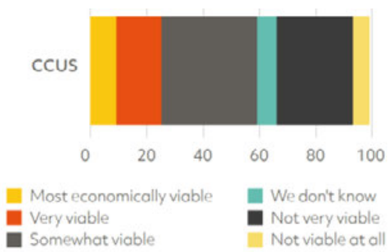
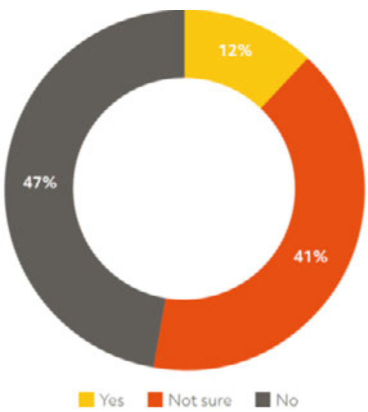


Figure 1.2: Do you feel the CCUS value chain currently offers a clear path for your business in terms of carbon markets and uses



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[26] Platt et al 2017. A novel approach to assessing the commercial opportunities for greenhouse gas removal technology value chains the case for a negative emissions credit in the UK. Journal for Cleaner Production.

[27] Decarbconnect 2022. Scaling Up CCUS - Market Insights. A report by Decarb Connect in association with Carbon Clean. Conducted anonymised survey of 70 hand-picked senior executives, chosen to represent prevailing thoughts and experiences across the industry, with just under 60% of respondents representing hard-to-abate asset owners, and 40% chosen from industry thought leaders such as policymakers, financial executives, academics in the subject area and industry experts.

- Given pressure from shareholders and customers is only going to increase, there is every reason to believe the adoption of carbon capture will accelerate massively.
- Talent is also going to be crucial for CCUS development and attracting young people with new skills and fresh ideas into the industry is vital.

Of the two broad dimensions associated with technological diffusion[28], technology readiness levels (TRL) have tended to be where the energy innovation community have focused their assessments of CCUS's potential for scalability. It has allowed benchmarking, risk management and funding decisions, enabling consistent, uniform discussions of technical maturity across different sectors - see section 2.1.1 and Appendix 2. When a technology has reached the top level of TRL 9 - does not necessarily mean that it is commercially ready. At this stage, there are still further matters that need to be satisfied relevant to widespread diffusion and scaling. Commercial factors, which include affordability, disruptive competition, public acceptance, environmental and regulatory considerations, and long-term reliability.

The questions for this project are: (1) what are the commercially relevant barriers for CCUS to overcome; and (2) specifically would indices assist in catalysing communication as to when those barriers to CCUS establishment and deployment have been adequately addressed?

1.3 Study Scope

This study assessed the underappreciated broader dimensions of technological scaling beyond TRL for CCUS. It assessed which aspects of commercial readiness and bankability are important to different actors/stakeholders within the CCUS diffusion ecosystem. Furthermore, evaluation of the indices most relevant/appropriate to those actors to allow better management of risk and uncertainty for accelerated CCUS scaling across a range of economic sectors was undertaken. To this end, the project is structured around the following tasks:

- Exploration of the meaning and dimensions of commercial readiness with regards CCUS technologies;
- Assess the relevance of indicators that influence commercial readiness beyond technology maturity;
- Developing a wide-ranging understanding of what commercial readiness means and how indices can be applied to those issues for the core stakeholders fundamental to the deployment of CCUS at scale; and
- Critically assess and make recommendations as to the relevance of indices and how they might be aligned to net zero.
- Recommendations for further work will also be made.

1.4 Work Packages, Structure of Report and Research Approach

The *Role of Indices in assessing the Maturity of Carbon Capture and Utilisation Technologies and Readiness for Deployment* project is structured around four work packages (WPs) which were conducted as described in table 1.1, below.

Table 1.1: Project Structure, Work Package composition and Research Process

Work Package 1 (WP1) - Exploration of the meaning of commercial readiness for CCUS • Enabling factors for scalable technological deployment • Barriers to realising CCUS's identified potential

[28] Bloomberg New Energy Finance. 2010 Crossing the Valley of Death: Solutions to the next generation clean energy project financing gap dated 21th June 2010.

Research Process - Meta study of the technology diffusion, energy transitions, infrastructure and CCUS literature - Covered in Appendix 1.

Work Package 2 (WP2) - Assess relevance of commercial readiness indicators beyond technology maturity

- Indicators influencing Commercial Readiness and market potential
- Critical review of existing, new and potential CR indices
- How indices might apply to CCUS and barrier identification
- Role of CCUS indices on meeting UN SDGs
- Successful analogues - what CCUS can learn*

Research Process - A non-exhaustive critical review of indices which are used by other economic and technology sectors was then undertaken assessing how they might be applied to inform aspects of CCUS scaling and bankability in commercial readiness. Covered in Section 2.

Work Package 3 (WP3) - Stakeholder Engagement what commercial readiness means and how relevant indices can be applied

- CCUS stakeholder mapping - government, industry, regulators & finance - and roles in scale-up ecosystem
- Stakeholder perspectives on CCUS readiness for scaling based around three value chains (1) Synfuel sector particularly those around DAC; (2) Bioenergy Carbon Capture and Storage Power Plant; and (3) Steel and Cement production.
- Stakeholder perspectives on CR indices relevance and how used
- Effectiveness of existing CCUS policy
- Role of policy measures and incentives to address CCUS deployment and barriers
- Analogues of successful CR policy interventions

Research Process - Interviews and workshops have been undertaken with 26 specialists from across the CCUS project developer community, policy makers, finance specialists, regulators and civil society representatives - to assess which aspects of commercial readiness and bankability are important to different actors/stakeholders within the CCUS diffusion ecosystem. Evaluation of the relevance of indices and metrics more broadly is then undertaken including their role in addressing the SDGs. Where metrics are considered applicable, the most relevant/appropriate to relevant actors to allow better signposting as to the extent of risk and uncertainty being sufficient to allow CCUS investment and scaling were elicited.

Where relevant, analogues of successful policy interventions for other technologies were developed including how they might apply to the CCUS sector to better address bankability and invest-ability. Covered in Section 3.

Work Package 4 (WP4) - Critical assessment and recommendations for further work.

Research Process - Critical Review of study insights in the context of the established literature and study scope. Covered in Section 4.

** this was originally in WP 1 in the proposal and moved to WP2 to allow a more logical report structure*

WP1, the exploration of the meaning of commercial readiness for CCUS, is placed in Appendix 1. This allows the focus of the main report to concentrate on the role of metrics. It is worth emphasising, however, that as part of WP1, justification of the research framing as a complex problem is made[29]. This better systemises the methodological framing/approach and allows the generation of deeper insights as to what is required for the realisation of CCUS bankability and deployment[30]. It also justifies broader coverage of insights regarding systems and other networked infrastructures to be applied to the research e.g. how capital investment operates as a critical enabler of different pathways for energy transitions - see Figures 1.3 and 1.4[31,32].

[29] A complex problem is defined as consisting of interdependent drivers such as political, economic, regulatory, cultural which are reflexive in that a change in any one dimension having non-linear and unpredictable impacts on others etc.

[30] Workman M, Darch G, Dooley K, et al., 2021, Climate policy decision making in contexts of deep uncertainty-from optimisation to robustness, Environmental Science and Policy, Vol:120, ISSN:1462-9011, Pages:127-137

[31] Bolton, R. and Foxon, T.J., 2015. A socio-technical perspective on low carbon investment challenges–insights for UK energy policy. *Environmental Innovation and Societal Transitions*, *14*, pp.165-181.

[32] Barazza, E. and Strachan, N., 2020. The co-evolution of climate policy and investments in electricity markets: Simulating agent dynamics in UK, German and Italian electricity sectors. *Energy Research & Social Science*, *65*, p.101458.

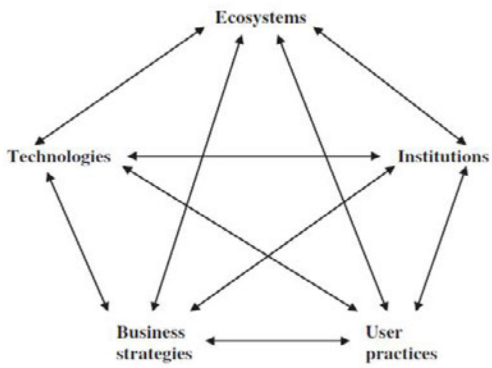


Figure 1.3: Foxon's Co-evolutionary framework[33]

Figure 1.4: Nested hierarchy of likely systemic needs to address CCUS deployment and the likely drivers of transformational change

The project uses the Geels[34] Socio-technical transitions framework throughout to emphasise that designing policy interventions and market structures in complex systems involves dealing with risk, uncertainty and emergence at a number of scales. Furthermore, the range of factors needed to diffuse technology portfolios within the socio-technical systems which make up modern economies are substantial. It is in this context that this project will critically evaluate the role of CCUS ecosystem relevant indices, how they might assist the range of actors likely to be involved in the early scaling of CCUS by providing the relevant signals.

2. Metrics and Indices - Mapping and Assessment

2.1 Indices - Their role in commercialisation and bankability assessment

Indices allow benchmarking, risk management and funding decisions. They enable consistent, uniform discussions of technical and commercial maturity of novel technologies across different sectors. They also allow the adjustment of interventions to address unintended consequences or better align technology commercialisation.

In the two broad dimensions associated with technological diffusion[35], technology readiness levels (TRL) have tended to be where the energy innovation community have focused their assessments of CCUS's potential for scalability. The importance of broader indices relevant commercial readiness has only just started to be incorporated in CCUS assessments[36]. This is replicated by the proliferation of other indices which seek to accommodate broader readiness - such as affordability, disruptive competition, public acceptance, environmental and regulatory considerations, and long-term reliability - that have been generated from other economic and technology sectors.

In this section, elements of WP2 are undertaken as follows:

- An understanding and origins of Technology Readiness Levels and how they are applied as conceived by NASA and the US Department of Energy (US DoE),

[33] Foxon, T. J. 2011. A coevolutionary framework for analysing a transition to a sustainable low carbon economy. Ecological Economics, 70, 2258–2267.

[34] Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research policy*, *31*(8-9), pp.1257-1274.

[35] Bloomberg New Energy Finance. 2010 Crossing the Valley of Death: Solutions to the next generation clean energy project financing gap dated 21th June 2010.

[36] IEA 2021. Energy Technology Perspectives 2020. International Energy Agency February 2021 pp400

- A mapping and critical review of existing, new and potential commercial readiness indices,
- How indices might apply to CCUS and allow barriers to be identified. This is undertaken by mapping the existing and potential indices relevant to the ecosystem of CCUS scale up. System wide metrics have also been mapped,
- The potential role of a suite of CCUS indices on meeting UN SDGs, and
- Case studies of successful analogues of the realisation of other technologies with systemic insights as to what CCUS can learn from these case studies. The intention being to allow better understanding of the benefit of indices to inform stakeholders.

2.1.1 Technology Readiness Levels - Origins and Construct

An understanding and origins of Technology Readiness Levels and how they are applied can be found in Appendix 2. Technology Readiness Level (TRL) measures how ready equipment is for use now in a broader system. Characterisation of TRL in the context of energy systems is broken down as follows[37]:

- **Technology -** This refers to a technological process, method, or technique such as machinery, equipment or software needed for the plant, facility, process and/or system to achieve its purpose.
- **Readiness -** This refers to time. Specifically, it relates to readiness for operations at the present time.
- **Level** - This refers to the level of maturity of the technology equipment. Equipment that is already being used for the same function in the same environment has a higher level of maturity than equipment that is still being developed. The levels are a nine-point scale based on a qualitative assessment of maturity.

The application of TRL requires three steps:

(1) Mapping of the system within which the specific technology is being developed - the way that the `system' is mapped has a bearing on the boundary, detail identified and in turn the visibility of risk and uncertainty for the overall programme;
(2) Assigning a TRL to each of the technologies within that system which involves independent assessment of evidence to validate a given TRL to each technology; and
(3) Plan the technology development which is the technology maturation plan. This involves a number of components but one of the most important are the establishment of success criteria to progress through each TRL classification.

The following is relevant regarding how the TRL is applied as prescribed by the US DoE:

- ***It is a tightly bounded construct.*** Not all R&D activities can be assigned a TRL e.g., learning by doing.
- ***It is a time specific construct.*** TRL provides a snapshot in time of the maturity of technologies and their readiness for insertion into the project design and execution schedule.
- ***TRL is context specific.*** A technology which is considered mature in one operating system cannot be assumed to be mature in a different one.
  - The assumptions to which a technology is to be applied need to be explicit and documented.
  - TRL when applied to a technology in another industry and/or sector may not be relevant to the application to the relevant system to which a TRL assessment was originally being applied.
- ***TRL applies an ordinal scale.*** The 9-level classification are in order but the distinction, resources (in time and money) and effort which require to be applied between neighbouring classification levels are rarely the same.
- ***High TRL is not necessarily `good' and low 'bad'.*** This is better assessed in development plans. Technologies at a low TRL may move quickly from low TRL to high given the appropriate stimuli

[37] Adapted from NDA 2014 - Guide to Technology Readiness Levels for the NDA Estate and its Supply Chain dated 6th November 2014 505/02 Issue 2

- ***TRL is a qualitative classification scale, not quantitative.*** Related to the above, the numbers within the classification cannot be used arithmetically in that TRL 4 is not twice TRL2.
  - Classifications for individual technologies are assessed by independent panels using prescriptive processes benchmarking against descriptive benchmarks.
  - Technologies can go up as well as down the classification as a function of the context / system to which they are being applied.

The following are also of note regarding the construct:

- The technology development process within which the TRL process operates is not limited to the pre-acquisition and conceptual development stages, but instead, transitions throughout the life of the project. Indeed, technology improvement will often take place for some-time even once a technology has reached TRL9. For example, the mobile phone attained TRL 9 in the mid-80's but have substantially advanced since then including the radical evolution of the smart phone in 2007 some 40 years after the original mobiles attained operational maturity.
- TRL 6 is also used as the level required for technology insertion into design by NASA; it is normally the last stage where technology has been demonstrated in the engineering/pilot scale in the relevant environment - i.e., starts taking on characteristics of being commercially viable with implications on its bankability. However, this again will be predicated on a specific technology being applied to a specific system. The extent of risk assigned to a technology to assess commercial viability even at TRL 6 likely being a function of the extent of capital intensity. The following is relevant in this regard: (1) Electronic technology being less capital intensity will be more readily invested in at TRL 6 where-as technology as capital intense as CCUS will not; and (2) Some renewable technologies tend to be smaller, have a smaller commercial valley of death (between TRL4 to 6), limited systemic infrastructure adaptation i.e., can plug straight into existing electricity system e.g., Solar and Wind.

Based on the above analysis the following insights can be generated regarding the TRL classification system and its application to CCUS technologies and energy systems more broadly:

- TRL is an assessment of the risk and uncertainty that an individual technology has ***and*** the context of its application to the specific system to which it is being applied.
- It is a useful mechanism by which to communicate a common understanding of risk and uncertainty assessment for individual technologies across multiple stakeholders within the timely and cost-effective execution of a bounded technology programme.
- In turn it allows a common framework to understand the processes for maturing technology within a technology programme.
- The limitations of TRLs lies mainly in how they are applied rather than in the concept itself. These include:
  - They are a measure of technical risk for a specific technology to be integrated into operating plant / broader system at the present time. The TRL indices do not provide a transferable and/or an anticipatory dimension regarding risk and uncertainty if a specific technology is being applied within another energy system and/or future technology programme.
  - TRL is applied to an individual technology. It does not have any bearing on the ability to integrate a suite of technologies or will be able to fulfil its role within a programme and the successful delivery of that programme.
  - Though classifications for individual technologies are assessed by independent expert panels using prescriptive processes benchmarking against descriptive benchmarks for TRL there are processes which circumvent this. For example, the USAF has a TRL calculator[38] which is a Microsoft Excel spreadsheet application that allows the user to answer a series of questions about a technology project. Once the questions have been answered, the calculator displays the TRL achieved. This is a

[38] Nolte, William L., et al., "Technology Readiness Level Calculator," October 20, 2003, Air Force Research Laboratory (AFRL).

limitation in that descriptive benchmarking by experts is by-passed negating the ability to unpack the reason for the lack of advancement of a technology up the TRL scale.

- The TRL process according to the US DoE involves the assignment of responsibility and accountability in the form of technology development plans. When applied in the energy sector such as for generic technology publications[39] this is not undertaken. Furthermore, the heterogeneous nature of CCUS technologies and its multiple applications to technology systems across economies means that the application of TRL to CCUS would be comprised of multiple TRLs dependent on the specific component of CCUS technology, the broader technology system to which it was being applied. These range from cement, steel, sustainable aviation fuel production, power generation, negative emissions amongst others - and for those value chains that involve an element of geological sequestration geographical context as a function of how well characterised those storage sites are[40].

In summary TRL are for assessing whether individual items are mature enough for active operation but they do not necessarily address other project needs such as integration, transition to operations and manufacturing. The assessment of the TRL indices and its application emphasises the specificity as to how a technology is applied to a system context. It requires the need for specialist knowledge and input to make the relevant assessments as well as taking place within a very tightly curated project management process within which the attribution of responsibility for the reconciliation of barriers to progress is assigned in a time-bound manner. ***On this basis it can be seen how they are (mis-)applied in generic innovation publications in that specificity and system context is lost as well as the all-important attribution of responsibility to address process through the TRLs.***

2.1.2 Other Indices relevant to commercial readiness and bankability

Technology readiness is one of a number of factors that are required by stakeholders to support their decision at various stage gates. Here a survey of new indices which seek to cover issues relevant to commercial readiness is made. It is noteworthy that the study makes the distinction between ***generic indices*** such as those used in the Australian Renewable Energy Associations Commercial Readiness Indices e.g. Stakeholder, Regulatory, Finance Readiness etc which are assessed by specialists and translated into these indices and ***metrics*** which are associated with different aspects of CCUS development e.g. geological storage capacity, weighted average cost of capital, levelised cost of electricity, etc., which do not need assessment by specialists to be translated into a generic variable. Furthermore, indices are often comprised of multiple metrics including TRL which often forms a subset of the indices.

As part of the study, over 45 readiness indices have been mapped and 38 critically reviewed. These can be found in Appendix 3 where the table breaks down the name of the individual index, the relevant source/reference, the sector that it seeks to assess `readiness', the metrics that are involved and a description of the notable features of the indices. Examples of the indices that have been generated to cover different scales to assess the commercial bankability of different propositions and technologies can be found in Table 2.1, below.

[39] IEA 2020. Energy Technology Perspectives 2020. International Energy Agency February 2020 pp400

[40] Zimmermann, A and Schomcker, R 2016 - Assessing Early-Stage CO2 utilization Technologies - Comparing Apples and Oranges? Energy Technol. 2017, 5, 850 – 860. *`The term CO_2 utilization includes a heterogeneous portfolio of technology concepts; evaluation is much like comparing apples and oranges. Analysis of recent literature assessing CO_2 utilization technologies unveils gaps in used assessment methods and indicators, which makes comparison difficult.'*

Table 2.1: Summary of indices generated to cover different scales of issues relevant to commercial bankability

Scale through the nested hierarchy of transformational change		**Examples of Readiness Levels**
Systemic: Economy Wide	***Societal Capacity***	• Societal Readiness Levels by the Innovation Fund Denmark, 2018. • How to Assess Market Readiness for an Innovative Solution by Hjorth and Brem, 2016 • End User Readiness Level by Luscinus, 2020.
Increasing in scale and decreasing in extent of bounding	***Governance, Regulatory and Finance***	• Legal-Social-Technology Readiness Levels by Bruno et al., 2020 • Green bonds shades of green by CICERO 2020
	Sector System Innovation	• Service innovation Readiness Level by Yen et al., 2012 • Transformation Readiness Level by Gudergan et al., 2015 • Aspects of Innovation by Energy Systems Catapult, 2020
	Sector Business Model	• Small Medium Enterprise readiness for Manufacturing 4.0 by Chonsawat & Sopadag, 2020 • Small Medium Enterprise readiness to implement service design by Teso and Walters (2016) • Nanotechnology Commercialisation Readiness Scale by Duret et al., 2012 • Change Readiness Levels - Change Readiness by Combe, M., 2014 • Business Transformation Readiness Assessment by TOGAF, 2011
	System and Service Readiness	• System of Systems Technology Readiness Level Assessment by W. Majumdar, 2009 • Advancement Degree of Difficulty (AD2) by Bilbro, (2008) • Manufacturing Readiness Level by the Automotive Council (2011) • System Readiness Assessment by Austin et al., 2015 • Carbon Capture and Storage Readiness Index by Global Carbon Capture & Storage Institute 2018.
Atomistic: Bounded	***Technology Readiness Level***	• Technology Readiness Level by Department of Energy 2006 • Expansion of the Technology Readiness Levels Perspective by IEA 2020

The following observations are relevant to this study:

- Chronologically, the literature appears to transition from NASA in the 1980's, through the defence and energy sector in the late 1990s, and then in the late 2000 to the present where there has been an explosion in the generation of indices.
- Corresponding this explosion in the last 15 years***, the sector and domain coverage is extensive*** - see Table in Appendix 3 - covering Social readiness to adopt technologies; the greenness of bonds in the finance sector; legal and regulatory readiness; culture of an organisation and its readiness to adapt to change and/or transform; Small Medium Enterprises readiness for industrial manufacturing 4.0; and ability to implement service design; the readiness of manufacturing supply chains to produce products at scale; the readiness of a system to adopt new technologies etc. These correspond to a range of scales from economy wide and essentially unbounded e.g., Societal Readiness and End User Readiness Level - to - atomistic and bounded e.g., Business Transformation Readiness Assessment.
- The ***extent of intricacy/complexity and extent of sophistication is highly variable*** with some comprising the addition of another set of levels to an existing liner index e.g. the IEA Energy Technology Perspectives adding two additional levels to its traditional TRL scale (TRL10 commercial and competitive and TRL 11 achieves predictable growth); a number of subsets of metrics within the indices e.g. Manufacturing readiness levels brings together two sets of indices (Technology Readiness and Manufacturing Readiness); others such as Legal-Social-Technology Readiness Levels have four (Technology, Societal, Organisational and Legal); and the Australian Renewable Energy Agency's Commercial Readiness Levels has eight - Regulatory Environment; Stakeholder Acceptance; Technical Performance; Financial Proposition - Costs; Financial Proposition - Revenue; Industry Supply Chain and Skills; Market Opportunities; and Company

Maturity. Some focus on the interoperability of technologies e.g., the Systems of Systems Readiness Levels consists of assessment of the degree of interoperability so that systems are acquired which can operate relatively independently within a collection of other independent systems.

- Though the majority involve ***qualitative assessment*** requirements to evaluate different aspects of readiness levels some are highly quantitative e.g., Sausers 2006, 2009 and Ross 2016 system of system and integration readiness which develop intricate mathematical computations to assess a clear indicator of when a component technology or system is ready for further advancement.
- The majority of indices are ***snap-shots of the state of readiness of a technology, system, service*** etc. Only the Advancement Degree of Difficulty (AD2) (Bilbro, 2008) and Project Definition Rating Index (CII, 1995) are predictive in that they develop an anticipatory description of what is required to move a system, subsystem or component from one TRL to another and how a construction project will perform based on preparation. Again, they require deep knowledge of both the technology and the applied system.
- ***As the level of intricacy increases the resource to develop the indices increases and there tends to be a decreasing ability for un-initiated audiences to comprehend them.*** This is attributed to definitional issues being very important in the rating scales. In this regard, there is a clear balance between simplicity and clarity for ease of generation and comprehension across multiple audiences with insight as to the complexity of issues which need to be considered for addressing the relevant indices establishment, development, and scaling. The more detailed and intricate the indices the more useful it is to assess the nature of interventions but there is likely only a small audience which will be able to interpret the indices to sufficient level of comprehension to be useful.
- ***Few of the indices assessed involved the assignment of responsibility and accountability for the progression of any aspect of the metrics*** which made up the indices. The implementation of technology development plans was such an integral component of the NASA and US DoE project management system.
- The indices that have been reviewed could relatively easily be adapted to the CCUS sector - see below.

A final observation is that the transition from relatively simple linear indices as exemplified by TRL to multi-metric indices is symmetrical around the branching in the transitions and innovation theory literature (section A1.2) and the realisation of the importance of Multi-Factor Learning curves over One Factor Learning Curves (Section A1.5). It is notable in the review from WP1 that there was an absence of data of sufficient fidelity, temporal resolution and in different geographical jurisdictions for Multi-Factor Learning curves. ***This questions the ability to generate indices to inform broader stakeholders and innovation policy for the establishment, scale up and deployment of CCUS technologies***.

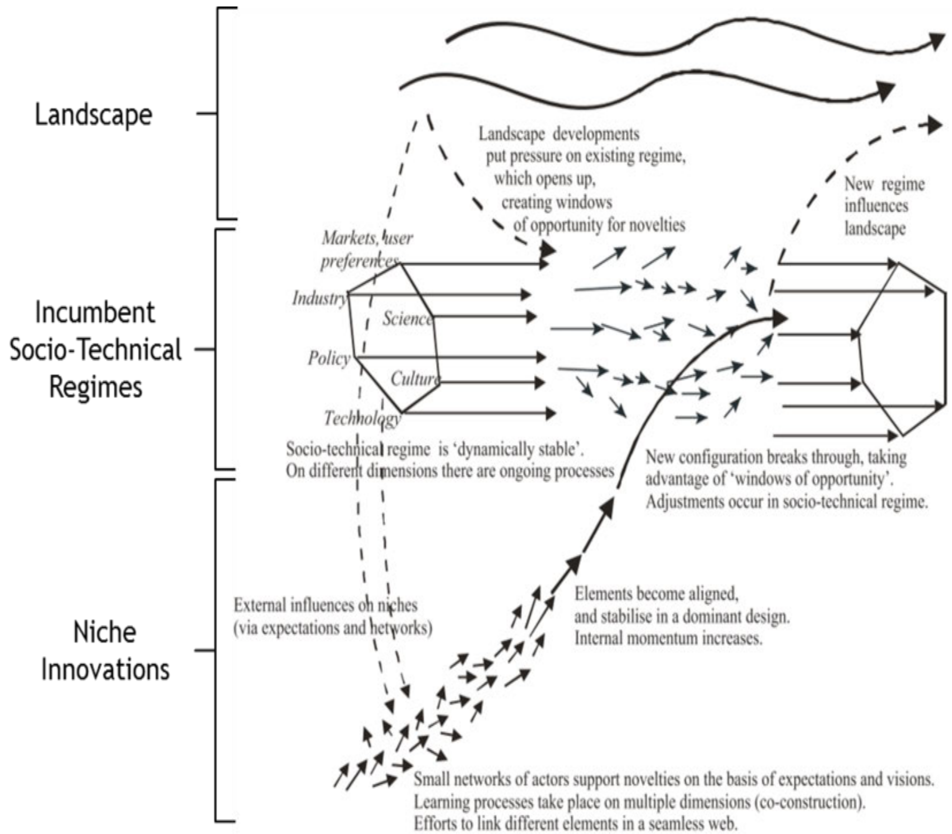
2.2. Application of Indices to address the scaling, commercialisation and bankability of the CCUS

An aspect of the WP2 review of indices was to assess how they might allow barriers to be identified by different audiences across the extent of commercialisation. On the basis that the indices are adaptable to the CCUS sector, Figure 2.1, below - shows the mapping of the indices reviewed in Appendix 3 and how they might be applied based on the socio-technical multi-level framework prescribed in section A1.2.1.

The following observations can be made:

- The ***reviewed indices can be applied across the full extent of anticipated range of components that are likely to be important to establish, scale and diffuse CCUS technologies and their associated value chains across an economy***. This ranges from niche factors associated with the CCUS value chain e.g., Manufacturing Readiness Levels; Regime level associated with CCUS business models e.g., Business

Figure 2.1: Mapping of reviewed indices detailed in Appendix 3 onto Geels multi-level framework to assess how indices might be applied to the CCUS sector. **[X]** represents the line item in the Appendix 3 table. Some of the indices are stated in full. Where they are not, then they are similar in construct to the item against which the line item is assigned to the indices stated in full.



Systemic Indices: **[1].** Systems Readiness Level **[2],[3],[4],[12],[13],[14],[15],[16],[20]** System of Systems Technology Readiness Level Assessment; **[5],[6]** Aspects of Innovation; **[37]** Green bonds shades of green

*The socio-technical **landscape** provides the exogenous environment for regime change and is a source of major selection pressures on prevailing regimes. Transitions, i.e., shifts from one stable sociotechnical regime to another, occur when regimes are destabilized through landscape pressures, which in turn provide opportunities for niche innovations."*

Indices: [19] Nanotechnology Commercialisation Readiness Scale; **[21],[22]** How to Assess Market Readiness for an Innovative Solution;**[23]** ARPA Commercial Readiness Levels; **[33],[34],[35]** Legal-Social-Technology Readiness Levels; **[36]** End User Readiness Level

***Regimes** and niches develop in the context of a socio-technical landscape, which consists of both hard geographical features, such as resource availability and infrastructure, and "soft" elements, such as political conditions, societal trends, and economic fluctuations.*

Indices: [17] Commercial Readiness Levels; **[18]** Service engineering methodology and Energy Services; **[24]** Readiness to Transform; **[25]** Change Readiness Levels - Change Readiness; **[27]** Organisational sustainability readiness; **[31]** Business Transformation Readiness Assessment; **[32]** Organizational AI Readiness Factors

*A **niche** is a network of similar projects carried out by innovating actors who seek to challenge the incumbent and dominant socio-technical practice (regime).*

Indices: [7] Automotive Technology and Manufacturing Readiness Levels; **[8]** Manufacturing Readiness Levels; **[9],[10]** Small Medium Enterprise Service Readiness; **[11]** Service innovation readiness: Dimensions and Performance Outcome; **[26]** Innovation Readiness Levels; **[28]** Project Definition Rating Index; **[29]** Scientific Readiness Levels; **[30]** Operational Readiness Reviews; **[38]** Carbon Capture and Storage Readiness Index

Transformation Readiness Assessment; systemic Landscape factors such as Legal-Social-Technology Readiness Levels and End User Readiness Level.

- There were also a set of ***multi-scale metrics which cut cross the levels relevant to the capacity of technologies to integrate within systems of systems.*** The Energy Systems Catapults `Aspects of innovation' which incorporates technology, operation and people metrics at niche, regime and landscape scales respectively and even interoperability as a systemic component. Green bonds index is also cross-cutting as a function of the importance of finance for all aspects of CCUS scale up.
- Though this macro and generic application of metrics demonstrates how indices could and might be applied to the CCUS sector to assess commercial readiness - ***it does not address the utility and perceived benefits of their application by specialists in the CCUS sector****.* This is addressed in Section 3.

2.3. Application of Indices to broader global public goods beyond net zero

Another component of WP2 included an assessment of the potential role of a suite of CCUS indices on meeting UN Sustainable Development Goals (SDGs)[41].

This warrants a high-level review of SDG for which the following observations are relevant:

- There are 17 SDG indices - see figure 2.2, below - within which there are 169 associated target metrics.
- The Infrastructure SDG, of which CCUS would be integrated, either directly or indirectly influence all 17 of the SDGs, including 121 of the 169 targets (72%)[42]. Infrastructure is part of SDG 9 (industry, innovation and infrastructure) and SDG 13 (Climate action) are the most direct of the links for CCUS. CCUS impacts 10 directly, 2 indirectly and 5 have limited interaction[43]
- There is no set approach nor methodology for assessing the interaction of sectors and technologies with the SDGs though approaches are being developed[42,43].
- Data availability, comparability and quality impact the way that nascent approaches are being developed.
- There are substantial research gaps and indeed calls for more research and systemisation of assessing the impact of infrastructure and CCUS on SDG[42,43].
- From the early research undertaken it is considered that some interactions will be positive, for example, CCUS can promote sustainable economic growth (SDG 8)[44] and some negative in that the energy penalty for CCUS will impact energy efficiency targets (SDG 7) and others are likely to be in tension as a function of life cycle emissions in SDG 3 (good health/wellbeing), 6 (Clean Water/Sanitation) and 15 (Life on Land).
- An important aspect of the limited research undertaken in this space is that the interactions between infrastructure and SDGs are interdependent - see figure 2.3 - and that they are synergistic and reflexive. *`There is a feedback mechanism between infrastructure systems and the SDGs, with infrastructure enabling delivery of the SDGs, while the targets provide a framework for guiding and constraining the provision of infrastructure so that it is sustainable'*. [45]

[41] UN 2015 'Transforming our World: the 2030 Agenda for Sustainable Development'
[42] Thacker S et al. Infrastructure: Underpinning Sustainable Development. UNOPS, Copenhagen, Denmark.
[43] 'IEAGHG 2020 Carbon Capture and Storage and the Sustainable Development Goals, 2020-14, December 2020.
[44] Patrizio, Pratama and Mac Dowell (2020).Socially equitable energy systems transitions
[45] Thacker et al 2019 - Infrastructure for Sustainable Development In Nature Sustainability dated April 2019 324-331 https://doi.org/10.1038/s41893-019-0256-8

Direct interaction	Indirect interaction	Limited interaction foreseen
3. Good health and wellbeing	1. No poverty	2. Zero hunger
6. Clean water and sanitation	4. Quality education	5. Gender equality
7. Affordable and clean energy		10. Reduced inequalities
8. Decent work and economic growth		16. Peace, justice and strong institutions
9. Industry, innovation and infrastructure		17. Partnerships for the goals
11. Sustainable cities and communities		
12. Responsible consumption and production		
13. Climate action		
14. Life below water		
15. Life on land		

Figure 2.2: Direct and Indirect interaction between CCS and SDGs

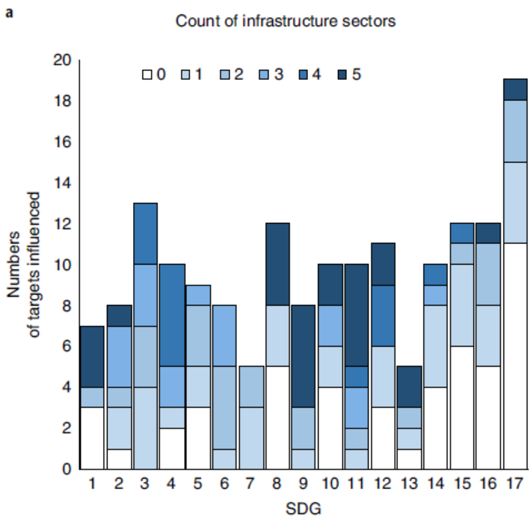


Figure 2.3: SDG infrastructure interdependencies[46].

Considering the analysis undertaken in the previous two sections regarding how limited some of the data is likely to be for metrics in some geographical jurisdictions and the limited interpretability of intricate metrics to un-initiated audiences. ***One would question the merits of integrating CCUS commercial readiness indices some of which have 8 metrics with the 169 metrics established on meeting UN SDGs.*** It would require considerable resource effort and result in questionable transparency or communication value to relevant audiences as to whether CCUS was meeting SDGs. It would likely be more sensible to simply assess CCUS technology development directly as to the ability to meet SDGs on a project-context specific basis.

2.4. How Indices might have provided systemic insights - CCUS Analogous Case Studies

A final component of WP2 was the assessment of case studies of successful analogues for other technologies which have been roll-out in other sectors. On this basis insight was sought as to what CCUS can learn from these other successful technology rollouts. From this, the role of indices to inform stakeholders as to when various thresholds regarding uncertainties regarding commercial and bankability had been realised might be deduced from these case studies.

A study which undertook a comprehensive review on this basis was undertaken by Watson et al[47]. Though 10 years old the findings remain relevant today. The findings of the study including the metrics and analogues can be found in table 2.2, below.

Table 2.2: A review of the range of risks that CCS technologies face, metrics which might be used to assess the extent of risk and uncertainty and analogues of technologies which successfully scaled in the energy sector.

Uncertainties	Metrics	Analogues
1. Variety of pathways. Diversity of technological options represents an uncertainty for investors and policy makers. Early selection might accelerate development, but risks locking in weak technologies.	• Number of technology variants • Relative importance of variants for technology developers • Market share of technology variants • Extent of lock-in / dominance of particular technology variant	The French Nuclear Programme, 1950s-1980s

[46] Counts of the number of different infrastructure - energy, transport, water, solid waste and digital - sectors that influence the SDG targets (where 5 is the maximum) that are identified as being able to influence different targets of the SDGs.
[47] Watson, J (ed.) et al. 2012, Carbon Capture and Storage: Realising the Potential? UK Energy Research Centre

2. Safe storage. There is uncertainty as to whether geological storage of CO2 will be secure over long time periods, as well as if and how the associated risks can be reliably assessed and managed.	• Availability of storage site data, including agreed robust estimates of their capacity • Nature of legal / regulatory framework to share risks / liabilities • Levels of public awareness / acceptance of risks	The management of radioactive waste in the UK, 1956-2011
3. Scaling up and speed of development and deployment. There is uncertainty about whether and how fast CCS technologies can be scaled up and developed to maturity	• Unit size, capacity and efficiency • Speed of unit scaling • Cumulative investment / installed capacity - Relative importance of market niches	The UK 'Dash for Gas', 1987-2000 Flue Gas Desulphurisation in the USA, 1960s-2009
4. Integration of CCS systems. It is unclear how CCS systems will be integrated. Integration is a technical challenge, as well as an issue of organisation and governance.	• Whether full chain integration has been achieved? • The allocation of responsibility for integration • Presence, role and importance of 'system integrator' firms/ actors • Nature of development, including roles of key actors and the relative importance of 'bottom up' / emergent and 'top down' / directed development	Natural Gas Network in the UK, 1960-2010
5. Economic and financial viability. The future cost and financial risk of implementing CCS are very uncertain. The economic and financial uncertainty is heavily dependent on policy.	• Costs, including assessment of quality of cost data • Key financial risks and 'financeability' • Role of subsidies, other forms of economic / financial support, and other sources of finance Emissions reduction policies - e.g. Carbon tax on offshore gas, the ETS in Europe, Q45. (Both last two bullet points shared with uncertainty 6)	Flue Gas Desulphurisation in the USA, 1960s-1970s Investments in landfill in the UK, 2001-2011
6. Policy, politics and regulation. CCS development is strongly influenced by uncertainties about extent of political support, as well as the choice and design of policies and regulations.	• Nature of legal / regulatory framework to share risks / liabilities • Role of subsidies, other forms of economic / financial support, and other sources of finance (shared with uncertainty 5) • Role of other forms of policy support - Extent of political commitment / legitimacy	Flue Gas Desulphurisation in the UK, 1980s to 2009
7. Public acceptance. Public acceptance may be crucial to CCS development but is uncertain. Attitudes to CCS are shaped in social interaction.	• Levels of public awareness / acceptance of risks • Specific manifestation of public opposition (or support) • Quality of public engagement	Natural gas infrastructure development in the UK, 2000-11

A number of observations can be made from this study regarding the role of indices:

- The analogues are all as capital intensive as CCUS e.g., the UK Natural gas infrastructure development, French Nuclear Programme and UK Dash for Gas;
- The metrics that are elicited from the study for CCUS - see 2nd column in table 2.2, above - are found within the suite of indices and metrics that have been surveyed in this study - Appendix 3; and
- The systemic findings from the study detailed in Appendix 4 and summarised below:
    - Keeping options open or closing them down?
    - Which public policy incentives for CCS demonstration and deployment?
    - CCS deployment as a marathon, not a sprint.
    - Dealing with storage liabilities

It is unlikely that any of these issues would benefit substantially by the development of indices. As a quartet of observations, the study strongly suggests the need for sustained development of sufficient systemic interventions to justify the business case to build CCUS facilities[48,49]. The complexity of each analogue would unlikely have benefited from the addition of indices.

2.5. Summary

The review of the TRL process and its application to technologies is highly specific and takes place within a tightly bound programme management process whereby the attribution of responsibility for the addressing of issues is clearly made. It requires considerable resources in time and specialist knowledge to manage. It is also often miss-applied and miss-interpreted, the value of the indices can only be indicative and has no anticipatory aspects as to the ability for the technology to be commercialised.

A review of 38 commercial indices indicates the following:

- As the level of intricacy increases the resource to develop the indices increases and there tends to be decreasing ability for un-initiated audiences to comprehend them,
- They can be applied to the CCUS sector across the range of barriers and commercialisation needs for scale up in socio-technical systems - though whether they provide benefit to actors is questionable,
- The benefits of applying and/or integrating CCUS scale up indices with the 169 metrics established on meeting UN SDGs would also be of questionable benefit as a function of data gaps, inconsistency in methodological approach and interdependencies, and
- Where successful CCUS analogues have been delivered such as the French Nuclear Programme or the UK Gas Grid build out - the role of indices as improving understanding of barriers to commercialisation is also questioned.

3. CCUS Stakeholders and Government Perspectives

3.1 Introduction

An integral aspect of this study was to involve interviews and workshops with specialists in the CCUS. Their insights would be sought to elicit perspectives as to the role of indices in providing the CCUS community with a common understanding of the state risk and uncertainty for different commercial components of CCUS establishment and scale up. In this section, work package 3 of the study is described for respective cohorts:

CCUS Stakeholders:

- CCUS stakeholder mapping - government, industry, regulators and finance - and roles in scale-up ecosystem around CCUS value chains;
- Stakeholder perspectives on CCUS requirements for readiness for scaling and bankability; and
- Stakeholder perspectives on commercial readiness indices relevance to manage complexity, risk and uncertainty.

Government:

- An assessment of the effectiveness of existing CCUS policy in a number of geographical jurisdictions; and
- The role of policy measures and incentives to address CCUS deployment and barriers.

The engagement involved 10 x interviews and 2 x workshops undertaken with 26 specialists from across the CCUS project developer community, policy makers, finance specialists, regulators and civil society

[48] Clean Air Task Force 2021. Examining the Current Policy Landscape of Carbon Management in Europe. Policy Paper on why carbon management is a catalyst in meeting the climate challenge. October 2021

[49] Clean Air Task Force 2022 - Decarbonising European industry: Enabling carbon capture and storage through the EU ETS. Fact Sheet dated 15th Feb 2022

representatives. The interviews were undertaken on a one to one basis; the first of the workshops involved 10 representatives from CCUS developers, finance and environmental NGO community; and the second workshop 6 representatives from UK and US government including a UK regulator.

The intention was to develop patterns and insight regarding how the disparate actors are operating in the CCUS sector along the following lines:

- *Deployment activity relevant to CCUS* - What are actors doing relative to that which is needed to establish and scale CCUS in the three case study sectors?
- *CCUS actors patterns of behaviour* - What trends are the CCUS ecosystem of actors taking over time regarding possible net zero futures and CCUS deployment, what are their risk appetites, R&D and investment strategies etc and what indices do they use to monitor risk, how are they used and their effectiveness?
- *CCUS systems structure* - How are the parts related and what influences the patterns?
- *CCUS actors mental models* - What values, assumptions and beliefs shape the CCUS eco-system?

With regards the first two points, there is insufficient deployment of the relevant CCUS case study value chains to warrant mapping beyond that covered in the CCS Global Status Report[50] where the following is salient:

- Deployments are mainly taking place in North America and Europe - see Appendix 5, figure A5.1 for a world map of CCUS facilities at various stages of development;
- Projects are becoming more diverse in scale and applications ranging from Direct Air Capture to Power and Hydrogen Generation - see Appendix 5, figure A5.2 for CCUS projects by sector and scale; and
- There is a rise in the development of CCUS networks whereby capture projects share transport and storage infrastructure - see Appendix 5, figure A5.3.

On the topic of deeper insights on CCUS actor's patterns of behaviour regarding risk appetites, system structure and actor mental models - these were elicited during the interviews and workshops and are described in sections 3.2.2, 3.2.3 and 3.2.4, respectively. Insights as to indices recommended and might be used to monitor risk and their effectiveness is unpacked in section 3.4.

3.2 Perspectives on CCUS requirements to realise readiness for scaling and bankability

3.2.1 Mapping of Risks and Barriers to CCUS development

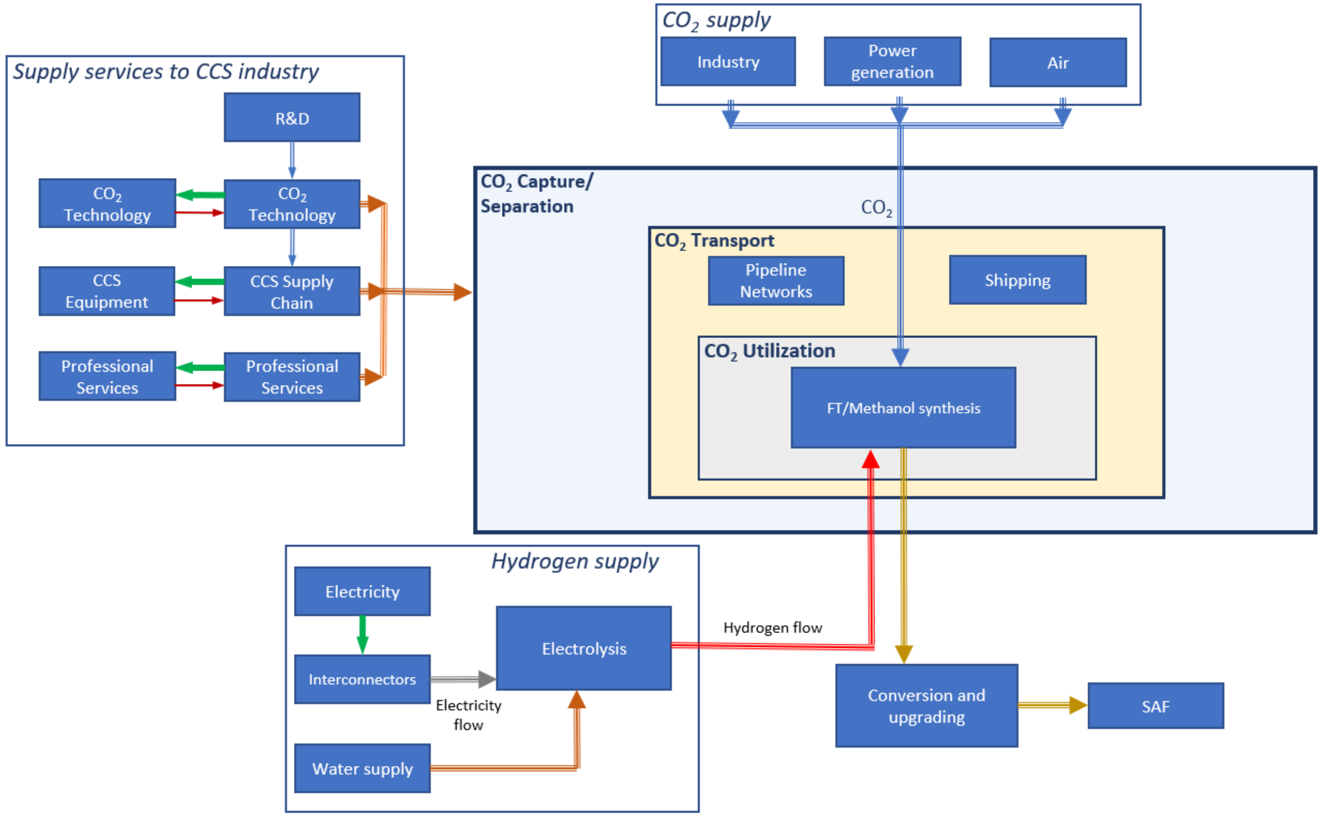
The risks and barriers mapping specific to the three case studies was undertaken based on the literature survey undertaken in Appendix 1. Generic risks common to all three are outlined in table 3.1. Those that are spatially relevant and specific to each value chain are annotated in figures 3.1 to 3.3 for sustainable aviation fuel production, bioenergy carbon capture and storage and cement and steel, respectively.

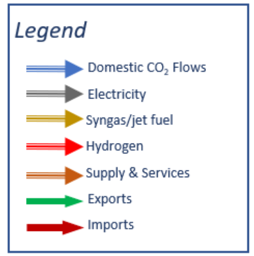
[50] Global CCS Institute 2021. Global Status of CCS 2021 - pp43

Table 3.1: Mapping generic risks and barriers to CCUS deployment for Sustainable Aviation Fuels, Bioenergy and Power and Cement and Steel value chains[51].

Risk	Risk and Barriers
Policy	• Requires targeted policy support to enable large-scale infrastructure • Require government support either as a cost of carbon or emissions performance standard to make projects viable
Operational	• Counterparty risk, project on project, X-chain • Complex supply chain creates interdependencies between all parts of the value chain. If one part of the supply chain breaks, the whole system will fail. • Limited number of large-scale CCUS projects means there is still opportunities for optimisation, e.g., optimise siting of CCS plants to share T&S infrastructure. • Power plants and industrial hubs could be susceptible to extreme weather events caused by climate change, e.g., bushfires (instances in Australia), or severe storms or freezing conditions (US). • Biomass supply chain – low yield due to climate change impacts, limited supply of sustainable feedstocks.
Market	• Commercial scale CCS will have CAPEX of billions which will require significant upfront investment. • If efficient carbon policies and carbon market are in place, a volatile carbon price could present a significant risk. • In some countries, there are potential EOR opportunities (although this does not align with net zero policy, EOR could provide support for CCUS) • Who is going to buy CCS-derived products?
Legal and regulatory	• Indefinite storage of CO2 will be over very long timeframes of 1000 years, creating potential liability for future leakage. The UK handles similar risks under the 1998 Petroleum Act. • Current uncertainty whether government or private companies will bear the long-term CO_2 storage risk/liability – will possible be a variation in policies in this space over time. • Transition from a CfD regime to one where CO_2 stores get a “CO_2 storage certificate” for every tonne of CO_2 stored, which will create a demand pull for CCS projects • The issue of “long term liability” to be revised so as to require MRV until such time that that the stored CO_2 can be shown to be behaving predictably, and moving towards permanent immobilisation, at which time liability for the CO_2 store reverts to the state. Here lessons can be learned from the nuclear sector
Environmental, social and governance (ESG)	• CCS sites, including CO2 removal tech (e.g., BECCS, DACCS), will need to be co-located with existing power and industrial facilities which may make permitting challenging/easier, depending on the location and country. • The chemical solvents and processes used by CCS are technologies which industry should already be familiar with.
Technical	• Has minimal technical risks as the industrial technologies employed are generally mature and well-established. • CCS system performance risk with new technologies
Mitigating risk of FOAK CCS	• UK Contract for Difference (feed in tariff) • Transition to regime where CO_2 stores get a “CO_2 storage certificate” for every tonne of CO_2 stored – could create a demand pull for CCS projects

[51] Adapted from Donavan, C., Hardy, J., Hindle, J., Mac Dowell, N., Ostrovbnaya, A., 2019. Lending to Low Carbon Technologies. Report by researchers from Imperial College London for the HSBC Centre of Sustainable Finance.



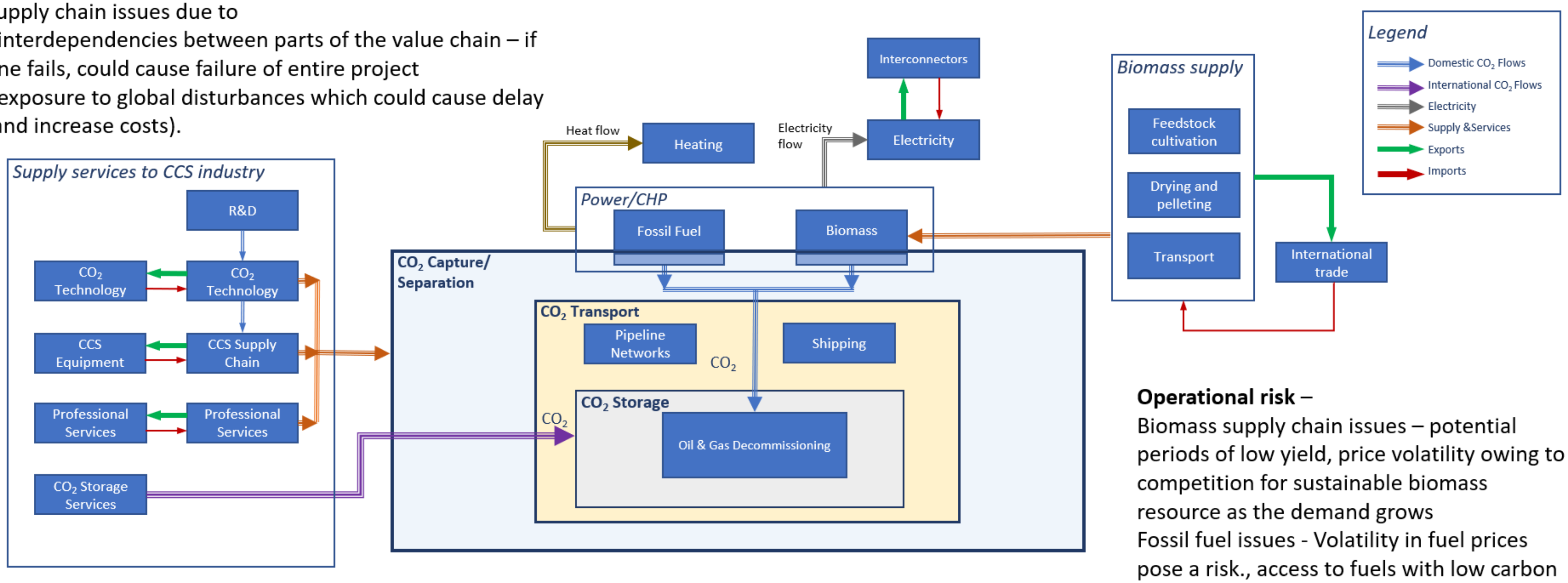


Risks that present potential barriers:
Policy – requires support from gov and policy frameworks, e.g., CO_2 emission intensity standards for fuels.
Market/financial – need to develop a market for CO_2-derived fuels, which will be significantly more expensive than fossil fuels
Legal/regulatory – ensure CO_2-derived SAFs meet specification requirements for aviation fuel. The aviation industry has very strict requirements, changes to regulations will likely be needed to increase uptake of SAF.
Environmental/social – should be able to address so minimal risk (i.e., not a barrier).
Technical – only very small pilot scale tests, potentially will encounter technical risk with scale up. Meeting fuel specifications is still technically challenging. More R&D is needed.

Operational – same supply chain risks as "CCS/BECCS to power" case, but additional risks with the production of low carbon green hydrogen, e.g., need access to low carbon intensity electricity.

Figure 3.1: CCU - Sustainable aviation fuels value chain risk mapping

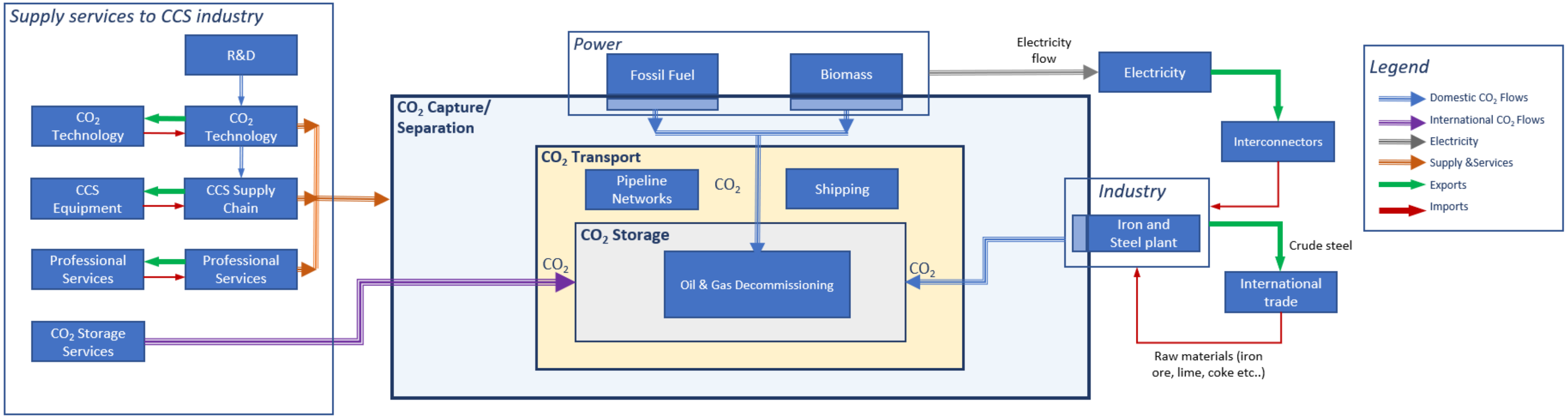
Operational risks –
Supply chain issues due to
- interdependencies between parts of the value chain – if one fails, could cause failure of entire project
- exposure to global disturbances which could cause delay (and increase costs).



Operational risk –
Biomass supply chain issues – potential periods of low yield, price volatility owing to competition for sustainable biomass resource as the demand grows
Fossil fuel issues - Volatility in fuel prices pose a risk., access to fuels with low carbon intensity (e.g., natural gas from GB vs middle east).

Other risks that present potential barriers:
Policy – requires support from gov and policy frameworks, e.g., CfD, carbon price
Market/financial – need for large upfront investment (CAPEX)
Legal/regulatory – dealing with long term CO_2 storage risk/liability.
Environmental/social – should be able to address so minimal risk (i.e., not a barrier)
Technical – several commercial-scale projects exist, using mature technologies, thus no technical barriers

Figure 3.2: CCS/BECCS to power value chain risk mapping



Risks that present potential barriers:

Policy – requires support from gov and policy frameworks, e.g., CO2 emission intensity standards on iron and steel products, Carbon Border Adjustment Mechanism (CBAM), i.e., a proposed carbon tariff on carbon intensive products

Operational – same supply chain risks as "CCS/BECCS to power" case

Market/financial – need to develop a market for CCS-derived iron/steel products, which are likely more expensive than conventional steel

Legal/regulatory – long term CO_2 storage risk/liability, ensure CCS-derived iron/steel products meet specification requirements

Environmental/social – should be able to address so minimal risk (i.e., not a barrier)

Technical – not yet demonstrated at commercial scale, but several pilot plants have demonstrated feasibility, small to moderate technical risk with scale up

Pilot scale test with real BFG streams at the Nippon steel plant at scales of 1 tCO2/day and 30 tCO2/day

Korea has demonstrated capture from BFG stream at scale of 10 tCO2/day with ~23% CO2 BFG gas

Figure 3.3: CCS in industry: Iron and steel value chain risk mapping

Of the barriers to development in the three case studies, as was found in Appendix 1, the majority of risks lie in the policy, operational, market, legal and regulatory and ESG i.e., the commercial domain. In the case of the technical dimensions there are risks involved in scaling the technologies. These risks were then calibrated by interviewing and workshopping specialists as described in section 3.2.2.

3.2.2 Stakeholder perspectives - barriers to CCUS deployment

The interviews and two workshops stakeholder perspectives as to requirements to realise readiness for scaling and bankability for CCUS is summarised in Appendix 6, table A6.1. The quotes are laid out within the framework justified in Appendix 1 based on Geels's socio-technical framework.

The following patterns are salient:

- ***The barriers to CCS development elicited from interviewees were non-exhaustive, fragmented with little convergence around specific dimensions****.* They tended to focus on the challenges as perceived by the individuals from their specialist perspectives within the CCS eco-system:
  - CCS developers focused on political will, market design and knowledge sharing,
  - financiers on the state of policy and the need for greater awareness of technology and commercial risk, and
  - civil society the lack of public engagement and integration into CCS deliberative processes.
- ***The barriers, like the mapping work for the three case study value chains were very much posited around the political and commercial aspects of CCS development as follows:*** At the political end of the spectrum, (1) The need for an overarching vision and narrative as to the role of CCS in addressing net zero was raised along with the need to address societal reluctance to see fossil fuel incumbents benefit; (2) With regards Governance, Regulatory and Finance - the need for governments to enact the relevant policy. Capacity building amongst policy makers and the finance sector to better understand the sector was also commonly raised; (3) In the domain of commercial issues, the need for CCS policy to account for the varying levels of risk appetite of industrial actors and sectors looking to adopt CCS and investors was aired; and at the technology end of the spectrum - limited technical issues were raised other than the need to (4) ensure that the scaling leaps that are made between demonstration projects was sufficiently incremental to allow learning to be undertaken.
- Two new themes were captured in the process that are underreported and not encountered in the literature search undertaken in Section 2. Those were of ***enhanced knowledge sharing*** and ***extent of technological leaps introducing more risk in scale up***.

3.2.3 CCUS Stakeholder interactions and ecosystem influence dynamics

The CCUS stakeholder mapping for WP3 was initially posited around the case studies of sustainable aviation fuel production, bioenergy carbon capture and storage and cement and steel. Figure 3.4 is based on analysis undertaken by BEIS[52] which has been adapted to the case studies.

The following observations are salient:

- The three case studies have multiple actors that are common across all the supply chains, suggesting that there are multiple shared steps among different CCUS pathways. If interventions in one CCUS value chain were to unlock value, there would be spill-overs in others.

[52] BEIS 2021. CCUS Supply Chains: a roadmap to maximise the UK's potential Annex A - Supply Chain Mapping dated May 2021. The Energy Industries Council has provided a table below, breaking down and compartmentalising the CCUS supply chain into its constituent parts across capture, transportation and storage.

- The skills, trades, services and capacity requirement to establish the supply chains are all in existence today though their co-ordination around different components of the CCUS case studies will require non-trivial effort as for the majority of components require the coalesce of >80 actors.
- The BEIS mapping is bounded to the technical dimensions of the development of CCUS supply chains rather than the broader ecosystem of CCUS enabling actors such as finance, investors, lawyers and publics that Appendix 1 highlighted will be fundamental in establishing the sector. This is explored in figure 3.5, below - which was compiled based on the stakeholder interviews and workshops.

Figure 3.4: Mapping analysis of the interconnected dynamics between actors, relationships and processes for the three CCUS case study CCUS value chains/ecosystems

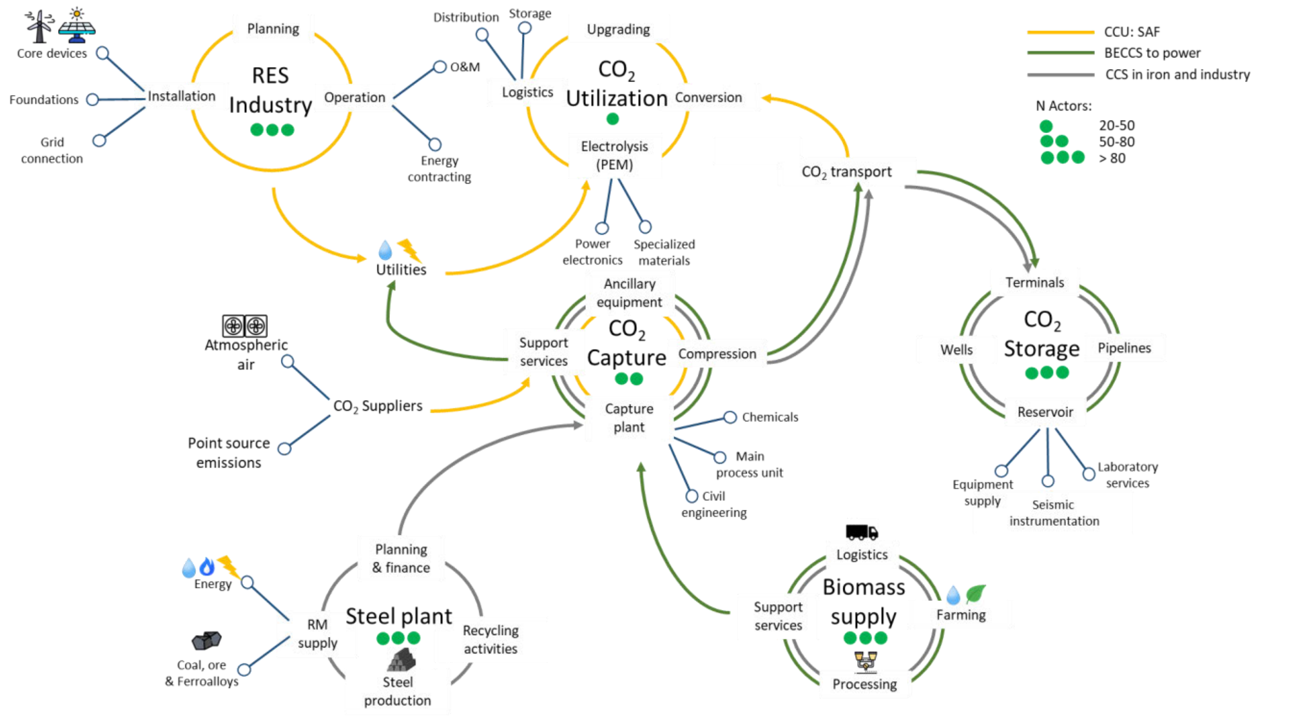


Figure 3.5, identifies a broader number of actors and relationships that this study has identified as salient to CCUS sector establishment and development within the Geel's framework across landscape, regime and niches. Based on the interviews and workshops, the nature and strength of those relationships are explored in A to E, below[53]:

A. Society and publics - government and policy. This relationship - including engagement of opinion formers such as Environmental NGOs, journalists and other intermediaries - is considered weak. It enables support for CCS deployment through the co-generation of visions as to the role of CCUS in net zero. Societal and publics are, however, limited in their ability to provide timely and technical input and challenge to CCS policy design to enable it to be futureproofed. For example, membership of the UK CCUS council is heavily dominated by businesses. Much of the discussion on business models, fundamental to how cost-effective CCUS and which applications are adopted, is only made available to wider stakeholders when nearly finalised - i.e. once out for consultation, at which stage some options are already excluded.

[53] Note there is no link between the size of the arrows and the strength of the relationships. These are explored in A to E. The arrows simply emphasis the need for the relationship.

Figure 3.5: Simplified actor and influence map of CCUS sector showing types of actors, their concerns, motivations and how they interact [A, B, C, D & E]. These interactions occur within geographically distinct policy/societal contexts being influenced by numerous actor specific and cross-industry organisations.

Landscape

1. Publics and Societal Actors:
- Capacity development to enable better understanding as to the role of CCUS in addressing net zero as well as GVA and job opportunities.
- Project consents as a function of societal acceptability of risks e.g. CO_2 Storage
- Integration into CCUS development and decision-making process and policy design

A

2. Governments and Policy:
- Economic Growth and Net Zero - cross-departmental co-ordination
- Integration of CCUS into broader infrastructure sectors - Energy, Transport, Water, Digital, Waste. Dealing with path dependencies and lock out effects whilst addressing long term planning uncertainties.
- Visions as to the role of CCUS within Net Zero
- Policy design to minimise risk and uncertainty - especially in the early stages of CCUS development.
- Accommodating the different risk appetites of different actors/sectors which need to develop CCUS.
- Refinement of decision support through calibration from CCUS projects to better tailor time sensitive policy interventions - Multi-Factor Learning Curves.

C

Regime

3. Finance, Legal and Investors:
- Capital Requirement of $Billions: Capacity development as to risk and uncertainty of CCUS technologies/value chains and how policy and regulatory ecologies have addressed these.
- Learning by doing based on FOAK in different contexts
- Legal capacity to understand risk and uncertainties
- Visibility of international CCUS developments to allow investment to be allocated to relevant projects.
- Regulation which is consistent and stable.

B

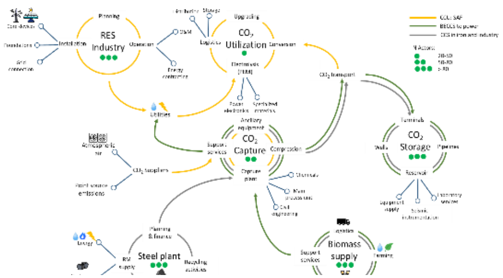
4. Project Developers and Supply Chain
- Generation of Spill-over effects: Knowledge exchange - project to project, other technology sectors and finance sector
- Continued funding beyond TRL9
- Learning by doing and Learning by Using
- Pull through of manufacturing supply chains and skills base development.
- Scale Economies to be realised.

D

E

Niche

5. CCUS Technology Value Chain Operators
- See Figure 3.4, above: Highly heterogenous technologies requiring system integration. New Business models with market risk - who is going to purchase the product?
- Heterogeneous actors who don't traditionally work with each other across multiple infrastructure sectors with different regulatory regimes and actor ecologies. All have different cultures.
- Geographically and context specific co-location needs.



Public engagement work done by BEIS[54] highlighted people's support was conditional on CCUS's effectiveness - based on costs and safety. It also identified that not all CCUS demand is equal with the degree of support amongst the public varying depending on application. The policy design process does not allow this to be accommodated. The relevance of the paucity of this relationship extended to other countries was aired - specifically as to how a lack of public engagement can impact project consents processes.

B. Government and policy - Project Developers and Supply Chain. This relationship is considered moderate to strong with multiple public-private CCS fora already in existence e.g., CCS Development Forum, China Australia Geological Storage (CAGS), UK CCUS Council, International CCS Knowledge Centres etc. However, there are still requests for the development of a common lexicon and an accessible up to date corpus of knowledge as a function of the requirement of cross-sectoral co-operation and the need for actors to operate in domains that they are not traditionally used to working in e.g., the power, cement and/or steel sector having to understand geological storage.

It was also found that there was a lack of up to date awareness in the CCUS stakeholder workshop where participants requested policy actions already underway e.g. incentives such as the development of a CCS Contract for Difference (CfD) in the UK. Furthermore, though the value stack for CCUS business models is slowly being developed in certain geographical jurisdictions via policy initiatives and instruments - e.g., CfD, 45Q, Tax Credits, Carbon Pricing etc. There is a need to develop more targeted policies that accounts for varied risk appetites of different stakeholders and sectors that need to deploy CCUS. Finally, calls were made for government funding to be available once CCUS technologies get beyond TRL 9.

C. Government and policy - Finance, Legal and Investors. This relationship is considered weak to moderate - see E below.

D. Project Developers and Supply Chain - Finance, Legal and Investors. This relationship is considered weak to moderate - see E below.

E. Finance, Legal and Investors - CCUS Technology Value Chain Operators. This relationship is considered weak to moderate. Relevant to C to E - that there needs to be greater capacity to be developed beyond the traditional project developer community, policy makers, finance specialists, legal professionals, regulators and civil society representatives but to also specifically include a much broader cadre of the finance community such as the Development Banks, Rating Agencies, Environmental Social & Governance Funds, Philanthropy, Investment Banks, Insurance sector etc. These aspects of cross project learning could form the basis of the evolution of the generic set of already established metrics to provide an international perspective as to the state of readiness in different geographical jurisdictions and project contexts as well as the development of capacity as to how metrics should be applied. It was considered that the International Energy Agency would be in a good position to co-ordinate this - leveraging existing knowledge sharing initiatives e.g. the Technology Collaboration Programmes, tracking ongoing projects as well as ensuring the dissemination of CCUS policies already under development. The organisations convening power, its unmatched reputation for objective analysis of energy matters and its focus on policy would make this a good fit.

The application of the Geels socio-technical framework to the stakeholders within figure 3.5, and comparing the commercial indices mapped in using the same framework in figure 2.1 - highlights the fact that for the issues raised by participants in the study - indices already exist. We can now turn to analysis as to the willingness of CCUS practitioners to adopt and/or nominate the indices and metrics that were mapped in WP2.

[54] BEIS 2021 Carbon Capture Usage and Storage: Public Dialogue. By Traverse pp 132.

3.2.4 CCUS Actors Mental Models

The CCUS sector requires a broad range of culturally divergent actors to coalesce for the sector to establish and scale. These range from project developers, a multiplicity of financial actors, regulators, policy and publics. This was manifest during the interviews and workshops where different actors had different mental models and perspectives regarding CCUS prioritisation for development. The differences in perspectives between actors are summarised below and detailed in Appendix 6 - Table A6.2:

- Developers versus policy makers - What TRL means and how it impacts public innovation funding in CCS technologies.
- Finance / Investors versus Developers - How commercial risk will be addressed.
- CCUS Developers versus Policy Makers - Need for a policy maturity and stability.
- Government versus Investors - Insufficient policy to develop a robust business case for CCUS across the range of sectors that need to develop CCUS projects.
- Investors versus developers - need for a transparent assessment of technology readiness and bankability
- Developers versus government/societal - means-end perspectives
- Developers versus civil society - the role of Oil and Gas companies in the establishment and scaling of CCUS.

The different mental models are sufficiently jarring that it is likely further understanding as to how CCUS projects perform over their investment cycle will only be realised from learning by doing from the construction and operation of actual CCUS plants. With such a capacity gap and tangential views amongst stakeholders it is questionable how easy it would be to: (1) cogenerate indices should they be desired; and (2) the ability for widespread comprehension and understanding amongst different audiences.

3.4 Stakeholder perspectives on indices relevance and how used to manage complexity, risk and uncertainty in CCUS.

In the previous sections, the ability for existing commercial indices to map onto the concerns and barriers to CCUS sector development expressed by specialists and the relationships that they had was identified. What is unclear is whether, with the lack of CCUS deployment, limited capacity across stakeholder groups and their fragmented perspectives - they would consider indices as providing a useful tool in managing risk. Therefore, as part of the interview and workshop process, stakeholder perspectives on the role of indices relevant to commercial readiness and how they might be used to manage complexity, risk and uncertainty were explored. These are summarised in Appendix 6 - Table A6.3.

Like the fragmented and atomistic perspectives of the specialists regarding the commercial barriers to CCUS development, this spilled over into the role of metrics. Experts elicitations around indices tended to be symmetrical around the same specific barriers that they raised. The indices/metrics were very much posited at the political and commercial aspects of CCUS development. There was acknowledgment that:

- familiar metrics were useful to manage risk between relevant audiences e.g. WACC, Credit Rating etc;
- they allow scrutiny and transparency as to CCUS project progress - especially when project funding is underpinned by pubic grants;
- It is essential that they are simple to be comprehensible and appeal universally;
- A specialist stated that they advocated the application of the ARENAs CRI index and another nominated a new regulatory readiness metric;

- A number of CCUS related metrics are being evolved but that this is being undertaken in a fragmented way. There is an urgent need for them to be systemized and made comprehensible across broad audiences; and
- It was regularly emphasized the need to consider the time that it takes for practitioners in different parts of the CCUS community to understand broader readiness issues beyond TRL. This is non-trivial considering the capacity gaps and symmetries within the sector.

Finally, the need to systemise and generate broader understanding as to the state of CCUS development culminated in a set of stakeholders advocating the need to create a dialogue between policy makers, industry and the entire finance ecosystem in the broadest sense - as advocated in relationship C, D and E in section 3.2.3, above.

3.5 Assessment and role of policy measures and incentives to address CCUS deployment and barriers

A final component of the study included the undertaking of an assessment of the effectiveness of existing CCUS policy in a number of geographical jurisdictions; and the role of policy measures and incentives to address CCUS deployment and barriers. The former has already been systematically undertaken in Vivid-Element Energy Report[55] pages 39 to 45 - so rather than replicating that work this study has used the insights generated from stakeholders during the interviews and the workshops to fulfil the latter requirement. These are articulated as follows in the respective boxes below:

- With the need for robust policy measures to incentivise CCUS development - Box 2 covers the role of a Contracts for Differences' successful application to the Offshore Wind Sector and how it might be applied to the CCUS sector.

Box 2: Contract for Difference (CfD) for Offshore Wind[56]

- The success of the CfDs for windfarms stemmed from their ability to give certainty to financiers. The CfD mechanism gave certainty by managing risk effectively and efficiently. The party best placed to the manage the risk, held the risk.
- The CfD strike price was the total necessary to repay debt and equity raised to finance the project. Either the necessary revenue would come from the Low Carbon Contracts Company and Electricity Settlements or from the electricity markets; neither of which carried any credit risk.
- The windfarm developer took on resource and availability risk. Both could be modelled with appropriate levels of certainty for each of the equity and credit cases. Adding the two was certain to deliver the overall strike price.
- With this certainty, the markets focused on delivery and performance, with the clear benefits over time on the costs of windfarms and their production of electricity.
- Even today though the strike price for wind is <£40 investors still want the CfD as it provides certainty.

- Regarding the need for government to pump prime the CCUS sector the analogue raised was how governments under wrote the establishment and scaling of the Liquified Natural Gas Sector - Box 3. The need for the government to balance the tension between the need for disruptive innovation to catalyse the rate of CCUS diffusion and the need to balance the technological scale up so as to allow manageable

[55] Vivid Economics-Element Energy 2018. Policy mechanisms to support the large-scale deployment of Carbon Capture and Storage (CCS). Dated 9th May 2018.
[56] Adapted after Davies 2022 - Effectively Managing Carbon price pass through risk. A CfD is a mechanism by which a pre-agreed strike price is agreed between a developer and the government. When the market whole-sale price of comes below the strike price the government compensates the developer to ensure that their development risk is covered. If the whole-sale price is above the strike price then the developer gives the difference back to the government. The mechanism provides revenue certainty to the developers and the investors.

increments of technology scale-up is covered in Box 4 which highlights the example from the Combined Cycle Gas Turbines scale up in the 1990s.

Box 3: Liquified Natural Gas (LNG) shipping market and role of governments in priming market

- Growth in natural gas consumption was made possible by a revolutionary means of sea transportation. It was stimulated via government backed project finance to build first ships which in turn created this global market[57]. Today, shipment of liquefied natural gas (LNG) is a routine maritime event. There is a fleet of over 300 ships capable of carrying such cargoes, including many ships with the ability to carry 100,000 tons or more.
- However, it was only 62 years ago that the first shipment of LNG occurred. The ship named Methane Pioneer sailed from Lake Charles, Louisiana, to Canvey Island, England. Union Stock Yard decided to join forces with Continental Oil Co. to form Constock Liquid Methane Corp. and later worked with the British Gas Council (Government) to build shore facilities and the ship.
- The ship was renamed Methane Pioneer and put under the British flag. After three months of sea trials, the 339-foot-long ship of 5,058 gross tons sailed with a cargo of 2,000 tons of liquefied natural gas at a temperature of minus 258 degrees F on Jan. 31, 1959.
- After seven successful trips, the results were analyzed, and the $11 million gamble proved to be a success. Based on the results, two new, larger ships were contracted to be built.

Box 4: Combined Cycle Gas Turbines (CCGT) Scale up in the UK's `Dash for Gas'[58]

CCGT is a good analogue for CCS because of the quick growth of this technology in the UK power sector, and because CCGT became the dominant power generation technology in the UK for new capacity in a relatively short time frame.

In terms of upscaling, the analysis showed the long-time frame involved in upscaling the technology to a size of relevance for the power sector. Moving from the first industrial CCGT plants to a competitive, full-scale power sector technology in the 1990s took about 30 years. It required:

- long-term, sustained R&D investment mainly by the heavy equipment manufacturers (General Electric, Westinghouse, Siemens and ABB).
- Sales in niche markets enabled reinvestment of revenues into R&D.
- The technological development also profited from substantial and prolonged public R&D investment in the development of jet engines which are technologically closely linked to the industrial gas turbines.
- Technology transfer from jet engines to industrial gas turbines enabled important developments in terms of efficiency and increases of turbine size.
- Alliances between equipment manufacturers and jet engine companies played a major role in this process.
- There was also some public R&D investment in industrial turbines, for example in the US and Japan.
- While the process of scaling up can in retrospect be considered a success, it is important to note that the history of the CCGT shows that the very quick improvements in efficiency and size of the turbines at several points in time also led to significant reliability issues and that upscaling therefore is not a trivial process.

The following was observed:

- upscaling of the technology took several decades roughly between 1950 to 1980 when the size of the turbines used roughly tripled every decade.
- The rapid upscaling of gas turbines led to major reliability problems which were eventually resolved but initially led to complications and slowed down the development of the technology.
- The quick roll out of CCGT in the UK benefited from previous experience with CCGT deployment in the US and other markets.

- The need for knowledge sharing across CCUS projects is covered in - Box 5 and the capacity to develop learning by doing and sharing best practices as exemplified by the Nuclear sector is covered in Box 6.

[57] After https://www.freightwaves.com/news/maritime-history-notes-pioneering-lng-carriers

[58] After Kern 2012. The development of the CCGT and the `dash for gas' in the UK power industry (1987-2000)

Box 5: Learning from previous carbon capture and storage deployment: lessons for the next wave[59]

Over the last two decades, there have many more attempted CCUS projects than successful ones.

It would be helpful if practical lessons, related to what to do and what not to do, could be widely learned from previous projects, but a major obstacle to this has been, and continues to be, the very limited disclosure of technically-relevant information from previous projects, including the vast majority of those which have received significant government support.

This review illustrates and seeks to explain the gaps in knowledge-sharing and suggests how improvements might be made regarding general lessons which are categorised as follows:

- Take note of fundamental principles: basic characteristics for CCS technologies that are likely to apply to all projects;
- Prioritise local environmental concerns: issues not related to climate change but to the effect of emissions from CCS facilities on the environment and people in their vicinity, including environmental justice aspects;
- Mitigate technology risks effectively: the next wave of CCS projects will involve significant amounts of first-of-a-kind technologies and mitigating the risks of failure or underperformance is essential to overall project success;
- Keep options open: CCS projects take many years to develop so options that can be exercised in response to future events may be very useful;
- Start out with realistic ambition looking ahead: climate change policy has been characterised by ever more demanding targets.

Government-supported projects aspiring to have effective Knowledge Transfer (KT) ought to involve third-party practitioners in critiquing KT plans, and ensure that scope before funding is agreed. A robust mechanism to achieve this would be to review the full list of documents to be prepared in e.g., a FEED study and commence with the expectation that all of these would be made publicly available in full - which can readily be done electronically.

Deployment is a very complex activity. No written communications can fully transfer the information required; face-to-face discussions between practitioners are necessary for the best results. This raises an issue of timing; old project teams may have been shut down and dispersed and the personnel may have forgotten some of the details before new project teams, who have learned what questions to ask, are formed. Hence the need for deployment plans to facilitate the learning by doing as articulated in Box 6, below.

Box 6: Building Nuclear Reactors: Copy, paste, repeat. Driving down the cost of nuclear plants requires standardising construction[60].

Nuclear plants are pricey, and much more so if they are bespoke. Reusing plans, suppliers and people to crank out identical ones should make construction cheaper.

EDF, the French utility with ultimate responsibility for both Hinkley Point C and Sizewell C, says that making construction more predictable will cut the cost of financing - which at Hinkley accounted for 60% of the total. Investors are more likely to offer capital at reasonable rates if they believe a plant will start pumping out electricity on schedule.

Three other plants of the same kind have already been built, in Finland, France and China. The Hinkley C lead engineer has visited all three, and brought what was learned back to Britain. At Flamanville in France, for instance, the metal casing that shields the nuclear-reactor vessel was assembled outdoors, which meant poor-quality welds and hold-ups during bad weather. So welders at Hinkley manoeuvre components inside vast temporary structures, something like tents crossed with cathedrals, with the help of the world's largest crane.

The copy-paste process between Hinkley's reactors similarly yielded incremental improvements. The average time saved on each task has been 20-30%. With Sizewell C's two reactors as "Unit 3 and Unit 4"—not merely identical to those at Hinkley, but are seen as a continuation of the same build. Efficiency gains are kicking in even before construction starts, as most of the paperwork is the same. This could likely result in time savings at least as great as those between the Hinkley reactors.

[59] After Gibbons, J. and Lucquiaud, M. Under Review. Learning from previous carbon capture and storage deployment: lessons for the next wave

[60] Economist dated 26th March 2022. Copy, paste, repeat. Driving down the cost of nuclear plants requires standardising construction

These efforts are considered crucial to ensuring that both Hinkley and Sizewell go to plan, and that consumers pay as little as possible for Sizewell before the electricity starts flowing. Making construction faster, cheaper and more predictable will be the difference between success and failure.

4. Critical Evaluation of Commercial Readiness Indices and their Application to the CCUS Sector

4.1. Main Findings

In this section, the outputs from WP 4 are described - as follows:

- Compile the insights and findings from WPs 1-3 and formulate recommendations; and
- Discuss results, conclusions and recommendations for further study.

The following salient study findings have been put forwards:

1. ***The generation of generic indices in providing the relevant insight as to broader commercial factors which need to be considered for CCUS bankability - is likely to be considered a distraction by a majority of CCUS specialists.*** Though generic indices such as Commercial Readiness Indices as used by the Australian Renewable Energy Agency were not considered a priority - metrics were seen as having an important role in identifying aspects of CCUS commercial readiness and deploy-ability. It was largely considered that the metrics which are important to specific stakeholders within the CCUS ecosystem are already in existence e.g., credit ratings, weighted average cost of capital, geological storage capacity and reservoir characterization etc. The relevant communities and audiences understand these long-established metrics, they are ubiquitous and have widespread application and acceptance.
    - ***There were two circumstances where generic metrics might be considered useful.*** Firstly, ***metrics should be available for the CCUS community, which would be context and geographically specific***. These could be applied to provide a global perspective of CCUS commercial readiness and deploy-ability. It would provide an assessment of the relative progress and initiatives being employed to close the risk gap in different geographical jurisdictions and project contexts e.g., storage capacity and policy stability - see finding 2, below. ***Secondly, was at the CCUS project specific scale to facilitate cross-stakeholder and audience insight as to when progress had been made regarding different aspects of CCUS establishment*** thereby allowing scrutiny and transparency as to progress. This is especially relevant when project funding is underpinned by pubic grants.
    - The main justification to negate the need for a generic set of new indices was that much time and resource would be expended generating capacity to understand them across the broad range of audiences.
    - It was found that there is limited benefit in integrating CCUS relevant indices on meeting UN Sustainable Development Goals again as a function of effort, questionable transparency and communication value.
    - The benefit of indices based on the successful scale-up of other capital-intensive energy sector technologies such as the French nuclear programme, the UK gas grid and US desulphurisation programme was again assessed as being limited.

2. ***There was consensus amongst specialists that the main barriers to the establishment, bankability and widespread deployment of CCUS presently lies in the domain of commercial, policy and regulatory risk.***

There was, however, a lack of widespread agreement as to which of these specific barriers were a priority to be addressed[61].

- It was agreed that there is: (1) a lack of systemic, in-depth common understanding across the CCUS community as to the technological state of CCUS development; and (2) pipeline of policies and initiatives being developed by governments.
    - The need for the development of a common lexicon and widespread up to date corpus of institutional knowledge is especially relevant to the CCUS community as a function of the requirement of expertise, specializations and competencies that lie beyond that traditionally required in industrial sectors e.g., the power, cement and/or steel sector having to understand geological storage.
    - The lack of up to date awareness was best exemplified from the CCUS stakeholder workshop where participants requested policy actions already underway e.g. incentives such as the development of a CCS Contract for Difference (CfD) in the UK.
- A number of knowledge sharing fora already exist within the CCUS community e.g., CCUS Development Forum, China Australia Geological Storage (CAGS), UK CCUS Council, International CCS Knowledge Centre, etc. This finding suggests emphasis of two further insights:
    - That knowledge sharing is likely better undertaken at a CCUS project-programme level by the actors developing the projects themselves to generate learning by doing across projects whereby assignment of responsibility for aspects of progress can be made to specific actors within the project-programme - see Box 6 (above) to develop insights as to how this is being undertaken in the Nuclear sector. The ability to exploit this opportunity is timely with the establishment of CCUS industrial clusters in a number of geographical jurisdictions[62]. Sustained government curated CCUS implementation plans would give the CCUS sector confidence to invest resources and allow co-ordination of cross-project learning to be maintained over a prolonged period of time.
    - That there needs to be greater capacity to be developed beyond the traditional project developer community, policy makers, finance specialists, legal professionals, regulators and civil society representatives but to also specifically include a much broader cadre of the finance community such as the Development Banks, Rating Agencies, Environmental Social & Governance Funds, Philanthropy, Investment Banks, Insurance sector etc as well as societal actors. It was considered that the International Energy Agency would be in a good position to co-ordinate this.

  These aspects of cross project learning could form the basis of the evolution of the generic set of already established metrics to provide an international perspective as to the state of readiness in different geographical jurisdictions and project contexts as well as the development of capacity as to how metrics should be applied - see finding 1, above. This could be used to create convergence and critical mass around a beneficial dialogue whereby a common lexicon and capacity across the CCUS ecosystem could be enhanced. It was considered that the International Energy Agency would be in a good position to co-ordinate this leveraging existing knowledge sharing initiatives tracking ongoing projects as well as ensuring the dissemination of CCUS policies already under development.

3. ***A set of important considerations regarding the process of CCUS policy design were raised by stakeholders during the research. The following are salient:***

   (1) There is a need for an overarching vision and narrative as to the role of CCUS in addressing net zero;

   (2) The role of broad based inclusive societal engagement mechanisms to be integral to CCUS policy design processes; and that

[61] Not all of the lack of consensus could be attributed to CCUS value chain variability or geographical differences in the cohort of specialists engaged.
[62] Global CCS Institute 2021 - Global Status of CCS 2021. CCS accelerating to net zero

(3) CCUS policy needs to account for the varying levels of risk appetite of industrial actors and sectors looking to adopt CCUS and investors. Similarly, different financial institutions each vary in their risk appetites.

- The need for government led national visions as to the role of CCUS in achieving net zero was considered integral to providing confidence to investors as to the long-term trajectory of CCUs policy and to establish societal buy-in. The need for reframing the way that CCUS is articulated to audiences is also important. Rather than being a technology to decarbonise heavy industrial sectors - it should be framed as a service which facilitates the provision of zero carbon goods and services which stands to add to economic resilience through the establishment of jobs, skills, regional economic development and other environmental benefits. The latter might be achieved though the development of a societal cost benefit analysis framing[63]. This strategic reframing is considered important at a project level to facilitate CCUS project permitting and consents amongst local fence line communities.
- Public engagement - including engagement of opinion formers such as environmental NGOs, journalists and other intermediaries - is essential not only to ensure support for CCUS deployment, but to provide timely input and challenge to CCS policy design to enable it to be futureproofed and industrial sectors to be held to account. This means that the policy processes involved in the development of the CCUS sector should integrate societal stakeholders throughout the project process rather than consider these actors at the end. This needs to be balanced with the urgency of the need to deploy CCUS projects.
- Though the value stack for CCUS business models is slowly being developed in certain geographical jurisdictions via policy initiatives and instruments - e.g., CfD, 45Q, Tax Credits, Carbon Pricing etc. There is a need to develop more targeted policies that accounts for varied risk appetites of different stakeholders and sectors. For example, the US 45Q tax credit has a 12-year time limit which seems well suited for the Oil and Gas sector but unsuitable for other sectors such as steel/cement. Without this there will be the perception that policy has failed to encourage wide-scale CCUS development. There are also other non-financial dimensions which have a material impact on CCUS risk such as CO_2 storage compliance timeframes which extends beyond what most insurance companies are willing to underwrite.

Limitations of Study

The study was undertaken over a period of five months - with the meta studies undertaken at the front end of the project. The ethnographic components which involved 10 interviews and two workshops was where the majority of the study insights were generated taking place in the 4th and 5th months. To this end, the limitations of the study include but are not limited to:

- The ethnographic approach applied is an inherently resource intensive process and realising systemic perspectives globally and across all industrial sectors that CCUS will be applied was challenging. Consequently, the findings tend to have been primarily but not exclusively generated from UK and US centric perspectives.
- CCUS is a highly heterogeneous technology with multiple value chains cutting across a number of sectors of the economy - though the main findings are likely robust - the applicability of findings to all aspects of CCUS establishment and scaling will likely require further detailed research on specific CCUS value chains.

5.2. Recommendations for Further Work

Aside from the opportunity to systemise the findings to address the limitations of the study the following are suggestions for further work:

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[63] Hackett, L. Industria Mundum, 2018. Commercialisation of CCS. Conference Presentation at Calabria, Italy dated June 2018 - slide 7

- ***What would a national CCUS implementation plan look like for a number of geographical jurisdictions which would effectively catalyse spill-over effects?*** A finding from the research was the need for an implementation plan beyond CCUS targets. This would give confidence to the development of the CCUS sector in a number of jurisdictions. It would allow learning by-doing spill-over effects at a project-programme level which is where this more effectively takes place and the application metrics is most effective. It also allows the requisite CCUS supply chains and skills based to be progressively developed. This might, for example, involve a closer relationship between regulators, policy makers and innovators within the CCUS sector - which was demonstrated as being highly effectively in the rapid innovation envelop for C-19 vaccination programme[64].

- ***How institutional knowledge is established and best disseminated at a project-to-project level?*** Related to the first recommendation, the research found that the application of metrics was best undertaken at a project-to-project level. It would be good to gain better understand at an operational level how projects best transfer knowledge - see Box 6. For example, how knowledge might be transferred from a UK industrial CCUS cluster to another international CCUS project, how these learnings are translated into cost savings and how as broad set of actors are reached to establish institutional knowledge and capacity.

- ***How greater institutional knowledge can be generated across a broader stakeholder group and societal actors can be integrated into the design of CCUS regulation and policy.*** This is especially relevant to the broader ecology of the finance community and how the IEA would convene this body accommodating for the landscape of existing CCUS initiatives. Insights on the study finding as to the need to better bring in societal actors and communities to future proof the CCUS sector in different contexts could also be considered.

- ***Improvement of net zero decision support analysis to enable better generation of time sensitive CCUS innovation requirements into policy.*** A finding from the study was that there were limitations as to the ability of whole systems modelling to design net zero and CCUS policy[65]. It was also found that there is a need for the calibration of models from real world CCUS projects to allow better calibration of multiple learning curves. The inability for policy makers to access adequate and appropriate analysis and decision support to enable appropriate, time sensitive interventions and decision making for the multiple aspects of CCUS policy design is retarding sector development. How this might be addressed is important.

5. Conclusions

This project sought to explore the potential role of commercial readiness indices in effectively communicating with the CCUS community. This was undertaken via a literature review, interviews, and workshopping with 26 specialists from the CCUS project developer community, policy makers, finance specialists, regulators and civil society representatives. The study mapped which aspects of commercial readiness and bankability were important to different actors/stakeholders within the CCUS community. Based on this, an assessment of the likely benefits of a broad range of indices was elicited.

The conclusions regarding each project objective for respective WPs are outlined below:

WP1 - What are the enabling factors for scaling CCUS; and Mapping of the barriers to realising CCUS's identified potential in possible net zero futures?

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[64] Economist dated 27th February 2021 - Sparks Fly: Lessons from Britain's pandemic on promoting innovation. Move fast and remove barriers are the best things the government can do

[65] Workman M, Darch G, Dooley K, et al., 2021, Climate policy decision making in contexts of deep uncertainty-from optimisation to robustness, Environmental Science and Policy, Vol:120, ISSN:1462-9011, Pages:127-137

- These were mapped in detail. A range of variables which broadly come under the categories of commercial, policy and regulatory risk were the main barriers identified to CCUS being considered bankable. Without these enabling issues being addressed deployment at scale will be problematic.
- In institutional awareness regarding up-to-date CCUS technology and engineering state of development in the policy, regulatory and finance communities need to be enhanced.
- Even amongst CCUS specialist's knowledge sharing was considered an area for improvement. As there are already many knowledge transfer fora that have been established. It is suggested that it could be more effectively realised at a project-programme level.

WP2 - Technology Readiness Levels application as conceived by NASA and the US Department of Energy

- It is an assessment of the risk and uncertainty that an individual technology has *and* the context of its application to the system to which it is being applied.
- It allows *responsibility is assigned an actor within a specific program* to address the progression of a technology up the TRL scale relative to the system to which it is being applied;
- It requires considerable effort, time and expertise to curate and manage the TRL process within tightly bounded technological development programmes; and
- TRL is miss-interpreted in the innovation literature in that it is assumed that once at TRL9 no more innovation is required and when applied generically no allocation of responsibility is attributed to address how a technology will go up the scale.

WP2 - Mapping and critical review of existing, new and potential commercial readiness indices relevant to technological diffusion and scaling.

- Over 45 readiness indices have been mapped and 38 critically reviewed. These have tended to be domain or sector specific - some are systemic.
- As the level of indices intricacy increases the multi-disciplinarily required in terms of the assessment process increases whilst the ability to comprehend the indices decreases for general audiences.

WP2 - Application of indices to allow barriers to be identified in CCUS establishment and scaling.

- The indices that have been reviewed cover all aspects likely to be relevant in CCUS establishment and scaling and would be easily adapted to do so.
- The utility and perceived benefits of their application by specialists in the CCUS sector was limited.

WP2 - the potential role of a suite of CCUS indices on meeting UN SDGs.

- It was found that there is limited benefit in integrating CCUS relevant indices on meeting UN Sustainable Development Goals again as a function of resource required, questionable transparency and limited communication value.

WP2 - Case studies of successful analogues of the realisation of other technologies. What CCUS can learn from these case studies as to the role of indices in informing state of commercial development.

- The benefit of indices based on the successful scale-up of other capital-intensive energy sector technologies such as the French nuclear programme, the UK gas grid and US desulphurisation programme was again assessed as being limited.

CCUS Stakeholders:

WP3 - CCUS stakeholder mapping - government, industry, regulators & finance - and roles in scale-up ecosystem around the three CCUS value chain case studies.

- Though the CCUS supply chains are complex, the three case studies have multiple actors that are common. Therefore, if interventions in one CCUS value chain were to unlock value there would be spill-overs in other chains.
- The skills, trades, services and capacity requirement to establish the supply chains are all exist today.
- Official mapping of the CCUS value chains in the UK omit important enabling actors such as the finance, legal sector and societal actors.

WP3 - Stakeholder perspectives on CCUS requirements for readiness for scaling and bankability

- The risk mapping for the three-case study and stakeholder perspectives identified that *"the main barriers are all related to commercial risk"*.

WP3 - Stakeholder perspectives on commercial readiness indices relevance and how used to manage complexity, risk and uncertainty.

- The generation of generic indices in providing the relevant insight as to CCUS bankability is likely to be considered a distraction by a substantial number of CCUS specialists.

Government:

WP3 - An assessment of the effectiveness of existing CCUS policy in a number of geographical jurisdictions; and the role of policy measures and incentives to address CCUS deployment and barriers.

- The former has already been systematically undertaken in Vivid-Element Energy Report[66] pages 39 to 45 - so rather than replicating that work this study used the insights generated from stakeholders during the interviews and the workshops.
- The policy measures elicited included: (1) the role of a Contracts for Differences' successful application to the Offshore Wind Sector and how it might be applied to the CCUS sector; (2) The need for government to pump prime the CCUS sector as exemplified by the governments role in the Liquified Natural Gas Sector; (3) the need to balance the technological scale up so as to allow robust technology scaling increments as exemplified by the scale up of Combined Cycle Gas Turbines in the UK's Dash for Gas; (4) the need for knowledge sharing across CCUS projects; and (5) the capacity to develop learning by doing and sharing best practices as exemplified by the present Nuclear sector development.

References

As footnotes in report format.

[66] Vivid Economics-Element Energy 2018. Policy mechanisms to support the large-scale deployment of Carbon Capture and Storage (CCS). Dated 9th May 2018.

Appendix 1: Capture Utilisation and Storage in the Net Zero Transition - Dimensions of Commercialisation, Bankability and Policy Design

A1.1 Introduction

This section seeks to understand the dimensions required for CCUS to be considered `bankable'. Only once the technology and its associated value chains have been de-risked and uncertainty reduced will it stand any chance of being established and scaled to the extent projected to address net zero emissions targets.

In this section, elements of WP1 of the study are covered involving a review of:

- Enabling factors for scalable technological deployment of capital-intensive technologies; and
- Mapping of the barriers to realising CCUS's identified potential in possible net zero futures.

The results of a meta study of the technology diffusion, energy transitions, infrastructure and CCUS literature undertaken are presented below.

A1.2 Energy Systems Transitions

A1.2.1 Analytical Approach and Boundaries

The realisation of a global net zero economy by 2050 from one which consumes over 550 EJ of energy per year and emits over 50 $GtCO_2$ pa represents an energy transition unprecedented in the post-industrial era. Therefore, an important source of insight as to the dynamics of technological diffusion and the initiatives which might be deployed to catalyse the transformation of industrial sectors and integration of CCUS is through the analysis of how past energy transitions have unfolded.

The energy transitions literature is substantive and has expanded substantially in the past 15 years. A systemic review is not warranted presenting here; rather issues that are salient to generate insights relevant to the cross-economy take up of CCUS are covered.

The first observation is that the majority of the historical literature has focused on single transitions within a single economy. As such the transitions literature often bounds energy systems as a sub-component of global systems e.g., '*the combined processes of acquiring and using energy*'[67] and '*the switch from an economic system dependent on one or a series of energy sources and technologies to another*'[68]. As a function of this, the interdisciplinary nature of transitions tends to be neglected. In contrast, the Global Energy Assessment defines energy transitions as "*long-term change processes (decadal or longer) in technology, the economy, institutions, ecology, culture, behaviour, and belief systems*", thereby emphasising their systemic and multidisciplinary nature[69]. This multi-disciplinary approach is exemplified in Geels socio-technical framework which multi-level - landscape, regime and niche - perspective ***provides a useful frame of reference of subsequent observations around technology diffusion including CCUS. It will be used as the methodological framework to assess CCUS barriers and the ability for indices to map these barriers throughout this study*** - see figure A1.1, below.

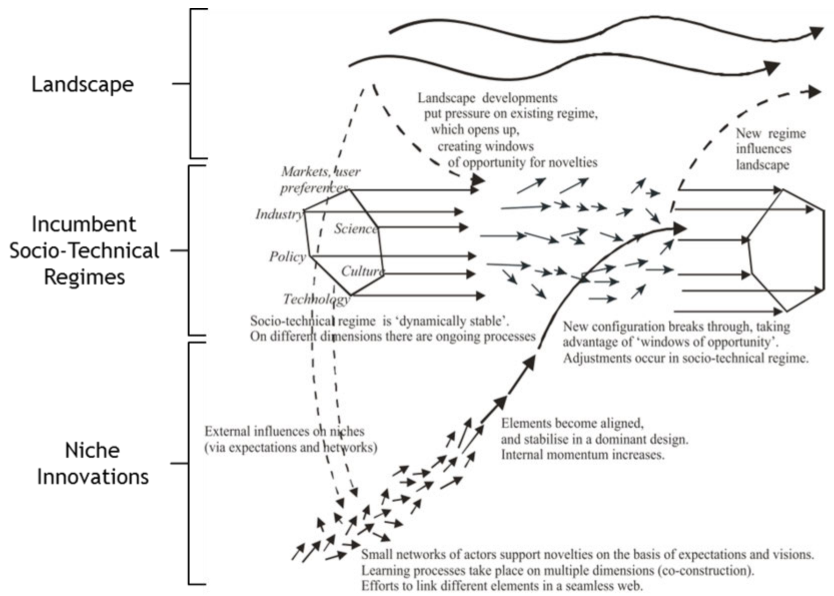
Figure A1.1: Geel's socio-technical framework which emphasises a multidisciplinary approach by identifying seven domains to transitions[70]: "(1) technology, (2) user practices and application domains (markets), (3) symbolic meaning of technology, (4) infrastructure, (5) industry structure, (6) policy, and (7) techno-scientific knowledge" / "orientation and co-ordination [of] the activities of relevant actor groups"

[67] Jaccard, M. (2005). *Sustainable fossil fuels*. Cambridge, UK: Cambridge University Press.
[68] Pearson and Fouquet, 2012. Past and Prospective energy transitions: Insights from History In Energy Policy 50 (2012) 1-7.
[69] IIASA (2012). Global Energy Assessment - Toward a Sustainable Future, Chapter 16: Transitions in Energy Systems, Cambridge University Press, Cambridge, UK and New York, NY, USA
[70] Geels , F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multilevel perspective and a case-study. Research Policy, 31 : 1257 ‐ 1274

The socio-technical ***landscape*** *provides the exogenous environment for regime change and is a source of major selection pressures on prevailing which in turn provide opportunities for niche innovations."*

Regimes *and niches develop in the context of a socio-technical landscape, which consists of both hard-geographical features, such as resource availability and infrastructure, and "soft" elements, such as political conditions, societal trends, and economic fluctuations.*

A ***niche*** *is a network of similar projects carried out by innovating actors who seek to challenge the incumbent and dominant socio-technical practice (regime).*



Secondly, when framed as a systemic, multi-scale and emergent process energy transitions ***can be seen to take on a number of characteristics and trends which suggest that stimulating net zero will be very much a long-term economic transition*** to ensure that externalities and public goods are better integrated into goods and services. A summary of transitions trends identified in the literature can be found in Table A1.1.

Table A1.1: Summary of transition trends identified in literature (Fouquet, 2008[71] and 2010[72]; Allen, 2009[73]; Smil, 2010[74]; Pearson and Fouquet, 2010 and 2012; Cleveland and Morris, 2014[75])

	Trends	Transition
General	Long timeline	To progress from niche to market dominance, the minimum time taken is 40 years e.g. railways to automobile. Usually takes a century to complete a transition that involves an entire economy (Pearson and Fouquet, 2012). The average duration of the innovation chain (i.e., from the invention of the key technology to 80% share of energy consumption, or to the peak) was 95 years (Sovacool, 2016)[76]. Note. Wind turbine and Solar were invented in 1880 and 1954, respectively and are only just starting to play a material role in national electricity systems.
	Inter-disciplinary factors	A number of factors play a significant role leading to transitions: external circumstances including timing, market failure, landscape forces, barriers to entry, culture, geographical distribution of sources etc Geels 2007[77].
Technical	Superior quality energy of source	High energy density sources that are flexible, easily stored and dispatchable are seen as better quality and will reach market dominance faster than low-quality sources e.g. transition from wood to coal.
	Scientific progress	Improved technological design leads to better energy conversion/decrease in intermittency/ease of use etc.

[71] Fouquet, R. (2008). *Heat, power and light*. Cheltenham: Edward Elgar
[72] Fouquet, R., (2010). The slow search for solutions: lessons from historical energy transitions by sector and service. Energy Policy 38 (10), 6586–6596.
[73] Allen, R.C., 2010. The British Industrial Revolution in Global Perspective. Cambridge University Press, Cambridge.
[74] Smil, V. (2010). Science, energy, ethics and civilization. In: Chiao, R.Y., Cohen, M.L., Leggett, A.J., Phillips, W.D., Harper Jr., C.L. (Eds.), Visions of Discovery: New Light on Physics, Cosmology, and Consciousness. Cambridge University Press, Cambridge, pp. 709–729.
[75] Cleveland, C. and Morris, C. (2014). Transitions. *Handbook of Energy*, pp.831-843
[76] Sovacool 2016. 'How long will it take? Conceptualizing the temporal dynamics of energy transitions.' Energy Research & Social Science 13 202-215.
[77] Geels , F. W. and J. W. Schot (2007). Typology of sociotechnical transition pathways. Research Policy, 36 : 399 ‐ 417

	Increase or decrease in emissions	Higher energy density of fuel and higher energy conversion rates result in higher emissions per unit of energy e.g. Wood to coal coal to gas
Economic	Energy service price	The resultant energy services of a new source or technology must prove to be cheaper to compete with the services of an incumbent source/technology in the long term.
	Increase in demand	Past energy transitions that involved a switch to a new primary energy source, also led to the increase in energy demand and primary energy use.
	Unique selling point	The emerging niche must provide an improvement of quality, ease of use or another benefit that would encourage uptake. The fastest diffusion was from horse to railways in the mid-nineteenth century and steam engines to electricity in the first-half of the twentieth century. These new technologies and energy sources provided cheaper and better quality services. As a result, despite the need for an infrastructure to use the new energy source or technology, both made the transition very quickly - in 30 years.
	Depletion of sources	The depletion of incumbent sources would lead to the need for alternative niches and regimes.
	Economic inertia	Established capital stock and economic instruments can lead to lock-in effect, hindering transition.
Socio-political	Public acceptance	Historically, if substantial difference was present in the energy service prices and worker's wages, the niche met less public resistance.
	Social inertia	Institutional, cultural and habitual norms formed under one primary energy supply, can lead to a lock-in effect, hindering the transition to another.

Thirdly, the literature highlights that the broader outcome of transitions was not only ***determined by*** endogenous, direct factors such as price and the consequent rate of technology uptake, but rather ***a set of exogenous, indirect economic aspects that proved to be influential at the time such as geopolitics which influenced timings, highlighted market failures which stimulated Geel's landscape forces***[78]. For example, the peak in oil prices experienced in 1973 and 1979 created a substantial push for nuclear power exploitation, reducing the demand for the incumbent fossil fuel sources in many economies, while encouraging investments in the new technology and networks.

Fourthly, the ***speed which some of the previous transitions took place might not be replicable with the net zero transition. Specifically, the roll-out of CCUS technologies may be slowed down due to the lock-in that industrial processes are presently subjected***. Fouquet[79], suggests that the strong path dependence in modern energy systems has delayed the uptake of certain technologies. Inertia is a further trend observed in energy systems and major long-term transitions. Capital stock has a range of life-times - e.g., a couple of years for appliances; decades for power stations, transmission lines, pipelines; proportions of centuries for industrial processes; and centuries for buildings and components of infrastructure - which can be especially long-lived in the energy sector. This can lead to a '*lock-in*' effect, stopping markets from reaching efficiency even with the imposition of new policies and regulations[80,81]. Due to this notion of inertia in energy systems and the cost of premature capital stock retirement, desired changes might take longer under the requirement of a gradual termination[82].

Fifthly, departing from the more economic perspectives of the previous observations to one that is ***framed anthropologically and culturally***[83]***, modern energy transitions can also be seen as sub-components of broader clusters of technologies supported by a set of organisations and institutions, emphasising the role***

[78] Pearson and Fouquet, 2012. Past and Prospective energy transitions: Insights from History In Energy Policy 50 (2012) 1-7.
[79] Fouquet, R., 2016. Historical energy transitions: speed, prices and system transformation. Energy Research & Social Science, 22. pp. 7-12.
[80] Unruh, G.C. 2000. 'Understanding carbon lock in.' Energy Policy 28 817-830
[81] IEA, (2002). *Beyond Kyoto - Energy Dynamics and Climate Stabilisation*.
[82] Jones, C.F., 2013. Building more just energy energy infrastructure: Lessons from the past, Science as Culture, 22:2, 157-163
[83] Freeman, C., Louca, F., 2001. As Time Goes by: From the Industrial Revolutions to the Information Revolution. Oxford University Press, Oxford.

of social[84,85], behavioural factors[86,87,88], organisational structures[89] within the landscape of economic and political factors in shaping energy transitions[90]. This posits the successful uptake of transitions as having tended to depend on the co-evolution of technologies, industries and institutions that enable new energy sources to emerge from niches and become core elements in the regime. This allows new 'technological clusters' to dominate and ultimately create 'lock-ins'. Using a multi-dimensional framework, Geels et al[91] show that, although economic and technical factors may drive a transition - external pressures, political, social and cultural factors play a pivotal role in directing the pressures and determining the reactions to them. It also highlights the role of societal imagination and `buy-in' into the development of aspirational transition futures and the role of actors in stimulating the narrative around net zero[92]. This likely being important in liberal democracies - especially those with liberalised energy markets.

A sixth observation is that though traditional trends and drivers of energy transitions - as articulated in table A1.1 - should not be neglected. It can be assumed that the purposeful policy programmes designed today to stimulate a net zero transition will have a very different set of characteristics to those that have taken place in the past. Table A1.2, below, schematises the likely differences between past emergent and net zero purposeful transitions[93].

Table A1.2: Schematised likely differences between emergent past with purposeful net zero transitions.

Emergent Past Transitions	Net Zero/Low Carbon Purposeful transition
Single substitution e.g., biomass to coal	Multiple substitutions
Extension of naturally occurring trends	Predominantly not in line with trends
Low extent of intervention by government	Prescribed by interventions
Transition between general purpose technologies	Transition to low carbon technologies
Introduction of new energy carriers	New energy carrier is not necessary
Predictable improvement in service quality	Unclear if major improvement will take place
Clear private benefits to producer and consumer	Unclear private benefits to producer and consumer.

In summary, ***the transitions literature is biased to empirical, micro-economic and sector specific studies***. Past transitions when analysed as narrow technology and even as energy transitions miss important dimensions which realised successful economic transitions in the past. The exclusion of systemic and particularly social dimensions - and the requisite ethnographic and exploratory research - has likely resulted in the development of an incomplete understanding of past transitions. These gaps are further intensified by the fact that the net zero transition will likely stem from simultaneous and intertwined transitions. A such, it will be subject to complexity, uncertainty and emergence. This forms an important framing for this project.

A1.2.2 Energy Transitions Perspectives - Implications on Innovation Theory

The positing of research on energy transitions on empirical and narrow sector specific studies and the subsequent knowledge gaps is translated into the corpus of work on innovation theory. Indeed, it is only

[84] Miller, C.A. et al 2013. The Social Dimensions of Energy Transitions, Science as Culture, 22:2, 135-148
[85] Laird, F.H., 2013. Against Transitions? Uncovering Conflicts in Changing Energy Systems, Science as Culture, 22:2, 149-156
[86] MacKenzie and Wajcman (Eds) 1999. Introductory Essay in The Social Shaping of technology 2nd Edition Open University Press Buckingham UK
[87] Williams and Edge 1996. The social shaping of technology. In Research Policy 25 (1996) 865-899.
[88] Lawson 2014. Chapter 2: A speeding up of the rate of Social Change? Power, Technology, Resistance, Globalisation and the Good Society. In MS Archer (ed) Late Modernity: Trajectories towards Morphogenic Society. Social Morphogenesis
[89] van den Bergh, Faber, A., Idenburg, A.M., Oosterhuis, F.H. (2007). Evolutionary Economics and Environmental Policy: Survival of the Greenest. Edward Elgar Publications, Cheltenham and Northampton, MA.
[90] Bolton, R. and Foxon, T.J., 2015. A socio-technical perspective on low carbon investment challenges–insights for UK energy policy. *Environmental Innovation and Societal Transitions*, *14*, pp.165-181.
[91] Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research policy*, *31*(8-9), pp.1257-1274.
[92] Sovacool, B.K. and Brossmann, B., Fantastic Futures and Three American Energy Transitions. In Science as Culture, 22:2, 204-212
[93] Fouquet, R. 2010. 'The slow search for solutions: lessons from historical energy transitions by sector and service.' Energy Policy 38(11) 6586-96.

relatively recently that a more systemic perspective of innovation theory has become established[94]. The innovations literature can be simplistically split along the following lines of cleavage:

- An *"Emerging technology"* perspective[95] which is focused on linear perspective of the innovation that takes place for a particular product or service. It tends to analyse the induced and emergent impact of that technology on the broader `system'. Though it recognised that these phenomena are interconnected it tends to be reductive categorising change pressures by technology, institutions etc which results in a loss of complexity[96]. Projections of technology diffusion tend to be relegated to single metrics and `One Factor Learning Curves' - which will be expanded upon in section 2.5.
- *"Technological Innovation Systems"* is a composite theory which brings together innovations systems, transitions and the multi-level perspective strands of theory[97]. It considers a multitude of levels - a broad and slow-changing landscape developments - heuristically determined sociological rules in the form of socio-technical regimes and technological niches in which innovations can flourish - to analyse how the interaction between the levels allows for broader transitions over long periods of time. It considers a highly interlinked innovation system which iterates and has multiple feedback loops with broad and slow-changing landscape developments including institutions. Projections of technology diffusion tend to embrace bottom up and `Multi-Factor Learning Curves' - again to be expanded upon in section 2.5.

The two innovation constructs are summarised in figure A1.2, below.

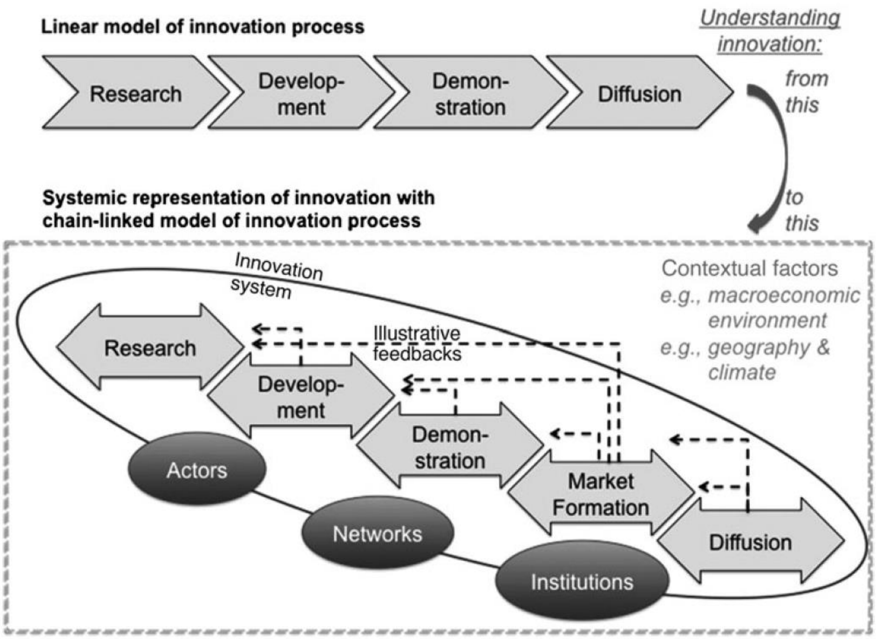


Figure A1.2: Innovation as a linear process to one which is highly interlinked system which iterates and has multiple feedback loops[98].

The fragility of transitions theory in developing insights and prescriptions for the realisation and diffusion of innovations for net zero is under appreciated. ***It is significant as to the implications of how net zero decision support analysis - which are mostly entirely based on whole systems energy models - are used to generate the relevant innovation policy insights for net zero***. Given that outputs from energy system models are widely used as evidence base for policy decisions, the inadvertent flawed representation of energy innovation

[94] Gallagher et al 2012. The Energy Technology Innovation System. Annu. Rev. Environ. Resour. 2012. 37:137–62
[95] C. Edquist, Systems of Innovation: Technologies, Institutions and Organizations, 1st ed. Pinter (A Cassell imprint), 1997.
[96] UKERC, 2016 A review of the evidence on the time taken for new technologies to reach widespread commercialisation. TPA - see link
[97] J. Markard and B. Truffer, "Technological innovation systems and the multi-level perspective: Towards an integrated framework," Res. Policy, vol. 37, no. 4, pp. 596–615, May 2008, doi: 10.1016/j.respol.2008.01.004.
[98] Gallagher et al 2012. The Energy Technology Innovation System. Annu. Rev. Environ. Resour. 2012. 37:137–62

processes will potentially contribute to inadequate policy design if inappropriately used. Furthermore, with many of the technologies required to realise net zero having undergone limited global deployment the use of landmark learning rates from one technology as projections for another are likely to be flawed since the development stages and associated innovation dynamics will be very different. This is explored further in section A1.5 and has direct implications on the application of metrics to assess technology and commercial readiness - which is analysed in section 2.

A1.3 Infrastructure - Systems of Systems Complexity

One of observations from the energy transitions literature surveyed in section A1.2.1 was that of path dependencies i.e. the fact that capital stock has a range of often long lifetimes which can lead to '*lock-in'* effects for established technologies and `*lock-out'* of new technologies. This inhibits markets from responding to the imposition of new prospective policies and regulations to address net zero as a function of the cost of premature capital stock retirement.

With CCUS being an assemblage of technologies/value chains which will need to be integrated across modern economies will likely result in the development of dependences not only within energy infrastructure systems but also other infrastructure systems more broadly. The need for an understanding of modern infrastructure systems is therefore warranted as CCUS systems will have to co-evolve and integrate within them.

Modern infrastructure systems (energy, transport, digital communications, water, and waste) provide essential services to society[99]. Historically, they have been developed in silos, unconnected and in a piecemeal fashion. Increasingly, modern infrastructure systems are recognised as being integrated, interdependent[100] and increasingly complex. As a function of this they are seen more as `systems of systems' and indeed some analysis makes a case for them to be treated as `complex adaptive systems'[101] in order to both understand and manage their cross-economy physical and institutional dimensions. Such a situation is in direct tension with institutional cultures regarding infrastructure governance - where there is little tradition of thinking cross-sectorally regarding infrastructure system performance. Furthermore, liberalisation agendas in OECD economies with a drive for privatised infrastructure provision, and competition in infrastructure sectors has led to a more complex governance landscape where a substantive range of actors are involved in infrastructure planning and decision making - see table A1.3, below.

This complexity is compounded by the fact that infrastructure lead times are extremely long with substantive potential for lock-in makes the ability to assess the implications of multi-decadal to century long planning projections problematic. Anticipated future performance will be shaped by drivers, interdependencies and impacts which will be subject to substantive uncertainty making the strategic planning of infrastructure a complex undertaking[102].

This situation is yet further compounded when it is considered that CCUS infrastructure, though possessing its own discrete capital-intensive infrastructure characteristics which will interact with other sectors, is often not considered within the system of system ensemble of national infrastructure decision support and planning tools. It also cuts across other sectors and does not possess its own explicit governance mechanisms. This situation is exemplified by the intended development of a UK Greenhouse Gas Removal Sector which is anticipated to sequester 60 $MtCO_2$ pa by 2050 and therefore on the scale of the present UK water sector[103] -

[99] Hall, J. et al 2014. Assessing the Long-Term Performance of Cross-Sectoral Strategies for National Infrastructure. DOI: 10.1061/(ASCE)IS.1943-555X.0000196. American Society of Civil Engineers.
[100] Hiteva, R. et al 2015. Policy Note - Enhancing governance of energy and water interdependencies pp2
[101] Oughton et al., 2018. Infrastructure as a Complex Adaptive System Hindawi Complexity Volume 2018, Article ID 3427826, 11 pages https://doi.org/10.1155/2018/3427826
[102] Marshall, T.2014. Infrastructure, the economy and planning: the case for new approaches he future of national infrastructure systems & economic prosperity conference, Cambridge, UK, March 27–28, 2014.
[103] National Infrastructure Commission 2021. Greenhouse Gas Removal Technologies. A study examining how emerging greenhouse gas removal technologies can support the UK's climate ambitions.

yet its integration into UK infrastructure decision support tools e.g. ITRC / NIC NISMOD and the UK digital twin initiatives has yet to be realised.

Table A1.3: Characteristics of the UK infrastructure system[104]

	Energy	Transport	Water	Waste: Wastewater	Waste: Solid Waste	Digital Communications
Scale	National International	Regional National International	Regional	Regional	Regional	National International
Ownership	Private	Mixed (by mode)	Mixed (by region)	Mixed (by region)	Mixed (public responsibility with private operation	Private
Governance and Regulation	Varies e.g. electricity has unregulated market prices but regulated network charges	Varies e.g. rail has regulated efficiency targets; roads and government planned with some private provision	For England and Wales, price and investment regulated by Ofwat, drinking water quality regulation by DWI, environmental regulation by EA.		Local Authority run. Environmental regulation by EA/DEFRA in England and Wales, SEPA in Scotland	Competition regulation by Ofcom; universal service obligations; spectrum licences and coverage obligations
Issues	Security of supply; GHG emissions	Congestion; high speed rail; airport capacity	Demand management; climate change; environmental regulation	Energy costs; environmental regulation	Waste minimisation and recycling targets; resource management	Technological innovation; rural coverage

A1.4 CCUS - As a distinct infrastructure asset class

The complexity of planning for infrastructure needs over long time horizons is intensified when it is considered that CCUS is an untried technology and as such needs to be considered a distinct infrastructure asset class.

CCUS not only possesses the same characteristics of conventionally established infrastructure but also that as a function of its nascent deployment is a distinct asset class which possess additional risks before it can be considered commercially viable and bankable.

In any large conventional capital project, the challenge is one of risk limitation and in this regard CCUS is no different. The market understands these `conventional risks` and can price them appropriately. Moreover, for projects where there is a well-defined `market demand` for products, e.g., steel, cement, etc., the combination of risk dictates market price. With capital being supplied via a combination of equity, debt, and government grants (or non-dilutive equity). The availability of these sources of financing can be thought of through the lens of where a technology is along the TRL scale:

- Usually, government grants are available for projects at TRL4 -7;
- Equity is available for projects in the region of TRL 5 – 9; and
- Debt is available only for TRL 8 – 9.

Combined, the `cost of this capital' results in the Weighted Average Cost of Capital (WACC) which impacts the cost per tonne of CO_2 avoided, or the cost per MWh, or per tonne of low carbon steel, cement, *etc.*

Debt is usually the cheapest, and most desirable, source of capital as it both reduces project costs and doesn't require sacrificing project equity. The challenge is that it is also the most risk averse form of capital - if you have project equity, you stand to gain from project success, but if you provide debt, the best case is you get your money back, regardless of how successful the project becomes.

[104] after Hall, J.W. et al. 2015 Responding to adaptation emergencies. Nature Climate Change, 5(1): 6-7.

Therefore, the question is to identify what elements of the risks associated with a CCUS project are `new risk' and what elements are `conventional risk`. In this regard the following is relevant: The underlying plant is `normal risk` - the market for power, cement, etc. is `standard`. From a CCS perspective, new risk includes:

- ***`Technology risk'*** for new capture technology i.e., something other than amine scrubbing. To some extent, this can be bought down if technology suppliers will provide the capture technology on a `total asset management` basis, i.e., they will build and operate the capture tech for the emitter and essentially take ownership of this risk. However, this is rare for anything other than technologies like amine scrubbing or ASUs, etc., i.e., options with significant "real world" operating experience.
- ***`Market risk'*** i.e., who is going to buy CCUS product, and can a sufficient price be established to cover costs. Whilst renewable energy may command access to market via renewable portfolio standards etc. - the same is not true of power/industrial CCS products. Industrial products are further complicated owing to the international dimension of imports which will be cheaper if produced without CCS technologies unless Carbon Border Adjustments are enacted.
- ***`New infrastructure risk'*** CCUS needs CO_2 transport and storage (T&S) infrastructure. This makes CCS distinct to other "clean energy/tech" options which can be integrated with existing electricity grid infrastructure. In most locations no CO_2 T&S infrastructure exists. Whilst any of this *could* be readily deployed, one would need confidence that there will be a sufficient supply of CO_2 to justify the investment. This is further complicated by the fact that whereas once it was considered that CCS projects would be simply "source to sink" lines - this is no longer the case. The move to CO_2 hubs means that CO_2 T&S will need to be "oversized" so as to accommodate future CO_2 flows - assuming they appear. This can have the impact of appreciably inflating FOAK projects costs.
- ***`Geological storage risk'*** though the technical challenge of geologically sequestering CO_2 is limited e.g., Sleipner field has long run data, but though it has been done wrong and mistakes have occurred, e.g., Gorgon - this can nevertheless be financed. The component of this risk that is difficult to price is the long-term liability for the stored CO_2. This is further complicated by the fact that CO_2 stores will be accepting CO_2 from a number of point sources, and hence CO_2 injection and storage may carry on far beyond one project lifetime.
- ***'Cross-chain' or `project on project' risk*** the power/industrial point source, capture plant, CO_2 pipeline, and CO_2 store are likely to be separate projects. If a project is financed on the assumption that it is getting a tax credit for CO_2 storage, or a CfD for clean power, etc. and then because of something outside of the projects control, this is no longer possible e.g., the pipeline or store is temporarily/permanently unavailable, the whole project fails.

A1.5 CCUS Integration into Net Zero Decision Support and Policy Design

Sections A1.3 and A1.4 highlight the complexity that is involved in CCUS technology and value chain establishment and development. This complexity along with the capital-intensive nature of the value chains results in substantive risk and uncertainty for stakeholders seeking to invest in the sector. They need to be addressed in order for it to become a commercially viable and bankable asset class. This section focuses on how insights around innovation support for CCUS technologies are generated. It will allow an understanding as to the extent to which decision support tools are used and their ability to prescribe CCUS innovation policy. It builds on issues raised in section A1.2.2.

Innovation policy is informed by the assessment of learning curves that technologies go down as they are developed, scale and actors become more confident with deploying them and integrating them into the relevant infrastructure `system(s)'. This is important as it allows support mechanisms to be designed, timed and targeted to manage risk and uncertainty for the different discrete technology development needs. Actors can then be incentivised to deploy technologies throughout these stages. It also compounds the policy blind-spots that result from whole systems modelling - particularly those which optimise for least cost[105].

According to Gambhir et al[106] learning rates to allow cost reductions are comprised of a combination of a number of components - as summarised in table A1.4, below.

Table A1.4: Literature based assessment of important components in assessing cost curves for technologies

- Learning by doing of different sub-components[107].
- Importance of institutional factors including regulatory regimes and networks between technology innovators, users and finance[108].
- Focus on learning rates and returns on innovation investment of granular technologies[109].
- Technology learning rates are inversely proportional to unit size[110].
- Faster learning rates in commodifiable and mass customised technologies[111].

There are a number of ways that these components of learning curves can be quantified. These include: (1) the generation of `*One Factor Learning Rates*'; (2) Expert elicitation; (3) Engineering assessment of technology cost components and manufacturing processes; and (4) hybrid methods.

A number of observations have been made regarding the present development of learning curves to inform technology innovation policy:

- In a review of onshore wind and solar PV technologies, Elia et al[112] found that most of the published learning curve analyses are focused on addressing the impact of drivers related to (1) manufacturing process improvements (i.e., learning by-doing); and (2) technology feature improvements (i.e. learning by-researching). Other learning drivers such as market dynamics and learning by-interacting across different stakeholders and geographical areas were poorly quantified; and
- The tendency to utilise *One factor Learning Curves* (OFLC) due to the legacy of model function. As OFLCs conflate the distinct stages of technology development, the resulting simplification can lead to misleading analogies and comparisons between technologies. For example, the use of landmark learning rates from one technology (e.g. solar PV) as projections for another technology are likely to be flawed since the development stages and associated innovation dynamics will be very different. Unrealistic cost reduction projections can therefore exacerbate technology hype cycles and result in inappropriate policy interventions.

In line with the substantive gap between what is modelled and how technologies actually go down learning curves the following recommendations were made:

- The application of Multi Factor Learning Curves (MFLC) and Bottom Up Cost Models (BUCM) approaches can facilitate more robust energy innovation analysis and decision making by considering the different

[105] Workman M, Darch G, Dooley K, et al., 2021, Climate policy decision making in contexts of deep uncertainty-from optimisation to robustness, Environmental Science and Policy, Vol:120, ISSN:1462-9011, Pages:127-137
[106] Gambhir et al 2021. How are future energy technology costs estimated? Can we do better? *International Review of Environmental and Resource Economics*, Vol: 15, Pages: 1-48, ISSN: 1932-1465
[107] Thomassen, G., et al. 2020. A review on learning effects in prospective technology assessment. Renew. Sustain. Energy Rev. 130, 109937. https://doi.org/10.1016/j.rser.2020.109937
[108] Grubb et al 2021. 2021. Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO2 mitigation. Environ. Res. Lett. 16, 043007. https://doi.org/10.1088/1748-9326/abde07
[109] Wilson et al., 2020. Granular technologies to accelerate decarbonization. Science 368, 36–39. https://doi.org/10.1126/science.aaz8060
[110] Sweerts, B., et al 2020. Evaluating the Role of Unit Size in Learning-by-Doing of Energy Technologies. Joule 4, 967–970. https://doi.org/10.1016/j.joule.2020.03.010
[111] Malhotra, A., Schmidt, T.S., 2020. Accelerating Low-Carbon Innovation. Joule 0. https://doi.org/10.1016/j.joule.2020.09.004
[112] Elia et al 2020. Impacts of innovation on renewable energy technology cost reductions. Renew. Sustain. Energy Rev. 110488.

technology development stages and their inherent dynamics to allow tailoring and timing of policy support mechanisms; and

- Collation and interrogation of more energy technologies in various geographical areas to allow investigation of how drivers correlate with market development and geographical spill-overs is essential to allow a global perspective as to the potential for technologies relevant to net zero to be established and scale.

The ***linear emerging technology perspectives of energy transition theory as articulated in section A1.2.2 and the lack of data / the inability for decision support modelling to accommodate multi-factor learning curves very much limits the role of decision support to inform innovation policy.*** This translates into perspectives regarding the role of indices in prescribing the commercial readiness and bankability of technologies and their associated value chains that are fundamental to the realisation of net zero. This is further expanded upon in section 2.1.2.

A2.6 Summary

The review of the energy transitions and innovations literature has revealed a number of issues salient to this study. It highlights ***substantial epistemological gaps in our understanding of energy transitions which then spills over into a somewhat fragmented corpus of innovation theory***. These patchy theoretical underpinnings then carry over into decision support tools. The reliance on One Factor Learning Curves conflate the distinct stages of technology development which then negate the ability to target the relevant timely policy interventions and/or incentives. The need for innovation datasets across the different forms of learning, in different geographical jurisdictions, to realise multifactor learning curves and bottom up cost modelling strongly indicates that the calibration of modelling decision support ***from real-world data sets is a fundamental requirement to allow the generation of more insightful decision support outputs*** to inform innovation policy around net zero technologies more broadly but also specifically around CCUS value chains. To do this, more CCUS projects need to be established and developed - whereby basic research is important at every stage of the innovation process including the take up of know-how from other infrastructure and technology sectors[113].

With CCUS being a nascent and unestablished set of heterogenous capital intensive technologies - which will bring together multiple actors not used to working together. ***This will involve substantial complexity as a function of the interdependencies of infrastructure systems which involve a numerous and eclectic range of actors who again have limited experience of working across infrastructure sectors.*** This makes the development of long-term planning over increasingly interdependent and economically vital infrastructure for a technology that has yet to be fully established fraught with risk, emergence and deep uncertainty.

[113] R.K. Lester, Regionalizing Energy Technology Demonstrations , MIT Carbon Sequestration Forum 16, Cambridge, MA, November 12 13, 2014

Appendix 2: Technology Readiness Levels - Origins and Construct

NASA developed the concept of technology readiness levels (TRL) in the 1970s to assess emerging technology relevant to space exploration. The TRL concept was subsequently applied across a number of US department agencies in the 1990s - particularly the Department of Defence (DoD) and the Department of Energy (DoE). The concept has since proliferated across a number of sectors and applications.

The need to better adapt the initial NASA concept to energy technology project development[114] lead to the production of a US DoE TRL Guide[115]. The guide describes the formal process by which energy programmes and their associated suite of technologies are project managed through formal assessment of TRL, how visibility of technology risk is enhanced and identifies any follow on activities that need to take place to mitigate those risks including the development of roadmaps, matrices and technology maturation plans. Technology Maturation Plans (TMP) provide a detailed technology development path forward for successful deployment of the selected technology within a programme process ***including the assignment of responsibility and execution of each element of the development*** plan. Those assigned responsibility are accountable to an Independent Panel Review whose role is to acknowledge, identify, and reduce technical risk and uncertainty within the overarching technology development process model which in turn inform technology development plans.

Technology Readiness Level (TRL) measures how ready equipment is for use now in a broader system and in the case of CCUS in an operating plant. The scale based on the DoE can be found in table A2.1, below.

Table A2.1: Technology Readiness Levels as prescribed by the US Department of Energy

Phase	TRL	Stage	Description
Operations	9	Operations	The technology is being operationally used in an active facility
Deployment	8	Active Commissioning	The technology is undergoing active commissioning
	7	Inactive Commissioning	The technology is undergoing inactive commissioning. This can include works testing and factory trials but it will be on the final designed equipment, which will be tested using inactive simulants comparable to that expected during operations. Testing at or near full throughput will be expected
Development	6	Large Scale	The technology is undergoing testing at or near full-scale size. The design will not have been finalised and the equipment will be in the process of modification. It may use a limited range of simulants and not achieve full throughput
	5	Pilot Scale	The technology is undergoing testing at small to medium scale size in order to demonstrate specific aspects of the design
	4	Bench Scale	The technology is starting to be developed in a laboratory or research facility.
Research	3	Proof of Concept	Demonstration, in principle, that the invention has the potential to work
	2	Invention and Research	A practical application is invented or the investigation of phenomena, acquisition of new knowledge, or correction and integration of previous knowledge
	1	Basic Principles	The basic properties have been established

[114] US DOE - Highlights of GAO-07-336, a report to the Subcommittee on Energy and Water Development, and Related Agencies, Committee on Appropriations, House of Representatives

[115] US DOE G 413.3-4A 9-15-2011 Technology Readiness Assessment Guide U.S. Department of Energy Washington, D.C. 20585 www.directives.doe.gov

Appendix 3 - Non-systemic meta-study of indices to assess components of Commercial readiness across a range of domains and economic sectors.

As part of the project a non-systematic meta-study of indices to assess elements of commercial readiness was undertaken. Forty-five were mapped and 38 reviewed as shown in table A3.1 below - whereby the indices, author/year - including citation, sector origin, individual component metrics involved and notable features are outline.

Table A3.1: Non-systemic meta-study of indices to assess components of Commercial readiness across a range of domains and economic sectors.

Ser	Indices	Author / Year	Sector Origin	Metrics Involved	Description of Notable Features
1	Systems Readiness Level	Knaggs et al., 2015[116]	US Fossil Fuel Sector application adopted from US Department of Defence.	• System RL • Technology RL • Integration RL	Shows how to integrate Technology Readiness and Integration Readiness Level in order to assess System Readiness Level. Application was in the US fossil energy sector based on a US Department of Defence methodology. Advanced fossil energy systems need to be tested at full-scale in an integrated facility before they can be considered ready for commercial deployment. Commercial-scale demonstrations of energy technology present numerous challenges associated with first-of-a-kind facilities, one in particular being the need to integrate multiple emerging technologies that were previously demonstrated in pilot-scale applications into a design that can be constructed and operated under commercial plant operating conditions. Application unites individual TRL for each technology with Integration Readiness Levels expressed as a function of the need for each of these technologies to be integrated with each other. Used matrix algebra approach is used to estimate overall systems readiness.
2	System of Systems Technology Readiness Level Assessment	W. Majumdar, 2009[117]	US Department of Defence (DoD)	• System of Systems RL • Technology RL; Technology Readiness Assessment (TRA) • Information Technology (IT) system TRA • Software TRL • Hardware TRL • System RL • Integration RL • Interoperability Level	Systems of Systems (and interoperability) perspective rather than being about readiness levels. Advanced technologies must be matured simultaneously to support the degree of interoperability and/or integration required to operate as a complete system. Assessed US Department of Defence guidance with respect to technology development and assessment is focused on a acquisition of a system which operates relatively independently within a collection of other independent systems. An approach to technology development and technology readiness assessment of advanced technologies which support network-centric systems was considered an important requirement for successful development and fielding of network centric warfighting capabilities. Fundamental activities of technology maturation and assessments is the definition of a relevant environment and the ability to identify the critical technologies that provide for interoperable or interdependent functions.

[116] Knaggs et al. 2015 Application of Systems Readiness Level Methods in advanced fossil energy applications
[117] W. Majumdar 2009 - System of Systems Technology Readiness Level Assessment

3 & 4	From Technology Readiness Level to System Readiness Level: The concept of systems readiness levels Defining an Integration Readiness Level for Defence Acquisition.	Sauser et al., 2006 and 2009[118]	Engineering and Defence Acquisition	• Technology RL • Integration RL • System RL	Makes the case regarding the NASA and US DoD adoption of Technology Readiness Level (TRL) and the difficulty in assessing the ability to integrate multiple technologies into a single effective system; the ability to assess the extent of uncertainty in advancing along the TRL scale; and the lack of comparative analysis for alternative TRLs. The System Readiness Level (SRL) index is an index of maturity applied at the system-level concept with the objective of correlating this indexing to appropriate systems engineering management principals. Integration Readiness Levels is a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points Undertook survey to assess robustness of SRL concept amongst 30 engineers using a cell phone and headset maturity. Too small sample size to extrapolate probabilities. Attempt to bring together a model for systems engineering built on the fundamental theory of a system Assessed that integration is complex topic and assessments biased based on integration experience of assessors. The defence study also undertook a survey amongst 33 SMEs across govt and industry. Produced a Systems Readiness Level Guide
5	Whole system energy capability	UK Energy Systems Catapult, 2019[119] and 2020[120]	Energy Innovation	• Technology • Consumer • Infrastructure • Information system • Business Model • Value Chain • Regulation	The whole systems energy capability was based on thinking undertaken as part of the Energy Town Concept whereby a more holistic and systems perspective of energy technology maturity was taken. It then formed part of the service for the Energy Revolution Integration Service, With the development of decentralised and digitisation characteristics in the energy system the need for systems thinking and systems engineering concepts were introduced into the assessment. The approach highlighted novel insights to the way that innovation might be undertaken conceptualising the energy sector as a complex adaptive system. Emphasised the need to integrate technologies across a wider boundary within a more systemic perspective of the energy system; allowed consistency of language used; enabled risks to integrating elements of the overall solution to be identified in a structured way; as well as a mechanism to co-ordinate the parallel development of different aspects of capability that need to be brought together to deliver a project.
6	Aspects of Innovation			• Technology • Operation • People • Information • Infrastructure • Interoperability • Commercial • Legislation	

[118] Sauser et al. 2006 - TRL to SRL: The concept of systems readiness levels / Defining an Integration Readiness Level
[119] Energy Town 2019 - Presentation Deck by Tim Stiven for Energy Systems Catapult Management Board and Energy Revolution Integration Service
[120] https://es.catapult.org.uk/tools-and-labs/our-place-based-net-zero-toolkit/aspects-of-integration/

7	Automotive Technology and Manufacturing Readiness Levels	Williamson and Beasley 2011[121]	UK Automotive Sector	• Technology RL • Manufacturing RL Both scaled to 10	A guide was developed based on the ongoing need for greater cooperation, joint exploration of new designs and acquisition of evolutionary and revolutionary products in order to rebuild the strengths of the UK's Automotive Sector. The set of 'readiness' levels assists the sector by providing specific, identifiable stages of maturity, from early stages of research through to supply chain entry. The intention of the metrics were to communicate the accomplished and expected stages of technology development and readiness for manufacture across a range of audiences - vehicle manufacturers, identification of need for public sector support, angel investors, venture capital, self-assessment and sector wide assessment.
8	Manufacturing Readiness Levels	Joseph A. Fernandez [122]	US National Lab innovation and project management	• Manufacturing RL - scaled to 10.	Manufacturing Readiness Levels (MRLs) have been proposed for improving the way manufacturing risks and readiness are identified; they were introduced to the defence community in 2005. A tool which considers the ability of the system to produce a product to the correct quality and of the required throughput.
9	Small Medium Enterprise Service Readiness	Teso and Walters, 2016[123]	Business Enterprise	• Service RL	Assessing manufacturing Small Medium Enterprise's readiness to implement service design. Undertook interviews with three firms which had started to embrace service design. From the interviews a conceptual framework within 9 dimensions which provide an aid understanding of a company's potential readiness for servitization through service design: (1) Effectiveness; (2) Experience; (3) Service History; (4) External Engagement; (5) Culture and development; (6) Creativity; (7) Risk Propensity; (8) Communication; and (9) Awareness.
10	Small Medium Enterprises Readiness Indicators	Chonsawat & Sopadag, 2020[124]	Business Enterprise	• Organisational Resilience • Infrastructure System • Manufacturing System • Data Transformation • Digital Technology	Assessing readiness of Small Medium Enterprise's to realise Industry 4.0 (Smart Manufacturing) which can increase production efficiency, reduce energy consumption and decrease costs. Used literature survey to assess indicators. Most occurrences such as the Industrial Internet, Cloud Manufacturing, Collaborative Robot, Business Model, and Digital Transformation. The indicators were trialled by SMEs and it was found that 23 indicators were validated as supporting smart manufacturing.
11	Service innovation readiness: Dimensions and Performance Outcome	Yen et al., 2012[125]	Business Enterprise	• Service innovation RL	Taiwanese study: service innovation as a potential enabler for creating competitive advantage. Literature study based on organisational change and the awareness-motivation-capability perspective.

[121] Williamson and Beasley 2011. Automotive Technology and Manufacturing Readiness Levels. A guide to recognising stages of development within automotive industry.
[122] Contextual Role of TRLs and MRLs in Technology Management, Joseph A. Fernandez, Sandia National Laboratory, SAND2010-7595
[123] Tesoa, G and Waltersb, A. 2016. Assessing manufacturing SMEs' readiness to implement service design. Product-Service Systems across Life Cycle, Procedia CIRP 47 (2016) 90 – 95
[124] Chonsawat, N and Sopadag, A. 2020. Defining SMEs' 4.0 Readiness Indicators. Appl. Sci. 2020, 10, 8998; doi:10.3390/app10248998
[125] Yen et al., 2012. Service innovation readiness: Dimensions and Performance Outcome. Decision Support Systems 53 (2012) 813–824

					Six dimensions identified: (1) Strategic investment; (2) Risk tolerance; (3) Service Innovation Champions; (4) Inter-org collaborations; (5) Service Innovation experience; and (6) Information Technology experience. Facilitates an organisations application of management strategies and an organisations willingness to continuously improve.
12	Application of System and Integration Readiness Levels to Department of Defence Research and Development	Ross 2016[126]	Defence	• Technology RL • Manufacturing RL • Integration RL • System RL	Application of System and Integration Readiness Levels for DoD R&D. Study proposed a modification to the Sauser (see No 3&4 above) mathematics of Integration and System Readiness Levels as well as Manufacturing readiness levels that allows a single System Readiness Level metric that gives a clear indicator of when a component technology or system is ready for further advancement and allows for standard verbal definitions of System Readiness Level.
13	Advancement Degree of Difficulty (AD2)	Bilbro, 2008[127]	Generic / Defence	• Technology RL • Advancement Degree of Difficulty (AD2)	It is an "predictive" (anticipatory) description of what is required to move a system, subsystem or component from one TRL to another whilst accommodating aspects beyond TRL. It provides information in the form of: (1) Liklihood of occurrence of an adverse event. Risk; (2) Cost to ensure that such an event does not occur; and (3) The time required to implement the necessary action. Develops a set of questions in 5 specific areas: (1) Design and Analysis; (2) Manufacturing; (3) Software Development; (4) Test; and (5) Operations. Assessment is resource focused in terms of availability of people, skills, tools, facilities, etc. to design, manufacture, test and operate a component of the system and experience of resources to address that risk?
14	A comprehensive overview of techniques for measuring system readiness.	Bilbro, 2009[128]	Review across sectors	• System Readiness Levels (UK MOD) • Systems Readiness Levels (Stevens Institute - see Sauser in No 3&4 above). • Technology RL • Integration RL • Advancement Degree of Difficulty (AD2) • RI3 (Risk Identification, Integration, and 'Ilities) • Technology Readiness Assessment (TRA) • Systems Engineering Checklists • Design RL	• Advanced, complex Missions cannot meet their goals and objectives without having to rely on advancements in technology. • Even "heritage" systems can require technology development when they are incorporated into a new architecture with different operational environments or goals. • Consequently, all "system" assessments must have a technology assessment as a component. Summarises some of the common frameworks - see next column. Recommends using a tailored combination of the following metrics: • Design Readiness Level (DRL) • Manufacturing Readiness Level (MRL) • Integration Readiness Level (IRL) • Software Readiness Level (SRL) • Operational Readiness Level (ORL) • Human Readiness Levels (HRL)

[126] Ross 2016. Application of System and Integration Readiness Levels to Department of Defence Research and Development. Air Force Research Laboratory. Directed Energy Directorate

[127] Bilbro, J. 2008. Advancement Degree of Difficulty (AD2). Presented at the Technology Maturity Conference held in Virginia Beach, Virginia on 9-12 September 2008.

[128] Bilbro, J and Yang. K., 2009. A comprehensive overview of techniques for measuring system readiness. Presentation at 12th Annual Systems Engineering Conference Oct 26th to 29th 2009.

					• Capability Readiness Level (CRL) • Organizational Readiness Level(ORL) • Programmatic Readiness Level (PRL) • Any successful approach for system maturity assessment must balance the need for data against the resources required to obtain that data.
15	System Aware Concept	Andy Compton[129] (ND)	Energy Sector	• Flexibility • Efficiency • Self-sufficiency • Responsivity & availability • Integrated • Predictive • Sustainability • Future proofing • Resilience • System supportive	System Aware characteristics of energy technologies and their readiness for integration into energy systems - proposed by Compton Energy Associates
16	System Readiness Assessment	Austin et al., 2015[130]	Engineering	• System RL • Technology RL • Integration RL	Another variant on Technology Readiness Level; Integration Readiness Level and System Readiness Level. Based on the premise that as systems become more and more complex, it is critical to develop a more comprehensive understanding of the development status, or "system readiness," to aid more informed system-level technical and managerial decisions throughout the life cycle.
17	Commercial Readiness Levels	Australian Renewable Energy Agency[131]	Energy Sector	Matrix set-up with 6-point scale as follows: 1. Readily financial support of the technology by banks 2. Market Competition industrial acceptance driven by widespread application of the technology 3. Multiple commercial acceptance of the technology 4. Commercial scale-up of the technology 5. Commercial trials of the technology on a small scale 6. Technology and commercially untested and unproven Within this 6 point scale the following indicators are relevant: (1) Regulatory Environment; (2) Stakeholder Acceptance; (3) Technical Performance; (4) Financial Proposition - Costs; (5) Financial Proposition - Revenue; (6) Industry Supply Chain and Skills;(7) Market Opportunities; and (8) Company Maturity.	
18	Service engineering methodology and Energy Services	Benedetti et al., 2016[132]	Energy Sector	This paper does not specifically address readiness levels. Nevertheless. it gives some insight into the application of a Service Engineering methodology to Energy Services, with particular reference to the transformation to the Product-Service System (PSS). The SErvice Engineering Methodology (SEEM): (1) aims at supporting companies in these design and implementation phases. The methodology is in its development phase and its applicability in industry has been mainly tested in one specific	

[129] Andy Compton, ND. Presentation
[130] Austin et al., 2015. System Readiness Assessment (SRA) An illustrative example. 2015 Conference on Systems Engineering Research. Procedia Computer Science 44 (2015) 486 – 496
[131] Australian Renewable Energy Agency 2014. Commercial Readiness Index for Renewable Energy Sectors. Australian Government pp16
[132] Benedetti et al., 2016. SErvice Engineering Methodology and Energy Services: applicability analysis and case study. Product-Service Systems across Life Cycle. Procedia CIRP 47 (2016) 358 – 363

				context. This paper deals with the application of SEEM in the context of Energy Services (ESs) where the design phase can be much more complex than in other areas due to the variety of industries offering this kind of services and to the number of stakeholders involved during the service provision.	
19	Nanotechnology Commercialisation Readiness Scale	Duret et al., 2009[133]	Nano-technology Sector	• Technology RL • Manufacturing RL • Marketing & Communication RL • Organisational & investment RL	The methodology for the analysis of barriers relied on a set of building blocks grouped into the following two main categories: • Commercial Development Parameters: (1) - Technology; (2) Manufacturing; (3) Marketing and strategy; (4) Investment and organisation. • Innovation Management & Business Support Policies: (1) Innovation management; (2) Open innovation; (3) Funding policies; and (4) Local support Surveys and records from Industry were then used to assess maturity based on TRL scale to then identify common success factors ad challenges for different geographical jurisdictions.
20	System Readiness Assessment	Kallio., N. 2015[134]	Energy Sector	• System RL • Technology RL • Integration RL	Another variant on Technology Readiness Level; Integration Readiness Level and System Readiness Level themes developed in a number of studies. Seeks to assess technological maturity of future energy systems in a quantitative way
21	How to Assess Market Readiness for an Innovative Solution	Hjorth, S. S. and Brem, A. M., 2016[135]	Energy Case Studies	• Market RL • System RL • Technology RL • Integration RL • Demand RL	Describes a framework of market readiness and use it to assess the asymmetry between existing solutions and opportunities in the market. The aim is to identify which steps can be taken in order to introduce more energy optimizations into SMEs, and who should be taking those steps. Undertook four case studies in Denmark in different parts of the value chain in the food processing industry, view energy efficiency improvements, focusing on the potential reuse of waste heat, along with what they consider important for taking on such projects. The findings show that while the companies operate very differently, they share common motivations and barriers when it comes to energy efficiency
22	Expansion of the Technology Readiness Levels Perspective	IEA 2020 Energy Technology Perspectives 2020	Energy Sector	**Beyond the TRL 9** stage: • technologies need to be further developed to be integrated within existing systems or otherwise evolve to be able to reach scale; • other supporting technologies may need to be developed, or supply chains set up, which in turn might require further development of the technology itself. For this reason, the IEA has extended the TRL scale to incorporate two additional levels of readiness: • **TRL 10** - where the technology is commercial and competitive but needs further innovation efforts for the technology to be integrated into energy systems and value chains when deployed at scale; and • **TRL 11** - where the technology has achieved predictable growth.	
23	ARPA Commercial Readiness Levels	US Department of Energy 2014[136]	Technology	• Market and Industry Knowledge	More an integrated project management process which includes product, applications, market, consumer and business model considerations. Projects submit an initial Technology to Market (T2M) Plan to the ARPA-E Technology to Market

[133] Duret et al., 2009. NanoCom Lowering Barriers for Nanotechnology Commercialisation Barriers and Success Factors; Commercialisation Readiness Scale dated 1st December 2009.
[134] Kallio., N. 2015. How to assess the technological maturity of future energy systems? Masters Thesis University of Groningen dated September 2015
[135] Hjorth, S. S. and Brem, A. M., 2016. How to Assess Market Readiness for an Innovative Solution: The Case of Heat Recovery Technologies for SMEs. Sustainability 2016, 8, 1152; doi:10.3390/su8111152
[136] US Department of Energy 2014. Commercial readiness level scale - ARPA-E. Appendix B.

				• Intellectual Property Management • Cost-Performance Modelling • Regulatory Issues • Business Model/Plan • Manufacturing/Scalability/ Supply Chain • Next Stage Funding • Team Development	advisor and the Program Director, and obtain approval prior to the execution of the award. The T2M Plan serves as a roadmap for advancing the proposed technology toward commercial viability, and provides an opportunity to set goals and identify issues and opportunities related to technology transfer and commercialization of your ARPA-E funded technology.
24	Readiness to Transform	Gudergen et al 2015[137]	Manufacturing	• Strategy; • Design; • Delivery; • Leadership; and Communication.	Future competitiveness of manufacturing based on development and delivery of integrated solutions. This is accommodated by business model transformation, structures, process and behaviours. Indices and metrics seek to gain better understanding of these variables in the ability for manufacturing organisations to transform towards a solutions business into a product-service system provider.
25	Change Readiness Levels - Change Readiness	Combe, M., 2014[138]	Digital	Organisational Readiness Level (ORL). Multiple in the context of different sectors but mainly driven by the Digitisaiton of services revolution	1. Change readiness is a measure of confidence, backed by defensible data and information. This concept acknowledges that readiness is a perception, and is measured both by judgment and by more structurally sound data (subjective and objective observation). 2. Change readiness, like change agility, considers three key drivers that impact readiness (Combe, 2014a): • Cultural readiness—the degree of alignment between cultural norms and the proposed change. • Commitment readiness—the degree of resolve and ability of the organization, through its leaders at all levels, to see the change through to successful and sustainable completion within the organization's overall strategic agenda. • Capacity readiness—the degree to which the organization is able to bring supportive work processes, historical knowledge and experience, current knowledge, skills and abilities, and resources to bear to aid in successful implementation and sustainability of the change. 3. Being change ready does not require an organization achieve an ideal state. Change readiness is measured in degrees toward a desired target that will supply sufficient capability that varies in proportion to distance from the goal state. 4. Change readiness takes into account a compilation of multiple viewpoints to assess not only whether various audiences feel confident in making the change, but also to establish root causes of discomfort. 5. Change readiness is carried out through both assessment and decisions/actions based on the assessment. As such, it goes beyond helpful knowledge and assumes action derived from that knowledge.

[137] Gudergen et al 2015. Evaluating the Readiness to Transform towards a product-service system provider by capability maturity modelling approach. Procedia CIRP 30 (2015) 384 – 389
[138] Combe, M., 2014. Change Readiness Capacity

26	Innovation Readiness Levels	University of Cambridge[139]	European company sector	• Technology RL • Market RL • Innovation RL	A tool for considering the innovation lifecycle particularly in terms of the market competition;
27	Organisational sustainability readiness	Barletta et al 2021[140]	Manufacturing Sector	• Manufacturing processes; • Assets; • Materials; • Data-driven decision support; • Information systems; • Organisational competences	Posited on the premise that production and consumption models are still largely unsustainable. Therefore, strong industrial actions are required to move towards safer and cleaner practices respectful of the planetary boundaries. Proposes a novel approach for top and middle management in manufacturing companies to build capabilities for sustainable manufacturing by assessing their organisational sustainability readiness. The proposed model and tool for organisational sustainability readiness are developed based on themes emerging from empirical data collected via interviews and focus groups in six companies.
28	Project Definition Rating Index	Construction Industry Institute [141]	Industrial Projects	• Products • Capacities • Technology • Processes • Process Flow Sheets • Site Location • P&IDs • Site Characteristics Available vs. Required • Market Strategy • Project Objectives Statement	A project management tool that provides a numerical assessment of how well a project is defined and planned. Analysis of effectiveness in predicting project performance to the U.S. construction industry.
29	Scientific Readiness Levels®	European Space Research and Technology Centre[142]	Satellite Earth Observation Programmes	• Scientific Readiness Levels - scale 1 to 9.	A tool for considering the maturity of underlying science in predicating behaviour of feedstock on products.
30	Operational Readiness Reviews	US Department of Energy[143]	Nuclear Generation Power sector	• The relative importance to safety, safeguards, and security; • The magnitude of any hazard involved; • The life cycle stage of a facility; • The programmatic mission of a facility; • The particular characteristics of a facility;	A tool which consider whether a Nuclear plant is ready for active operation from an operability perspective;

[139] Developing the Concept – Innovation Readiness Levels (IRL), Tao Lan, University of Cambridge
[140] Barletta. I., et al 2021. Organisational sustainability readiness: A model and assessment tool for manufacturing companies. Journal of Cleaner Production 284 (2021) 125404
[141] Project Definition Rating Index (PDRI), Construction Industry Institute, RR113-11
[142] ESTEC 2015. Scientific Readiness Levels (SRL) Handbook. EOP-SM/2776 pp22
[143] Planning and conduct of Operational Readiness Reviews (ORR), DOE Standard, DOE-STD-3006-2000

				• The cause and circumstances of the facility shutdown; • Complexity of the weapons-related or research activity; and • Other relevant factors	
31	Business Transformation Readiness Assessment	TOGAF, 2011[144]	Business Model	Used for evaluating and quantifying an organization's readiness to undergo change. Comprised of the Baseline to Target Architectures: (1) Vision; (2) Desire, Willingness and Resolve; (3) Need; (4) Business Case; (5) Funding; (6) Sponsorship and Leadership; (7) Governance; (8) Accountability; (9) Workable Approach and Executable Model; (10) IT Capacity to Execute; (11) Enterprise Capacity to Execute; and (12) Enterprise Ability.	
32	Organizational AI Readiness Factors	Jan Johnk et al., 2021[145]	Businesses ability to adopt AI	• Strategic Alignment; • Resources; • Knowledge; • Culture; • Data	An Interview Study of Organizational AI Readiness Factors with five categories and 58 indices.
33	Legal-Social-Technology Readiness Levels	Bruno et al 2020[146]	Public Services	• Technology RL • Societal RL • Organisational Readiness Level • Legal Readiness Level	Technology Readiness revisited: A proposal for extending the scope of impact assessment of European public services to include legal, organisational and societal (see No. 30 below). Assessed that technology, organisation and society tracked each other and legal did not. Developed 4 axis chart and assess the process for new and existing digital technologies. Proposed adoption of this framework as a public sector innovation policy tool to evaluate the performance of EU funded Research, Development and Innovation projects in the next programming period 2021-2027.
34			Legal Sector	• Legal Readiness Level	
35	Societal Readiness Level	Innovation Fund Denmark, 2018[147]	Innovation Fund	• Societal Readiness Level	Societal Readiness Level (SRL) is a way of assessing the level of societal adaptation of, for instance, a particular social project, a technology, a product, a process, an intervention, or an innovation (whether social or technical) to be integrated into society. If the societal readiness for the social or technical solution is expected to be low, suggestions for a realistic transition towards societal adaptation are required. Naturally, the lower the societal adaptation is, the better the plan for transition must be.
36	End User Readiness Level	Luscinus[148]	Creative Sector	Translation of the Technology Readiness Level for Creative Sector	An End-User Readiness Level model sets expectations within the team and to inform target end-users on where you are and what the next major steps will be. They let everyone have an overview of the journey and how to get to the end, or even just the next phase of the project. It can indicate the current status of the project (at level x) or progress towards a goal (moved from readiness level x to y, expect to go to level x…).

[144] TOGAF, 2011. Business Transformation Readiness Assessment. https://pubs.opengroup.org/architecture/togaf91-doc/arch/chap30.html
[145] Jan Johnk et al., 2021. Ready or Not, AI Comes— An Interview Study of Organizational AI Readiness Factors. Bus Inf Syst Eng 63(1):5–20 (2021)
[146] Bruno et al 2020. Technology Readiness revisited: A proposal for extending the scope of impact assessment of European public services. Electronic Governance (ICEGOV2020), Athens, Greece, March 11-13, 2020, 00 pages.
[147] Innovation Fund Denmark, 2018. Societal Readiness Levels (SRL) defined according to Innovation Fund Denmark
[148] Luscinus 2020. https://www.luscinus.be/2020/02/06/how-ready-is-your-idea-the-end-user-readiness-level/

37	Green bonds shades of green	CICERO's[149]	Bond Markets	Shades of Green, an assessment framework for green bond investments • Dark Green Bonds allocated to solutions aligned to climate resilient future • Medium Green Bonds representing steps to a long-term climate resilient future but are not there yet • Light Green - environmentally friendly but not aligned to climate resilient future.	Independent, research-based evaluations of green bond investment frameworks to determine their environmental robustness. Our Second Opinions includes a green shading to show how well a green bond aligns with a low-carbon climate resilient future. Our mission is to shift the bond market towards greener investments and improved transparency without creating undue transaction costs for the financial sector.
38.	Carbon Capture and Storage Readiness Index	Global Carbon Capture & Storage Institute 2018[150]	Carbon Capture and Storage Sector	• Inherent CCS interest • Policy developments • Legal and regulatory frameworks • Geological CO2 storage development.	Collectively, these indicators establish the CCS Readiness Index (CCS-RI). The 2018 CCS-RI examines over 50 countries using 70 discrete criteria and enables a comparative assessment of countries globally.

[149] CICERO 2020. Shades of Green. www.cicero.green
[150] Global Carbon Capture & Storage Institute 2018. Is the world ready for Carbon Capture and Storage?

Appendix 4 - Systemic findings from the assessment of successful technology roll out analogues which provide insight for CCUS scaling[151]

The report also concludes that if CCS is to be a low carbon option for the UK in future, comprehensive policy support is required now to reduce the uncertainties we have identified. In particular, the re-launched demonstration programme needs to yield firm commitments to build several projects as soon as possible. Even if such progress is made, there will be difficult choices for government and other decision makers. Our research has highlighted four areas where such choices need to be made:

1. Keeping options open or closing them down? Whilst strong policy signals and support are required for CCS, there are also risks associated with accelerated innovation and deployment. It is tempting to focus resources on one technological variety early on as the French government did with the PWR for its nuclear programme. This may help to speed up development, but comes with increased risks of picking inferior technology. It is too early for government and industry to close down on a particular variant of CCS technology. Several substantial demonstration projects are needed, for example so that uncertainties associated with scaling up and system integration can be tackled.

2. Which public policy incentives for CCS demonstration and deployment? A menu of options is available for public policy support of CCS technologies. A regulatory approach will only work if technologies are sufficiently well developed and the additional costs can be passed on to consumers. CCS technologies are not yet at this stage. In the meantime, the government is right to emphasise the need for demonstrations. Public finance for these demonstrations should be designed to maximise performance rather than novelty. Since not all demonstrations are likely to perform as expected, systematic learning and evaluation by government is also essential.

3. CCS deployment as a marathon, not a sprint. [The]…historical case studies show that developing new energy technologies can take a long time. Their costs do not necessarily fall from the first day they are deployed. Whilst learning can bring costs down, costs can rise for several years first as technologies are scaled up. Whilst this requires some patience, it is therefore important to monitor progress carefully to inform decisions on whether to continue with public funding – or, if there is little sign of positive progress over a prolonged period of time, when to divert resources to other options.

4. Dealing with storage liabilities. Our case study of UK nuclear waste management policy has highlighted how complex liability arrangements for CO_2 storage could be. For CCS, a balance needs to be struck between limiting liabilities for investors (so that they will be able to invest in full scale CCS plants) and protecting the interests of future taxpayers (who should not be un-necessarily exposed to liabilities). Agreements are therefore needed about how liabilities should be divided, when a privately run storage site should revert back to the State, what arrangements are needed to fund potential liabilities, and what insurance site operators may require. The nuclear experience suggests that an independently managed fund may be required for carbon storage liabilities.

[151] Watson, J (ed.) et al. 2012, Carbon Capture and Storage: Realising the Potential? UK Energy Research Centre

Appendix 5 - CCUS Deployment Activity and Patterns

Appendix 3 extracts excerpts from the CCS Global Status Report[152] showing:

- A world map of CCUS facilities at various stages of development to allow *Deployment activity relevant to CCUS* - What are actors doing relative to that which is needed to establish and scale CCUS in the three case study sectors - to be elicited;
- The diversity of CCUS projects by sector and scale in scale; and
- The rise in the development of CCUS networks whereby capture projects share transport and storage infrastructure to elicit *CCUS actors patterns of behaviour* - What trends are the CCUS ecosystem of actors taking over time regarding possible net zero futures and CCUS deployment.

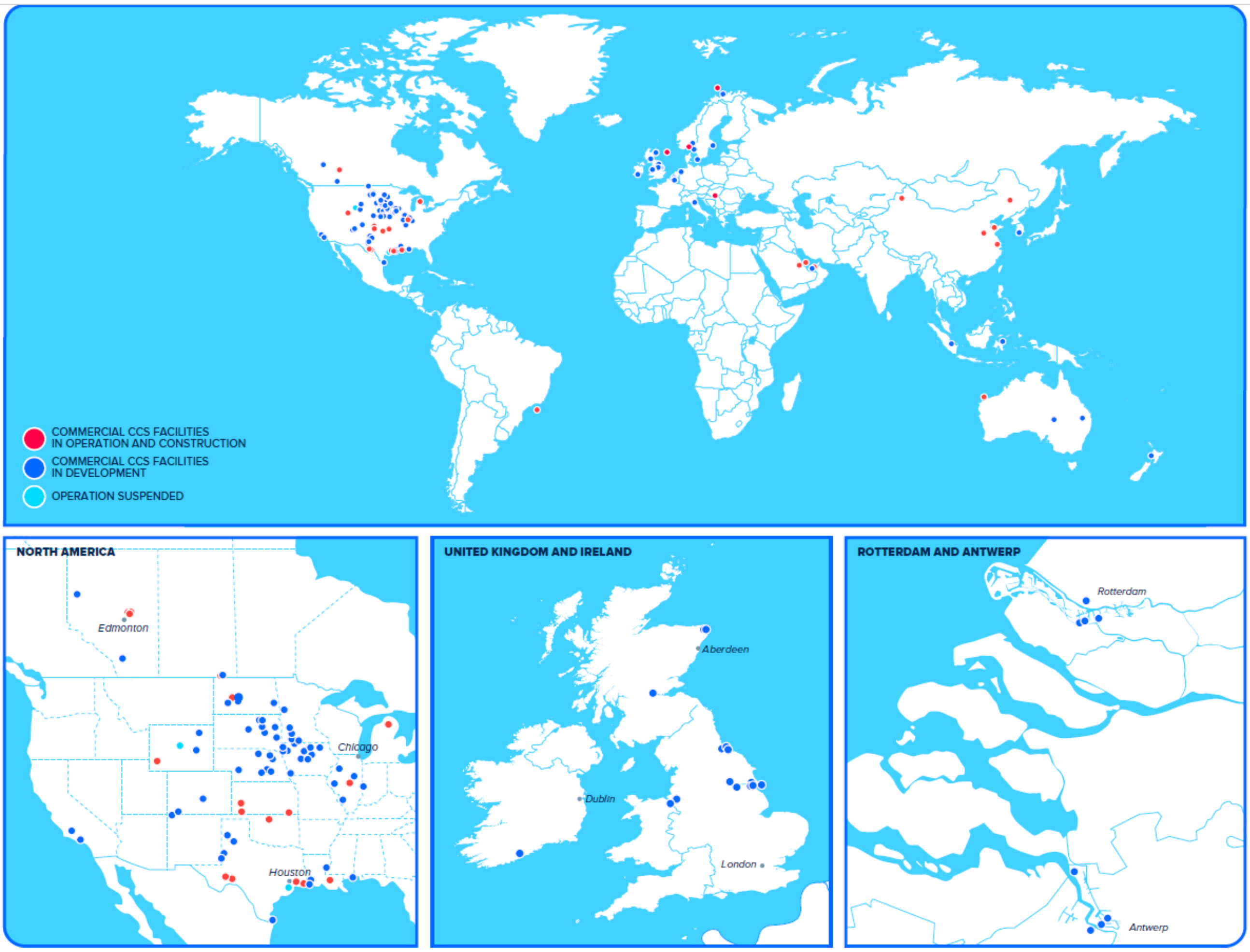


Figure A5.1: A world map of CCUS facilities at various stages of development

[152] Global CCS Institute 2021. Global Status of CCS 2021 - pp43

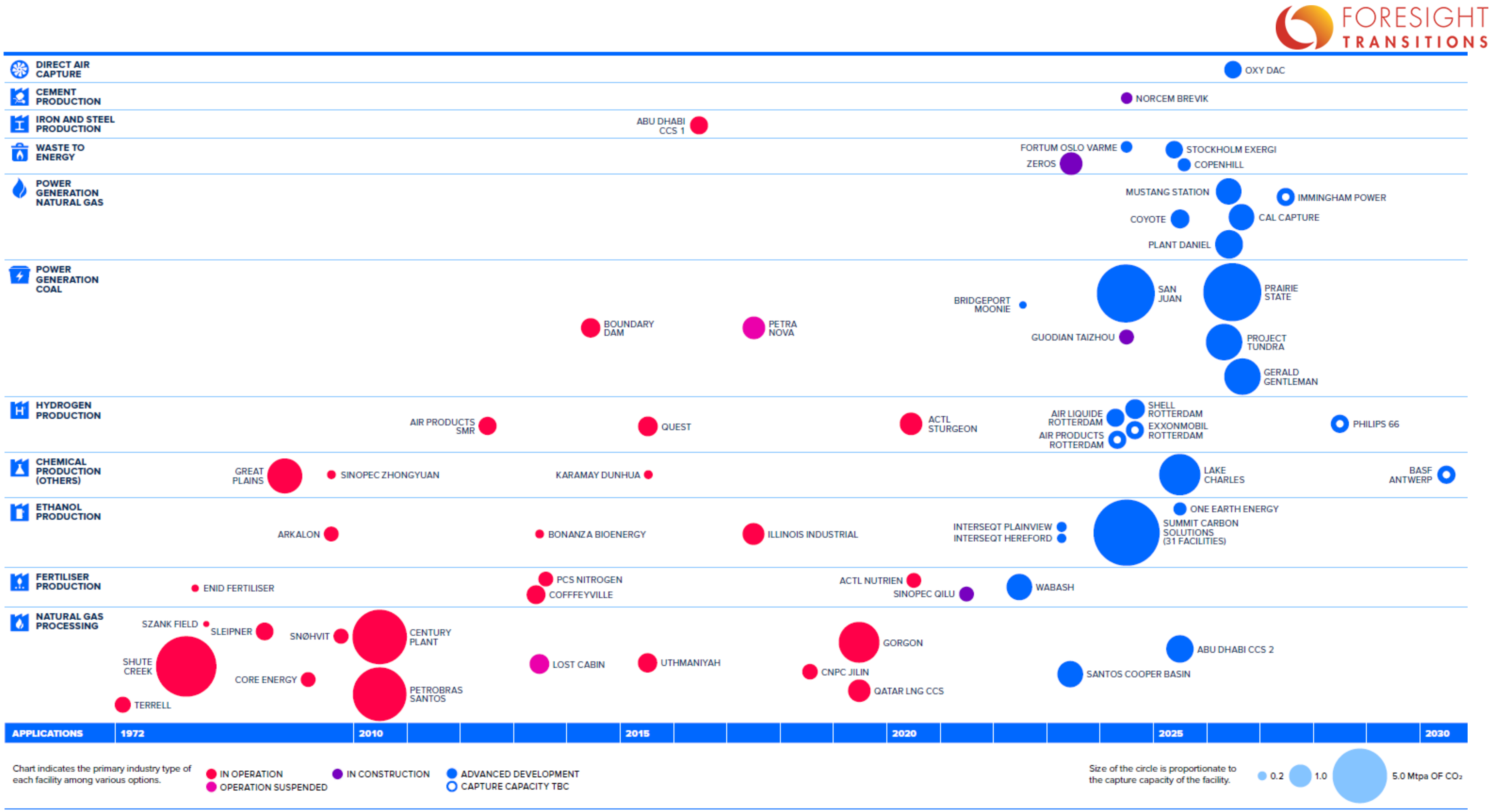
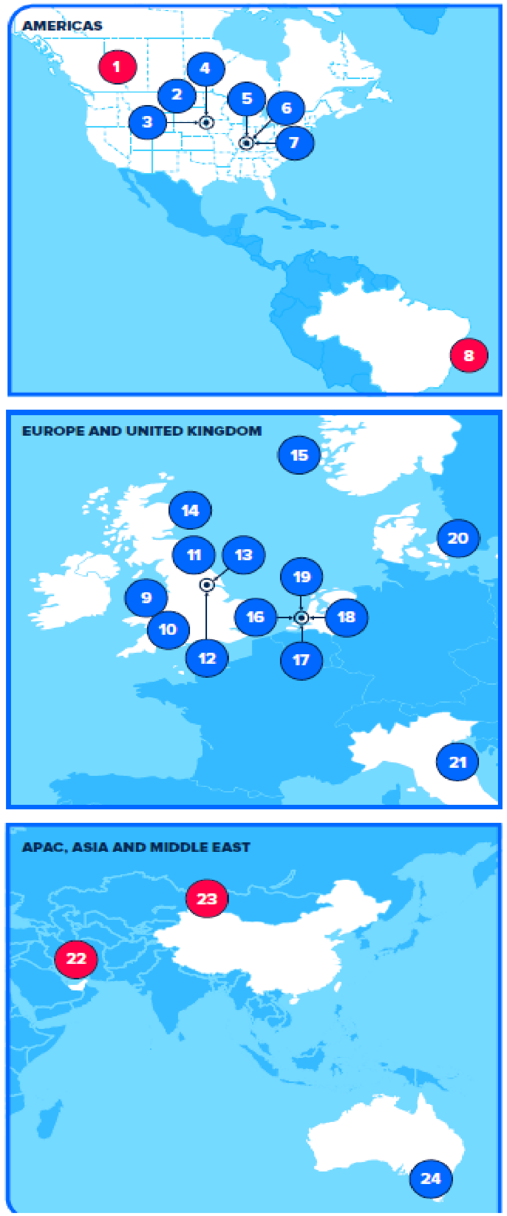


Figure A5.2: Diversity of CCUS projects by sector and scale in scale



No. / Status	FACILITY	CAPACITY (Mtpa)	SECTOR: COAL FIRED POWER	NATURAL GAS POWER	NATURAL GAS PROCESSING	FERTILISER PRODUCTION	HYDROGEN PRODUCTION	IRON AND STEEL PRODUCTION	ALUMINIUM PRODUCTION	CHEMICAL AND PETROCHEMICAL PRODUCTION	CEMENT PRODUCTION	OIL REFINING	ETHANOL PRODUCTION	WASTE INCINERATION	BIOMASS POWER	DIRECT AIR CAPTURE	TRANSPORT: PIPELINE	SHIP	ROAD	DIRECT INJECTION	STORAGE: DEEP SALINE FORMATIONS	ENHANCED OIL RECOVERY	DEPLETED OIL AND GAS RESERVOIRS	VARIOUS OPTIONS CONSIDERED
1 (In operation)	ACTL	1.7 - 14.6				●	●			●							●					●		
2 (Advanced development)	North Dakota Carbonsafe	3.0 - 17.0						●									●							●
3 (Advanced development)	Integrated Mid-Continent Stacked Carbon Storage Hub	1.9 - 19.4	●								●		●				●							●
4 (Advanced development)	Summit Carbon Solutions	7.9											●				●				●			
5 (Advanced development)	CarbonSafe Illinois	2.0 - 15.0	●										●				●							●
6 (Advanced development)	Illinois Storage Corridor	6.5	●										●				●				●			
7 (Advanced development)	Wabash CarbonSafe	1.5 - 18	●	●						●	●				●					●				●
8 (In operation)	Petrobras Santos Basin	3.0			●															●		●		
9 (Advanced development)	HyNet North West	4.5 - 10.0				●	●				●						●				●			
10 (Advanced development)	South Wales Cluster	9.0		●			●			●		●					●	●			●			
11 (Advanced development)	Net Zero Teesside	0.8 - 6.0		●		●		●		●							●				●			
12 (Advanced development)	Humber Zero	8.0		●			●										●				●			
13 (Advanced development)	Zero Carbon Humber	Up to 18.3					●	●		●	●		●				●				●			
14 (Advanced development)	Acorn	5.0 - 10.0		●	●		●									●	●				●			
15 (Advanced development)	Langskip	1.5 - 5.0									●			●			●	●			●			
16 (Advanced development)	Antwerp@C	9.0					●			●		●					●				●			
17 (Advanced development)	Porthos	2.0 - 5.0					●			●							●						●	
18 (Advanced development)	Athos	1.0 - 6.0					●	●		●				●			●							●
19 (Advanced development)	Greensand	3.5									●			●			●	●					●	
20 (Advanced development)	C4 Copenhagen	3.0		●										●			●				●			
21 (Advanced development)	Ravenna Hub	Up to 4.0		●	●		●										●						●	
22 (In operation)	Abu Dhabi Cluster	2.7 - 5.0			●		●	●									●					●		
23 (In operation)	Xinjiang Junggar	0.2 - 3.0	●				●			●							●		●			●		
24 (Advanced development)	CarbonNet	2.0 - 5.0			●	●	●							●		●	●				●			
(Early development)	Alberta Carbon Grid	More than 20.0	●	●						●		●					●				●			
(Early development)	Barents Blue	1.8					●			●								●			●			
(Early development)	Dartagnan	10.0						●	●								●	●						
(Early development)	CarbonConnectDelta	6.5						●		●							●	●			●	●	●	●
(Early development)	Houston Ship Channel CCS Innovation Zone	Up to 100.0								●		●												●
(Early development)	Aramis	More than 20.0					●	●		●		●		●			●	●			●			
(Early development)	Edmonton Hub	10		●			●			●	●	●					●				●			
(Early development)	Louisiana Hub	5.0 - 10.0					●	●		●		●	●				●				●			

● IN OPERATION ● ADVANCED DEVELOPMENT ● EARLY DEVELOPMENT

FIGURE 10 CCS NETWORKS AROUND THE WORLD

Figure A5.3: Rise of CCUS Networks around the World

Appendix 6: Stakeholder perspectives - barriers to CCUS deployment, mental models and metrics

Table A6.1: Stakeholder perspectives on CCUS requirements to realise readiness for scaling and bankability from interviews and workshops

Geels, Level		***Stakeholder perspectives on key challenges to realise readiness for scaling and bankability***	
Politics	***Societal Capacity***	• *Visions and Societal Realisation of Value*	• *"Recognition around the societal value that is being generated by CCUS."* • *"Societal narrative - role of CCUS in generating jobs, value etc. [£1 invested potentially generate £5 GVA]"* • *"The GtCO$_2$ scale at which CCUS is developed in mitigation modelling could be too be leap for society to find politically acceptable. This places pressure on transformational policies, too large leaps in scale and the baking in of commercial risk. Perhaps the narrative needs to be more nuanced and evolve incrementally".* • *"Is the vision for CCUS appropriate?"* • *"Permitting can be a real barrier and an entire project can be held back by an individual."* • *"Renewables - producing something that we want vs's CCUS is storing something that we don't want. Who pays and where is the money coming from?"*
		• *Tainted legacy association with fossil fuel incumbents.*	• *"Public acceptance - people do not want to see the Oil and Gas Sector profiting from CCUS, especially as this is seen as them cleaning up the mess that they created."* • *"It is not about deploying CCUS. It is about the development of low carbon products. This perspective is important as it makes the deployment of CCUS a global opportunity and broadens the narrative appeal e.g. DAC and the premium for cement which would be twice conventional cement."* • *"Blanket CCS government support policy can lead to building CCS where it is cheaper (higher concentration), but not necessarily where it's crucial to do so. e.g. we don't want to see CCS on coal power plant (they need to be decommissioned and replaced with zero carbon alternatives), but we will have to see CCS on cement where there is no zero-carbon alternative. Also, any CCS government subsidies are yet again socialising the costs of decarbonisation while privatising the profits. Therefore, any oil company, utility, chemical etc which will be taking government money for CCS - is not paying for the pollution it produces. This has ethical and societally acceptability connotations."*
	Governance, Regulatory and Finance	• *Political Economy and Policy Maker Institutional Capacity*	• *"There are a lack of political champions around CCUS"* • *"There is a need for longer term thinking - beyond 4 year political cycles"* • *"There is a need to address the political economy around CCUS….we need to get rid of the dogma"* • *"[Government has got to] …get the market going and the industry will do the rest." As it did with the Liquid Natural Gas Sector - See Box 5.2.* • *"The public sector should take on the early risks which can eventually be transferred to the private sector. Govts will have to carry some long-term residual risks."* • *"EU governments are worried about overpaying but ensure targeted incentives which involve protracted processes. US uses untargeted incentives and is less concerned about overpaying"* • *"Governments belief that what they invest will result in national economic value capture is miss-placed"[153].*

[153] Economist. 16th January 2021. Molecules, missions and money. Economists are convinced that governments can increase economic growth by spending more on research and development. Are they right? `*David Edgerton of King's College London, Britain's foremost historian of technology, argues that "Only in techno-nationalist fantasies…does national invention drive national economic growth. In the real world, global*

			• *"There will be division in terms of the extent of the role of government. In Transport and Storage they will need to be more involved whereas in the capture less so."*
		• *Markets design*	• *"Governments are creating risks from the way that their regulatory systems are set up i.e. creating cliff-edge risk rather than incremental incentives e.g. specifications for % of capture which are required to be met to qualify for an incentive."* • *"There is a need for transparency in policy design to give incentives to developers. For example, in the introduction of 45Q in the US had a 75 MtCO_2 cap. Actors therefore didn't know how long they would be able to rely on the tax credit."* • *"Policies need to be targeted and durable to remove volatility and ensure that the value stack adds up for first movers."*
		• *Finance*	• *"With this level of contractual……and price uncertainty, ….CCUS… is not financeable."* • *"Even though the strike price for wind is <£40 investors still want the CfD as it provides certainty"* • *"…..we could have had the £140 CfD [CCUS] project seven years ago. We could be near as to the £40 project [as for wind. As things stand because of this] ……we haven't cracked the commercial model"* • *"Cost of alternatives for least cost abatement which are much cheaper than CCUS"* • *"The Finance sector needs to better understand CCUS across the whole ecosystem"* • *"not enough projects have been undertaken to understand the risk."* • *"To issue debt, the company/project needs to generate revenues. To generate revenues, they need to sell the product they are producing (here, CO_2). Given the nature of technology, it can only function in the right policy environment."*
Commerce	***Sector System Innovation***	• *Knowledge sharing*	• *"There is too much privatisation of knowledge"* • *"The gap in the transfer of scientific knowledge into policy is substantive"* • *There is a need for the….."Co-ordination of international efforts with specialisation within national jurisdictions and sharing of learnings"* • *"There is no incentive to share data. Participants appear to be seeking to gain commercial advantage"* • *"Information sharing is important. It is not as easy as it sounds due to sensitivity and legal rights of commercial actors. It is done at the moment but very informally."* • *"Who do you go to undertake due diligence?"* • *"Need for long term data to get the true cost of CCUS."*
		• *Incentives for the individual actors*	• *"Private sector incentivisation and commercialisation is the missing link."* • *"Need for a sufficiently high and stable carbon price to compete with unabated fossil fuel".* • *"Though Net Zero Nationally Determined Commitments have been established for countries - their policies are insufficient to realise net zero but corporations have established net zero pledges so they are in a no-mans land at the moment as corporate reputation is at stake. However, the lack of definition about what net zero is and the mosaic of initiatives (SBTi, CDP etc) and how they treat Scope 3 emissions is retarding their ability to act."* • *"Economics comes into play for some industrial sectors as the amount of investment which is required to decarbonize the industrial clusters can represent as big investment as re-establishing the sector in another geographical location e.g. chemicals sector in UK."*

innovation leads to national growth, and national innovation leads to global growth." At most times and places, most of the technology which creates growth is imported from elsewhere, not made at home. In a globalised world, investing in domestic R&D will never be purely to a country's own advantage; it will help others too, willy-nilly.'

	Sector Business Model	• *Risk mitigation - commercial, developer and finance risk* • *Path dependencies and Costs*	• *"the main barriers are all related to commercial risk"* • *"CCUS projects need over £400 M of capital. Only a handful of actors who have the balance sheet to manage and deliver an Engineering, Procurement and Construction contract…… See what happened to PFI contracts when too much risk was transferred by govt [Carillion went bust]"* • *"There is insufficient broad policy / value stack to generate a market driver and price signal to provide the financial certainty though 45Q has to some extent addressed this in the US - only 12 years"* • *"How can business make money out of providing CCUS services?"* • *"Need to work on projects which can be undertaken relatively easily and then at least establish one project from which actors can learn from with a view to adding greater levels of complexity where circumstances are less favourable."* • *"The decision making of individuals and organizational behaviour in the context of the uncertainties and risk is problematical and little understood."*
Technology	***System and Service Readiness***	• *Too big technological leaps introducing more risk*	• *"Barriers are: (i) lack of funding - as a function of a lack of policy to subsidise the technology; (ii) Cost; and (iii) Policy."* • *"The scale at which technologies can be considered bankable is highly varied e.g. Plant 50% scale running for a year is needed but for Amine testing and reliability 10t/day for a year is all that is required e.g. Alum Cycle Case Study - Le Port and Kemper County."* • *"Need to understand what represents a reasonable scale to consider technical robustness."*
	TRL	• *Technology*	• *"Technology is not the risk though there is room for improvement."*

Table A6.2: Different actors in the CCUS sectors mental models and perspectives.

Developers *versus* policy makers - ***What TRL means and how it impacts public innovation funding in CCS technologies***. CCUS developers need public research grants for CCUS technologies at TRL9 - as technologies still undergo innovation beyond TRL9. ***Whereas*** policy makers are inclined to remove grant funding once technologies reach TRL 9.
Finance / Investors *versus* Developers - *How commercial risk will be addressed.* Finance sector wants stability of CCUS and value chain design and a `cookie cutter' approach so that risk is completely taken out of the system - developers will have done all the learning based on the FOAK and early deployment as took place with Offshore Wind (OSW) design. ***Whereas*** developers are acutely aware that CCUS is a context specific technology predicated on the specific industrial ecosystem to which the technology value chain is being developed. You are very unlikely to get technology risk to be removed from one project to the next and the stability demanded by investors. Rather, developers advocate the need for regulatory stability so that the ability to reduce as many aspects of risk when technologies are applied in different geographical jurisdictions is an important priority. ***Note.*** In reality, investors are happy to adopt some context specificity risk as exists in different OSW farms locations each having their unique aspects.
CCUS Developers *versus* Policy Makers - *Need for a policy maturity and stability*. Developers would like policy stability to ensure that technology risk is reduced when CCUS is applied in different contexts. ***Whereas*** policy makers consider that disruptive innovation is an important requirement to attain timely net zero targets. This can lead to too much risk as has been manifest in the scale-up increments for CCUS technologies - see Box 5.3, below.
Government *versus* Investors - *Insufficient policy to develop a robust business case for CCUS across the range of sectors that need to develop CCUS projects*. The CCUS policy needs to account for the varying levels of risk appetite of industrial actors and sectors looking to adopt CCUS and investors. Government feels that there is sufficient policy to allow CCUS to be established and scale. ***Whereas***, though some sectors have the risk appetite over short timeframes such as the 12 year horizon for 45Q (e.g. Oil and Gas sector. Other sectors such as cement and steel will not have that risk tolerance. This situation is compounded as some sector work in nationally `captured markets' e.g. the electricity sector whilst others operate in globalised markets subject to international competition e.g. the cement sector - where leakage can occur as a function of national differences in decarbonisation policies.
Investors *versus* developers - *need for a transparent assessment of technology readiness and bankability*. Once a first mover finance actor has successfully undertaken a CCUS project then other financial sector actors will have a tendency to follow quickly. ***Whereas*** developers have struggled with transparency as a function of commercial sensitivities around early CCUS technology development. How does the finance sector know what it is financing?
Developers *versus* government/societal - *means-end perspectives.* Policy makers see CCUS technologies and their associated value chains as a requirement to decarbonise heavy industry. ***Whereas*** developers would like CCUS technologies to be considered as providing net zero services to society to enable broader and more compelling narratives to be cultivated around CCUS development across the economy and therefore societal audiences.
Developers *versus* civil society - *the role of Oil and Gas companies in the establishment and scaling of CCUS.* Developers see the role of Oil and Gas companies as being integral to the establishment and scaling of CCUS. It is where the critical mass of resources and expertise is for the effective establishment and scaling of CCUS. ***Whereas*** society sees that the Oil and Gas sector as partners of dubious reliability which are being granted public funds from general taxation to clear up the mess that they created.

Table A6.3: Summary of stakeholder perspectives and nomination of indices and metrics to assess extent of commercial readiness of different aspects of CCUS.

Stakeholder	***Suggested metrics***[154]
Finance Perspective	• "Cashflow Certainty" if I deliver will my debt and equity get paid?'" • "Credit Ratings" • "Credit Structure"
UK Developer Perspective	• "Maturity of revenue certainty" • "Risk' and `Reward"
Anglo-Dutch IOC Perspective	• "Social readiness"
N. Am Developer Perspective	• "Extent of government support for scaling" • "Knowledge availability"
Anglo IOC Perspective	• "TRL is useful - for the predictability of the technology system and allows warrantees to be established which reduces risk for operators once technologies are installed" • "there is a lot of work taking place to calibrate risk e.g. `non-permanence risk' for $CO_2$ credits; assessing `additionality' and Monitoring, Reporting and Verification for capture of CO2 from Enhanced Oil Recovery[155]. There is also an ISO for CCS[156].
SOE Chinese perspective	• "System readiness and value chain readiness" • "Regulation Readiness and Confidence"
CCUS developer (UK)	Understanding policy readiness is very important. For example, you could have a readiness level for active (required to establish and scale a sector by addressing commercial barriers Broad policy intention by government) and enduring (required to maintain a sector without government subsidy and the sector can be left to the free market) policy - as follows: ***Active Policy Readiness Level*** 1. Is there a broad business model for capture and for transport and storage? 2. Shape of business model agreed and relevant policy 3. Detailed business model defined 4. Government funding is agreed 5. Early project experience 6. Ongoing project experience ***Enduring Policy Readiness Level*** As per 1 to 7 less step 5. To a situation whereby the market does not need support
Former National Department CCUS development. Did not recommend any metrics/indices rather suggested a process to better systemise the ability for actors to be aware of the state of CCUS sector development in different geographical locations.	
CCS Academic.	• Advocated the use of ARENA's Commercial Readiness Index
National Department CCUS development	• "Societal readiness levels" • "How closely tied a technology sector is to the fossil fuel sector" • "Job creation and economic benefits - to get through permitting process" • "Regulatory readiness level e.g. underground injection requirements only just realised in US and stability"
Government	• "Weighted Average Cost of Capital" (WACC)

[154] The study makes the distinction between ***generic indices*** such as those used in the Australian Renewable Energy Associations Commercial Readiness Indices e.g. Stakeholder, Regulatory, Finance Readiness etc which are assessed by specialists and translated into these indices and ***metrics*** which are associated with different aspects of CCUS development e.g. Geological Storage Capacity, Weighted Average Cost of Capital etc which do not need assessment by specialists to be translated into an indices and are well used amongst communities.

[155] American Carbon Registry

[156] https://www.iso.org/obp/ui/#iso:std:iso:tr:27915:ed-1:v1:en

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Pure Offices, Cheltenham Office Park, Hatherley Lane,
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911

mail@ieaghg.org
www.ieaghg.org