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# Business Models for Carbon Capture, Utilization and Storage Technologies in the Steel Sector: A Qualitative Multi-Method Study

**Hasan Muslemani [1,*], Xi Liang [1], Katharina Kaesehage [1] and Jeffrey Wilson [2]**

[1] University of Edinburgh Business School, 29 Buccleuch Place, Edinburgh EH8 9JS, UK; Xi.Liang@ed.ac.uk (X.L.); Kathi.Kaesehage@ed.ac.uk (K.K.)
[2] School of Environment, Enterprise and Development, University of Waterloo, Waterloo, ON N2L 3G1, Canada; Jeffrey.Wilson@uwaterloo.ca
* Correspondence: H.Muslemani@ed.ac.uk

Received: 15 April 2020; Accepted: 7 May 2020; Published: 13 May 2020




**Abstract:** Carbon capture, utilization, and storage (CCUS) is a combination of technologies capable of achieving large-scale reductions in carbon dioxide emissions across a variety of industries. Its application to date has however been mostly limited to the power sector, despite emissions from other industrial sectors accounting for around 30% of global anthropogenic $CO_2$ emissions. This paper explores the challenges of and requirements for implementing CCUS in non-power industrial sectors in general, and in the steel sector in particular, to identify drivers for the technology's commercialization. To do so we first conducted a comprehensive literature review of business models of existing large-scale CCUS projects. We then collected primary qualitative data through a survey questionnaire and semi-structured interviews with global CCUS experts from industry, academia, government, and consultancies. Our results reveal that the revenue model is the most critical element to building successful CCUS business models, around which the following elements are structured: funding sources, capital & ownership structure, and risk management/allocation. One promising mechanism to subsidize the additional costs associated with the introduction of CCUS to industry is the creation of a 'low-carbon product market', while the creation of clear risk-allocation systems along the full CCUS chain is particularly highlighted. The application of CCUS as an enabling emission reduction technology is further shown to be a factor of consumer and shareholder pressures, pressing environmental standards, ethical resourcing, resource efficiency, and first-mover advantages in an emerging market. This paper addresses the knowledge gap which exists in identifying viable CCUS business models in the industrial sector which, with the exception of a few industry reports, remains poorly explored in the academic literature.

**Keywords:** carbon capture; utilization and storage; business model; steel sector; decarbonization

## 1. Introduction

Climate change, driven by anthropogenic greenhouse gas (GHG) emissions, remains one of the most pressing global challenges. The 2015 Paris Agreement set out a global action plan to limit global warming to well below 2 °C above pre-industrial levels, and to pursue best efforts to limit this increase to 1.5 °C [1]. To achieve this target, the agreement emphasized the need for global GHG emissions to peak as soon as possible and to seek rapid reductions thereafter so as to achieve a balance between emissions and removals by the second half of the century [2].

Carbon capture, utilization and storage (CCUS) has been identified as a vital large-scale option for mitigating emissions from the power and the industrial sectors, while also playing a crucial role in

maintaining security of supply [3]. The International Energy Agency (IEA)'s Sustainable Development Scenario (SDS) [4] estimates that CCUS will contribute to around 9% of global cumulative emissions reductions between now and 2050. The business case for, and the value brought about by, early deployment of CCUS has been highlighted in terms of the significant cost reductions that it brings about in overall decarbonization and towards society over time. The IEA [5] further estimates that the exclusion of CCS as a carbon mitigation tool for the power sector would increase costs of emissions mitigation by around $3.5 trillion by 2050—a 70% increase in mitigation costs if alternatives, including renewables, were instead employed over that time period. Moreover, the International Panel on Climate Change (IPCC) [6] reports that it would be 138% more expensive to decarbonize energy-intensive sectors without CCUS in the mix.

The 'utilization' of $CO_2$ here refers to the act of industrially or agriculturally utilizing $CO_2$ for its physical, chemical or biological features, for the purpose of producing products of commercial value, which may or may not reduce emissions compared to business-as-usual (BAU) products, depending on the relative carbon intensity between captured and BAU carbon dioxide. By comparison, 'storage' of $CO_2$ generally has the sole objective of climate change mitigation, as the storage of $CO_2$ typically has no commercial value (unless intentionally subsidized). $CO_2$ utilization has been suggested as a means of enhancing the financial viability of traditional CCS projects, and the term CCUS has been promoted by industry bodies such as the Carbon Sequestration Leadership Forum since at least 2011 [7]. In this study, the term 'CCS' is used to refer to $CO_2$ capture and storage value chains that do not include any $CO_2$ utilization, while the term 'CCUS' refers to value chains that may involve utilization and/or storage in various combinations.

Despite its promising potential, CCUS remains a pre-commercial technology in most industries and still lacks a viable business model to incentivize the private sector to invest in the required technology and infrastructure. This is especially true for industrial CCUS (i.e., CCUS deployed in the industrial sector as opposed to the power sector) as the relevant technological understanding predominantly exists in other sectors such power generation, natural gas processing and hydrogen production ($CO_2$ capture), and oil and gas sectors ($CO_2$ storage), with main opportunities for capturing carbon lying in the power sector.

While fossil fuels are the primary source of energy and raw material supply for the power, steel, cement, and petrochemical industries, direct and indirect emissions from the non-power industrial sector accounted for 14.5 billion tonnes of carbon dioxide ($tCO_2$) in 2015, equivalent to 30% of total anthropogenic $CO_2$ emissions [8]. As one of the largest industrial subsectors by overall emissions, second only to cement, the iron/steel industry remains heavily reliant on fossil fuel consumption—especially coal consumption—and emits significant amounts of $CO_2$ into the atmosphere [9]. According to the World Steel Association [10], the steel industry today contributes between 7% and 9% of direct emissions from the global use of fossil fuels.

A range of options exist to reduce the carbon footprint of steel production, including fuel switching, energy efficiency improvements, reducing overall output and adopting less energy-demanding production routes [11,12]. However, multiple studies [13–15] have concluded that the scope for reducing emissions via these measures remains limited, and that 'breakthrough' technologies such as CCUS are indispensable for meeting international $CO_2$ emission reduction objectives [3]. In order to allow CCUS to realize its decarbonization potential, both robust business models and reliable financial support mechanisms are required to incentivize early projects and drive cost and risk reductions. Nevertheless, there is a general consensus that the lack of established business models is first among several fundamental reasons hindering the introduction of CCUS applications within major industries such as steel and cement [16–21].

Despite its evident importance, research on CCUS business models, both in the power and industrial sectors (and especially in the steel sector), remains very limited [22]. A knowledge gap exists in identifying the most important elements driving success in industrial CCUS business models, and it was not until recently (summer 2019) that the UK Government's CCUS Advisory Group (CAG) issued a

report that explores business models which allow the rollout of CCUS in different industries including steel [23]. This was complemented by an industry stakeholder consultation by the UK Department for Business, Energy and Industrial Strategy (BEIS) (ending September 2019) [24].

To address the aforementioned gap, this paper explores the theoretical underpinnings of successful CCUS business models. This is discussed in the context of innovation in business model formulation for low-carbon technologies whose primary objective is achieving sustainability. The study characterizes the elements of a successful CCUS business model, identifies market failures of previous CCUS applications which offer learning opportunities, and outlines a range of challenges to be overcome in order to build a commercial case for private sector investments in CCUS in the steel sector. This is based on a comprehensive review of the academic literature, complemented by consultations (through a survey and interviews) with key stakeholders with practical experience with CCUS projects.

The paper is structured as follows: Section 2 presents an overview of the status and potential of available technologies to enhance energy efficiency and reduce emissions in the steel sector, followed by a justification of the indispensability of CCUS as an emission-reducing technology in the sector. Section 3 reviews the theory behind formulating business models—and innovation in business models—in the context of sustainable practices as presented in the academic literature, where CCUS is subsequently conceptualized as a critical enabling combination of technologies towards achieving sustainability. Section 4 outlines the multi-qualitative methods employed in this study. Sections 5 and 6 present and discuss results, respectively, while Section 6 concludes and highlights the contribution of this work, its limitations, and scope for further research.

## 2. Background

The IEA [25] estimated that, in 2012, the steel industry contributed approximately 22% of total industrial energy use and 31% of industrial direct emissions, making it the second-largest industrial sector globally (after cement) in terms of $CO_2$ emissions. Expected emissions from the largest integrated iron/steel blast furnace plants are in the range of 5–8 Mt$CO_2$/year [14], putting them amongst the largest point sources of $CO_2$ emissions in the world [26]. The scale of the sector's emissions makes it essential for the sector to contribute to achieving significant emission reductions in line with Paris Agreement objectives.

Efforts to reduce $CO_2$ emissions from the steel sector have been made in two principal directions: some aim to accelerate the uptake of already-existing energy efficiency measures, i.e., what is dubbed 'best available technologies/techniques (BATs)', while the other lies in identifying 'breakthrough' innovative emission reduction technologies.

Energy efficiency in steel production varies significantly based on production route, type of iron ore and coal used as inputs, operation control technology, steel product mix, and material efficiency [14,27,28]. Over the past 20 years, the iron/steel industry has achieved critical efficiency gains with technologies that reduced energy consumption while maintaining a plant's productivity. There is substantial evidence that potential for further efficiency improvement exists in almost all stages of steel production, including both primary and secondary production routes [29–31]. The IEA [30] (pp. 397) estimates that, by applying BATs, the iron/steel industry has the technical potential to reduce its energy consumption by around 20%. A more recent study [15] based on steel production in China, where the emissions intensity of production is much higher than elsewhere [32], estimates that the cumulative potential for emission reductions using a combination of the most applicable abatement options amounts to about 40% of average $CO_2$ emissions per tonne of crude steel produced. Therefore, there is no doubt that a broader use of BATs could significantly reduce energy intensity and $CO_2$ emissions from the steel sector [13,14,29,30].

However, due to thermodynamic limitations, there is only so much improvement that can be achieved in terms of energy efficiency, and therefore, to achieve further emission reductions in line with the Paris Agreement goal of carbon neutrality by the second half of the century, innovative breakthrough technologies will be necessary. Among the portfolio of breakthrough technologies, three

options are in focus globally: blast furnace with CCUS (BF-CCUS), and using low-carbon electricity or hydrogen as alternative reducing agents [33–35]. Of these, the technologies associated with CCUS are likely candidates for early maturity and market penetration as, in contrast with the other two options, the technology has been technically demonstrated at scale but still lacks a viable business model [36]. This is the central challenge that our paper addresses. First, however, we discuss what can be learned from the literature on business models for sustainability in the next section.

## 3. Business Model Theory

According to Hayek's spontaneous order theory [37], business models emerge spontaneously from business activities. Business models influence a firm's possibility of creating and capturing value [38]. Osterwalder & Pigneur [39] define business models as the 'fundamental structures for how companies create, deliver and capture value'. More simply put, a business model defines the problem that a business aims to solve and how it can do so in a profitable manner. Boons and Lüdeke-Freund [40], following Osterwalder [41] and Doganova and Eyquem-Renault [42], identify the following four key components of a generic business model: (1) a value proposition (the value embedded in the product/service offered by the firm); (2) supply chain relationships (how they are structured and managed); (3) a customer interface (how these relationships are structured and managed); and a financial model which aggregates the costs and benefits of the above, and defines their distribution across relevant stakeholders. Viewed in this way, 'innovation' in business model design does not necessarily entail creating 'new' products or processes, but can also mean changing how a company organizes its supply chain, its relationship with its customers or other stakeholders, or its financial model.

Apart from certain niche applications, CCUS has not, to date, arisen in response to conventional market forces: rather, it represents a special case of business activity where the main driver is broad social concern about a global sustainability challenge (in this case, climate change). A key challenge associated with the concept of sustainability is designing business models that enable industries or firms to capture economic value for themselves *while also delivering social and environmental benefits [43]*. Here, we present an overview of the theoretical underpinnings of business models for sustainability in general, and the literature on CCUS business models in particular.

### *3.1. Business Models for Sustainability*

Neoclassical economic theory asserts that the primary objective of firms is to maximize profits for shareholders [44–46], making social and environmental goals subordinate, if not irrelevant [47]. Over recent decades, however, many commentators have called for moving beyond the concept of the 'organization as an economic entity' [48–50], towards exploring the possibility of creating commercially viable business models that also promote broader social and environmental sustainability [51–54]. This recognizes that, although businesses are a major cause of social and environmental problems in the first place, they have the intellectual, financial, and structural capacity to generate and widely disseminate solutions to existing and emerging sustainability challenges. Without successful diffusion within society, which the private sector (given a viable business model) is powerfully equipped to achieve, such solutions would have little effect [40].

Sustainability is now largely accepted as a significant driver of innovation in firms [55]. A large body of empirical research has explored the influences that lead businesses to shift into more sustainable practices [56–58]. These factors include environmental standards and regulations, a drive to be 'first-movers' or market leaders, shareholder and employee pressure, customer pressure, supply chain pressure, and resource limitations [59–62].

Boons and Lüdeke-Freund [40] explore three 'ideal types' of innovation in business models for sustainability: technological innovation, organizational innovation and social innovation. Due to the nature of CCUS as a collection of technologies, we focus on the former as the relevant ideal type. Within technological innovation, they point out that there are four possible combinations of either new

or existing business models with new or existing technologies. Three of these entail innovation (the fourth being the application of existing technologies under existing business models, or business as usual): (1) an existing technology can be commercialized using a new business model (for example, the US carpet manufacturer Interface shifted from selling carpet as a product to selling floor-covering as a service); (2) an existing business model can employ new technologies (for example, incandescent light bulb manufacturers shifting production to LEDs); or (3) new business models can be used together with new technologies (an example cited by Boons and Lüdeke-Freund is the Israeli-US start-up Better Place, launched in 2007 with the aim to sell battery-charging and switching services for electric cars under a subscription model. Electric vehicle networks by Better Place were implemented in Denmark and Israel, with charging stations produced by Renault-Nissan. Unfortunately, the example also serves to highlight the challenges facing such radical innovations: Better Place filed for bankruptcy in 2013).

### 3.2. CCUS Business Models

Although CCUS involves largely existing individual technologies, and examples exist of large-scale demonstration of these technologies in combination, it is best considered as a 'new' technology, for which there is no existing business model.

The development of CCUS technologies is driven by several of the aforementioned factors. For instance, CCUS has emerged as a critical enabling technology option to mitigate large quantities of $CO_2$ produced by coal-fired plants and other energy-intensive industrial sources [63,64]. It remains the most promising solution to drastically reduce emissions in production processes, where operators are under political pressure to abide by international climate agreements and cut down on their emissions. Secondly, while CCUS ensures that environmental standards and regulations are met in the present, it also ensures resource longevity and an ethical resourcing in the future, as fossil fuels may continue to be used efficiently and sustainably [65]. Thirdly, if performed safely and in a cost-effective manner, CCUS would allow nations to preserve economic and energy securities through a continuous use of these non-renewable fossil fuels over the medium term, while allowing for a smoother transition towards using more sustainable, renewable options over the long term. The reduction in economic costs due to mitigated environmental impacts and avoided climate-related regulations (e.g., carbon tax or requirements to purchase carbon credits), coupled with creating value both for consumers and for society as a whole is described as a 'win-win' situation by Gaziulusoy & Twomey [66].

Fourthly, the development of CCUS is driven by shareholder and consumer pressures in a carbon-stressed world [67–69], one which is witnessing a shift in tendency towards consuming green products such as renewable energies, and towards divesting from environmentally-damaging business activities. Fifthly, with limitations in renewable energy resources, exacerbated by their intermittent nature, CCUS emerges as a sustainable complement that ensures economic prosperity and energy security. Finally, the drive to secure a first-mover advantage in a fast-growing field is another factor that should not be underestimated, as governments seek to establish supply chains and create export markets for components of a technology that is expected to be around for decades.

For CCUS, 'value' is captured in the form of emissions avoided and/or economic revenue created through $CO_2$ sales or the creation of low-carbon products. CCUS business models ensure the technology's viability and describe how risks and rewards are allocated. Promising CCUS business models eventually encourage new entrants to the market while providing a competitive advantage to developers. A number of seminal works have explored the evolution of CCUS business models during the 2000 s and identified barriers to commercial deployment [20,21,70–72]. More recent studies [18,73,74] reveal that most of the same barriers are still relevant today. These barriers are presented in the empirical findings of this study, preceded by a description of the methods employed in reviewing the literature.

## 4. Materials and Methods

To address the aforementioned barriers, we apply a qualitative research methodology consisting of first, a literature review, and second, semi-structured interviews and an online questionnaire targeting experts from the CCUS and steel industries. Here, the review of existing literature was used as a base to inform and guide the design of the complementary qualitative research approaches employed.

Studies focusing on stakeholder opinions on CCUS and employing a similar research design include Kainiemi et al. [75], Brunsting et al. [76], and Sala & Oltra [77], to name a few. The three-tiered research approach adopted here allowed for a comprehensive investigation of key issues identified in each preceding step (Figure 1). Ultimately, the most pressing topics identified in the reviewed academic literature (Tier 1) and questionnaire responses (Tier 2) were discussed in-depth with selected interviewees (Tier 3) with expertise in corresponding aspects of CCUS development (i.e., technology, policy, and/or economics).

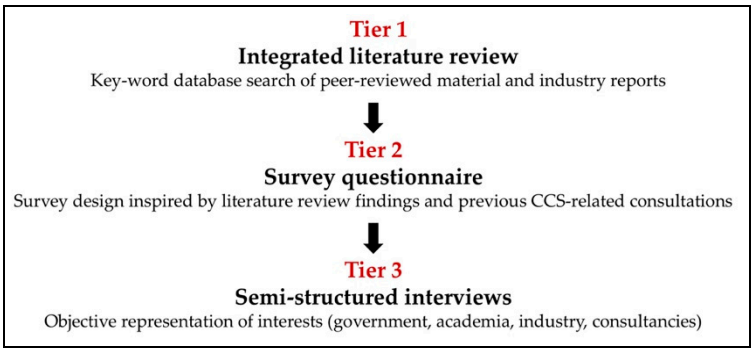



**Figure 1.** Qualitative multi-method research approach.

### *4.1. Review of Relevant Literature*

A comprehensive and integrated literature review on CCUS business models was initially undertaken. An integrated literature review examines and synthesizes knowledge from a variety of sources [78], and is often used for new topics where a number of data sources are needed to formulate new conceptual models [79]. A systematic literature review, in contrast, generally aims for a holistic analysis of the literature in a mature subject, and is often conducted from one knowledge domain's perspective [80]. This integrated review covered peer-reviewed publications, as well as published industry reports from organizations invested in CCUS developments, in both the power and industrial sectors.

The selection of peer-reviewed material was conducted following a structured key-word search, and the publications selected for inclusion in this study's analysis were gathered in three phases. In the first phase, the Web of Science database was used to search for publications using the search strings 'carbon capture and storage business models', and the combination of 'carbon capture and storage' and 'steel' as a topic. Note that, in both search strings, the term 'carbon capture and storage' was used instead of 'carbon capture, utilization and storage' as the results generated using the former were inclusive of the latter, but the opposite was not true. Of the 82 resulting items for the former search and 326 for the latter, duplicates were first eliminated and all publications which were unrelated to business models—or not covering economic, technical, and/or political aspects that are relevant to business modelling—were then eliminated. The remaining publications, 21 and 55 from both searches respectively, were ultimately selected for a narrower and deeper analysis; selected publication types included journals, books (-chapters), conference proceedings, and working publications.

As the vast majority of peer-reviewed papers on CCUS business models are specific to applications within the power sector, in the third phase, abstracts of the selected 76 papers were scanned for information on aspects of CCUS business models that are specifically applicable to non-power industrial sectors, or for information on elements of business models that are potentially transferable

from the power to the industrial sectors. The selected papers were complemented by 9 Chinese studies which are related to CCUS business models, both in power and industry, and which were accessible through China's largest academic literature database, the CNKI (Chinese National Knowledge Infrastructure) database.

After reviewing the business models of global large-scale CCUS projects, data on which are publicly-available, common features amongst the models were identified and elements which differentiate models from one another were characterized. A number of identified barriers and challenges for industrial CCUS were then summarized based on relevance, priority, or those in need of immediate action. A list of possible funding mechanisms was also collated based on their likelihood of supporting industrial CCUS. Business models that were found to be irrelevant or inapplicable to iron/steel CCUS applications, whether due to a limiting political or economic climate or due to the current phase of technology maturity, were eventually eliminated.

### 4.2. Questionnaire Design

The online questionnaire, consisting of 21 identical questions, was subsequently designed based on key challenges identified within the reviewed literature. The questionnaire design complemented past CCUS stakeholder surveys and consultations [68,81–83]. On surveys that investigate the public's perception of CCUS, Malone et al. [67] acknowledged that the lack of knowledge on CCUS can be a formidable barrier to conducting a valid survey of opinions. As a survey questionnaire aims to gauge respondents' opinions, it implies that respondents have enough knowledge to have formed an opinion in the first place. For CCUS-related surveys, knowledge-based questions are thus often used to measure the 'worth' of other answers. On this, Bradburn et al. [84] and Robinson and Meadow [85] further advised to 'ask knowledge questions to screen out respondents who lack sufficient information or to classify respondents by level of knowledge'.

As such, in this study's questionnaire, only individuals who are well-informed of (1) the purpose of CCUS development, (2) its role in climate change mitigation, and (3) the status quo of the technology's implementation in different sectors were surveyed. Respondents have first-handed, experimental knowledge with CCUS, which provided a 'sound empirical basis for forming an opinion' [67]. The survey included questions on climate change that are unbiasedly worded and which have also been tested in other surveys [82]. However, to the best of the authors' knowledge, and with the exception of an industry consultation by the UK Government's BEIS on CCUS business models [24], no academic studies have deployed survey questionnaires to collect stakeholders' views on CCUS business models, and especially ones that are specific to the industrial/steel sector.

The survey questionnaire was sent out by email in July/August 2019 to a target group of 217 experts. We identified experts as: authors/collaborators in industry and academic publications, speakers at or organizers of CCUS-related events, leading scholars at CCUS research institutes, and individuals employed at existing CCUS projects and relevant supporting governmental bodies. The respondent contact details were compiled from a range of sources, including national and international conferences, and academic institutions, management of industrial companies and governmental bodies' websites. The survey had a 33.1% response rate, i.e., 72 individuals, belonging to more than 60 organisations and representing the following groups: (i) government and public bodies, (ii) technology analysts, engineers, and scientists, (iii) industrial sectors, and (iv) associations and foundations. The majority of the respondents were UK-based, with others based in China, Japan, and across Europe and North America. The objective here was to include a target population large enough to capture a sample that would minimize biased results, and which is representative of different entities with different interests and views on CCUS.

For all questions, respondents were given multiple choice questions. Note that respondents were asked to answer the questionnaire based on an individual basis, thus only reflecting their personal knowledge, and that responses were not indicative of the official stance of their corresponding stakeholder organizations. This is especially worth noting as multiple survey respondents belonged

to the same organization. However, where applicable, only one key stakeholder per organization was interviewed.

The 21 questions were further categorized into sub-themes that investigate the respondents' views on (1) climate change impacts on businesses, potential mitigation options, and the role of CCUS in national climate debates in their corresponding countries (5 questions); (2) the development of CCUS in the industrial sector, including main technical and economic challenges (5 questions); and (3) financial/regulatory enablers of business models for industrial CCUS projects (11 questions). The questions are outlined in Table 1, and results reflect the overall number of respondents opting for each possible answer. Note that respondents were allowed to choose multiple answers per question, up to 3 without ranking, and that they were further provided the option to state their own answers/comments in certain questions (i.e., Q7–Q19, Q21).

The data compiled from the survey questionnaire were later coded into themes and sub-themes based on the most common answers. This coding frame is provided as Supplementary Materials. The identified themes and sub-themes were later discussed in depth with selected interviewees.

**Table 1.** Questions included in the survey questionnaire. Answering options given in brackets.

| Questionnaire themes |
| --- |
| **Theme 1: Climate change impacts on business** |
| **Q1.** How serious do you consider the threat of climate change to be? (Serious problem in the near future; serious problem in the distant future; moderate problem in the near future; moderate problem in the distant future; minor problem in the future; minor problem in the distant future; not a problem at all)<br>**Q2.** How important is the role of climate change at your organization? (Very important; important; moderately important; less important; not important; unsure)<br>**Q3.** Has your organization formulated an internal carbon price? (Yes, clearly formulated; yes, but under review; yes, but not publicly available; discussions underway; no, no intention in the near future; unsure)<br>**Q4.** How would you characterize the role that CCUS (Carbon capture, utilization, and storage) plays in the current national climate change debate in your country? (Major; significant; minor; negligible; non-existent; unsure)<br>**Q5**. How do you perceive the potential for global emissions reduction using CCUS technologies in the industrial sector (e.g., steel, cement) as opposed to the power sector? (Much higher; slightly higher; same; slightly lower; much lower; unsure) |
| **Theme 2: Development of CCUS in the industrial sector** |
| **Q6.** How do you perceive the development status of CCUS technologies in the industrial sector, in particular steel, at present? (Immature and impossible to implement; Research and development (R&D) is still heavily needed for most processes; partly mature but some components need R&D; very mature/technology is fully developed)<br>**Q7.** In your opinion, what are the major economic challenges of retrofitting industrial plants with CCUS technologies?<br>(Lack of reliable cost information; lack of clear business models; uncertainties in future carbon prices; high capital costs; high operational costs; fear of losing market competitiveness with international suppliers; lack of an established CCUS supply chain; other)<br>**Q8.** In your opinion, what technical challenges most hinder the introduction of CCUS technologies into the industrial sector? (Lack of sufficient onsite space for capture equipment; complexity of integrating CCUS into production process; poor knowledge of, and expertise with, retrofit option; environmental risks; technical risks; lack of nearby storage/utilization sites; sites of carbon storage assessments; other)<br>**Q9.** What technical barriers exist for the application of current commercially-available carbon capture technologies in steel plants? (Technical performance of capture technologies; lack of reliable pre-treatment technologies; high maintenance costs due to existing impurities in the off-gas; pollutants generated from the capture process; other)<br>**Q10.** In your opinion, what are the major reason(s) why the adoption CCUS technologies has lagged behind other emissions reduction techniques in the transition towards a low-carbon economy? (Lack of supportive regulatory framework or penalties for non-compliance; stakeholder/public perception; lack of industry commitment to reducing emissions; no effective long-term incentives rewarding carbon usage/storage; other) |

**Table 1.** *Cont.*

| Questionnaire themes |
| --- |
| **Theme 3: Financial and regulatory enablers of industrial CCUS business models** |
| **Q11.** What is the most economical technology for large-scale $CO_2$ utilisation in the near future? (Enhanced Oil Recovery ($CO_2$-EOR); food-grade $CO_2$ sales; organic transformation; microbiological culture; other) |
| **Q12.** Which of the following financial mechanisms do you consider most likely to support large-scale CCUS projects in the steel sector? (Command measures such as legal actions, forced plant closure etc.; 'sticks' or penalties such as pollution taxes, fines etc.; 'carrots' or incentives such as grants, low-interest loans, subsidies and tax credits; market-based instruments such as tradeable carbon allowances; other) |
| **Q13.** 'CCUS readiness' refers to a design concept requiring minimal up-front investment in the present to maintain the technical potential for CCUS retrofit in the future. To what extent do you agree with the statement: *"The Government and the financing community should consider requiring CCUS readiness when providing financial support to new steel industry projects"*? (Strongly agree; agree; not sure; disagree; strongly disagree, other) |
| **Q14.** Which of the following do you think would be the most important factor(s) in accelerating the adoption of CCUS technologies (both in industry and power sectors)? (Removal of high-risk perception through demo projects/technology proving; government funding commitment to CCUS projects; demonstrating economic feasibility through high and certain future carbon prices; more stringent national or corporate GHG emissions targets; other) |
| **Q15.** Which of the following do you perceive as the most urgent element(s) to be addressed in building a successful business case for CCUS steel projects? (Availability of funding sources for project development; definition of and certainty provision on revenue streams; clarity on project ownership; elimination of perceived project risks; other) |
| **Q16.** What other regulatory/financial enablers can support the business case for first large-scale CCUS projects in the steel sector? (Enhance CCUS regulatory framework; provide public funding for early-stage R&D; develop carbon capture and storage measurement/assessment methodologies; delegate the authority to examine and approve projects to local governments; include CCUS in national emission trading (ETS) mechanisms and China Certified Emission Reduction (CCER) projects; accelerate $CO_2$ utilization, including providing subsidies for EOR enterprises; government support for developing transport and storage (T&S) infrastructure; channel financial support from developed countries; other) |
| **Q17.** Which of the following support mechanisms do you perceive as most likely to support a revenue stream for CCUS steel projects? (Contracts for Difference (CfDs) with strike price set at cost of carbon abatement; tax credits such as the US 45Q credit law; carbon taxation; cost-plus mechanism; Regulated Asset Base (RAB); tradeable CCS certificates with increasing obligation over time; carbon credits + Emission Performance Standard (EPS); creation of a low-carbon product market; other) |
| **Q18.** Do you consider international joint investment with information being openly accessible as a viable model for financing early-stage CCUS demonstration projects? (Viable; somewhat viable; somewhat not viable; not viable; not sure, other) |
| **Q19.** If it became mainstream practice, who should bear the responsibility of financing CCUS applications in the steel sector? (Industrial emitters, following a 'polluter pays' principle through obligations or taxes; fossil fuel suppliers, through an obligation to pay for storage of a % of their carbon emissions; gas and electricity consumers; industrial product (steel) consumers; public through general taxation; other) |
| **Q20.** Research has shown the introduction of carbon capture technologies to the steel sector may increase costs production by up to 20%. Do you think that the establishment of a low-carbon steel product market is a viable option to subsidize the application of energy efficient technologies, particularly carbon capture technologies, within the steel production process? (Yes; no; unsure) |
| **Q21.** If you answered yes to the previous question, who do you perceive as the most likely option to cover the costs of low-carbon steel production? (Costs passed on to all steel consumers; costs covered by a premium paid by a group of consumers seeking value-added products; costs borne by producers through an obligation to produce % of low-carbon steel products; other) |

### *4.3. Semi-Structured Interviews*

Following the collection and analysis of questionnaire data, 6 key experts were selected to conduct detailed in-depth interviews (typically lasting 1 h). Here, the term 'expert' is used to describe an individual with a professional interest in industrial CCUS. Experts were selected based on the most common and relevant results collected through the questionnaire, with the aim of objectively representing a variety of key interests and expertise from energy businesses, government and research institutions. The experts belonged to management and/or research and development (R&D) teams of

their affiliation organizations, with some directly involved in CCUS research within or applications by their organizations. Other experts had less knowledge of CCUS and more regarding climate change mitigation options for the industry within which their companies operate (e.g., energy efficiency options in steel production).

The interviews were designed to ensure that technical, economic, political and social issues were addressed with all interviewees. Underlying issues which are widely discussed in the literature were critical in supporting the interviews; however, the interviews were conducted in a more organic manner, allowing the interviewees to frame their thoughts freely with as little interference from the interviewer as possible. Expert opinions provided a range of perspectives and inputs from practical real-world experience with CCUS projects from countries with different political frameworks and climate agendas. This also ensured that the majority of project risks—independent of project locations—and potential business models were taken into account. The interviewees were initially presented with a summary of the purpose of this study and asked whether they opted to make their feedback publicly available: all interviewees opted for anonymity. Table 2 presents the roles of the interviewees within their organizations; each interviewee was denoted by a letter to attribute comments or information to specific interviewees within the text. Data compiled during these interviews were based on semi-structured, open-ended questions which revolved around the themes and sub-themes identified in the coding system of the collected questionnaire data (refer to the Supplementary Materials for the coding frame and interview guide, including the set of questions).

**Table 2.** List of interviewee roles within their affiliation organizations.

| Code | Position | Type of Organization |
|---|---|---|
| A | Co-founder | low-carbon energy projects consultancy |
| B | Technology Analyst | Leading international agency in CCUS research |
| C | Senior Consultant | Leading UK consultancy on industrial CCUS |
| D | Project Leader | Large industrial CCS project |
| E | Lecturer in Chemical Engineering | UK academic institution |
| F | Researcher, Environment | Global steel producer |

## 5. Results and Discussion

The findings of this study are separated into two overarching parts: one presenting findings from the reviewed literature (Section 5.1, Section 5.2, Section 5.3), and the other presenting findings from the questionnaire, supported by inputs from the interviews (Section 5.4, Section 5.5, Section 5.6).

The first section provides an overview of the status quo of research on CCUS business models, including a list of barriers and drivers of these business models as discussed in the literature (Section 5.1). We then describe a typical CCUS value chain (Section 5.2), and proceed to classify existing large-scale CCUS applications around the world into four different business model types, discussed individually (Section 5.3).

The second section reflects the structure of the coding frame which categorized findings from the questionnaire and interviews into different themes/sub-themes. These themes are then discussed in detail. Here, it is worth mentioning that due to the limited number of questionnaire responses (i.e., 72 responses), findings are not presented as necessarily statistically significant, or as stand-alone sections in this paper for that matter, but general trends in perceptions are identified and discussed, and are complemented and merged with findings from the more-focused interviews.

### 5.1. Literature on CCUS Business Models

In the energy sector, while there is vast literature on business models of energy service companies [86–88], the literature on CCUS remains mostly focused on techno-economic analyses [89,90]. Studies focusing particularly on CCUS business models remain largely limited to industry consultancy reports [16,17,19,91], with the exception of a small number of academic works [18,20–22]. The authors

of some of these studies also provided valuable input to this study either as questionnaire respondents or interviewees, or both.

It is evident that due to insufficient incentives from the government, only a few organizations have taken the initiative to adopt CCUS technology as there is no current profit model, making the technology commercially unfeasible at this time [92]. Aside from the risks associated with this lack of technical experience, and due to its long industry chain (Section 5.2), CCUS developments remain limited due to difficulties in synchronizing collaboration amongst industries. This echoes research observations from more than a decade ago, where Kheshgi et al. [21] had, in 2009, acknowledged that 'there is currently no broadly viable business model for the large-scale deployment of the technology'. In addition to its high costs, the lack of feasible CCUS business models still hampers the technology's development today.

Indeed, a growing consensus amongst scholars and CCUS developers in the industrial sector is that high costs of CCUS [93,94] and the lack of established revenue models to cover them remain a complicated issue [16,21], as large-scale applications have not as yet provided results on actual commercial operation. The costs of CCUS are highly influenced by a variety of geopolitical and technical factors. On the former, capital cost estimation, energy and materials prices, the location of the plant, carbon pricing, and pay-back periods are factors that particularly influence CCUS applicability and affordability, all of which differ significantly from state to state. On the technical factors, costs of capture are determined by three primary drivers; these are, in order: (1) $CO_2$ concentration of source gas streams, i.e., the more diluted the stream, the more expensive capture becomes; (2) degree of contamination of gas stream, i.e., additional gas clean-up may be required; and (3) source mass flow rate, where costs are reduced due to economies of scale [93]. A corollary to this is the fact that even when employed, whether in the power or industrial sectors, CCUS business models tend to be unique in nature.

After investigating the structure of business models of the world's largest CCUS projects (note: a selection of CCUS business model case studies are provided as Supplementary Materials), two common themes prevail. The first is that there are notable differences in and uniqueness to the structure of each model, driven by differences in design, technology selection along the CCUS chain, incentives for action, regulatory frameworks and market conditions. The second observable trend is the indispensability of public funding for making a business case for CCUS. Carbon pricing remains the most widely assumed business driver for non-EOR CCUS, which materializes either in the form of a carbon tax or a cap-and-trade system. Other drivers include a feed-in tariff on electricity, grants, and tax credits, such as the newly implemented 45Q tax credit in the US. It here becomes clear that CCUS business models depend on whether and what type of carbon policy exists.

For instance, a carbon price or tax adds to the production costs, meaning that cost avoidance is the CCUS business model. Another option is to introduce an emission performance standard or a CCS mandate, meaning that costs are transferred to the consumer when all producers are facing the same mandate, while a subsidy can cover the additional costs of CCUS. As these mechanisms remain mostly absent, it is critical to design business models that can operate with minimal to no governmental support. Here, utilization of the captured carbon, especially from high-purity sources and for enhanced hydrocarbon recovery purposes, has emerged as an economical solution, at least in the short-term, for early demonstration projects [95].

### 5.2. Literature on CCUS Value Chain

The literature review reveals that defining a value proposition is at the core of designing successful business models for CCUS, as was the case for early models of now-mature clean technologies. Here, the value proposition of CCUS is assumed to be the eventual 'burial' of $CO_2$ in case of $CO_2$ storage, or $CO_2$ recycling in case of utilization, and a CCUS value chain has been described by Pieri et al. [96] in six major stages, as presented in Figure 2. The first stage involves characterizing the carbon source on two levels: a) based on data, including its location, $CO_2$ output flowrate, $CO_2$ purity, and based on

b) the type of output stream. Most of the technical studies on carbon source characterization have classified sources based on purity (i.e., high: >90%, secondary highest: 50–90%, moderate: 20–50%, and low: <20%) [97–99].

The second stage involves capturing the $CO_2$, i.e., separating it from the output stream using technologies compatible with the stream type. This is the most extensively-explored component of the value chain, and capture technologies are widely categorized within one of three groups: a) post-combustion, b) pre-combustion, or c) oxy-fuel combustion technologies [100–103]. Others [104] have classified capture technologies in terms of $CO_2$ partial pressure, i.e., $CO_2$ concentration level in the flue gas stream (high: 30–70%, medium: 35% and low: 3–20%).

After separation, the $CO_2$ is purified and compressed based on the means of transportation to be used and the purity level required by the recipient. The $CO_2$ is then transported to the recipient, where the stream characteristics (i.e., purity and flowrate), distance to the recipient, and other local characteristics determine the most appropriate means of transportation. The final stage is utilization and/or storage, where $CO_2$ is delivered to the recipient and converted to finished products or stored permanently in geological reservoirs. Figure 2 depicts these six stages, including a selection of key studies on technical and economic characteristics pertinent to each stage [8,15,26,97–141].

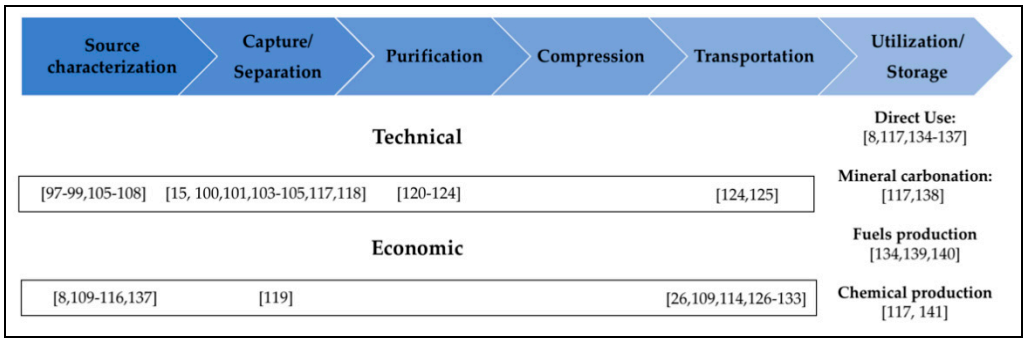



**Figure 2.** The six stages of a CCUS value chain.

In reviewing the individual stages of a CCUS value chain, common barriers and risks for the successful implementation of industrial CCUS become evident. These barriers are categorized here within four groups: (1) technical/operational, (2) political, (3) economic, and (4) cross-chain. Figure 3 summarizes the overarching risks and challenges as presented in the literature within these groups. For any industrial CCUS contract, the following five challenges are further prioritized in the literature: (1) upfront capital investment for $CO_2$ capture, (2) recurring costs for capture plant operation, (3) technical performance risks, (4) benefits of reduced carbon emissions, and (5) a clear solution once carbon exits the boundary of the capture site [19].

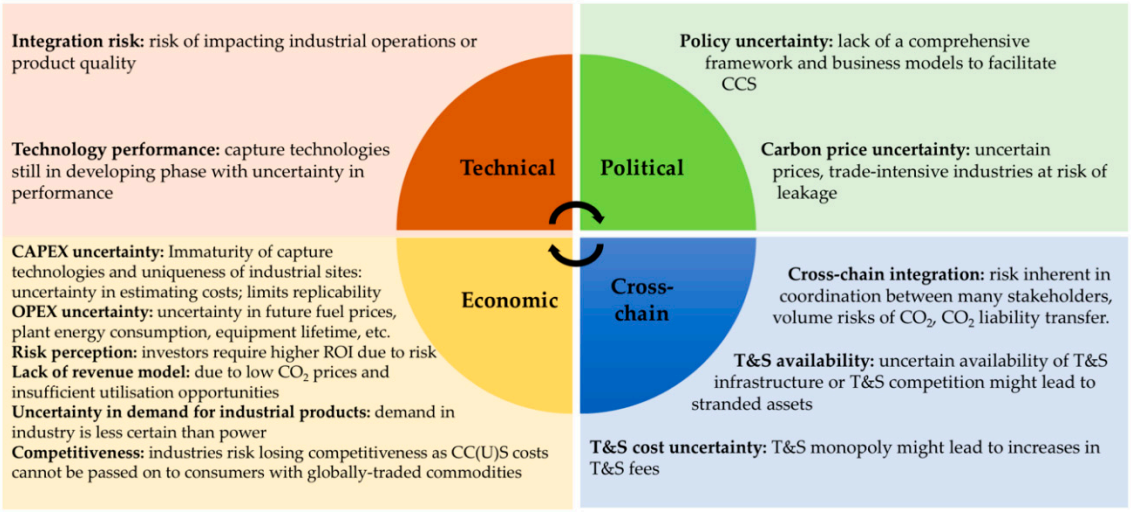



**Figure 3.** Key challenges of implementing industrial CCUS.

### *5.3. Classification of CCUS Business Models*

An investigation of existing large-scale CCUS projects shows that three routes exist to contractually organize projects: (1) within an individual company (i.e., vertical integration), (2) between more than one company (i.e., joint venture), and (3) in collaboration with a CCS-service company (i.e., pay at the gate). The latter can either involve a CCS operator or a CCS transporter entity. The resulting four business models are discussed here.

#### 5.3.1. Vertically Integrated CCUS Business Model

Operations are vertically integrated in this self-build model, where industrial or power companies use their technical and commercial capabilities to support and link each element of the CCUS chain. Examples of vertically integrated CCUS projects include the Uthmaniyah $CO_2$ EOR Demonstration project, China's Yanchang Integrated Carbon Capture and Storage Demonstration Project and Sinopec's Shengli Power Plant CCS project. Here, the company must operate capture and storage/utilization sites as well as have means of transportation, and must also be integrated to a high degree. This in effect limits market players to only specific enterprises with the resources to invest heavily in and manage an entire CCUS chain. This, however, alleviates the risks associated with synchronizing efforts among different sectors [22]. The high degree of integration also serves to eliminate transaction costs as $CO_2$ is directly transported from the capture plant to be utilized. The revenue generated in this model comprises (1) revenue from $CO_2$ utilization, and where applicable, either (2) a direct subsidy for $CO_2$ storage from the government and/or (3) revenue from selling extra carbon emission credits in the carbon market. Figure 4 depicts the structure of a generic vertically integrated CCUS model which may be applicable in both the industrial and power sectors.

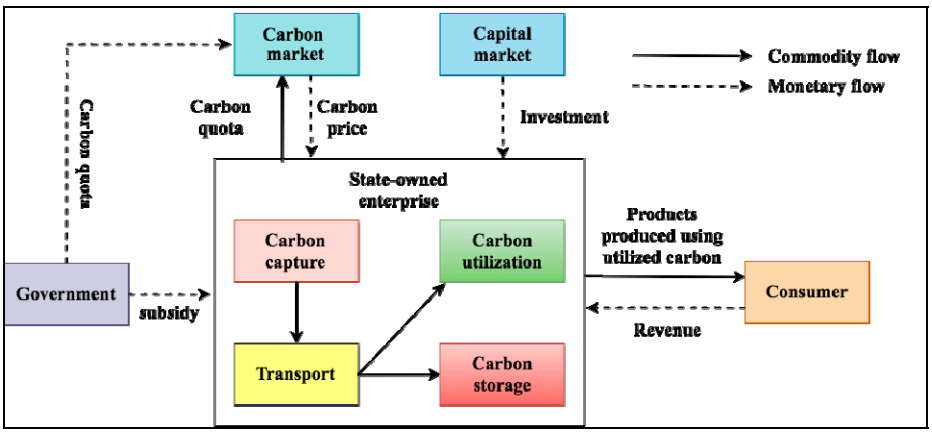



**Figure 4.** Vertically-integrated CCUS business model.

### 5.3.2. Joint Venture CCUS Business Model

A JV (Joint Venture) model is based on a partnership between the industrial/power company and external $CO_2$ users or storage consultants. In this model, the industrial company may be liable for costs and operation of $CO_2$ capture, but transport and storage would be managed jointly, resulting in a more equitable distribution of risks and revenues. Examples of CCUS projects adopting a JV business model include the Quest CCS project, Norway's Snohvit $CO_2$ Storage project, Brazil's Petrobras Lula Oil Field CCS Project, and Algeria's In Salah $CO_2$ Storage project. Here, as opposed to a vertically integrated model, cooperation amongst different sectors is key for the success of the project. In a JV model, $CO_2$ is captured from an industrial or power plant owned by a third party, where $CO_2$ is then transported to a storage/utilization site, also owned by a third company. Yao et al. [22] describe a typical ownership structure of a JV business model as 40% (industrial/power company), 30% (transport company), and 30% ($CO_2$ user). Revenue accrues from the sale of $CO_2$ rather than from utilization, where the $CO_2$ user can decide on the proportion of $CO_2$ to be purchased for utilization, with the rest of $CO_2$ used for storage (Figure 5).

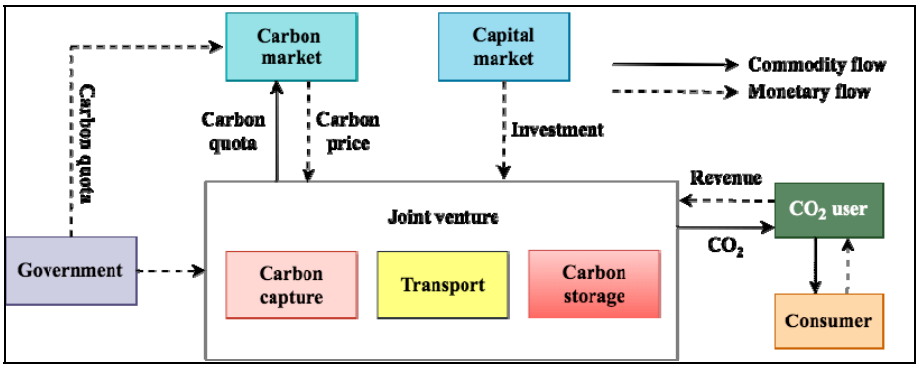



**Figure 5.** Joint venture CCUS business model.

### 5.3.3. CCUS Operator Business Model

In this pay-at-the-gate model, an industrial/power company cooperates with a third party featuring high technical and engineering capabilities to handle the $CO_2$ after it has been captured. The third party will then, for an agreed fee, appraise different utilization/storage options and take responsibility for transporting the $CO_2$. Examples of CCUS projects adopting an operator model include the Coffeyville Gasification plant, the Great Plains Synfuel Plant, Canada's Weyburn-Midale project, and the US Enid Fertilizer $CO_2$-EOR project. The parties to this model include the industrial/power company, CCS operator, and $CO_2$ user.

The expenses in this model are split as follows: the CCS operator bears costs of capture, transport and storage equipment and their associated operation and maintenance (O&M) costs, while the $CO_2$ user covers $CO_2$ purchasing costs and costs of utilization equipment and their operation. Note that if the company in question is a power plant, it may generate no profit in this model if it is legally required to produce low-carbon electricity. If the company is an industrial plant, unless there is a legal requirement to produce low-carbon products, it will generate a profit either in the form of a premium on produced low-carbon goods and/or a government subsidy. The CCS operator generates revenue in the form of a direct subsidy from the government for storing $CO_2$ and revenue from selling carbon credits and $CO_2$. The $CO_2$ user may save on their costs of production by purchasing $CO_2$ at a discounted price (Figure 6).

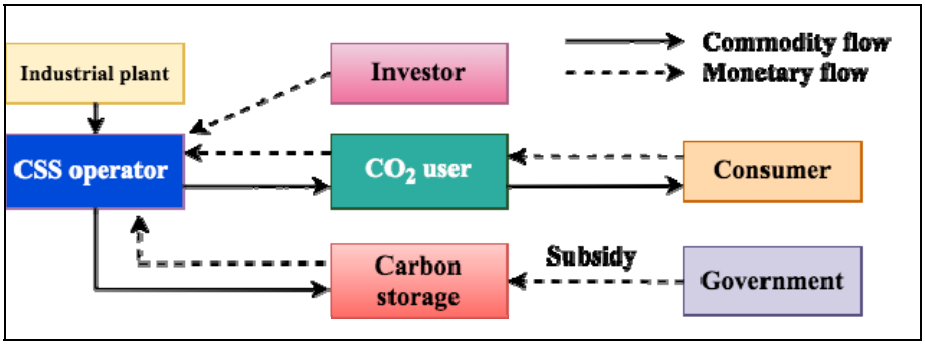



**Figure 6.** CCUS operator business model.

### 5.3.4. CCUS Transporter Business Model

Examples of CCUS projects using a transporter model include the Val Verde Natural Gas Plant and the Shute Greek project. In this model, a third party is only responsible for the transportation part of the CCUS chain. The industrial/power company is responsible for capturing $CO_2$, including covering capture equipment and O&M costs, and generates revenue from $CO_2$ sales and trading carbon credits. The transport company covers costs of transport equipment and their O&M and charges a fixed fee for $CO_2$ transport, one which is pre-agreed upon among the stakeholders. Finally, the $CO_2$ user covers $CO_2$ purchasing costs and costs associated with utilization or storage equipment and their O&M. The $CO_2$ user in this case generates revenue from a storage subsidy and/or a discounted price on purchased $CO_2$. Here, the $CO_2$ transport company and the industrial company bear relatively lower risks compared to an operator model as revenue is guaranteed through a long-term purchasing contract, while the $CO_2$ user guarantees revenue as long as it maintains larger profit margins on their products (Figure 7).

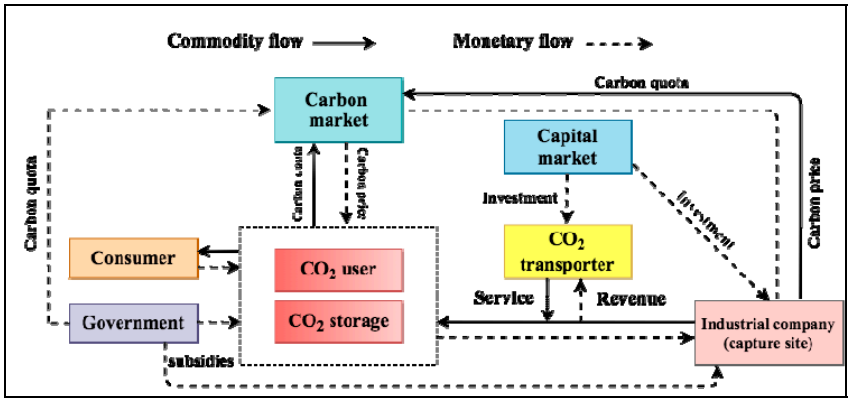



**Figure 7.** CCUS transporter business model. Adapted from [20].

### *5.4. Challenges of CCUS Implementation in the Steel Sector*

The first theme of the questionnaire and interview coded results was identifying challenges to implementing CCUS in industry. Here, on the most pressing *economic* challenges of retrofitting steel plants with CCUS, two major challenges prevail: (1) lack of clear business models and (2) fear of losing market competitiveness with international suppliers. On this, interviewee A further asserted that 'the technology is not the main problem for CCUS. The technology is mature and well-proven, but the real stumbling block is the lack of a viable business model, at the heart of which is a clear revenue stream'. However, interestingly only around a quarter of stakeholders chose one or both of the aforementioned challenges, with many prioritizing other challenges (Figure 8), reflecting the diverse nature of challenges facing CCUS in the sector. Other surveyed stakeholders, along with interviewees C and E, noted other challenges including the need for complete and costly plant redesign for process integration.

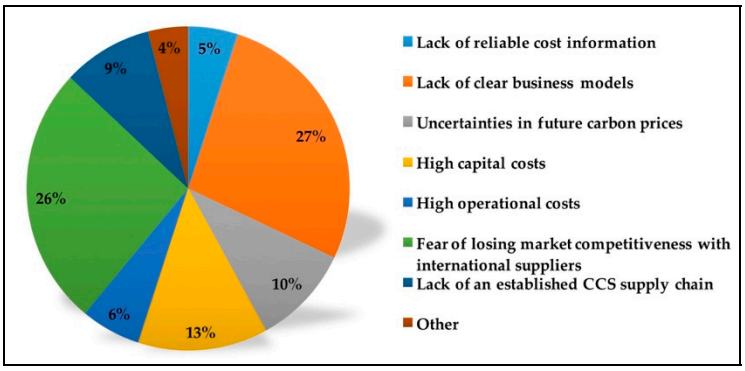



**Figure 8.** Perceived economic challenges of integrating CCUS within the steel industry (Q7).

On technical aspects, around three-quarters of respondents believed that the developmental status of CCUS technologies in the steel sector is partly mature with some components needing R&D (72%), while around a quarter of stakeholders believed that R&D is still heavily needed for most processes (Q6). The most pressing technical challenges were further identified as follows: (1) complexity of integrating CCUS into production process, (2) lack of nearby storage/utilization sites, and (3) poor knowledge of, or experience with, retrofit options. The surveyed stakeholders further viewed the technical performance of capture technologies and the high maintenance costs due to existing impurities in the off-gas as main barriers for the application of commercially available capture technologies in steel plants (75%, Q9). Opinions were more diverse on why CCUS have lagged behind other emission reduction techniques in the transition towards a low-carbon economy, with (1) the lack of a regulatory support framework (34%) and (2) the lack of effective long-term incentives which reward carbon usage/storage (31%) quoted as the main two reasons (Q10).

### *5.5. Enablers of CCUS Business Models in the Steel Sector*

On drivers of CCUS implementation in the sector, $CO_2$-EOR was perceived, perhaps expectedly, by the majority of surveyed stakeholders (72%) as the most economical technology for large-scale $CO_2$ utilization in the near future. However, some stakeholders pointed out that, although it may offer a route to commercialization in the short term, $CO_2$-EOR is only applicable in certain areas and is not necessarily effective in mitigating climate change (Q11).

Five interviewees (B through F) advocated for financial mechanisms that reward projects, i.e., carrots, such as: grants, low-interest loans, subsidies and tax credits, or market-based mechanisms, such as tradeable carbon allowances, over measures that legally enforce them, i.e., sticks, such as: pollution or carbon taxation. This observation was further supported by around three-quarters of the surveyed stakeholders (Figure 9).

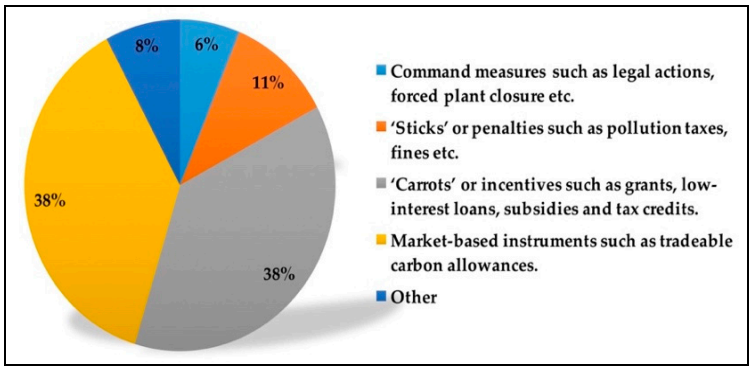



**Figure 9.** Stakeholder preferences for policy mechanisms to support CCUS steel projects.

Three quarters of stakeholders viewed that establishing joint international investment projects, where information is openly accessible, can be a viable model to financing early-stage CCUS projects. However, a notable third of the stakeholders did not support the view that new steel plants needed to necessarily be CCUS-ready in order to receive financial support from governments. This highlights the industry's divergence in opinions on the most effective and economical ways to achieve drastic emission reductions in the sector, where hydrogen reduction and electrolysis have recently emerged as likely options (interviewees E and F).

A majority of surveyed stakeholders believed that governments needed to commit funds to CCUS projects and remove the high-risk perception through demonstration projects in order to accelerate the adoption of CCUS in both the power and industrial sectors (60%, Q15). Others suggested that the establishment of an operational transport and storage (T&S) infrastructure and transfer of risk to the public sector are critical factors in creating an investable environment (Figure 10). Some stakeholders further emphasized a need to develop local transport, utilization, and storage clusters that steel projects could feed into. On risk alleviation, interviewee F maintained that 'the only body that is large enough to take on the risks of transport and storage and other stranded-asset-related risks is the public sector. One form in which the public sector could handle these risks is in a Regulated Asset Base model or by offering a form of financial shielding for the various participants. However, the question which follows is: where would the funds come from—the taxpayer, the consumer or from another source?'.

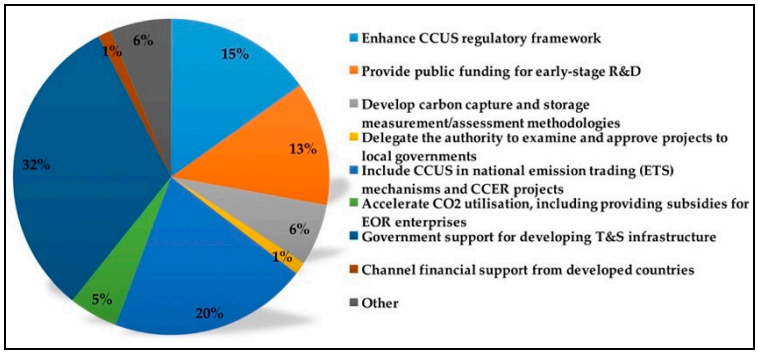



**Figure 10.** Regulatory/financial enablers of CCUS steel projects.

Based on the most common answers arising from the analysis of questionnaire and interview data, we here discuss the individual elements of a CCUS business model.

### *5.6. Business Model Elements*

To develop and select appropriate business models for industrial CCUS, the potential mechanisms, instruments and risk management strategies were selected based on our findings and a review of case studies. We subsequently characterized business models into 'elements' which fundamentally

differentiate them from one another. Here, the revenue model was identified as the most critical element driving the success of a business model (in agreement with 50% of respondents), one which dictates which supporting instruments are required to manage risks and enable capital financing. Supporting this, and based on a similar consultation exercise with private industry stakeholders, Element Energy [16] (pp. 8) reported that the 'fundamental barrier to industrial carbon capture from the private sector's perspective is the absence of a value proposition' where the 'revenue model is the central element in creating value for industrial carbon capture'.

The revenue model is thus considered as the central element in creating value for CCUS business models, around which three elements are then structured and defined; these are: funding sources, capital sourcing & ownership, and risk management. Here, revenue models refer to guaranteed income streams which cover capital and operational costs of the CCUS chain, and are thus primary drivers of CCUS business cases. Funding sources, on the other hand, refer to the entities funding those revenue streams: uncertain revenue streams, for instance, such as profits from $CO_2$ utilization, may help support the business case for CCUS but not make it, and are thus considered to be a funding source rather than a revenue stream in this analysis. Figure 11 presents an overview of various options available for each of the defined elements, where different combinations of options lead to the establishment of unique business models. A further description of the main options for revenue generation, funding sources, and risk management is provided in the following sections.

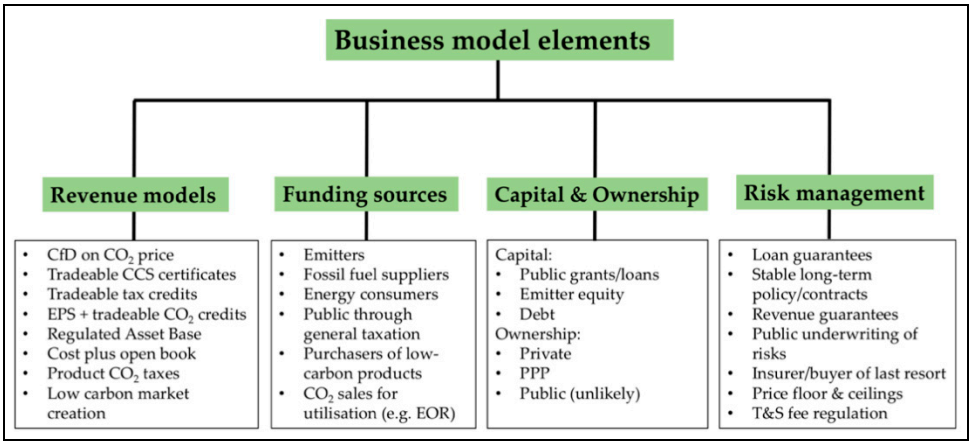



**Figure 11.** Elements of a CCUS business model.

### 5.6.1. Revenue Models

The most diversified set of questionnaire responses was reflected in the choice of financial mechanisms to support revenue models. These choices are here presented and discussed (Figure 12).

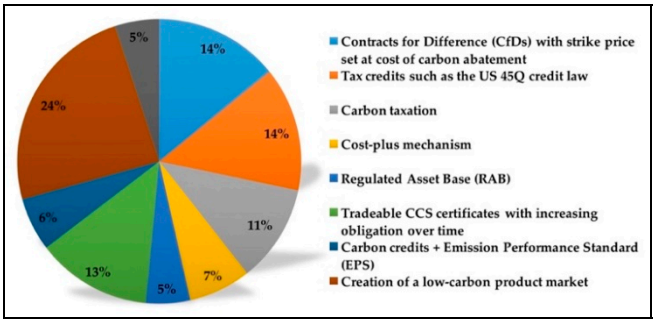



**Figure 12.** Stakeholder preferences for supportive revenue mechanisms of CCUS steel projects.

- Contracts for Difference (CfD)

A contract for difference is a contract between a buyer and a seller which involves a guaranteed price, called the 'strike price' for a product, where one party pays the other the difference between the strike price and the market price of the product. CfD mechanisms are not uncommon for low-carbon technologies in the power sector. The strike price provides revenue certainty to investors especially for technologies at nascent stages of development. For carbon capture, the strike price could be set on the cost of carbon abatement (called a $CfD_c$), which is paid by the government in £/$tCO_2$ over the market price (i.e., price of carbon avoidance), as proposed by Société Générale [142]. Alternatively, a $CfD_p$ could be set on the industrial product price (£/t product), either directly or, similar to power CfDs, as a price premium above the market product price. For instance, a CfD mechanism was at the core of the proposed business model for the UK Don Valley project.

- Tax credits

Tax credits are reductions in the tax liability of a firm if it meets certain requirements. A firm which implements industrial carbon capture could receive a tax credit valued at £/$tCO_2$ abated. Such a model is applicable in the US (Section 45Q credit law) to support CCUS developments, a specific tax benefit which interviewee A described as 'the base for a CCUS business model'. This newly implemented law rewards firms that geologically store carbon dioxide with a tax credit of \$50/$tCO_2$ stored, and those that utilize it with \$35/$tCO_2$. Tax crediting has also been suggested by the UK CCUS Cost Challenge Taskforce [143]. Factors which would impact the success of such a policy include the monetary value of credits, availability of capital and the ability to absorb changes in carbon prices. Along with a mechanism for tradeable CCS certificates and the creation of a low-carbon product market, a tax credit mechanism proved to be one of the most popular revenue generation streams amongst the surveyed stakeholders.

- CCS certificates, with obligation

Tradeable CCS certificates, combined with an obligation to decarbonize, has been proposed by this study's interviewees (A, C and E) as a market-led solution. CCS certificates are awarded per $tCO_2$ abated where emitters are obligated to ensure a certain amount of $CO_2$ is captured, with the level of obligation increasing over time. Certificates may be used to meet the obligation or can be freely traded so that parties with higher costs of industrial carbon capture can purchase cheaper certificates. While the price of certificates is determined by the market, governments can provide a buyout price which creates a floor price for certificate value and, conversely, a price ceiling can be created by imposing penalties for not meeting the obligation.

- Carbon tax

A carbon tax, much like taxes on tobacco or sugary drinks, aims to internalize external costs to society (only in this case due to carbon emissions). The tax can be calculated based on a product's carbon intensity ($tCO_2$/t product) compared to a product benchmark, or can be an absolute tax per $tCO_2$ produced. A carbon tax can promote a behavioral shift towards production with lower-carbon routes [144]. However, unless applied globally, the mechanism risks carbon leakage and may put certain industries at a competitive disadvantage if production shifted elsewhere.

On this, interviewees B and E pointed out that, unless border tax adjustments for embedded carbon were introduced, however politically-challenging those may be to implement, a carbon tax mechanism will almost certainly see steel companies lose market shares. Furthermore, it is evident from this study's questionnaire analysis that industry stakeholders had a higher receptiveness towards incentives which reward projects over those which legally enforce them, with only 20% of respondents opting to choose a carbon taxation system or legal actions as appropriate measures (Figure 9). It is worth noting, however, that a carbon taxation mechanism is still currently the main driver of CCUS developments in Norway.

- Cost plus mechanism

A cost-plus mechanism involves direct payments from the government to cover all yearly incurred costs, on an open book basis, with agreed returns on any emitter investments, and where the majority of the risks are borne by the public sector. A cost-plus mechanism is proposed in the Pöyry and Teesside Collective report on UK industrial CCS support mechanisms [18], as a strong and certain incentive with a fairer division of benefits between the emitter and government. This mechanism is also considered for use in the Rotterdam Porthos CCS project, where each emitter may be compensated for the incurred additional cost of CCS compared to the avoided $CO_2$ price. However promising, interviewee C asserted that while 'a cost-plus mechanism would be the most attractive financial incentive to industry (as it bears none of the risks), it is neither necessarily acceptable by government nor would the mechanism drive the highest efficiency in terms of costs to society as a whole'.

- Regulated Asset Base (RAB)

An RAB model values existing assets used in the performance of a regulated function and sets tariffs to pass the costs of these assets on to consumers [16]. The equity risk is low as the revenue risk is transferred to consumers (i.e., it can be seen as a commitment by future consumers to cover current investment). However, a RAB model raises affordability concerns as the risk of sunk costs is passed on to consumers, and in particular to vulnerable consumers. In a RAB system, energy providers may be stimulated to drive cost reductions if they were able to retain funds resulting from cost cutting [15].

- Carbon credits plus EPS

Similar to CCS certificates, emissions performance standards (EPS) on industrial products can also be combined with carbon credits. The carbon credits are awarded on sale depending on the carbon intensity of the product relative to the product benchmark. Again, they could be used to meet the obligation or traded freely, and the government may provide a price floor and ceiling. As with carbon taxation, this can directly incentivize lower-carbon production, yet financial support would still be required to address the risk of carbon leakage.

- Low-carbon product market creation

It has been suggested that a long-term solution to decarbonizing the industry is the establishment of a low-carbon product market [16] (pp. 27), where market mechanisms would incentivize decarbonization over time. One way to encourage the creation of such a market is to create a standardized certification scheme for low-carbon products and to raise awareness of the carbon intensity of goods amongst consumers. Other ways are through public procurement of low-carbon products or through regulations on end-products which may be placed to ensure a certain level of low-carbon material is purchased (e.g., energy performance certificates in new buildings regulations).

This option proved the most popular amongst questionnaire respondents (Figure 12). However, there was a clear variance in opinions on the likely funding source for such a mechanism, with around a third of respondents opting for each of the following options: (1) costs could be passed on to all steel consumers, (2) costs could be borne by producers through an obligation to produce a certain percentage of low-carbon steel products, or (3) costs could be covered by a premium paid by a group of consumers seeking value-added products. The creation, structuring and financing of such a market has thus emerged as an area worthy of further exploration.

On creating such a market, interviewee A warned that 'consumers may simply shift to consuming imported steel products if there were no taxes on embedded carbon in imported goods. The steel or cement industry will be very hesitant to pass costs on to their consumers due to fears of losing market share. On the other hand, passing on costs to specific groups of people that are interested in 'green' steel products is viewed as an act of absurdity, where people who are doing the right thing are

expected to take on the risks. The most logical solution is taking money from the general polluter to reward people doing the right thing'.

Here, while following a 'polluter pays' principle seems to be a fair resolution to allocate cost-bearing responsibilities, a question that then begs itself is: who is the polluter in this case? Is it the fossil fuel provider, the steel manufacturer, or the customer who is ultimately using the product? In a simple analogy, if one were to purchase a fossil-fuel-powered car and drive to a petrol station, the petrol provider would not be naturally expected to cover emission costs. With the option to buy low- or zero-carbon alternative products (e.g., an electric car in this example), the consumer should arguably be responsible for covering costs.

In addressing this, interviewee D highlighted a need for the aforementioned entities to play different roles at various stages of the market's development as it evolves and matures over time (i.e., in the short-to-medium term vs. long-term). Interviewee D viewed that 'in the short-to-medium term, the low-carbon steel product's premium could be covered by a combination of government incentives aiming at decarbonizing industry at a national level, as long as it is accompanied by a tax implemented on embedded carbon content in imported steel products in order to protect the national steel market's competitiveness as a whole. However, as the government is unlikely to sustain providing these subsidies in the long run, and as demand for emissions-free steel products grows over time, the market would gradually become fully supported by the general steel consumer.'

#### 5.6.2. Funding Sources

The challenge of securing funding to support these revenue streams further adds to the uncertainty revolving the potential success of CCUS projects. The nature of project development in different regions differs significantly, which explains the varied levels of engagement of financial institutions in these regions [145]. On this, more than a third of the stakeholders viewed that industrial emitters should play a direct role in financing CCUS steel projects through obligations or taxes if the application became mainstream practice, following a 'polluter pays' principle. In contrast, a quarter of respondents viewed that steel consumers should instead cover these costs through an obligation to pay for storing a proportion of their carbon emissions, while another quarter opted for fossil fuel suppliers to cover these costs. An option that was recurrently stated by a number of stakeholders was sourcing funds for early projects from the public through general taxation and later from the emitters (i.e., steel consumers). The set of options stated by the surveyed stakeholders and interviewees is here presented.

- Emitters

As aforementioned, following a 'polluter pays' principle, industrial emitters could help finance CCUS through obligations or taxes. The mechanism can involve an increased allocation of tradeable certificates (e.g., European Union Emissions Trading Scheme) to industrial carbon capture emitters, which can in turn be sold to other emitters. This, however, risks a high carbon leakage, unless all national emitters, from all sectors, are sourcing the funds through taxes or obligations.

- Fossil-fuel suppliers

Obligations could be implemented on all fossil fuel suppliers to store, or pay for the storage of, a given proportion of the carbon content of the fuel which they annually supply. The required percentage would have an increasing trajectory over time. The justification here is that the majority of industrial (and power) emissions are caused by fossil fuel combustion, so the cost of reducing emissions from these fuels should be shared by the suppliers [93].

- Gas consumers

As CCUS can contribute to the decarbonization of the gas grid, gas consumers could pay either through taxation or a RAB model. The cost could be spread over direct local consumers or all national

gas consumers. Additionally, electricity consumers could contribute to the cost of CCUS, to spread the consumer base over which costs are distributed.

- Industrial product consumers

A price premium could be paid for low-carbon products if a market was created through regulations and certification for low-carbon goods [16]. Alternatively, a price premium could be paid for high-carbon products, if additional taxation is applied based on product carbon intensity.

- Public through general taxation

As all members of society benefit from emissions mitigation, a case could be made for direct funding from the public through general taxation. However, this may be challenging in light of the public acceptance debate surrounding CCUS [146,147].

- $CO_2$ utilization (e.g., EOR)

Revenue from $CO_2$ utilization is a major and extensively discussed source of funding, especially at this stage of technology development. However, as the economics remain unfavorable at this stage, utilization revenue is only seen as complementary at best and has thus not been considered as a stable revenue source here. The majority of survey respondents viewed EOR as the most economical technology for utilizing the captured $CO_2$. However, some stakeholders pointed out that although it offers a route to commercialization in the short term, $CO_2$-EOR is only applicable in certain regions and is not necessarily effective in mitigating climate change.

#### 5.6.3. Risk Management

Risk management and risk allocation were perceived by interviewees E and F as the most fundamental reasons for the failure of previous large-scale CCUS applications, in particular UK-based ones. Interviewee F admitted that although existing projects differ significantly in how they are structured and run, 'the risks associated with CCUS projects are all more or less the same' and that 'at the highest level, all projects suffer from the same dilemma and that is finding mechanisms for risk allocation—everything starts with risk allocation and the potential rewards that are associated with the allocation of those risks'.

For example, featuring no EOR-component, in the UK's Whiterose CCS project it was difficult to allocate storage risk to certain parties, and the importance of finding an appropriate risk-reward allocation mechanism along the full CCS chain was the main learning experience from the project. 'In the UK, the main issue is not the lack of clarity of business models, it is simply that those models do not yet exist. Over the past few years, most of the projects had been choreographing a risk-allocation system with most of the risks allocated to a £1bn grant support from the government which was later scrapped, leading to a halt in the development of those projects' (interviewee B). On this, interviewee A emphasized that 'as a steel producer, you will have the same appetite for risk and you will want to operate independently from the transport and storage system. For investors in and operators of T&S infrastructure the question remains: what if $CO_2$ never arrives and no one uses the infrastructure? A successful business model has to account for and manage risks on both sides of the equation'.

To mitigate this risk, the UK Government has more recently called for separating capture business models (discussed in [16]) from those of transport and storage business models (discussed in [91]), in an effort to form clusters of $CO_2$ sources [17] and use shared transport and storage infrastructure to reduce costs [148]. Here, interviewee A suggested that 'the reason why the UK is separating the T&S business model from the capture business model is that the private sector is not willing to take on the risk at present'. Interviewee C further stated that the rationale for decoupling these business models is that 'T&S infrastructure, akin to national water systems, sewage systems and electricity networks, are publicly regulated, whereas capture facilities, being naturally embedded within the production site, cannot be publicly regulated.'

Moreover, interviewee F claimed that 'steel companies—and industrial manufacturers in general—have little to no knowledge of the subsurface and of storage mechanisms and would only be interested in capturing $CO_2$ and providing it to a separate entity that subsequently safely handles its disposal.' However, despite interviewee E recognizing the merit in separating T&S from capture business models, they cautioned that 'while common infrastructure can offer cost savings, the operation of multiple projects on common infrastructure could potentially lead to more failures. Another issue is that this infrastructure entails building large-scale T&S hubs which are very costly and difficult to justify for a market at such an early stage of maturity.'

## 6. Conclusions

The overall objective of this paper was to investigate the theoretical underpinnings and drivers of success in formulating CCUS business models in the industrial sector, and particularly in the steel sector. CCUS business models are framed in the context of business models for sustainable practices. The combination of technologies remains an indispensable and critical enabling tool towards meeting pressing climate targets, one that ensures a sustainable and responsible use of fossil fuels over the next decades and a safe transition to renewables in the longer run. However, the lack of business models has deterred governments and in turn the private sector from entering this market and moving the technology forward.

This paper emphasized the role of CCUSs as one of three interconnected pillars of sustainable production in the steel industry, alongside continuous efforts to improve energy efficiency and an increased dependency on renewable resources over fossil-fueled electricity sourcing into the sector. This work aimed to address the knowledge gap that exists in determining the main elements upon which CCUS business models are structured and to categorize existing large-scale CCUS projects within overarching business model types: (1) vertically-integrated models, (2) joint venture models, (3) CCUS operator models, and (4) CCUS transporter models. This paper remains, to the best of the authors' knowledge at the time of writing, the only study exploring full CCUS business models applicable to the steel sector. The main recommendations to drive a business case for industrial CCUS are presented as follows:

1. A need for government support to develop a transport & storage infrastructure, as companies remain hesitant to take the first initiative in capturing emissions without guarantee of emission exit points and hence of revenue generation. This resonates with findings of recent studies and is further reflected in the UK's move towards decoupling capture business models from T&S business models [16,91]. For industrial sectors such as steel, the move towards decoupling T&S from capture business models is especially relevant as failure to do so will translate to higher production costs and smaller profit margins, and hence to higher risks of losing international competitiveness in the absence of hedging mechanisms. Moreover, as T&S experience and knowledge of building pipeline infrastructure are more readily existent in the power sector, an opportunity emerges for industries to share infrastructure with the power sector, given a proximity of industrial clusters to geological storage sites or major users of captured $CO_2$. The effects of these economies of scale would also be more easily captured by the steel industry in particular, as steel plants are generally located closer to the coast, while cement kilns are often located close to inland mining facilities [149].
2. Creation of a clear risk-allocation system along the full CCUS chain.
3. Establishment a CCUS-specific regulatory framework.
4. Ensuring if CCUS becomes a mainstream technology for reducing emissions in the industrial/steel sector, that mechanisms are in place such that companies do not risk losing international competitiveness.

The need to define the remaining elements of a business model, in particular funding sources, capital & ownership structure, and risk management comes only secondary to defining the central

element responsible for creating value proposition for CCUS projects, and that is the revenue stream. This study makes it evident that the market is more receptive to mechanisms which reward CCUS initiatives over those enforcing them. We find that the main incentives for the uptake of industrial CCUS further echo Boons and Lüdeke-Freund [40], Brown and Wahler [59], and Orsato's [62] sustainability drivers in business models, which are here presented in terms of:

1. Customer-driven rewards, due to increased customer demands for carbon-free material, a market for which could be established within the next 5–10 years.
2. Regulator-imposed penalties, such as a stringent carbon price in the form of a carbon penalty for additional $CO_2$ emissions emitted above a certain benchmark or per absolute $tCO_2$ emitted.
3. Shareholder-related pressures, as shareholders become more vocal about a need to decarbonize the industry.

In addition to decoupling T&S from capture business models, other identified de-risking mechanisms for a full industrial CCUS chain may include:

1. Defining long-term storage liability; which should be borne by the state or by an insurance company, and not by a private enterprise, as private enterprises are likely unwilling to bear such a long-term burden on their balance sheets;
2. Provision of low-interest loans for an emerging industry; such as loan guarantees at reasonable rates provided by development banks; and
3. Embedding R&D initiatives on individual parts of the full chain within a strategic CCUS-specific masterplan which ensures that investment streams and the industry's efforts are in sync and are decoupled from political changes which may occur every five years.

The study also makes a clear case for exploring innovative business models, such as the introduction of 'low- or zero-carbon' steel products into the market. However, the regulatory framework, supporting bodies, funding sources, willingness to pay of steel consumers and the general public for such products are yet to be appraised, and remain an area for further investigation. Future research should also focus on exploring the influence that successful business models would have at the policy decision-making level.

This work, however, did not come without potential limitations. The sampling sizes for the qualitative methods employed do not substantiate results with statistical significance, but nonetheless offer general trends of perception within the market. Questionnaire respondents and interviewees were also predominantly UK-based, and so the results might not be indicative of the status, potential, and applicability of CCUS business models within other international regions, especially for South East Asian countries. The reviewed academic literature is further limited to publications available in English, with the exception of a few publicly-available publications in Chinese.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2227-9717/8/5/576/s1, Table S1: CCUS (Carbon capture, utilization and storage) business model case studies, Table S2: Questionnaire coding frame.

**Author Contributions:** Conceptualization, H.M., X.L.; methodology, H.M. and K.K.; investigation, H.M.; writing—original draft, H.M.; writing—review and editing, X.L., K.K. and J.W.; supervision, X.L. and K.K.; funding acquisition, H.M., X.L. and J.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded jointly by a collaborative fund provided by the Low Carbon College (LCC) at the University of Edinburgh and Shanghai Jiao Tong University, and a BHP-funded Industrial CCUS project at the University of Edinburgh.

**Acknowledgments:** The authors appreciate the grant support by the BHP-funded Industrial CCUS project at the University of Edinburgh and the Low Carbon College at Shanghai Jiao Tong University (SJTU), without which this work could not have been undertaken. The authors are indebted to Francisco Ascui at the University of Edinburgh Business School for his vigorous support and numerous perceptive comments on various drafts of the manuscript and helpful insights into this work. The authors also thank Yu Lujin and his students Xuan Lin and Lujie at SJTU for their valuable feedback and support in collecting Chinese literature on the topic.

**Conflicts of Interest:** The authors declare no conflict of interest.

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