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C⁴U

Advanced Carbon Capture for steel industries integrated in CCUS Clusters

Innovation Action

D6.1 Report summarising findings from the literature review on CCUS risks and challenges, and radical innovation and market creation (Task 6.1)

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Definitions and acronyms

ACTL	Alberta Carbon Trunk Line
ATR	Autothermal Reforming
BM	Business Model
BMC	Business Model Canvas
BMI	Business Model Innovation
BMIS	Business Model Innovation for Sustainability
CCUS	Carbon Capture Utilisation and Storage
CCU	Carbon Capture and Utilisation
CCS	Carbon Capture and Storage
CSE	Complete Solution Experiment
CEPA	Canadian Environmental Protection Act
CfD	Contract for Difference
DOE	United States Department of Energy
EOR	Enhanced Oil Recovery
ETS	Emissions Trading Scheme
FBC	Flourishing Business Canvas
FOAK	First-Of-A-Kind
FSSD	Framework for Strategic Sustainable Development
GCCSI	Global CCS Institute
JDA	Joint Development Agreement
LCM	Lake Charles Methanol
NSP	North Sea Port
NGCC	Natural Gas Combined Cycle
PPP	Public-Private Partnership
PSS	Product-Service System
RAB	Regulated Asset Base
SBMI	Sustainable Business Model Innovation
SOE	State Owned Enterprise
TRL	Technology Readiness Level

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1 Introduction

The C4U project is a Horizon 2020 funded programme that is working towards advancing two CO_2 capture technologies through demonstrations at an iron and steel plant in the North Sea Port, and detailed consideration of safety and environmental factors. In addition to the successful demonstration of novel technologies, C4U is also focused on investigating how these technologies may be adopted and integrated within industrial clusters such as that of the North Sea Port. In this aspect, the project will look at both societal readiness and public policy (work package 5, WP5) and the long-term business models that may be used for successful CCUS adoption (work package 6, WP6).

The findings presented in this deliverable (D6.1) form the initial basis for the WP6 business model analysis that will be conducted by Element Energy (lead) and Radboud University.

D6.1 Report summarising findings from the literature review on CCUS risks and challenges, and radical innovation and market creation

The deliverable consists of three components: sustainable business model innovation; CCUS risks and challenges; CCUS case studies. Each of these components have been investigated via a desk-based literature review, combining commentary from academic studies, industry focused reports, and project websites. The motivations and aims of each component are outlined below:

Sustainable Business Model Innovation. The adoption of sustainable practices and novel technologies may be facilitated by new and innovative business models, both at the system level as well as at individual firm level. This component reviews the concept of business model innovation (BMI) with a specific focus on sustainable business model innovation (SBMI). The review investigated the motivations and drivers for SBMI, as well as the frameworks and tools that are used to aid the development of such business models. The purpose of this component with respect to the wider goals of WP6 is to facilitate innovative thinking during the conceptualisation of long-term business models and to aid the development of a framework for assessing potential business models.

Risks and Challenges of CCUS. Carbon capture, utilisation, and storage (CCUS) projects bring some unique risks and challenges that may not be fully understood or realised. The lack of understanding of these risks may act as a barrier to the adoption of CCUS, and the lack of awareness of potential challenges (and how to overcome them) can lead to the unsuccessful completion or early cancellation of CCUS projects[1]. This component identifies risks and challenges associated with the implementation and continued operation of CCUS projects, including learnings from past projects and factors that may lead to success or failure. The purpose of identifying these risks and challenges is to facilitate the development of business models that can act to either eliminate risks or mitigate the impact that risks may have on the business case and CCUS project drivers[2].

CCUS Case Studies. As of 2019, there were approximately 51 ongoing, large-scale CCS projects, and a further 39 in pilot or demonstration phases[3]. The motivations, enabling factors, and business models adopted by these projects may provide valuable insights relevant to the adoption and integration of industrial clusters, such as the North Sea Port. This component presents a selection of case studies in which the motivations, enabling factors, and business models of specific CCUS projects are investigated. The purpose is to allow the business models developed within WP6 to take inspiration from existing approaches and existing mechanisms.

[1] Conclusions from previous Element Energy research (unpublished) in the field of factors impacting the constructability and operability of CCUS projects.
[2] The variable ability of different funding and revenue models to accommodate CCUS risks is illustrated in: Element Energy 2018, Industrial Carbon Capture Business Models
[3] Global CCS Institute, 2019. The Global Status of CCS: 2019. Australia.

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The findings from each of these components will be used to inform subsequent stages of the WP6 analysis, with the ultimate aim of determining viable long-term business models for industrial clusters with nearby geological storage, such as the North Sea Port. Subsequent analysis stages will include identification of learnings from UK industrial CCUS projects; engagement with key stakeholders via close cooperation with the North Sea Port and the Carbon Connect Delta project; development of a business model innovation framework; and the short-listing and further development of promising long-term business models for industrial clusters with nearby-geological storage, such as North Sea Port.

The following three sections summarise the findings ('results') for each of the research components listed above, with their own concluding discussions where appropriate. The final 'Conclusions' section is used to highlight the status of the work conducted and the results achieved in the context of the deliverable objectives.

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2 Drivers of Sustainable Business Model Innovation: A Systematic Literature Review

The adoption of sustainable practices and novel technologies may be facilitated by new and innovative business models, both at the system level as well as at individual firm level. This component reviews the concept of business model innovation (BMI) with a specific focus on sustainable business model innovation (SBMI). The review investigated the motivations and drivers for SBMI, as well as the frameworks and tools that are used to aid the development of such business models. The purpose of this component with respect to the wider goals of WP6 is to facilitate innovative thinking during the conceptualisation of long-term business models and to aid the development of a framework for assessing potential business models.

2.1 Introduction

Most parts of the world are suffering from global warming and global warming is even considered as the biggest threat for future generations (WEF, 2016). To mitigate the effects of climate change, the IPCC has set goals and governments have made contracts (UNFCCC, 2020). Private firms on the other hand have no such covenant. Because ‘being green’ often requires considerable investments, firms are not always incentivized by short-term economic arguments. However, by innovating their business models, firms might trigger a win-win solution, because they can add value to their company, while pre-sorting on sustaining profitability in the long-run and contributing to the goal of zero net emission in 2050.

In the past two decades, research on business models (BM) and business model innovations (BMI) has exploded (Foss & Saebi, 2017; Massa & Tucci, 2013; Zott et al., 2011). Because of the multi-disciplinary nature of the topic, the literature is diverse and scattered. Hence the multiple reviews on the topics, like Chesbrough (2010), Zott, Amit, Massa (2011), Schneider & Spieth (2013), Spieth, Schneckenberg, Ricart (2014), Massa & Tucci (2013), Foss & Saebi (2017), categorise the existing literature and shape order in definitions. Business models emphasize a system-level, holistic approach to explaining how firms “do business” (e.g. Zott et al., 2011), or more precisely how firms create, deliver and capture value (Teece, 2010: p.172). The innovation in a business model, BMI, is established as: “designed, novel, nontrivial changes to the key elements of a firm’s business model and/or the architecture linking these elements.” by Foss and Saebi (2017). In this paper we adopt this definition and highlight that the BMI is not merely a product innovation or a novel revenue model. Instead, BMI is aimed to change the value proposition of a firm and allows to operate in or create new markets, linking it to radical innovation.

With the outbreak of Covid-19 and the subsequent local and worldwide measures, BMI has been observed widespread. To ensure safety, firms had to be innovative in redesigning their existing products; designing alternative digital products and services; and/or rethinking their product and service delivery channels and mechanisms; and to look for strategic positions and partners in the new ecosystem who can help them achieve these (Seetharaman, 2020). Hopefully, this will give researchers empirics to bring more understanding in the field of BMI. The observed resilience of firms shows that, given changes in the business environment, firms are very well capable of adapting their activities. However, does this hold for all changes in the business environment, for example also for the more stealthily transition to a more sustainable system? To recover from the economic crisis some policy makers and scholars propose a sustainable focus (EU, 2020; OECD, 2020). Hence, the study of sustainable business model innovations could be important for the recovery of firms and economies worldwide while leading to better performance regarding sustainability.

Although BMI and sustainability are connected to each other in the literature, the exact connection between the two remains unclear and requires further investigation (Massa & Tucci 2014, Foss & Saebi 2017). In 2020, Shakeel et al. published their anatomy of sustainable business model innovation, in

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which the existing literature on BM, BMI, SBM and SBMI[4] is analysed and a comprehensive view of the derivative philosophy is made. Other publications on SBMI are of the explorative type and focus on the establishment and implementation of SBMI, or analysed the possible role it could play for a systemic change towards sustainability. Unfortunately, to date, little is known about the financial and sustainable performance of SBMI by a lack of empirics. Therefore, this literature review contributes by offering a managerial perspective and analysing the required drivers, that is, conditions, resources, processes to establish SBMI. The research question of this systematic review is:

What are the drivers of business model innovation for sustainability?

This is not only relevant for researchers, but also for policy makers and practitioners, for whom an overview of the tools to engage in BMIS is given. BMI is especially relevant for practitioners in mature sectors (Conway & Steward, 2009, p.190; Zott & Amit, 2007) with high global competition. CEOs have indicated to see BMI as important to create value and allow for future competitive advantages (Rometty, 2006) because it is more difficult to imitate than a single novel product (Amit & Zott, 2012) and it is linked with the creation of radical innovations (Bourreau et al., 2012). Besides, empirical evidence has shown that CEOs see sustainability as more important than ever for long term success (Laukkanen & Patala, 2014) and that sustainable development goals foster innovation capabilities and therefore also is a source of competitive advantage (Inigo et al., 2017). Successful businesses have realized that society's transition towards sustainability give rise to challenges and opportunities (França et al., 2017). For example, the raw material manufacturing industry, which is accounting for a large part of global emissions and feels pressure to take responsibility. Hence, BMI for sustainability has serious potential to contribute to abatement.

In this literature review it is found that SBMI can reduce operational costs (e.g. Schaltegger et al., 2012) and future risks (e.g. Pedersen et al., 2018), allows to capture the needs of stakeholders and consumers (Breuer & Lüdeke-Freund, 2017), can capture uncaptured value (Yang et al., 2017) and opens new markets (Karlsson et al., 2016). SBMI requires dynamic capabilities (Inigo et al., 2017), including creativity and knowledge, to sense and seize the opportunities of the sustainable transition. Such capabilities can be synergized by the formation of networks. For the diffusion of sustainable business models, knowledge dissemination suffices (Karlsson et al., 2016). However, radical innovation requires disruptive, multi-stakeholder, networks where responsibility is shared, inter-partner learning takes place and design processes are mutual (Inigo et al., 2017). Such collaborating networks allow for co-creation and co-innovation (e.g. Velter et al., 2020), which allows for reaping the benefits of a successful sustainable transition (Laukkanen & Patala, 2014; Pedersen et al., 2018).

[4] BMIS interchangeably to use with SBMI (e.g. Shakeel et al. 2020)

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2.2 Methodology

A systematic literature review was performed for this chapter. This allows to systematically characterize, assess and abstract appropriate information from the selected articles and is especially useful for topics transcending one research tradition. The literature on BMIS can be divided in two main research streams. The first considers business and management literature, which focusses on theorization, conceptualization and works towards research agendas. The comprised business and management journals are Academy of Management Journal, International Journal of Technology Management, Technological Forecasting and Social Change and International Journal of Innovation Management. The second, broader, stream of literature comprises interdisciplinary journals, which often take a more managerial perspective by discussing experiences from practitioners placed in a known theoretical framework or develop tools to be put in practice. Examples of such journals are the Journal of Cleaner Production and Business Strategy and the Environment. To filter relevant publications from the broad stream of literature it is suitable to conduct an article title search only, while important theories on BMIS demand a broader search scope and thus requires a topic search.

A systematic review is characterized by strict inclusion and exclusion criteria. This commences by defining the right keywords. Because the concept of business model emphasizes a bridge between the company level and the systems level (e.g. Pedersen et al., 2018; Zott et al., 2011), "business model innovation", "radical innovation" "systemic innovation" and "systemic development" are identified as important keywords. Furthermore, in this review interest lies in the radical character of SBMI and the implications to the systems level, as radical innovation can bring about systemic change. Hence, incremental innovations, like process efficiency or product innovation are discarded. Sustainability in the view of this paper is understood as "significant positive or reduced negative impacts for the environment". Therefore, ecological and environmental act as similar terms for sustainable when conducting the search. Hence, the search terms were the 12 combinations of the adjectives "sustain*", "ecolog*", "environment*" with "business model innovation", "systemic innovation", "systemic development" and "radical innovation". The search was conducted on Web of Science, comprising all years, limited the results to peer-reviewed articles, to ensure quality. The selection tree can be found in Figure 2.

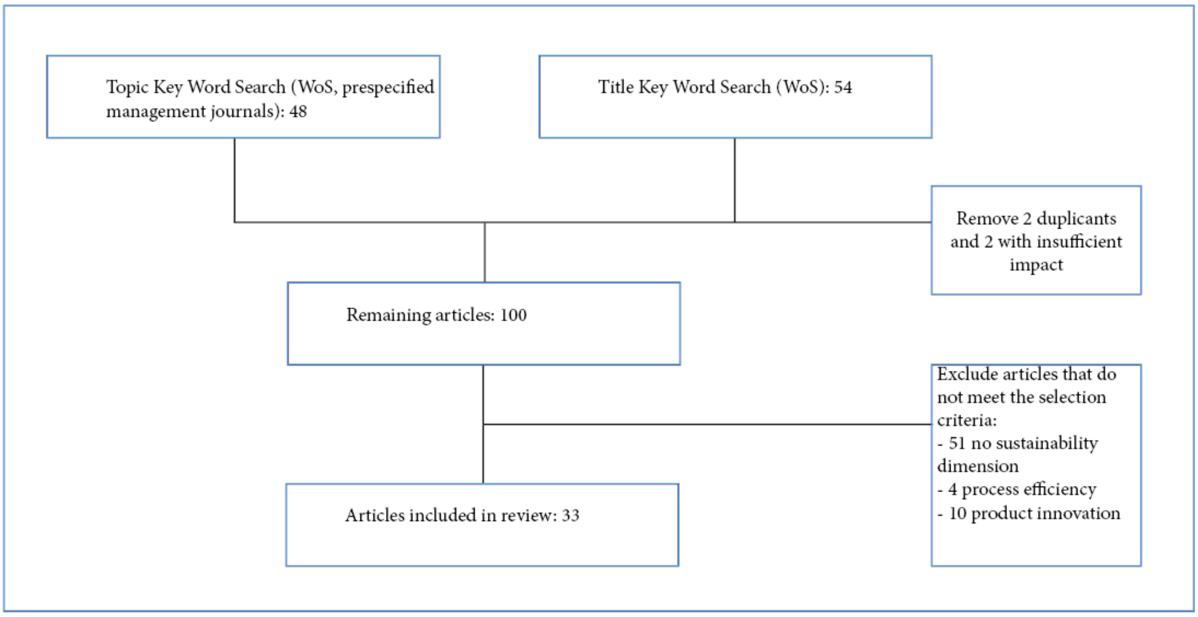

Figure 1: Literature selection tree

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The included studies on business models for sustainability and systemic sustainable innovation are indeed diverse. Scholars that have written about this topic have backgrounds in Economics, Policy, Industrial Organization, Industrial Engineering, Sustainability Management, Sustainable Development, Business Administration and Innovation Management. Theoretical perspectives used are amongst others the transitions perspective, intellectual capital, organizational learning and experimentation, innovation systems, boundary work, social enterprises, business modeling, networks theory, stakeholder theory, dynamic capabilities and uncaptured value theory. However, significant disagreements on the definitions in business model innovation for sustainability were not found, although some authors didn't specify a definition. The variety on perspectives leads to multiple abstraction levels of which the 'smallest' is entrepreneurial level, followed by the firm-level, market-level, cross-industry level and an entire socio-technical system level. Furthermore, to understand better why and how firms practice BMIS it is useful to look at entrepreneurial or firm-level motivations and capabilities (Inigo et al., 2017; Laukkanen & Patala, 2014; Peralta et al., 2019), while the successful shift to a sustainable system, and the role of SBMI therein, demands a system level approach (Dijk et al., 2015; Wesseling et al., 2020). The methodology of the included papers consists of literature reviews, case studies, surveys, interviews, the DELPHI method and action research and one quantitative factor analysis. It is thus important to compile the perspectives created by this explorative research and shine a light against their findings, to map their functionality and coherency.

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2.3 Literature Review

According to Pedersen et al. (2016) and Shakeel et al. (2020), in their papers exploring the relationship between sustainability and BMI, SBMI is at the intersection of Business Model Innovation and Sustainable Business Models, therefore, both are explicated separately below to give a theoretic overview.

2.3.1 Business Model Innovation & Structural Forms

Most authors adopt the definition of BM from Teece (2010, p.172) that positions a business model as the 3-pillar value creation, value delivery and value capture. I.e. the revenue model (value capture) is only a part of the business model. The two different definitions of a BM acknowledge this and adopt the value proposition and the organization of the downstream and upstream value chain (Boons & Lüdeke-Freund, 2013), and the value proposition, costumer interface and infrastructure (Schaltegger et al., 2012). An innovation in the business model considers designed, novel changes in the key elements of the BM and/or the components linking the elements (Foss & Saebi, 2016). Therefore, BMI is bigger than a one-dimensional product, service or process innovations (e.g. Pedersen et al., 2018) or changing the revenue model. Rather, the concept positions the firm in the value chain, and thus not only comprises internal structure of a firm, but also the organization with respect to the external business environment.

As a consequence, engaging with BMI is not an easy task. It is about positioning a firm fundamentally different in the market, while understanding and making use of its core competencies. Hence, BMI is strongly linked with radical innovation, opposed to incremental innovations resulting from one-dimensional product, service or process innovations (Inigo et al., 2017), see example box 1. A strong difficulty therefore is to cope with so-called limited cognition (Richter, 2013b), which means that managers tend to think in a status quo manner, they suffer from lock-in. As an example, German utilities have failed to incorporate renewable energy in their business model, losing a great market share to external investors and prosumers (ibid.). The problem is not the technology, but the commercialization, the fail of proposing a radical different value proposition (Chesbrough, 2007).

Example box 1: radical versus incremental innovation in the video rental market.

Radical innovation is aimed to create a new market instead of enlarging the market share by incremental innovation. Netflix is a good example of radical innovation, it created a new video-streaming market with a revenue model based on subscriptions to watch all of its owned video content, opposed to brick-and-mortar video rental shops. Nevertheless, the brick-and-mortar shops adopted incremental innovations strategies to withstand competition, such as renting Blu-ray-DVD's, a product innovation, snail mail video delivery, a new service, and optimizing this service by sending the ordered video from a close retail store instead of from centralized distribution to cut costs and delivery time, a process innovation. The bankruptcy of Blockbuster in 2010, and the commonality of Netflix now show that the old business model was unable to cope with the radical new business model of Netflix.

Although, the literature suggests that newcomers are often the ones that disrupt and lead to systemic innovations by introducing new business models, like AirBnB or Über (Antikainen & Valkokari, 2016), this does not mean that incumbents are incapable of performing BMI. Tools exist to assist analyzing core competencies and designing new (sustainable) business models (Antikainen & Valkokari, 2016; Karlsson et al., 2016; Mahmoud-Jouini & Charue-Duboc, 2017; Velter et al., 2020; Wadin et al., 2017; Yang et al., 2017). Also, multiple forms and structures of BMI exist (Bolton & Hannon, 2016; Richter, 2013b; Wadin et al., 2017). Richter (2013a) recognizes two approaches for improving BMI capabilities of incumbents: organizational structure and external partnerships. The organizational structure refers to

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three types of identified BMI: 1) complete BMI, 2) segmental BMI and 3) independent BMI (Richter, 2013b), see Figure 2. Complete BMI comprises a fundamental redesign of the existing core business model, however it usually is subject to strong barriers, of which the most common are conflicts with the current BM and cognitive barriers. Segmental BMI comprises innovation of parts of the business model. There is an organizational link between the innovative division and the parent, but usually gives the new venture room to grow to later become a more important part of the overall company. In independent BMI new activities are not directly linked to the core business in organizational terms. It can be seen as a strategical investment and almost completely avoids classical barriers to BMI. However, it can be difficult to later integrate the innovation into the core business.

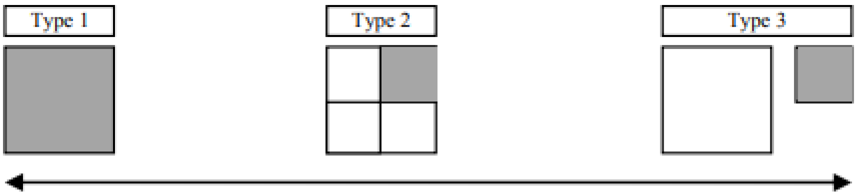

Figure 2: Types of business model innovation. The large quadrate represents complete business model innovation; the grey quadrant represents the area of innovation. Picture from Richter (2013b).

A special structure of the last typology is a joint venture. In a joint venture two or more actors found a new legal entity. It therefore isn't so much affected by the cognitive barriers, on the contrary, it can build on the knowledge and expertise of the founders. Historically, joint ventures are created to combine skills and capabilities to make new products, enter new markets and use assets and operations efficiently (e.g. Sony Ericsson, Dow Corning). However, cooperation does not need to end at product, process or service innovation, it can also be used to develop new business models. Wadin et al. (2017) have researched these so-called joint business model innovations in a David and Goliath setting. They developed a (game-)theoretical framework in which both the David and Goliath could adopt a cooperative and a competitive strategy. Conventionally, that is, when a Goliath is searching for a new codified technology, the large firm tends to choose a "race-to-learn" mode, eventually defecting the cooperation and appropriating most of the learning in the alliance while leaving the small firms with limited learning outcomes. In the case of BMI however, learning outcomes are not only codified, but there is also a lot of value in tacit knowledge. The transfer of tacit components of a business model requires more time and transparency and is hardly transferred in a "race-to-learn" strategy, see the pay-off matrix in Figure 3. Hence, they conclude that in the case of BMI the large firms have stronger incentives to cooperate. Finally, to overcome internal barriers like conflicting assets, culture and receptivity, a joint venture structure would be optimal, Wadin et al. conclude. Joint venture can also serve other purposes, for example Richter (2013a) and Bolton & Hannon (2016) describe Private Public Partnerships in the renewable energy and combined heat and power sector, respectively, leading to realization projects with relatively low financial risk. Cooperation thus leads to business opportunities in the case of BMI, later we will discuss the role of cooperation and networks for SBMI, but first we will turn our attention to sustainable business models.

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Example box 2: Joint venture in CCUS: Porthos

"Porthos is a joint venture between the Port of Rotterdam Authority, Gasunie and EBN. Each of the organizations brings its own experience and expertise to this CCUS project: The Port of Rotterdam Authority will be focusing on the local situation and market, Gasunie can offer extensive experience with gas infrastructure and transport, and EBN will be sharing its expertise in the area of deeper soil layers and offshore infrastructure." This joint venture is established to pursue innovation, to create a market for CCS and deploy the infrastructure. The Porthos project is an example of independent SBMI, because a new venture is established. It is sustainable because Porthos engages in pollution control. Furthermore, Porthos creates a new type of value; CO2 disposal, and delivers this value explicitly using the established network of the Port of Rotterdam Authority, which is an innovation with respect to the typical stakeholder approach of Gasunie and EBN, the value capture (revenue model) is yet to be established.

(Porthos, 2020)

	Large firm (LF)	
Small firm (SF)	**Cooperate**	**Compete**
Cooperate	**Cooperative BMI** SF = very high (very high tacit + very high codified) LF = very high (very high tacit + very high codified)	**Large firm "race to learn" BMI** SF = low (low tacit + low codified) LF = medium (low tacit + high codified)
Compete	**Small firm "race to learn" BMI** SF = medium (low tacit + high codified) LF = low (low tacit + low codified)	**Deadlock** SF = very low (very low tacit + very low codified) LF = very low (very low tacit + very low codified)

Figure 3: Pay-off matrix from Wadin et al. 2017 for a cooperative or competitive strategy between a large and a small firm in the case of BMI. Note that the pay-off for a large firm in a race-to-learn is low tacit + high codified, instead of only high codified.

2.3.2 Sustainable Business Models

Obviously, if one wants to change its BM to be more sustainable, knowledge is needed about what sustainable business models are. In a seminal paper, Bocken et al. (2014) specified 8 SBM architypes. Laukkanen and Patala (2014) increased it to 9 by adding the pollution control archetype, consisting of the aim of elimination of emissions by new product innovations. An adapted version of this can be found in Table 2. The strong point of these two representations is the clear structuring in archetypes, aims and examples, where it is easy to identify the relation between the aim and the sustainable impact of the BM. However, the creation of these classifications have been developed rather ad hoc and methodological explanation, transparency or external validation according to Lüdeke-Freund et al. (2018). Therefore, the classifications are partly overlapping - indeed, Laukkanen and Patala (2014) subdivided the first archetype - and possibly incomplete.

Nevertheless, Lüdecke-Freund et al. (2018) continued this work by developing a taxonomy. From 14 studies, they identified 45 business model patterns – generic solutions to recurring problems – and grouped this in 11 groups by consulting 10 international experts. A nice feature to their research is that

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the groups are subsequently ranked on a triple bottom-line scale, see Figure 4. The 4 groups and 20 patterns that are clearly related to ecological sustainability are given in

Table 1.

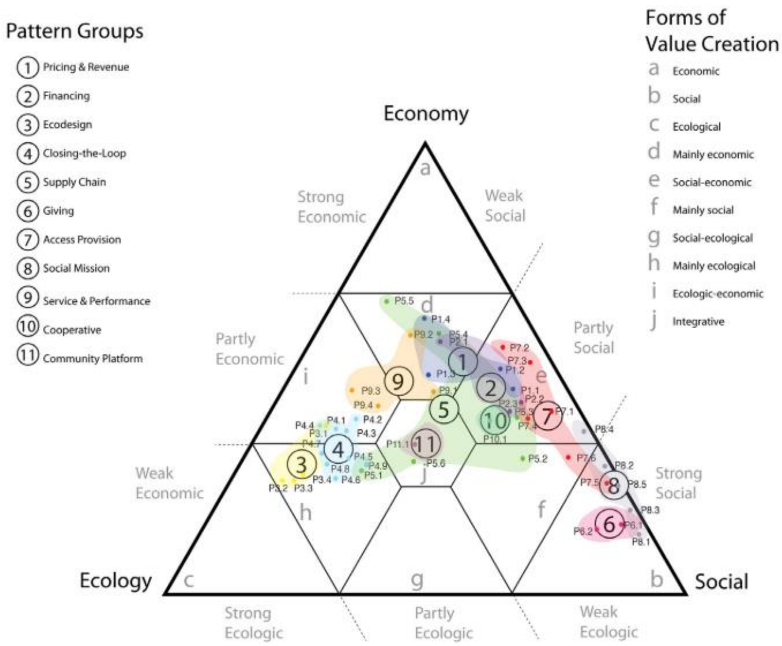

Figure 4: Triangle of the group level sustainable business model pattern taxonomy, by Lüdeke-Freund et al. (2018).

Table 1: Pattern groups and business model patterns creating ecological value. From Lüdecke-Freund et al. 2018.

G3 Ecodesign Patterns	G4 Closing-the-Loop Patterns	G11 Community Platform Patterns	G5 Supply Chain Patterns
Hybrid model / Gap-exploiter model	*Co-product generation*	*Sharing business*	*Green supply chain management*
Maximize material productivity and energy efficiency	*Industrial symbiosis*		*Inclusive sourcing*
Product design	*Online waste exchange platform*		*Micro distribution and retail*
Substitute with renewables and natural processes	*Product recycling*		*Physical to virtual*
	Remanufacturing / Next life sales		*Produce on demand*
	Repair		*Shorter supply chains*
	Reuse		
	Take back management		
	Upgrading		

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From Figure 4, it is clear that most of the identified patterns lack ecological sustainability. Where Bocken et al. (2014) define BMIS as "innovations that create significant positive and/or significantly reduced negative impacts for the environment and/or society, through changes in the way the organization and its value-network create, deliver value and capture value (i.e. create economic value) or change their value propositions." (p. 44), Lüdecke-Freund et al. (2018) use "[companies] enhance their ability to create multiple forms of value. In other words, they deliberately create forms of sustainable value" (p.147), and therefore adopt a larger definition than environmental sustainability. Moreover, there is no direct relationship between the patterns and groups of Lüdecke-Freund et al. (2018) and the archetypes, aims and examples defined by Bocken et al. (2014). For example, the pattern "reuse" relates to the architype "creating value from waste", while the group "closing the loop patterns" is only an example from the same architype. Also, the architype "maximize material and energy efficiency" is a pattern in the taxonomy of Lüdecke-Freund et al. (2018) and not identified as group. Nevertheless, additions to the framework of Bocken et al. (2014) can be identified. That is, where the first three columns of

Table 1 are traceable in the framework of Laukkanen and Patala (2014), e.g. pollution control relates to product design, closing-the-loop with creating value from waste, the fourth column (G5) is missing in their framework. Falling back on the business model literature, the up- and downstream organization is an important mode in the BMI. Therefore, an organizational archetype can be added to the framework: "Green supply chains management". This archetype would aim to create significant positive and/or significantly reduced negative impacts for the environment and/or society, through changes in the supply chain. Of which examples are: Produce on demand, Shorter supply chains (local suppliers), Inclusive sourcing, Micro distribution and retail, Physical to virtual. That this is an archetype is backed by the fact that such supply chains can lead to additional value creation and is environmentally beneficial according to the IPCC (Shukla et al., 2019). Further note, efficient supply chains are mentioned in Laukkanen and Patala (2014) but are incorporated under technology. Their focus lies on technological efficiency, while overlooking the fact that abatement can also be achieved by different forms of (up- and downstream) organization.

The resulting framework can be found in Table 2, with a demonstration for CCUS in example box 3. The first four archetypes in Table 2 focus on innovation in product and manufacturing processes. By creating sustainable products and/or using renewable sources in the manufacturing process, pressure on the environment can be relieved. The critical reader notes that these archetypes are not singular, but complementary. As an example, electric vehicles are a technical innovation reducing pollution with respect to combustion engine vehicles in end-consumer operation. On top of that, the manufacturing process could be eco-optimized by efficiently using resources. At the end of the cars lifetime, the battery packs can be used to take part in smart grid systems. Hence, the EV company can adopt multiple SBM types. An important note on the sustainability impact of technical innovations is unfortunately that cleaner products and more efficient processes can also have rebound effects, known as the Jevons paradox, as it can lead to more consumption.

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Table 2: Sustainable business model archetypes, adapted from Laukkanen & Patala (2014).

Innovation type	Technological				Social			Organizational		
SBM archetype	Pollution control	Maximize material and energy efficiency	Create value from waste	Substitute with renewable processes	Deliver functionality rather than ownership	Adopt a stewardship role	Encourage sufficiency	Re-purpose the business for society/environment	Develop scale-up solutions	Green supply chain management
Aim	Elimination of emissions via new product innovations and cleaner production	Optimized use of resources; "do more with fewer resources"	Elimination of the concept waste; Reduced waste and virgin materials	Reduced use of non-renewable resources, emissions associated with burning fossil fuels and synthetic waste to landfill	Maximized use of products; business focus on satisfying user needs without product ownership	Stakeholders' long term health and well-being, and maximized positive social/environmental impacts through upstream and downstream stewardship	Reduced production and consumption; reduced overconsumption on systems level	Prioritized delivery of social and environmental benefits (rather than economic profit maximization)	Maximized benefits for the society and environment by delivering sustainable solutions at large scale	Create significantly reduced negative impacts for the environment and/or society, through changes in the supply chain.
Examples	Low carbon manufacturing; low carbon supply chain; low carbon solutions	Lean manufacturing; dematerialization; increased functionality	End-of-life strategies (reuse, repair, recycle); closed-loop supply chain; cradle-to-cradle; industrial symbiosis	Move from non-renewable to renewable energy sources; biomimicry; green chemistry	Product-service systems	Ethical fair trade; biodiversity protection; resource transparency; radical transparency about environmental impacts; impact compensation	Consumer/user education; product durability and longevity; responsible product promotion; shared ownership; collaborative consumption	Social businesses; hybrid businesses; base of pyramid solutions; alternative ownership; cooperative collections	Licensing; franchising; co-creation; open innovation; crowd-funding; lobbying	Produce on demand; shorter supply chains (local suppliers); inclusive sourcing; co-creation; closed-loop supply chain management; micro distribution and retail

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Therefore, socially oriented eco-innovations are also important. Three social architypes can be found which focus on changing consumer behavior and innovations in consumer offering. Product-service systems are at this time, by far, the most researched sustainable business models. An example can be found in example box 4. The rationale is that tangible products are maximally used by being transferred between different users such that resources are more optimally used. Moreover, because the product stays in the ownership of the operator, the operator has higher incentives to create products that are easily repairable such that the longevity of the product increased, i.e. has an end-of-life strategy which captures yet uncaptured value (Yang et al., 2017). Adopting a stewardship role denotes ensuring the long-term wellbeing of stakeholders, for example by transparency and subsequent action/compensation, see example box 5. The information asymmetry between consumers and producers is reduced by this transparency, possibly changing the consumer behavior.

Such transparency can be related to technical performances, already commonly used in sales, but can have larger effect with respect to organizational innovations. Being transparent on a local supply chain or collaborating in a network to realize closed-loop products could significantly add value to the consumer. In order to realize such systems, innovation in organization and culture of business practices should take place.

Example Box 3: SBM for CCUS

To demonstrate the SBM framework in the context of CCUS, the CCUS process is divided into three parts, with three hypothetical companies. The CC-company, where CO2 is captured, the TS-company, which is responsible for transport and storage of CO2 and U-company, which uses CO2 to make products. Hence, the companies can engage with the following SBM archetypes:

CC: pollution control, create value from waste, green supply chain management (as a green source)

TS: pollution control, purpose the business for environment, develop scale-up solutions, deliver functionality

U: create value from waste, adopt a stewardship role (especially resource transparency)

Example box 4: Product Service Systems

Sousa-Zomer & Cauchick-Miguel (2019) investigate a company leasing water-purifying systems in Brazil. Additional value is created by offering free repairs and ensure clean water can be consumed at all times with respect to buying a water-purifying system which can break down. The financial model allows a large share of the population to purchase their service. The company has a clear incentive to make easy repairable systems, such that they can continue their service delivery. This could save the waste of thrown-away, but reparable, systems. On the other hand, the enlarged market also calls for more water-purifying systems to be installed. There is an ongoing debate about the performance of PSSs, where the provided service and stakeholder management seem to be leading indicators for economic and sustainable performance, respectively. Nevertheless, in this example, water-purifying systems save bottled water consumption.

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Example box 5: Adopting a Stewardship Role (and communicating it!)

In 1988, Ben & Jerry's was one of the first companies in the world to place a social mission in equal importance to its product and economic missions. True to their pioneering spirit, they became the first-ever wholly-owned subsidiary to gain Benefit Corp Certification, a new type of corporation that uses the power of business to solve social and environmental problems. Ben and Jerry's promote a fair and global economy, social justice, the environment, sustainable food systems and refugees, they have built a track record of projects implementing these values, and actively report their environmental impact.

In 2000, Ben & Jerry's is purchased by Unilever. Instead of changing the business model, it carried on with the social missions. Unilever might even have learned from this innovative way of doing business. In 2010, the company implemented its ambitious Sustainable Living Plan which aimed to double its growth, halve its environmental impact and triple its social impact. The plan succeeded, with Unilever's annual sales rising from $38 billion to more than $60 billion, and the company becoming a beacon for those who wanted their work to matter.

Ben & Jerry's (2020), Forbes (2020)

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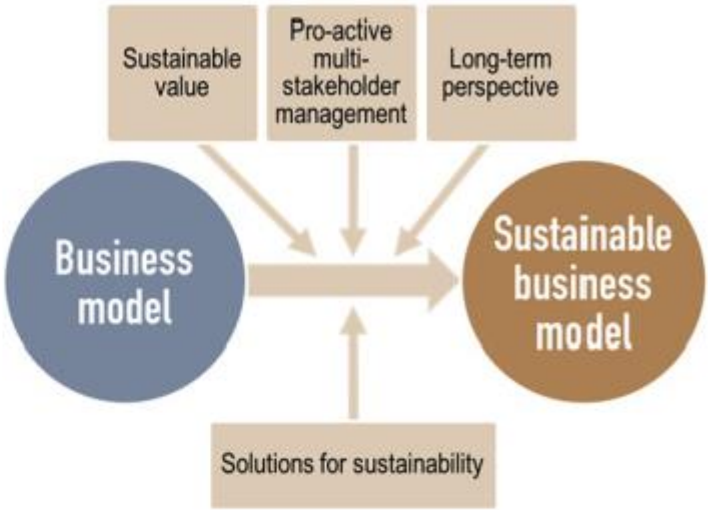

Figure 5: Perspectives on sustainable business models, from Geissdoerfer, Morioka, et al., (2018).

2.3.3 Drivers of BMIS

Drivers of BMIS are conditions, resources or processes that are vital for successful implementation of BMIS. The literature distinguishes economic drivers and organizational drivers. It turns out that cooperation between stakeholders is regarded as important for the establishment of BMIS. By adopting a pro-active multi-stakeholder attitude, non-monetary value for a broad range of stakeholders can be created and a long term perspective is more easily taken (Geissdoerfer, Vladimirova, et al., 2018), see Figure 5. As a consequence, developed processes, services or products capture the needs of stakeholders and consumers better (Breuer & Lüdeke-Freund, 2017), uncaptured value can be captured (Yang et al., 2017) and new markets can be opened (Karlsson et al., 2016).

Firm level conditions

Economically viability is an aspect on which the adoption of SBM is assessed and is a vital condition on which this innovation takes place. Economic arguments can be divided in two branches: cost and risk reduction and increased value capture. Cost reduction is seen as an important driver (Schaltegger et al., 2012). By saving energy or reduce material flows the company can lower operational costs. Others note that by adopting a SBM potential costs can be reduced, related to political and market risks or law suits (Pedersen et al., 2018). A special type of risk is explained by França et al. (2017) with the funnel metaphor. They state that organizations who stay relatively ignorant about the necessary and already ongoing paradigm shift towards sustainability, are also the organizations that are exposed to higher and higher economical risks. Because competitors are skillfully becoming part of 'the solution' firms lose their ability to innovate. The other way around, Pedersen et al. (2018) argue, stepping into BMIS can create a first mover advantage. Additionally, Schaltegger et al. (2012) contribute, by engaging in BMIS increased sales and profit margins can be realized, plus longer term benefits like reputation and brand value, which again lead to better customer relations (Pedersen et al., 2018) and a more stable revenue stream.

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System level conditions

The literature taking a socio-technical system perspective focus on the conditions for successful adoption of radical innovation leading to a sustainable system. This perspective advocates that the status quo, or regime, is hardly capable of performing radical innovations. The current market is namely instantiated in contracts, subsidies, joint used infrastructures, financial structures as well as expectations, behaviors, common interests, and routines between actors (Wesseling et al., 2020). On the other hand, niche actors are less bound by the status quo and are able to set new BMs in the market. Hence, they are able to *stretch-and-transform* the landscape, by capturing new value or developing new value networks (*ibid*.). The other way around, when external pressure is put on regime actors, for example by environmental policy, regime actors draw on niche expertise to *fit-and-conform* the new socio-technical system. The relationship between niche and regime actors can very well be symbiotic; the niche offers potential solutions to regime and landscape problems, yet the regime has the resources to mobilize these solutions. Moreover, a diversity of niche is important to have a multitude of potential solutions (Nykvist & Whitmarsh, 2008). Therefore, networks between niche and regime actors act as incubator for new solutions and business models, and result in regime transition or hybridization, depending on the share of niche actors in a particular market (Dijk et al., 2015).

Also, policy plays an important role (Mazzanti & Rizzo, 2017; Nykvist & Whitmarsh, 2008). Mazzanti & Rizzo (2017) examine the decarbonisation trajectory and environmental policy in EU energy, steel and ceramics sector in detail. Evidence highlights that incremental innovations prompted the trend towards achievement of 2020 targets. However, radical innovations, of which the most promising are energy storage and CCS, are necessary with respect to 2050 targets. However, technological innovation will only have impact if coupled with organisational and societal innovations. Because financial policy (carbon pricing, ETR, ETS) only brings about incremental innovations, they argue, policies directed at the environment and innovation are required for radical innovations. Notion should be taken in the design of policy to the fact that complementarity in innovation and knowledge exchange between sectors is a radical asset that can strongly enhance performance and results in a source of national competitive advantage. In other words, systemic change requires systemic innovation, coincident innovations across multiple disciplines, which can be facilitated with the business model concept. To successfully realize 2050 sustainability goals, interdisciplinary multi-actor networks should be backed by policy, such that technological, organisational and societal co-innovation takes place.

Resources

Nykvist & Whitmarsh (2008) and Wesseling et al. (2020) and point out that niche actors prove to be better in the creation of radical and business model innovation, while the status quo can mobilize it. This aligns with findings from studies taking a firm-level perspective. There, important resources for successful BMIS are identified to be creativity (Madsen, 2020; Pedersen et al., 2018) and organizational knowledge (Delgado-verde et al., 2015; Inigo et al., 2017; Laukkanen & Patala, 2014; Mahmoud-Jouini & Charue-Duboc, 2017; Richter, 2013a; Wadin et al., 2017). Resource-wise, engaging in SBMI can trigger a positive feedback loop. It is found that engaging in BMIS makes an organization more attractive as an employer (Schaltegger et al., 2012), and novel employees can bring creativity and knowledge. This resource-based view offers the positive effect of the funnel metaphor from França et al. (2017). Inigo et al. (2017) more specifically address the role of knowledge and creativity in BMIS, in their study about dynamic capabilities and BMIS. Dynamic capabilities are skills and structures, which characterize sensing, seizing and reconfiguring capacities of a firm. Both creativity and knowledge contribute to the sensing and seizing of sustainable business model opportunities by companies. To maintain competitiveness thereafter, they stress the importance of managing sustainability goals at all layers of

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the organization and share responsibility to reach these goals. A successful sustainable business therefore aligns intellectual capital with well communicated triple-bottom line or sustainable vision.

Delgado-Verde et al. (2015) discuss relationship between intellectual capital and radical innovation. They argue that social capital, defined as the way knowledge is exchanged and combined, and human capital offer the highest potential for radical innovation in high and medium-high technology manufacturing firms. In the current knowledge-based society it is therefore key to hire people with higher levels of education and abilities and invest in education and training. On the other hand, they prove empirically with data on 251 Spanish manufacturing firms, that firms lacking these resources, can attempt to influence social networks by encouraging communications within the organization to achieve radical innovation results. In other words, the sharing of knowledge in a social network can moderate for not possessing the knowledge needed for innovations.

Processes

Although, Delgado-Verde et al. (2015) discusses social networks at intra-company level, other authors look at the formation of multi-stakeholder networks for sustainable innovation. There is consensus about the importance the process of network formation and the role of networks throughout the literature and each research tradition. This can be traced back to three primary reasons: 1) increased intellectual capital, for breaking cognitive barriers and knowledge exchange, 2) to allow co-creation of value, 3) to trigger a systemic transition, networks shift firm-level innovation to ecosystem innovation.

The importance of knowledge exchange and breaking cognitive barriers is amongst others explained by Wadin et al. (2017), who encourage experimentation by large firms. They found that complex innovations like SBMI require both tacit and codified knowledge, of which the first is only transferred upon intensive cooperation. As an example, tacit knowledge like marketing capabilities are a lot harder to transfer across organizations than codified knowledge technical drawings, formulae or written text. Richter (2013a) point out the disability of new market penetration by utility firms in Germany by cognitive barriers, where the traditional utilities lost market share to investors and prosumers, as traditional utilities were unable to innovate their business model. Madsen (2017) raises the point that networks can handle complex issues, while making use of individual specialization, resulting in more effective gathering, allocating and maintaining of resources than a single organization. Building networks only for knowledge dissemination is related to a defensive corporate strategy (Schaltegger et al., 2012); although capabilities are not possessed by the company, the company needs to comply with legislation and hence innovates. Inigo et al. (2017) acknowledge this and notice that it does lead to integration of clean technologies, but pure knowledge dissemination by networks will only lead to evolutionary innovation. Nevertheless, Björklund (2018) stresses the importance of knowledge diffusion by networks in her case study on Swedish farms, to overcome internal barriers for BMI, which is hardly observed in this sector. This is recognized by Karlsson et al. (2017) in their study on biogas-producing farms, because external knowledge is key in the initiation and ideation phase. Summarizing, a network for knowledge exchange is a prerequisite for SBMI, albeit only for idea generation, but merely leads to incremental innovations.

For radical SBMI, establishing *disruptive* networks, including environmentally oriented stakeholders, is regarded as important (Inigo et al., 2017). After all, integrating sustainability into business models requires a systemic view that considers the global perspective and different elements of the system and their interrelations (Evans et al., 2017). Therefore, focus should lie on systems based sustainability challenges, trends and collective solutions according to Inigo et al. (2017). This goes further than knowledge diffusion. By including inter-partner learning, shared responsibility and participating in mutual design processes, co-creation occurs. Co-creation is the development of new value by collaborating with stakeholders. As a consequence, developed processes, services or products capture the needs of

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stakeholders and consumers better (Breuer & Lüdeke-Freund, 2017), uncaptured value can be captured (Yang et al., 2017) and new markets can be opened (Karlsson et al., 2016). This has the advantage that financial performance increase (Laukkanen & Patala, 2014; Pedersen et al., 2018), products are harder to copy and stakeholder relations increase. Also, interdependence and integration risks can be lowered with co-creation (Mahmoud-Jouini & Charue-Duboc, 2017). Furthermore, environmental value can be created, by enabling the entire value chain to participate, leading to a sustainable product. Networks help to find like-minded companies and could streamline reporting standards. However, a co-creation network does require some characteristics. Co-innovation is harmed by differing value frames, norms, expectations, unfamiliarity, mutual suspicion, cultural differences and misunderstanding (Velter et al., 2020). Therefore shared values are beneficial, a common vision or goal should be present (Breuer & Lüdeke-Freund, 2017; Karlsson et al., 2016; Madsen, 2020; Wadin et al., 2017), transparency and openness (Mahmoud-Jouini & Charue-Duboc, 2017; Wadin et al., 2017) should be given to a reasonable extent and actors need to be willing to take up new roles (Velter et al., 2020).

2.3.4 Tools for SBMI

To streamline innovation in business practices toward a more sustainable model, existing tools have been adapted and new tools have been created. The best-known business tool is the Business Model Canvas. A framework developed by Osterwalder & Pigneur (2010) to operationalize the value creation, delivery and capture mechanisms on one page. It consists of 9 basic building blocks: customer segments, value proposition, channels, customer relationships, revenue streams, cost structure, key resources, key activities and key partners. Although key partners are mentioned as principle building blocks, both França et al. (2017) and Antikainen & Valkokari (2016) complement this framework with multi-stakeholder engagement and a multi-level perspective to be more BMIS specific. Because business cases of sustainability are typically not understood profoundly enough as the planning horizon and system scope for classical business models are often insufficient.

One way of sharpening the business model canvas for BMIS is to complement it with the Framework for Strategic Sustainable Development (FSSD) (França et al., 2017). It has the competence to bring together people in systemic ventures, analysis sustainability, planning, cross-disciplinary and cross-sector cooperation. The FSSD consists out of five levels: the system level, the success level, the strategic guidelines level, actions level and tools level, and therefore helps structuring and unifying interests of stakeholders. It is created to offer a possibility to facilitate communication and coordination, which is applied in sessions where participants learned the FSSD, assessed the current situation, turn to creative thinking to co-create possible solutions to the gap between the vision and the current situation and subsequently synthesize a strategy. In their case study it was redeemed as helpful and the BMC-FSSD combination caused a firm to transform from a classic product-sales business to a product-service system. However, a general challenge was the lack of direct contact with all types of stakeholders. Also, one could ask whether the framework remains useful if different stakeholders cannot agree on a common vision. Nevertheless, the BMC-FSSD framework proved successful in redefining design, production, distribution, use, end-of-life processes, facilitating the BMIS. Furthermore, it is argued that the addition of the FSSD allowed to strengthen scalability, risk avoidance, investment strategy and partnerships and social integration.

Also Antikanen and Valkokari (2016) advocate an outwards perspective in their framework for sustainable circular BMI. The European Union wants to accelerate a circular transition by launching a Circular Economy Package (EC, 2015), but such a transition cannot be realized with single innovations, only in conjunction with related complementary innovations. Hence, there is, or should be, a dynamic business ecosystem, requiring interaction between all involved actors, including both the core-business network and other stakeholders (ibid). In other words, a multi-level analysis is needed on top of the

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BMC, with continuous iteration with sustainability and circularity evaluation, see Figure 6. The results show that the value propositions for different stakeholders, understanding the need of end-users and value creation for consumers, creating multiple possibilities for a revenue model was experienced as beneficial. Also, the framework is regarded as good tool to communicate to stakeholders, including financers and the media.

The importance of stakeholders, multi-stakeholder alignment and networks are also underlined by Karlsson et al. (2017), Mahmoud-Jouini and Charue-Duboc (2017) and Velter et al. (2020). Karlsson et al. (2017) use the Flourishing Business Canvas (FBC) developed by Upward & Jones (2016), in their action research on the emerging biogas market in Sweden. The FBC resembles the BMC, but links the building blocks to the environmental, societal and economic system, for example by linking partnerships (economical) to resources (societal). The participants in their action research, however found the FBC was somewhat complex. Nevertheless, it helped sharing, developing and structuring ideas. Moreover, the workshop contributed to a feeling of togetherness and working towards a common goal. This recognizes the importance of establishment of networks.

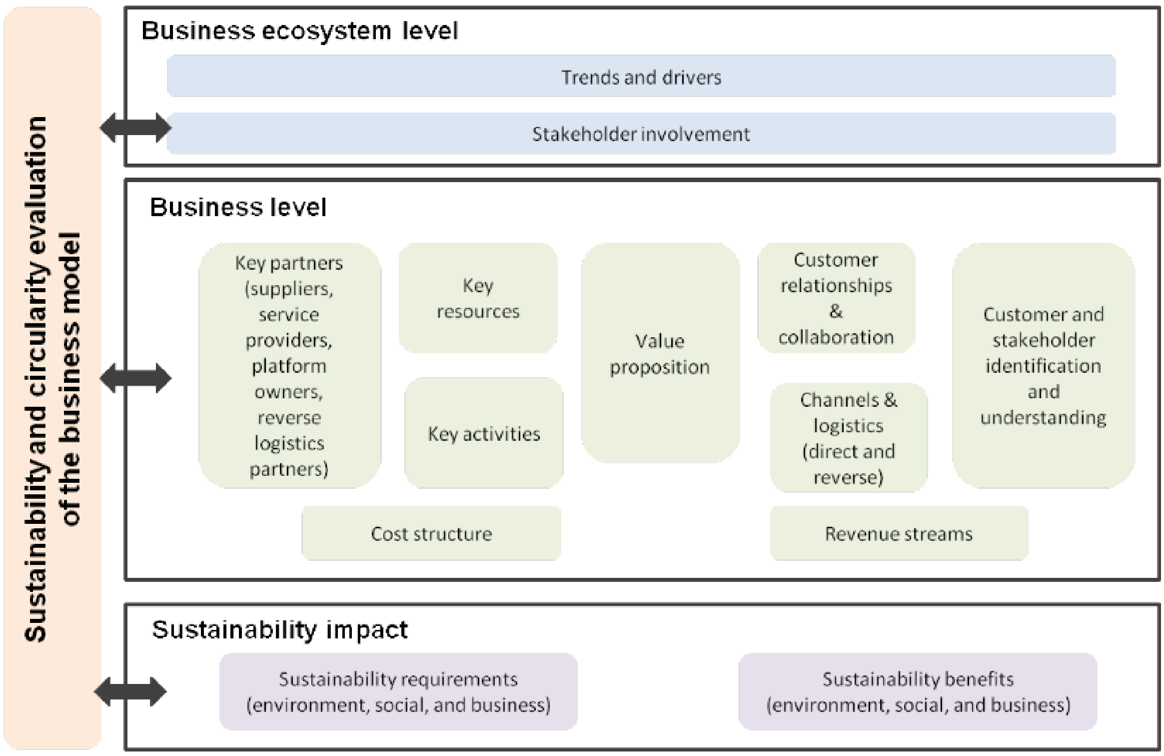

Figure 6: A framework for BMIS developed for circular business model innovation. Note the central level consists of the 9 dimensions of the BMC. Figure from Antikainen & Valkokari (2016).

Mahmoud-Jouini and Charue-Duboc (2017) investigate the role of experimentation. They set up a Complete Solution Experiment (CSE), involving all players required to deliver and operate a complete solution, amongst other costumers. Upfront clarity on validation and communication of the outcome crucial, as it helps to build trust between members. Experimentation helps building a common vision between the partners. Also, CSE allowed to gain more knowledge about the key factors that limit performance, operating costs, value to customer and capitalization of knowledge. By bringing together all players of an ecosystem, knowledge is generated that no partner could have developed alone.

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Experimentation leads to knowledge on technical and economic performance, interdependencies between sub-systems of the solution, the identification of bottlenecks and economic viable solutions to it and validated value propositions to costumers. Therefore, CSE reduces initiative risk, interdependence risk and integration risk.

Tools help communication and knowledge building to reduce risks, which opens opportunities for (co-)innovation. It turns out to be important however, that players are able to make a common vision or goal. Velter et al. (2020) take a boundary work perspective and ask what determines such alignment and engagement. Focal firms need to align their network on three distinct dimensions: normative, strategic and instrumental. Following the cross-sector innovations literature, barriers for alignment are differing value frames, norms, expectations, unfamiliarity, mutual suspicion, cultural differences and misunderstanding. Boundary work investigates the concrete practices that enable conversation, interaction and coordinated action between the focal firm and other actors. First, boundaries are explored. Second, boundary dissonances are defined, which identify misaligned business model elements, narrow understanding of value and responsibilities and legal boundaries between actors. Third, boundaries are brokered spaces, texts and objects, and solutions, called the boundary spanners. In their case studies on 9 companies engaging in SMBI, boundary changes of the initiating organization were found in all cases, i.e. actors took up new roles. It has led to novel multi-stakeholder networks, based on a shared understanding of value across the traditional sectors including non-market actors as municipalities, NGOs and policy makers. By exploring divergent interests, resources, motives and missions, value frames were fused to co-create value, however further operationalization and instrumentation is needed to assist organizations in the creation and management of value networks for a sustainable economy.

Yang et al. (2017) adopted a different approach in their framework focused on the manufacturing sector. Instead of taking the system and a broad range of stakeholders as the base of a framework, they place value in the center. To identify new business opportunities and map the value proposition better/more all-round, the notion of uncaptured value is used. This is defined as the potential value that could be captured but not yet is captured and comprises value surplus, value absence, value missed and value destroyed. Uncaptured value exists in almost all companies and can be visible, e.g. waste stream or co-products, or invisible, e.g. overcapacity of labor or insufficient use of expertise. Waste is a typical example of value surplus, value which exists, but isn’t required. Reversely, value absence is required value, which doesn’t exist, like missing expertise. Missed value refers to under-exploitation of value, by the fact that the value is inadequately captured. Lastly, value destroyed is value with negative outcomes for the company and other stakeholders, like pollution or safety problems, and should be minimized. When the value uncaptured is identified, it can be turned into value opportunities leading to innovation of the business model. The data of six manufacturing companies (China, UK, US) participating in the study led to the generation of 26 sources of uncaptured value, categorized in the beginning, middle and end of the products lifecycle. Especially for the middle and end of lifecycle, considerable value was uncaptured, explained by the fact that manufacturing firms seldom consider potential value in these stages (Yang et al., 2017), i.e. uncaptured costumer value by unprofessional use of products or no recycling. A parallel can be drawn between the 26 sources of uncaptured value and the 7 wastes of lean production (Bicheno & Holweg, 2010), paving the way for sustainable manufacturing innovation and significant industrial impact.

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2.4 Discussion and conclusions of SBMI review

This chapter has examined the drivers of business model innovation for sustainability from a managerial perspective. Also, tools are discussed to achieve BMIS on a company level. This article doesn't only contribute to the academic literature, but also acts as a handle for practitioners and policy makers.

SBMI requires a radical different value proposition and exceeds technological solutions (Chesbrough, 2007). SBMI is more complex than one-dimensional product, service or process innovations (e.g. Pedersen et al., 2018) and therefore allows for future competitive advantages (Rometty, 2006). Both the literature on the company level as the system level showed the need for technological, social and organizational innovation in order to establish SBMI. Hence, multi-stakeholder networks, in which new value propositions can be aligned, should be formed to establish SBMI (Antikainen & Valkokari, 2016; França et al., 2017; Karlsson et al., 2016; Mahmoud-Jouini & Charue-Duboc, 2017; Velter et al., 2020) and achieve environmental impact on the system level (Dijk et al., 2015; Mazzanti & Rizzo, 2017). Although the research tradition is still young, we would advocate for more empirics regarding adoption of sustainable values and business models in companies. In particular, symbiotic interaction between environmental stakeholders and companies can retrieve much information for the sustainable transition. Also, the empirical evidence for the sustainable performance of SBMs is rather thin, which is an important recommendation for further study.

The classification of Sustainable Business Models is still under construction. Although there exists literature on the performance of 'examples', see table 5, the archetypes and their relation should be further investigated. In the review, an archetype, Green supply chain management, was added into the mutual framework of Bocken et al. (2014) and Laukkanen & Patala (2014). to fit in the findings of Lüdeke-Freund et al. (2018). We saw that sustainable business models were categorizable in technical, social and organisational archetypes and that the archetypes are complementary.

Radical SBMI also calls for complementarity between technical, social and organisational innovation. This can be established by the formation of disruptive networks, in which multiple stakeholders interact, cooperate and co-create value. In such a structure new value can be captured leading to increased financial performance, while simultaneously allowing for efficient use of resources and capabilities (Madsen, 2020) and minimising integration and interdependency risks (Mahmoud-Jouini & Charue-Duboc, 2017). To be successful however, a common vision or goal should be present (Breuer & Lüdeke-Freund, 2017; Karlsson et al., 2016; Madsen, 2020; Wadin et al., 2017), transparency and openness (Mahmoud-Jouini & Charue-Duboc, 2017; Wadin et al., 2017) should be given to a reasonable extent and actors need to be willing to take up new roles (Velter et al., 2020). Several tools have been discussed that align multiple stakeholders and/or explore new value propositions. These tools accelerate the ability of co-creating value. At least one of the authors mentioned that after using their tools, novel structural innovation networks have been formed (Velter et al., 2020).

From a system perspective, networks also are a driver for sustainable innovation. This allows a multitude of niche solutions (Nykvist & Whitmarsh, 2008) to be mobilized, such that the regime can transform (Wesseling et al., 2020) towards sustainable solutions. Moreover, it is confirmed that technological innovation will only have impact if they are coupled with organisational and societal innovations (Mazzanti & Rizzo, 2017). To establish such synergy effects, policy makers should note the fact of complementarity and focus on environmental and innovation policies, rather than financial instruments.

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Implications for practitioners and the C4U project:

- With the multi-stakeholder network that is established in the C4U project, this innovation has higher chances of success.
- The implementation of capture technologies can be regarded as an SBMI if the value proposition of the firm changes. That is, additional value can be created next to the technical specifications of the product by earmarking sustainability value. This leads to a competitive advantage which is hard to imitate due to the necessary infrastructure and partnerships. If the captured CO_2 can be utilized, the additional value proposition is straightforward, the waste CO_2 can be sold. Otherwise, an adapted value proposition for the existing products should be found. Hence, it is advised to assess whether the purchasers or final consumer see additional value in sustainable produced steel to capture the sustainable value created. This sustainable value can also be co-created, by collaborating in the value chain. For example, fully 'green' end-consumer products require the manufacturer to combine 'green' building blocks, but can allow to capture sustainable value more easily.
- The inclusion of sustainability or stewardship in the vision/values of the company, and communication of these values through all layers of the company, increases the potential of successful radical sustainable innovation, while a policy-pull situation maximally leads to incremental innovations.
- Sessions with policymakers, environmental stakeholders and partners to experiment with a BMC-FSSD or the multi-level BMC help bringing new perspectives on the business model, while considering a larger value chain than internal value propositions. By including a larger stakeholder base, long-term perspectives are more easily included. Also, policy makers can assist with the implementation of new solutions. The value uncaptured perspective of Yang et al. (2018) can also be considered, it can help to capture additional value while paving the way for sustainable manufacturing innovation, for example by thinking about recycling from the front-end.

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3 Risks, Challenges and Transferrable Learnings for CCUS

Analysis by the Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA) has shown that carbon, capture and storage (CCS) is an essential part of the lowest cost path towards meeting climate targets. In addition to this primary incentive of emissions reduction, the GCCSI[5] highlights that there are numerous opportunities and benefits associated with CCS, including:

- Enabling a just transition to new low emission industries
- Protecting people from the severe social and economic impacts that would otherwise result from closing local industries
- Supporting high paying jobs
- Utilisation of existing infrastructure that would otherwise need to be decommissioned
- Building knowledge that may support innovation-based economic growth

Despite these associated opportunities, the cancellation of CCS projects is not uncommon with almost half of the projects announced since 2010 no longer being in the facility pipeline in 2020. This level of survival rate is not unique to CCS, with other large infrastructure projects such as LNG projects facing similar levels of survival.[6] It is therefore important to understand the risks and challenges associated with CCS projects and to take learnings from past projects.

Carbon Capture, Utilisation, and Storage (CCUS) projects bring some unique risks and challenges that may not be fully understood or realised. The lack of understanding of these risks may act as a barrier to the adoption of CCUS, and the lack of awareness of potential challenges (and how to overcome them) can lead to the unsuccessful completion or early cancellation of CCUS projects.[7] This chapter identifies risks and challenges associated with the implementation and continued operation of CCUS projects, including learnings from past projects and factors that may lead to success or failure. The purpose of identifying these risks and challenges is to facilitate the development of business models that can act to either eliminate risks or mitigate the impact that risks may have on the business case and CCUS project drivers.[8]

The work conducted involved a review of a wide variety of publicly available literature including reports published by the Global CCS Initiative, International Energy Agency and its Greenhouse Gas R&D programme, Zero Emissions Platform, and Element Energy. The commentary on CCUS risks and challenges within the literature stems from the primary sources of publications from individual CCUS projects, engagements with project representatives or industry experts, and press releases. Certain projects, such as the White Rose and Peterhead CCS projects in the UK,[9] have published detailed reports covering the knowledge and learning acquired. The wider literature on CCUS collects and aggregates this information, providing interpretations and analysis. A list of the sources used to determine the presented list of risks and challenges is included below. Much of this literature has been better understood through prior stakeholder

[5] GCCSI 2019, Global Status of CCS 2019
[6] GCCSI 2020, Scaling up the CCS market to deliver net-zero emissions
[7] Conclusions from previous Element Energy research (unpublished) in the field of factors impacting the constructability and operability of CCUS projects.
[8] The variable ability of different funding and revenue models to accommodate CCUS risks is illustrated in: Element Energy 2018, Industrial Carbon Capture Business Models
[9] White Rose and Peterhead CCS projects delivered 86 reports known as 'Key Knowledge Deliverables' to the UK government which were made publicly available here.

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engagement and discussions with study authors. A global CCS expert was also consulted to validate some of the key findings from the literature review.

Table 3: Literature review sources

#	Title	Author	Year
1	A Trans-European CO2 Transportation Infrastructure for CCUS: Opportunities & Challenges	Zero Emissions Platform	2020
2	CCS deployment at dispersed industrial sites	Element Energy for BEIS	2020
3	CO2RE database	Global CCS Institute	2020
4	Transforming Industry through CCUS	IEA	2019
5	Policy priorities to incentivise large scale deployment of CCS	Global CCS Institute	2019
6	Lesson and perceptions: Adopting a commercial approach to CCS liability	Global CCS Institute	2019
7	The role of CO_2 storage	IEA	2019
8	Gorgon carbon dioxide injection project fact sheet	Chevron	2019
9	Feasibility study for full-scale CCS in Norway	Norwegian Ministry of Petroleum and Energy	2019
10	Industrial carbon capture business models	Element Energy for BEIS	2018
11	The Carbon capture project at Air Products' Port Arthur Hydrogen Production facility	IEAGHG	2018
12	Demonstration of Carbon Capture and Sequestration of Steam Methane Reforming Process Gas Used for Large-Scale Hydrogen Production	Power et al.	2018
13	Telling the Norwegian CCS Story - CCS: the path to sustainable and emission-free cement	Global CCS Institute	2018
14	Close-Out Report Public Engagement - Rotterdam Opslag en Afvang demonstratieproject	Global CCS Institute	2018
15	Enabling the Deployment of Industrial CCS Clusters	Element Energy for IEAGHG	2018
16	CCS market mechanisms: Policy mechanisms to support the large-scale deployment of Carbon Capture and Storage (CCS)	Element Energy & vivid economics for OGCI	2018
17	CO_2 Transportation and Storage Business Models	Pale Blue Dot, Arup, Pinsent Masons for BEIS	2018
18	The Global Status of CCS	Global CCS Institute	2017
19	Case Study: Al Reyadah CCUS Project	Carbon Sequestration Leadership Forum	2017
20	A Business Case for a UK Industrial CCS support mechanism	Pöyry for Teesside collective	2017
21	Manufacturing our Future: Industries, European Regions, and Climate Action	Bellona Europa	2017

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#	Title	Author	Year
22	Working Paper 2: Financial Incentives for the Acceleration of CCS Projects	The University of Queensland	2017
23	Lessons Learned - Lessons and Evidence Derived from UK CCS Programmes, 2008 - 2015	CCSA	2016
24	Lessons Learned from CCS Demonstration and Large Pilot Projects	MIT	2016
25	White Rose Full-chain FEED Lessons Learned	Capture Power, National Grid for BEIS	2016
26	Development of a CO_2 specification for a CCS hub network	Global CCS Institute	2016
27	Peterhead CCS Project - FEED Lessons Learned Report	Shell	2016
28	Lessons Learned - Lessons and Evidence Derived from UK CCS Demonstration Projects, 2008-2015	CCSA	2016
29	K. 17 Financing Feasibility Report, White Rose	Capture Power for DECC	2016
30	Understanding Industrial CCS Hubs and Clusters	Global CCS Institute	2016
31	20 Years of Carbon Capture and Storage	IEA	2016
32	Lowest Cost Decarbonisation for the UK: The Critical Role of CCS. Report to the Secretary of State for BEIS from the Parliamentary Advisory Group on Carbon Capture and Storage	Oxburgh for BEIS	2016
33	Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station	IEAGHG	2015
34	Case study: Shell Canada – Quest Carbon Capture and Storage Project	Pembina Institute	2015
35	The Quest for less CO_2: Learning from CCS implementation in Canada	Global CCS Institute	2015
36	Peterhead CCS Project - Site Selection Report	Shell	2015
37	Industrial CCS on Teesside, the business case	Pale Blue Dot for The Teesside Collective	2015
38	Development of an Incentive Mechanism for an Industrial CCS Project	Société Générale for The Teesside Collective	2015
39	Roadmap for Carbon Capture and Storage Demonstration and Deployment in the People's Republic of China	Asian Development Bank	2015
40	An Executable Plan for enabling CCS in Europe	ZEP, European commission (Bellona CCSA)	2015
41	Infrastructure Financing instruments and incentives	OECD	2015
42	Life Cycle Assessment of Post-Combustion CO_2 Capture and CO_2 - Enhanced Oil Recovery based on the Boundary Dam Integrated Carbon Capture and Storage Demonstration Project in Saskatchewan.	Maunilova et al.	2014

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#	Title	Author	Year
43	W.A. Parish Post Combustion CO_2 Capture and Sequestration Project Final Public Design Report	Armpriester	2014
44	Demonstrating CO_2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A Techno-economic Study	Element Energy for DECC and BIS	2014
45	Financing Large Scale Integrated CCS Demonstration Projects	Société Générale	2014
46	Global Action to Advance Carbon Capture and Storage: A focus on Industrial Applications. Annex to Tracking Clean Energy Progress	CCUS action group, Clean energy ministerial for IEA	2013
47	Barriers to implementation of CCS: Capacity and constraints	IEAGHG	2012
48	Longannet Scottish Power UK Carbon Capture & Storage (CCS) Consortium Front End Engineering and Design (FEED)	UKCCS	2011
49	Kingsnorth Carbon Dioxide Capture and Storage Demonstration Project	e-on	2011
50	Technology Roadmap: Carbon capture and Storage in Industrial Applications	IEA	2011

The chapter is divided into three sub-sections. The first presents a list of the identified risks and challenges associated with the CCUS value chain, divided into the four categories: technical, economic & market, political, and cross chain. The second presents transferable learnings from planned and operational schemes including success factors and reasons for failure. The majority of the literature reviewed focuses on challenges associated with CCS specifically, with limited commentary on projects involving non-EOR utilisation of CO_2. It can be expected that CCS and CCU projects would share some similar risks and challenges, however there may be additional factors specific to utilisation projects that are not captured below due to the scope of the literature review conducted. An additional third section is therefore included to highlight the potential differences for utilisation projects.

3.1 Risks and challenges for the CCUS value chain

This section reports the key findings of a literature review identifying the risks and challenges of CCUS across the entire value chain. In this context, challenge and risk are taken to represent the following:

- **Challenge:** A challenge refers to a problem that needs to be solved or an obstacle/barrier that has to be overcome. Challenges may be known of in advance or may arise unexpectedly as the result of a risk occurring. For example, the need for a high amount of capital to implement a project may be a challenge, as there is difficulty in obtaining this capital and this is therefore a problem that must be solved.
- **Risk:** The chance of an event occurring with resultant adverse impact on the implementation, ongoing operation, or business case of a project. Risks are associated with uncertainty, including unknown or external factors that may impact a project. For example, project cost uncertainty is a risk because it represents the possibility that project

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costs might be greater than the budget or the capital raised, which is a situation which would adversely impact the project. It is often possible to assess the likelihood of risks occurring and to take actions in advance to mitigate the impact that risks may have on a project.

CCUS risks and challenges emerging from the literature review were evaluated and categorised according to their influence and underlying mechanisms. A summary of the considered categories is reported in Table 4 below. The key risks and challenges included in these categories are discussed more in depth in the following sections.

Table 4: Summary of risk and challenge categories in the CCUS value chain

Category	Associated risks and challenges
Technical	Risks and challenges presented by technical factors relating to the implementation and ongoing operation of facilities.
Economic and market	Risks and challenges affecting capital, operation, and finance costs, as well as market response and competitiveness.
Political	Risks and challenges related to policy and regulations.
Cross chain	Risks and challenges associated with the coordination of capture, transportation, utilisation, and storage operations.

3.1.1 Technical

Technical risks and challenges are related to technology maturity, technology performance, plant integration as well as efficient and safe operations. Some CCUS technologies are now relatively mature and proven, so low technical risk. However, some projects rely on new or complex technologies across some steps of the value chain. There are still some technical risks and challenges which affect infrastructure deployment and operations for capture, transportation, storage, and utilisation. Additionally, CCUS projects operations often require complex technical procedures and may involve a large number of different stakeholders, resulting in additional risks and challenges to success. Key technical risks and challenges to CCUS projects are covered below.

1. **Technology performance uncertainty:** The use of novel technologies or technologies that have not yet undergone large-scale demonstrations comes with the associated risk of performance uncertainty, where effectiveness cannot be guaranteed. This is particularly relevant to capture technologies, several of which currently have low technology readiness levels (TRL). In this case, a more specific risk may be that the desired capture rate is not achievable leading to greater than expected residual emissions. Furthermore, technology performance uncertainty can occur when applying a high TRL technology to a new industrial sector. In the case of capture technologies, this uncertainty may arise due to differences in flue gas compositions.
2. **Technology lock-in:** In the case of CCUS, the adoption of this technology requires significant interventions at the capture site, including both physical installations and operational changes. The extent of these requirements poses the risk of 'technology lock-in' in which early adoption of a technology prevents subsequent adoption of an alternative

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technology. For example, due to the technical challenges of removing or retrofitting equipment, or a reluctance to change operational procedures. Technology lock-in also poses an economic type of risk, as discussed later.

3. **Site-specific challenges:** The construction of CO_2 capture and transport infrastructure is expected to encounter location and site specific challenges. For example, the retrofit of carbon capture technology at an existing facility may be impeded by onsite space availability or may face the challenge of addressing multiple emission sources within one site. The transport of captured CO_2 may be impeded by factors such as shipping terminal capacity or restrictions on the location of pipelines (e.g. waterways or geographical features).
4. **Increased operational complexity:** The typical operation of an industrial site is rendered more complex with the addition of a carbon capture unit. This may bring numerous challenges for the capture facility. For example, required maintenance of the capture unit may increase plant downtime and thus impact annual production; the site may need to implement additional health and safety measures; and site-staff may need to undergo additional training. Furthermore, installation of CCUS technology may necessitate other changes in production processes and thus actions would be needed to ensure product quality is maintained.
5. **Variation in CO_2 purity grade:** Changes in gas purity levels pose a risk to transportation and storage operations, as infrastructure is designed for a specific set of gas specifications. For example, inclusion of impurities may alter gas pressure or lead to corrosion of pipelines. This risk is particularly relevant for multi-source systems, such as industrial clusters, where several sites supply to the same transport infrastructure. When new capture sites join the infrastructure, the purity grade of the delivered CO_2 may be affected.
6. **Maintenance of pipelines:** There are several challenges associated with maintaining pipeline infrastructure for CO_2 transportation. Firstly, pipeline integrity is difficult to monitor: there is no validated methodology to quantify fracture propagation for CO_2 pipelines and in complex pipeline networks it is challenging to maintain operations within a non-corrosive window. Secondly, pipeline networks require regular inspection and maintenance. This may result in disruption to users of the network such as CO_2 suppliers or utilisers. Lastly the use of shared pipelines needs to be coordinated so as to maintain appropriate flow rates.
7. **CO_2 storage well damage:** Injection of CO_2 into highly depleted gas fields has an associated risk of potentially damaging the storage well itself, due to the temperature drop induced by gas expansion. Potential damage includes blockages at the wellhead, perforations at the bottom of the well, thermal stress cracking of the steel well bore and backflow into the pipeline.
8. **CO_2 leakage:** There is a risk that CO_2 injected into a storage facility may 'leak' and thus not remain permanently stored. It is a technical challenge to mitigate this risk, however storage liability is also an economic risk, as discussed later.

3.1.2 Economic & market

Economic and market risks and challenges are those affecting capital, operation, and finance costs, as well as market response and competitiveness. Economic risks to CCUS project

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implementation are extremely relevant, due to the implications for the underlying business model of a project.

9. **High capital investment**: The deployment of capture plants, CO_2 pipelines and the appraisal of storage sites require a large upfront capital investment. There are challenges associated with both obtaining this upfront capital and the ongoing impact of the cost of capital.
10. **Capital cost uncertainty:** The cost of construction and operation of CCUS infrastructure is often highly uncertain, and the cost of capture technologies can vary significantly among industrial sectors. This uncertainty in capital cost requirements poses the risk that costs could become significantly greater than expected, which may then lead to projects going over-budget or running out of capital.
11. **Opportunity cost (technology lock-in):** The large investments required for implementation of carbon capture technology have the associated opportunity costs of not affording alternative abatement routes, such as fuel switching or new production processes, which may later become available. Having an existing abatement measure installed can be cost prohibitive to the business case of using new, potentially more effective, abatement measures.
12. **Poor finance opportunities**: The characterisation of CCUS projects as having novel risks and long lead times mean that it can be difficult for projects to obtain investments. External corporate funding to CCUS is scarce and may be offered with poor finance terms. Additional financing challenges are posed by the complexity of projects, the involvement of multiple parties, and the lack of a benchmark for measuring investment performance.
13. **Energy and utilities consumption**: Energy and water demand from the capture units at industrial sites is often uncertain, alongside uncertainty in energy prices, leading to uncertainty in the cost of CO_2 capture.
14. **Long investment timescales**: Long lead times for planning, permitting and construction result in an extended investment cycle which is uncommon for industrial decision-making timescales.
15. **Insufficient value proposition**: Developing a sufficient value proposition to justify the business case for CCUS can be a challenge. The currently low CO_2 price, limited potential for CO_2 utilisation, limited added value for “green products”, and a lack of viable revenue models render the proposition of CCUS economically unfavourable in many cases.
16. **Reduced competitiveness**: The additional costs for CCS may reduce profitability and competitiveness of industries and power, with a potential damage to the economic competitiveness on global markets.
17. **Revenue volatility**: Long-term variability of fuel prices and other operating costs may endanger economic profitability of operations if the additional costs cannot be integrated into the price of the product or the support mechanism.
18. **Transport & storage monopoly and fee uncertainty**: The size and communal utilisation of transportation and storage infrastructure renders this portion of the CCUS value chain very compatible with monopolistic ownership. Without government participation or regulation, capture sites are at risk of being exposed to excessive transport and storage fees.

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19. **Long-term CO_2 storage liability**: Long-term post closure monitoring and CO_2 leakage liability may constitute a showstopper[10] for potential project developers and investors without government carrying part of the liability.

3.1.3 Political

Political risks and challenges are related to policy and regulations in general. Addressing risks and challenges associated with policy and regulations is very important for the realisation of a CCUS project. Governments and legislators can play a key role in the reduction of these risks to promote the successful and widespread implementation of CCUS projects.

20. **Policy and regulatory uncertainty**: Delay or cancellation of programmes, lack of strategic clarity and changes in regulations and policy may reduce the appetite of CCUS developers, investors, and the supply chain. A comprehensive deployment strategy and a policy/regulatory framework must be in place, including permitting process, technical and environmental management standards, standards for cross-border CO_2 movement, liability issues, public engagement, and information disclosure. Regions that have not yet developed these tools are likely affected by high policy and regulatory uncertainty which may discourage investment in the sector.
21. **Carbon leakage and employment loss risk**: The imposition of regulations on more ambitious carbon emissions reduction may endanger business profitability for those industries with globally traded commodities that cannot pass the cost of CCUS on to the consumers. The potential closure or relocation of such industries to different locations where such restrictions are not in place, would potentially lead to job losses and offshoring of emissions.
22. **CO_2 price level and uncertainty**: There is uncertainty in the price of carbon that may be set within national policies, such as carbon taxes, or that may be obtained by trading emissions credits such as within the European Union's Emission Trading System (ETS). This can result in uncertainty in revenue streams associated with the price of carbon. Furthermore, the provision of free ETS allowances to trade-intensive sectors can lessen the drivers for CCUS projects in these sectors.
23. **Stringent conditions of government support:** Highly prescriptive and inflexible governmental support programme requirements may negatively impact the success of a project by restricting the choice of optimal technologies and procedures.
24. **Complex permitting processes**: Lengthy and complex permitting processes pose a risk to the success of CCUS projects by prolonging timelines and thus increasing overall costs. For emitters located in areas protected by environmental restrictions, the deployment of transportation infrastructure and additional utilities may not be consented.

3.1.4 Cross-chain and hubs

Cross-chain risks affect the interdependence of capture, conditioning, transportation and storage or utilisation infrastructure. While all stages of the CCUS value chain are associated with risks to success and timely completion of their own facility and infrastructure, the close interdependence of their operation results in an integrated development risk for the wider CCUS project.

[10] showstopper: an obstacle to further progress

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25. **Integrated development risk**: The close interdependence of each aspect of the value-chain means that the wider CCUS project is reliant on the success and timely completion of each component of the chain.
26. **Operational interface risk**: The uncertainty around the volume of CO_2 that can be supplied by each capture facility participating to a project (and by potential future new joiners) may result in inappropriate sizing of the transport infrastructure. Long-term underutilisation of a pipeline would result in large costs for the users, while lack of futureproofing by initial oversizing of the pipeline would limit the access of new capture facilities and therefore the loss of potential cost savings.
27. **Risk allocation:** The allocation of risk, CO_2 liability and intellectual property rights between parties of the same CCUS project may be subject to incompatibilities.
28. **Cross-border:** Where infrastructure crosses national borders there can be challenges associated with differences in national policies and support schemes. This is particularly relevant to cross-border clusters such as the North Sea Port.
29. **Cluster/hub coordination:** Hub and cluster projects face the additional challenges of coordinating a large number of players, each with differing technical challenges, motivations, business models, and resources. These challenges are on top of aforementioned technical risks and challenges, such as variability in CO_2 purity grade and pipeline maintenance, which become more prominent for cluster or multi-source projects.

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Table 5: Summary and segment applicability of risk and challenges to CCUS

Category	Associated risks and challenges	C	T	U	S
Technical and operational	1. Technology performance uncertainty				
	2. Technology lock-in				
	3. Site-specific challenges				
	4. Increased operational complexity				
	5. Variation in CO_2 purity grade				
	6. Maintenance of pipelines				
	7. CO_2 storage well damage				
	8. CO_2 leakage				
Economic and market	9. High capital investment				
	10. Capital cost uncertainty				
	11. Opportunity cost (technology lock-in)				
	12. Poor finance opportunities				
	13. Energy and utilities consumption				
	14. Long investment timescales				
	15. Insufficient value proposition				
	16. Reduced competitiveness				
	17. Revenue volatility				
	18. T&S monopoly and fee uncertainty				
	19. Long-term CO_2 storage liability				
Political	20. Policy and regulatory uncertainty				
	21. Carbon leakage and employment loss risk				
	22. CO_2 price level and uncertainty				
	23. Stringent conditions of government support				
	24. Complex permitting processes				
Cross chain	25. Integration risk				
	26. Operational interface risk				
	27. Risk allocation				
	28. Cross-border				
	29. Cluster / hub coordination				

Legend:

C Capture
T Transportation
U Utilisation
S Storage

Segment predominantly affected

Segment less affected

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3.2 Transferrable learnings from planned and operational schemes

Key transferrable learnings from planned and operational CCUS projects worldwide are reported in this section. Key learnings that are relevant for future CCUS projects mostly describe the factors that contributed to the success of planned and operational CCUS schemes, so that these can be considered for future developments.

3.2.1 Success factors

The most critical phases that determine the success of a CCUS project are generally the initial phase of the creation of a robust business case and the subsequent phase of planning the implementation of the project. The key learnings discussed in this section cover the main tools and winning strategies for the creation of a business case, as reported in Table 6. Additionally, the main success factors and best practices for the implementation of a CCUS project are reported in Table 7.

Table 6: Success tools – developing a business case

Success tools and strategies	Description
Enhanced Oil Recovery	A proven solution to ensure a profitable and steady revenue stream is the sale of CO_2 for the use in Enhanced Oil Recovery. Currently, the CO_2 captured at 15 out of 21 operating large-scale CCS facilities worldwide is destined for EOR. While the price of CO_2 for EOR is expected to be dependent on the price of oil, in some cases the revenue from the sale of CO_2 can alone be sufficient to support a CCUS business case.
Contract for Difference	Contracts for Difference (CfD) style support mechanisms between governments and project developers are receiving attention as an option to support CCUS projects. CfDs can provide a stable revenue source to strengthen the business case of a project, they are successfully used in other sectors and are particularly suitable for CCUS in the power generation sector. An example is the SDE++ scheme in the Netherlands of which capturers within the PORTHOS project hope to take advantage.
Tax credits	A form of financial support that can be provided by governments is the promotion of CCUS projects through tax credits. Companies operating in the CCUS value chain can be awarded tax credits to be utilised as tax relief or to be exchanged on tax equity market. Tax credits, such as the **45Q** program in the US, have facilitated the launch of several large-scale projects. The 45Q scheme awards a higher tax relief for geological storage than for CO_2 use in EOR, virtually matching the additional revenue from CO_2 utilisation of the latter option.
Carbon pricing	Financial support for CCUS from governments could also be provided through carbon pricing, which can be delivered in the form of a carbon tax or of an Emission Trading System (ETS). A fixed carbon tax in particular has proven to be a beneficial instrument for the promotion of

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	CCUS projects, as it associates a fixed value to stored CO_2. Both Sleipner and Snøhvit CCS projects were developed with the support of a carbon tax. Within an ETS style mechanism, the value of CO_2 is variable as it depends upon the supply and demand for emissions allowances.
Regulation of emissions	Regulations to limit the volume of emissions that large industrial and processing sites can release can be a driving factor for implementation of CCUS. For example, the Boundary Dam CCS project in Canada that was partly motivated by the need to comply with emissions standards imposed on power generation. An awareness of potential future regulations can also impact the decarbonisation strategy of a company. For example, the Gorgon project in Australia where environmental restrictions were imposed after the project initiation.
Capital grants	Capital grants provided by the government can support the implementation of CCUS projects, as evidenced by several past projects. This is particularly the case for those projects that would otherwise struggle to find sufficient financing (e.g. those implementing novel technologies) and therefore rely on the support of grants. Storage appraisal activities can also largely benefit from capital grants, due to their large upfront cost and long timescales. The recently completed Alberta Carbon Trunk Line project is a successful example of a CCUS project benefiting from capital grants.
State ownership of CCS facilities	Ownership of CCUS infrastructure by State Owned Enterprises (SOEs) is an additional form of government intervention. State ownership is particularly suited for segments of CCUS chain such as the development and operation of transport and storage infrastructure, which generally tends to be subject to monopolies.
Product regulations	Product regulations can be used to drive CCUS projects. For example, the 'Low Carbon Fuel Standard' in California acted as one of the drivers for the Quest project.

Table 7: Success factors – project implementation

Success factors	Description
Oversizing of T&S infrastructure (multiple emitters)	A common strategy for the implementation of transportation and storage infrastructure for industrial clusters is to install a larger capacity than required by the initial project. The expectation is that over time additional capture sites will be able to connect to the same pipeline and benefit from the shared infrastructure. As a result, the cost of transportation and storage per unit of CO_2 will be lower, as the infrastructure cost is spread over multiple users. Additionally, with multiple supplier and users connected to the same CO_2 transportation infrastructure, cross-chain risk is reduced.

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Design criteria / modularity	For the construction of a CCUS facility, different design and construction approaches may be more suitable for either retrofit or new build projects. However, a high level of modularity and off-site preparation is generally in both cases the key in reducing infrastructure construction costs and avoid project delays.
Stakeholder engagement	For projects located in populated areas, local community engagement from the early stages of the project has proven to improve public acceptance of CCUS projects. The wider C4U project will be looking to explore the societal factors further.
Cross-chain coordination	Coordination of timelines and liabilities among all stakeholders across the CCUS value chain of a specific project is critical. The timescales of CO_2 storage must be matched with those CO_2 capture and transportation.
Capture technology selection	The testing of a range of different capture technologies on the flue gas composition of a facility prior to installation is highly advisable to minimise associated technical risks. The utilisation of in-house capture technologies for industries in the chemical sector that own capture patents can provide competitive advantage and reduce costs.
Plant integration	For retrofitted capture units, the project could benefit from maximising the utilisation of existing infrastructure and utilities, where available and feasible. An example is the Acorn project in Scotland which aims to exploit redundant North Sea gas distribution assets.[11]
Operations preparation	A detailed simulation of all operations of a CCUS site should be produced and evaluated early in the planning phase, including operational parameters such as plant efficiency, maintenance schedule, personnel availability, and operational capacity.
Participation of public organisation	The likelihood of success can be influenced by the participation (and equity stake) of a public authority, council, or government. This helps a project through short-circuiting permit requirements and awareness of local regulatory requirements.

3.2.2 Reasons for project failure

A literature review was performed in addition to collect information and learnings around CCUS projects that were cancelled. A range of factors is imputable for overall failure of the various project and the main recurring issues are reported below.

- **Lack of long-term economic viability**: Ensuring long-term stability of the revenue streams of a CCUS project is key to its health and survival. Sudden change of uncontrollable factors such as carbon prices, oil and gas prices, electricity prices (for the power sector) have in the past played a critical role in the failure of multiple CCUS projects.

[11] ACT ACORN Infrastructure Reuse and Decommissioning

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- **Poor risk management**[12]**:** Thorough liability allocation is of high importance given the magnitude of the investments in all segments of the CCUS value chain. Recent studies proposed putting more emphasis on the role of the private and insurance sectors as a potential solution, describing it as “a commercial approach to CCUS-specific liabilities”.
- **Technical integration and compatibility when scaling up from demonstration to commercial scale**. The implementation of FOAK capture technologies at scale has sometimes proven challenging, bringing to light unforeseen problems that had not emerged during the demonstration phase, as happened for the Boundary Dam CCS project. The risk could generally be mitigated by testing the capture technology with the final flue gas of the facility prior to construction, such as was done at the Fortum Oslo Varme capture plant.
- **Over-reliance on Government subsidies**[13]: While government support is many cases can be vital for the success of a CCUS project, sudden changes in the political agenda may result in withdrawal of financial support and this could severely affect the outcome of a CCUS project.

A few additional reasons are more specifically tied to the failure of full-chain CCUS projects. These are generally related to the complexity of integration and coordination of multiple parties across all segments of a CCUS project.[14]

- Poor management of cross-chain liabilities and poor risk ownership allocation among project stakeholders
- Poor coordination of construction timescales or poor integration design between the interfaces of each CCUS segment (capture, transport, storage, utilisation)

3.3 CO_2 utilisation discussion

The literature review conducted did not focus specifically on utilisation and therefore the literature reviewed had limited commentary on CCU projects. The opportunities for CO_2 utilisation within the North Sea Port area will be investigated within a later component of WP6 and a more targeted review of literature relevant to these specific opportunities and significant stakeholder engagement will be conducted at that stage. For completion, some broad insights into the differences for utilisation projects are included below based on ongoing work being conducted by Element Energy.

CCU projects may share some similarities with CCS projects, particularly in the cases of EOR where utilisation results in geological storage, however for non-EOR CCU projects there can also be significant differences. These include the scale of projects, their location, purity requirements, transport requirements, business structures, and the revenue models involved. Products made with CO_2 utilisation span a wide range of end-uses, including chemicals, fuels, building materials

[12] GCCSI – Lesson and perceptions: Adopting a commercial approach to CCS liability.
[13] MIT Report : Lessons Learned from CCS Demonstration and Large Pilot Projects
[14] White Rose Full-chain Lessons Learned Report

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and polymers, with highly different techniques used to convert the CO_2 to a valuable product. Risks and challenges associated specifically with the utilisation step could include[15,16,17]:

- **New technology challenges**: Novel CO_2 utilisation applications, including most routes for converting CO_2 to higher value commodities, are yet to be deployed at large scale. Therefore, challenges may occur with at-scale engineering and risks of performance uncertainty.
- **High energy demands:** Some CO_2 utilisation pathways, such as CO_2 hydrogenation[18], are energy intensive and require significant amounts of renewable electricity. Challenges may occur if this energy is not consistently available and costs for utilisation will also be highly dependent on electricity costs, giving rise to operational cost uncertainties.
- **Lack of value proposition:** Chemicals and fuels produced from CO_2 are often significantly more expensive than their fossil-based counterparts. Without strong incentives, such as high carbon pricing or product mandates, the demand for such products is likely to be low, with consumers prioritising affordability over sustainability. The high cost premium and lack of product demand is a challenge for utilisation pathways.
- **Product regulations:** New production routes may need to undergo lengthy and expensive testing and approvals processes before commodities can be sold in the relevant market. Furthermore, CO_2 utilisation routes may not be recognised as 'sustainable' in existing product regulations preventing them gaining the associated benefits.
- **CO_2 accounting uncertainty:** Although some utilisation routes may result in permanent CO_2 sequestration, other routes only provide temporary sequestration with abatement arising from the avoidance of fossil CO_2. It is unclear what approach may be taken for accounting CO_2 which is not permanently sequestered and who may receive any of the associated benefits / credits.

From the perspective of a CO_2 supplier (such as an emitter that captures CO_2) there are differences between sending CO_2 to storage and the sale of CO_2 for utilisation. For example:

- The sale of CO_2 for utilisation can provide a revenue stream which may aid the business case for capture. This contrasts with storage of CO_2 which typically comes at a cost to the supplier.
- Utilisation facilities can be co-located with CO_2 emitters. This reduces transportation requirements and also allows capture to occur at sites that would not otherwise have access to storage facilities.
- Purity requirements for utilisation may be different. Some utilisation technologies will require high purity CO_2 inputs however others may be able to use flue gases directly.
- The demand for CO_2 from a utiliser may be influenced by market conditions. Therefore, the capturer may face the risk of not being able to dispose of captured CO_2 if demand drops, as well as the risk of uncertainty in the revenue from utilisation.

[15] IEA 2019, Putting CO_2 To Use
[16] GCI 2016, Global Roadmap Study of CO2U Technologies
[17] ICEF 2017, Carbon Dioxide Utilisation (CO2U) – ICEF Roadmap 2.0
[18] IEA 2019, The Future of Hydrogen

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- Potential differences in CO_2 accounting.

These factors may alter the impact, magnitude or relevance of the previously described risks and challenges. They also highlight the additional risks of **CO_2 demand uncertainty**, **CO_2 revenue uncertainty**, and **CO_2 accounting uncertainty**.

3.4 Conclusions from the review of risks, challenges, and transferable learnings

The risks and challenges associated with implementing and operating a CCUS project can be categorized into four types of risk: technical; economic and market; political; and cross chain. The extent to which risks are relevant will vary with the type of CCUS project, with potential influencing factors being the political environment, the market or industry involved, the location of the project, the stakeholders involved, the project scale, and the choice of technologies used.

There are different mechanisms for mitigating risks in CCUS projects with feasibility studies and the development of a business case being necessary components during early design stages. Factors for successful operation include careful and thorough design of technical system components (capture technology, infrastructure, capacity variability); strong co-operation and engagement with stakeholders, partners and funding bodies; and a robust business case.

An awareness of potential risks is crucial when designing a business model for CCUS projects. The impact of risks on the business case for a CCUS project can be mitigated by the development of business structures, funding mechanisms, and revenues streams that will accommodate risks. Business models may need to accommodate factors such as market variability, plant downtime, cost overruns, uncertain time scales, and future system expansions.

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4 CCUS Case Studies

The motivations, enabling factors, and business models adopted by existing CCUS projects may provide valuable insights relevant to the adoption and integration of industrial clusters, such as the North Sea Port. This chapter presents a selection of case studies in which the motivations, enabling factors, and business models of specific planned and operational CCUS are investigated. The purpose is to allow the business models developed within WP6 to take inspiration from existing approaches and existing mechanisms.

The Global CCS Institute (GCCSI) maintains a CCS resource database[19] and publishes a detailed annual review exploring the global status of CCS.[20] The 2019 review stated that there were 51 large-scale CCS facilities worldwide of which 19 were operational, 4 were in construction, 10 were in advanced development, and the remainder were in early development stages. An additional 39 pilot or demonstration projects were in advanced stages of development. Figure 7 and Figure 8 illustrate the global distribution of the large-scale CCS projects and the distribution of these across sectors and time.

According to the GCCSI global status of CCS report,[20] conditions that have enabled large-scale deployment of CCS include: taxation in the form of a tax on emissions or tax credits; grant support or involvement of government or state owned enterprises; regulatory requirements; revenue from the use of captured CO_2 for enhanced oil recovery (EOR); and the option for low cost capture or low cost transport and storage. The last two factors – EOR and low-cost CCS – have acted as enablers for the majority of existing large-scale CCS projects. Carbon tax and regulatory requirements have been less common as drivers.

[19] https://co2re.co/

[20] Global CCS Institute, 2019. The Global Status of CCS: 2019. Australia.

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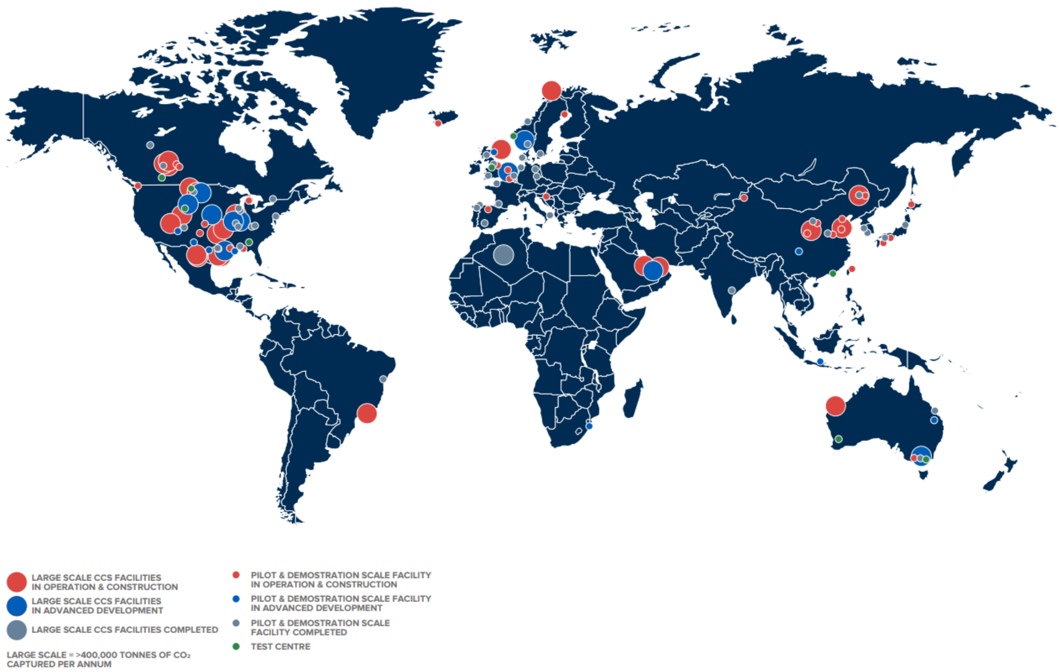

Figure 7: CCS facilities around the world. Taken from GCCSI 2019 Global Status of CCS[20].

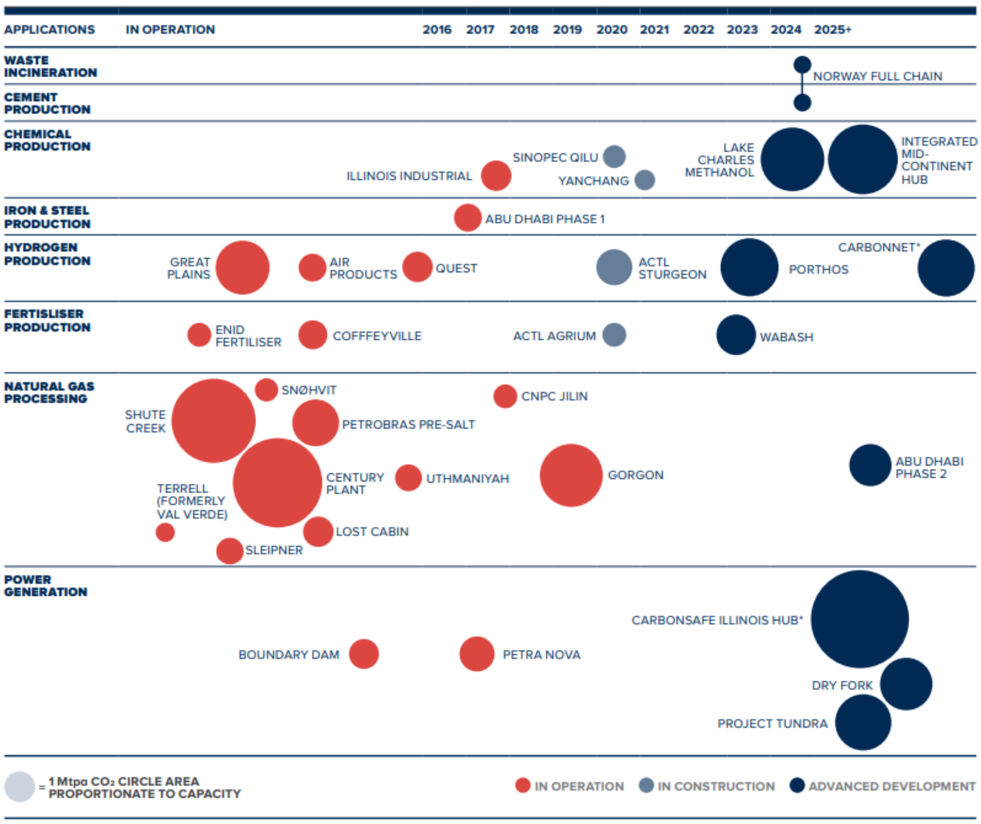

Figure 8: Applications of large-scale CCS facilities. Taken from GCCSI 2019 Global Status of CCS[20].

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4.1 Case studies of planned and operational CCUS projects

This section presents case studies of a selection of CCUS projects, with an emphasis on the motivations for the projects, the key players, and the format of the business model involved. Information was obtained from a variety of publicly available sources including project websites and published reports.

The projects selected for case study analysis were chosen to exemplify different conditions that may be relevant to CCUS projects at the North Sea Port cluster. The focus areas for selection spanned projects that involved multiple industrial sites, projects occurring in Europe, projects exemplifying government involvement, and projects with a range of policy drivers or motivations. Projects that were entirely driven by EOR or were entirely state owned were considered less relevant to the North Sea Port and were not considered beyond an initial review. A requirement for selection was the existence of sufficient information available to complete a detailed case study on the background and business approach.

Longship – Norwegian CCS Project[21,22,23]

Background
The Longship CCS project in Norway encompasses two capture facilities – Norcem Brevik and Fortum Oslo Varme – and links to the Northern Lights project for transport and storage infrastructure. The full-scale CCS project is supported by the Norwegian Government and coordinated by the state-owned enterprise Gassnova. Feasibility studies for the project commenced in 2016 and an investment decision to support the project was made by the Norwegian Government in 2020. Longship CCS is expected to undergo a three-year construction phase with operations commencing in 2024. **Industrial partners:** • **Norcem** in Brevik is a cement plant owned by Heidelberg Cement. It will capture approximately 0.4 Mt of CO_2 annually using amine-based technology. Addition of capture facilities will be a first-of-a-kind retrofit. • **Fortum Oslo Varme** plans to capture 0.4 Mt of CO_2 from their waste-to-energy facility in Oslo. The facility incinerates mostly household waste with approximately 60% being of biological origin. The recovered heat is used in the district heating system in Oslo. • **Northern Lights** is a consortium of Equinor (operator), Shell and Total building open access CO_2 transport and storage infrastructure. Northern Lights will ship liquified CO_2 from the capture sites to an onshore terminal on the Norwegian west coast. It will then be transported by pipeline to an offshore storage location in the North Sea. Equinor was awarded a permit to develop the CO_2 storage site in 2019 and has experience from operating both Sleipner West and Snøhvit CO_2 storage sites. The **Norwegian Government** has been a strong promoter for CCS, with an ambition to develop technology for CCS and "realise a cost-effective solution for full-scale CCS in Norway, provided that the project leads to technology development in an international perspective". Longships objective is to demonstrate the viability of CCS – technically, regulatory, and commercially –

[21] ccsnorway.com [accessed October 2020]
[22] langskip.regjeringen.no/longship/
[23] OECD (2016) Effective Carbon Rates - Pricing CO2 through taxes and emissions trading systems

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and contribute knowledge to future projects. It aims to establish an infrastructure with surplus capacity that other projects can use and create new industry and business activities in Norway. The Longship project builds on knowledge from existing CCS projects in Norway (Sleipner and Snøhvit) as well as Norway's experience with projects that were not fully realized. An identified challenge with previous European CCS projects was the development of commercial models spanning across industrial sectors. To address this, Longship chose a divided chain approach.
Business Approach
Structure: The Longship project is a public-private partnership with separate contractual agreements within each element of the CCS chain. Each partner will develop their own project (procedures, methods, operations) and be responsible only for their element of the chain. This division of the CCS chain aims to minimize cross-chain risk and address the challenges of cross-sector commercial agreements. **Financing:** The Norwegian government has separate agreements with each partner to subsidise both capital and operational costs. In the case of Fortum Oslo Varme, funding provision is predicated on the partner securing sufficient additional funding from the EU and other sources. Total project costs are estimated at NOK 25.1 billion, including initial investment and 10 years of operation. The Norwegian government expects to contribute NOK 16.8 billion, covering approximately two-thirds of the total project costs. **Revenue:** Avoidance of a carbon price on emissions may be an economic driver for capture facilities. Norway introduced a carbon tax in 1991 which now covers approximately half of industrial emissions at an average price of EUR 54 per tonne of CO_2. Norway is also subject to the EU emission trading scheme (ETS) which covers 83% of industrial emissions at an average price of EUR 7.2 per tonne of CO_2. **Risk management:** Cross-chain risks are minimized through the division of the CCS chain with each partner responsible only for their element and with each partner having separate financing agreements with the Norwegian government. Risks are shared with the government.
Transferable insights and relevance to North Sea Port
Longship provides an example of public-private cooperation, with individual projects managed by private entities but with funding and risk sharing support supplied from a state body. The project exemplifies the use of a delivery body (Gassnova) to undertake research, co-ordinate partners, and inform government actions. The project demonstrates a divided chain approach with each entity having separate responsibilities and agreements with the government. The project is relevant to the North Sea Port cluster as it involves multiple partners and includes two different types of industrial capture sites. The project is facilitated by a delivery body. The project operates in a region subject to EU ETS and where offshore storage is available.

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Lake Charles Methanol (LCM)[24]

Background
The Lake Charles Methanol project is an industrial CCS project in the state of Louisiana, USA. The project involves the construction of a new facility that will refine petroleum coke to syngas, which is then converted to high value chemical and energy products such methanol or hydrogen. CO_2 will be captured from the refining step, transported using existing infrastructure, and sold to domestic oilfield operators for use in enhanced oil recovery along the Golf Coast. As a result, methanol produced at LCM is expected to have 36% lower emissions than typical methanol production. The project is being developed by a private enterprise, **Lake Charles Methanol LLC**, which launched in 2015. The project expects to receive support from the US Department of Energy in the form of a loan guarantee. The process for raising additional equity is being led by Morgan Stanley with involvement from project co-sponsers, Aquamarine Investment Partners and MPC Capital. Construction on the project is ready to start once the financing stages have reached completion – the project is targeting financial closure in 2020. Construction is expected to take 3-4 years and employ 1000 workers. **Enhanced Oil Recovery (EOR)** uses CO_2 to extend the lifespan of mature oil fields by injecting it into depleted wells to facilitate oil recovery. EOR has been used since the 1970s, is a dominant end-use for CO_2, and has been a key driver for CCS in North America due to the revenue that can be achieved from CO_2 sales. The **US Department of Energy (DOE)** established a Loans Program Office aimed towards accelerating the deployment of clean energy projects that avoid, reduce, or sequester greenhouse gases. It has provided support in the form of loans, loan guarantees and commitments to projects including wind farms, solar generation, and auto-manufacturing plants.
Business Approach
Structure: The LCM project involves a private enterprise that acts to produce a lower-emission chemical product whilst simultaneously capturing CO_2 to sell as a product to oilfield operators for EOR. A construction contract for the facility is expected to be issued to Fluor Corporation in the format of a lump sum, turn-key, date-certain construction contract. **Financing:** A total capital investment of USD 4.4. billion is predicted for the project. This is expected to be partially financed with private long-term loans, backed by a DOE loan guarantee, with the remainder raised from equity financing. The DOE announced a conditional commitment of long-term loan guarantees up to USD 2 billion, suggesting that approximately USD 2.4 billion must be raised from equity financing. **Revenue:** Revenue is generated from sales of chemical products and from sale of CO_2 to Denbury Onshore for use in EOR. In addition, equity investors can claim investment tax credits under the Internal Revenue Code Section 48B which includes tax credits for investments in coke to syngas with CCS technology. It is thought that the marketing of chemical products as

[24] https://www.lakecharlesmethanol.com/ [accessed October 2020]

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lower emission alternatives could provide competitive advantage, although there is limited evidence of this in the market thus far. **Risk management:** The provision of loan guarantees from the DOE helps to secure private loans at lower costs and acts to lower financial risks from debt payments, with the risk of default on loan repayment being borne by government. The sale of CO_2 as a product to oilfield operators separates the capture risks from the transport and storage risks, with the use of existing infrastructure and established EOR technology lowering these risks. The focus on existing demands for CO_2 and chemical products provides greater certainty in securing revenue return.
Transferable insights and relevance to North Sea Port
The LCM project provides an example of a private enterprise using CCS as a major component of its business model. The use of CCS facilitates the obtainment of financing, through securing loan guarantees and allowing private equity investors to claim credits. The capture of CO_2 provides an additional revenue stream, with CO_2 sold for EOR. The LCM project exemplifies how government support can incentivize CCS and how CO_2 utilisation can act as an economic driver. The project is relevant to North Sea Port as there may be opportunities for captured CO_2 to be sold for utilisation purposes, such as in chemical production. The North Sea Port could also make use of existing pipeline infrastructure, and there is potential for new facilities to be built with business models focused on 'low emission' products (e.g. blue hydrogen production).

Boundary Dam CCS Project – SaskPower[25,26,27]

Background
The Boundary Dam project in Canada involved the retrofit of a coal power plant with post combustion CO_2 and sulphur dioxide capture technology. The retrofit allowed the continued operation (lifetime extension) of the facility under emission limits that were later imposed by the Canadian government. The project began operations in 2014 and was the first commercial-scale power plant with CCS in the world. The captured CO_2 is mostly sold for use in EOR in Cenovus' CO2–EOR operation but can also be stored in a nearby deep saline aquifer where monitoring and research activities occur. The power plant with CCS facility is owned and operated by the **public-owned power utility** company SaskPower. SaskPower is the principle supplier of electricity in the region. The **federal government** provided political backing and partial funding support for the project. It was expected that the clean coal power project would allow continued use of the regions extensive lignite coal reserves and support the regions oil production activities through EOR.

[25] IEAGHG 2015, Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station
[26] https://www.nrcan.gc.ca/energy/publications/16235 [accessed October 2020]
[27] CBC News: SaskPower looking for help to fix 'high cost' Boundary Dam carbon capture flaw [accessed November 2020]

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Associated benefits included the retention of jobs in a region with few alternatives for the work force, the continued use of existing assets, and the learning opportunity.

Emissions performance standards: In 2012 regulations were enacted, pursuant to the Canadian Environmental Protection Act (CEPA), to limit emissions from coal-fired power plants to a level equivalent to that of a modern natural gas combined cycle (NGCC) power plant. This applied to plants constructed post 2015 and existing units deemed to have reached 'end-of-life' stage. The SaskPower unit was due to become an 'end-of-life' unit at the end of 2019, meaning its operations could no longer continue unless CCS technology were adopted. The alternative was for SaskPower to build a new natural gas power plant.

The project encountered an **unexpected risk** in that the capture solvent degraded at a much higher rate than the technology licensor had predicted, meaning the amine maintenance costs almost doubled. This provided technical learnings, such as the need for pilot-scale testing to accurately emulate the flue gas streams of the project, however it also provides lessons for future business approaches and contracting arrangements. For example, the need for risk allocation to be clearly agreed in advance (e.g. allocated to licensor based on specifications) and for terms to include who is responsible for addressing resultant challenges if risks occur.

Business Approach

Structure: The power plant is owned and operated by a single, public-owned utility company. CO_2 is sold to nearby oil producers for EOR or sent to a nearby demonstration storage facility managed by the Petroleum Technology Research Centre (funded by industry and government agencies). Overall, the project was a partnership project between the Canadian government, federal government, SaskPower, and private industry.

Financing: The total cost to upgrade and retrofit the power plant with CCS was CAD 1.5 billion. The federal government provided financial aid of approximately 20% of project costs (CAD 240 million) to support the first-time project with engineering and design. The remainder was self-financed by SaskPower.

Revenue: Alongside the continued revenue from electricity generation, the economic driver for the CCS retrofit centred on the valuable by-products of CO_2 for EOR, sulfuric acid for fertilizer, and fly ash for cement.

Risk management: The project used operational flexibility to manage the risks associated with variable market dynamics and risks associated with commercializing a new technology. This allowed the capture facility to run at lower capacity when oil prices dropped and revenues from CO_2 for EOR were negatively impacted. The project encountered the risk of capture technology not performing as well as predicted, providing future lessons for contractual arrangements (see above).

Business case: At the time that the project was commissioned, an upgrade and retrofit of the existing coal-plant infrastructure, with additional revenue from by-products, was deemed to be economically competitive with the building of a new NGCC power plant. Natural gas prices and demand for CO_2 for EOR were high at the time. The business case did not require any continued reliance on government funding.

Transferable insights and relevance to North Sea Port

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The Boundary Dam project exemplifies the retrofit of CCS technology alongside the renovation of a plant, to both extend the operational lifetime and achieve compliance with emissions standards. It shows how CCS can allow existing assets to continue to realize value, and the potential wider motivations for this such as job retention. The project exemplifies the sale of CO_2 and other captured by-products as valuable commodities.

The Boundary Dam project illustrates a project driven by a public-owned utility with strong political backing. It is an example of good co-operation between an emitter, CO_2 end-user (oil producers), and government organizations.

The project has relevance to North Sea Port as the continued use of existing assets may be a motivator for industries in the region to adopt CCS. There may also be opportunities for companies interested in utilisation of CO_2 to co-ordinate with local emitters. The range of industries may allow additional by-products to simultaneously be captured and sold within the cluster.

PORTHOS – Port of Rotterdam[28]

Background

The PORTHOS project in the Netherlands is an **infrastructure backbone** project. It is focused on constructing CO_2 transport and storage infrastructure to take CO_2 from industry in the Port of Rotterdam area and store it in depleted gas fields under the North Sea. The intention is to build a collective pipeline that takes captured CO_2 to a compressor station, where it will then be piped offshore to a platform and pumped into the gas fields.

The project is a **joint venture** between EBN, Gasunie, and the Port of Rotterdam. Each partner has a different area of expertise: Port of Rotterdam has knowledge of the local market, Gasunie has experience with gas transport infrastructure, and EBN has expertise in offshore infrastructure.

PORTHOS will be set-up as an **open-access system** to which multiple companies can connect. Companies will sign a contract with PORTHOS and be charged a fee for the transport and storage of their CO_2 emissions. Companies will incur costs for capture but will not be required to pay EU ETS for the emissions. It is anticipated that the Dutch government will cover any overall cost differences incurred via the **SDE++ scheme**. Locations expected to capture CO_2 and supply to the pipeline are that of Air Liquide, Air Products, ExxonMobil, and Shell. These companies have signed Joint Development Agreements (JDA) with PORTHOS, committing to start permit procedures and design of capture installations.

A final investment decision is expected in 2021, and if successful the project plans to start construction in 2022 and be operational by 2024. The project is the most advance large-scale CCS project in the EU.

Business Approach

[28] https://www.porthosco2.nl/en/

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Structure: PORTHOS itself is a joint venture with shared project ownership and operation. The project takes a divided chain, 'as-a-service' approach. PORTHOS is responsible for developing the transport and storage components which it will provide as a service for a fee. Individual 'customers' are then responsible for construction of capture facilities, permitting, and applying for the government SDE++ scheme. Mutual progression is assured through Joint Development Agreements with initial customers. The business model of PORTHOS is separate from that of the CO_2 suppliers, with the link being the service fee. **Financing:** Total project costs are projected to be between EUR 450-500 million. The European Commission has proposed to provide EUR 102 million of funding from the budget of 'Connecting Europe Facility' due to the projects cross-border partnerships. The rest of the project is expected to be financed by both public and private investment, with investment costs likely to dictate the amount charged to customers for the service. **Revenue:** PORTHOS achieves revenue through transport and storage contracts with CO_2 suppliers. The CO_2 suppliers can apply for the SDE++ scheme to cover additional costs incurred above what they would otherwise have been be expected to pay for ETS emission allowances.
Transferable insights and relevance to North Sea Port
The PORTHOS project is an example of CCS infrastructure development based on advanced agreements and partnerships between multiple actors with different contractual responsibilities. It is a project that has been designed to allow future expansion with the addition of more CO_2 suppliers, treating companies capturing CO_2 as customers of a transport and storage service. PORTHOS is an example of a CCS project where CO_2 is treated as a waste product rather than a commodity with value. The driver for capture is reduction in emissions as opposed to revenue from CO_2 sales. Government subsidies are expected to allow CO_2 capture at no additional cost to industrial facilities. The project has technical relevance to North Sea Port due to its location and potential for new pipelines in the region to connect to the infrastructure developed. Broader relevance stems from the focus of connecting multiple sites within a region and the use of shared infrastructure. There is further relevance from the projects interaction with the European Commission and Dutch government.

HyNet North West – UK Hydrogen Network [29,30]

Background
The HyNet project is an **integrated low carbon hydrogen production**, distribution, and CCUS project in the north west of the UK. The intention is to build a new hydrogen production facility (autothermal reforming of natural gas) with carbon capture. The hydrogen would be supplied

[29] Cadent 2018, HyNet Project Report: From Vision to Reality
[30] https://hynet.co.uk/ [accessed October 2020]

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to local industrial gas users via a new pipeline, as well as blended into the existing gas distribution network for domestic heating. The project proposes to **re-use existing oil and gas infrastructure** owned by ENI to transport CO_2 captured at the hydrogen production facility and store it in a depleted offshore gas field.

A key driver of HyNet is **achieving decarbonization targets**. The project has the potential to decarbonize local industry, by allowing approximately 10 major industrial gas users to switch to 'clean' hydrogen as a fuel, to decarbonize domestic heating, and to supply hydrogen as a transport fuel. Different aspects of the project have received funding from the **UK government**, which has enshrined emission reduction targets in law. The project is actively engaging with government to help develop a suitable policy support framework.

HyNet is led by Cadent and Progressive Energy, with a consortium of additional partners involved with separate aspects of the project. The current focus is on building evidence and securing consents for the project. A final investment decision could be made in 2022, followed by an estimated 3-year construction period if successful.

Business Aproach

Structure: The business model is based on the production and supply of 'clean' hydrogen to a local customer base. Cadent owns and operates the existing gas distribution network in the area, and the hydrogen produced will partially substitute natural gas demand. The contractual arrangements and ownership structure are likely to be determined by the funding model adopted by the UK government. However, it could be anticipated that hydrogen production and gas distribution infrastructure could be owned and operated by Cadent as a single entity.

Financing: Capital costs for the reference project are estimated at GBP 920 Million, with most of the expenditure on hydrogen production and hydrogen pipeline. The oil and gas fields are expected to cease extraction in the project lifetime: repurposing of this existing infrastructure would therefore postpone or avoid the substantial decommissioning costs that would otherwise be incurred by the government and industry. The project hopes to receive partial funding support from the government, with the UK government having previously pledged to allocate GBP 800 million of capital funding towards CCUS projects. It is likely that separate mechanisms will be used to fund the different aspects of the project, with one potential mechanism being that of regulated asset base (RAB).

Revenue: Revenue is achieved through the sale of hydrogen to industrial gas users, domestic users, and potentially transport. Cadent expects that the levelized cost of hydrogen may be GBP 38 / MWh compared to GBP 15 / MWh for natural gas. Therefore, subsidies are likely to be necessary with a potential option being a Contract for Difference style mechanism similar to that used for the nuclear industry. As the gas distribution infrastructure is monopolistic, prices may be regulated by the economic regulator Ofgem.

Risk management: The HyNet project is targeted towards being a deliverable project, with a focus on the use of proven, cost effective technology and existing infrastructure. Stated actions to minimize risks include: multiple units at the hydrogen production facility to maximise supply reliability; multiple customers to reduce counterparty demand risk; multiple CO_2 stores to minimize storage risk; and commercial segregation of hydrogen and CCUS aspects to minimize cross-chain risks.

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Transferable insights and relevance to North Sea Port
HyNet can be seen as a project where a gas distribution operator is targeting decarbonization of its network, anticipating the future needs of its customers in reducing emissions. It is driven by private entities and backed by a broader consortium of business and researchers. The project actively engages with local stakeholders, making the argument that the project will benefit the broader area and therefore aligning itself with anticipated government incentives for funding. HyNet exemplifies a project that has focused on existing technology, expertise, and infrastructure. The key uncertainty is the funding support mechanism that may be implemented by government.

4.2 Conclusions from project case studies

Although existing large-scale CCS projects have primarily been enabled through the ability to generate revenue from CO_2 sales for EOR, there are a range of other factors that could drive the development of CCUS projects. Examples include emission taxes such as those imposed by Norway; regulations such as the emission standards imposed on coal power plants in Canada; tax credits to investors in CCUS projects; decarbonization targets and strong political backing; and market demand for low carbon products or capture by-products. Several examples highlight how the involvement of local government can enable the development of CCUS, with potential routes being public-private partnerships, government funding mechanisms, or risk sharing.

The North Sea Port cluster could take inspiration from a variety of existing and planned CCUS projects, with components of several existing business models being potentially relevant to the development of CCUS in the North Sea Port. Subsequent tasks in WP6 of the C4U project will explore the risks and challenges specific to the North Sea Port cluster and then the potential applicability of different business models and mechanisms to the project.

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5 Conclusions

This deliverable follows the completion of the first task within WP6 of the C4U project. It summarises the work conducted and key findings from a series of desk-based literature reviews related to: sustainable business model innovation; CCUS risks and challenges; and planned and operational CCUS projects. An understanding of these topics is considered highly important for the successful development and subsequent assessment of business models for CCUS in industrial clusters. **The conclusions ('results') from each of these components are outlined in the relevant chapters above.**

The work forms the initial basis for the WP6 business model analysis that will be conducted by Element Energy (lead) and Radboud University. Subsequent tasks will determine which of the risks, challenges and learnings identified are most relevant to CCUS projects in the North Sea Port cluster through engagement with stakeholders in the region as well as other industrial cluster projects. A business model innovation framework will then be used in the development of potential business models for CCUS in industrial clusters, with the aim of mitigating risks and providing a value proposition. **The applicability of the individual outputs to the future tasks is outlined below:**

- The results of the **literature review on SBMI** will be used to feed-in the business model innovation framework. The results show that perceived economic viability is a large driver for sustainable business model innovation, hence the pivotal role that policy plays in this matter will be researched in order to assess and/or construct this condition. Moreover, the results show that dynamic capabilities, such as knowledge and creativity, are resources that are important for sustainable business model innovation. This will be taken into account for the business model innovation framework. Lastly, the role of stakeholder engagement and participating in networks is discussed, these processes could reduce risk and lead to a systemic innovation by taking a holistic approach. For the business model innovation framework public-private engagement and the role of niche solutions in mature markets will be considered in particular.
- The **identification of risks and challenges** described within the literature provides a basis for assessing the risks and challenges that are applicable to specific industrial clusters such as the North Sea Port. An understanding of the key applicable risks and challenges will then be used within the process of developing and assessing business models for CCUS in the North Sea Port cluster. In particular, business models could be developed with the objective of negating or mitigating the impact of certain risks. The strengths and weaknesses of proposed business models could be identified by investigating the resilience of components, such as the revenue model, to the occurrence of risks, such as increases in capital costs.
- The **identification of transferable learnings** through collating the success factors and common failure factors of planned and operational projects provides a basis for understanding factors that may aid the success or lead to the failure of CCUS projects within other settings, such as industrial clusters and the North Sea Port. Some of the identified factors relate directly to the business model used, giving insights into how business models can impact project success and failure. Other success factors show how implementation choices instead can mitigate some of the previously identified risks. These learnings will provide inspiration for developing successful business models.
- The **study of relevant CCUS projects**, focusing on the business structures and financing/revenue models used, provides inspiration for the development of business

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models for future projects. In particular, the case studies illustrated concepts such as: public-sector involvement driving projects; a coordinating body facilitating operations; transport & storage provided as a service; involvement of multiple project partners; and revenue streams from utilisation. A selection of these concepts could be transferred to business models for new CCUS projects.

The status of the work performed for deliverable D6.1 is considered as complete. The desk-based review has provided a foundational understanding of the areas of importance for the development of business models in the field of CCUS in general. Nevertheless, it is expected that the review of relevant literature will be an ongoing component throughout subsequent research steps, with the potential for more information to be uncovered with the more detailed and specific analysis components of later tasks.

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