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Business model innovations for carbon capture and utilization

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Abstract: Carbon capture and utilization (CCU) has been recognized as an important pathway toward mitigating climate change, but research on this topic has been heavily technology-oriented. Hence, this study aims to build understanding of CCU from a business perspective by a) exploring and conceptualizing the types of business model innovations (BMIs) employed by companies to harness CCU and b) analyzing what factors drive and determine economic value capture of these BMIs. We conducted a qualitative thematic analysis from a multiple-case study with nine industrial companies supported by a document analysis. Our results display 12 distinct CCU BMIs across carbon dioxide processing, engineering, and system optimization business domains and 17 value capture determinants grouped under four drivers, namely, policy and regulation, technology, markets and demand, and business compatibility. This study integrates carbon circulation into the circular business model and innovation management literature and strengthens the business angle of CCU research.

Keywords: carbon management; climate change; net zero; business model innovation; business model; value chain; carbon capture and utilization; CCU; qualitative case study

1 Introduction

In recent years, society and markets have recognized the dire need to manage carbon flows and pursue decarbonization to achieve the net-zero targets that have been pledged and to avoid a climate disaster (Davis et al., 2018; European Commission, 2024). This awareness has led to considerable technological development and many innovations aimed at capturing carbon dioxide (CO_2) from industrial point sources or the atmosphere and to subsequently either store the CO_2 permanently (CCS) or utilize it as such or following its conversion to a range of potential products (CCU). Notably, the CCU approach pursues novel carbon cycles and, unlike CCS, promotes carbon recycling (Chauvy & De Weireld, 2020), which fundamentally links CCU with the circular economy (Budzianowski, 2017). The development and scaling up of CCU drive the transition to a net-zero economy in several ways, such as by replacing fossil products with those produced using recycled CO_2 (e.g., Chauvy et al., 2020) and by leveraging biogenic and atmospheric CO_2 to create products with negative carbon footprints (e.g., Sick et al., 2022). In parallel, CO_2 capture can mitigate the climate impact of several sectors that are challenging to fully decarbonize, such as cement or steel (Davis et al., 2018). The implementation of CCU thereby transforms the businesses of diverse industries and companies, pushing the latter to develop and harness related technologies and develop supply chains, internal material flows, and products, leading to the need to innovate business models supporting CCU. In brief, the substantial climate potential of CCU technologies cannot be leveraged without a variety of novel business model innovations (BMIs), that is, new configurations of business model elements of value proposition, value creation and delivery, and value capture (Richardson, 2008), which enable companies to profitably implement and scale up CCU-based business.

Even though CCU has been identified as an important pathway toward preventing climate change for multiple industry sectors, research on CCU has focused on individual capturing and utilization technologies and their development (Chauvy & De Weireld, 2020; Muslemani et al., 2020; Sick et al., 2022) whereas business development as a means of harnessing CCU has been neglected. For example, Naims and Eppinger (2022) argue that the development of business models to circulate carbon with CCU has suffered from a lack of value creation and innovation management research approaches. Established circular business model and business model innovation streams have not yet explored the carbon management or CCU context, but only acknowledged in passing the relevance of CO_2 emissions for circular business (Bocken et al., 2016; Geissdoerfer et al., 2020). Similarly, the circular innovation management literature has not explicitly tackled CCU or the circulation of carbon in general, even though some papers touch upon CCU in their data and cases (e.g., Gomes et al., 2023). The literature on CCU innovations is heavily technology-oriented and thin regarding business, with the exceptions of some early case studies (e.g., Yao et al., 2018) and a few scientific papers discussing the business and economic perspectives on CCU (Naims, 2020; Naims & Eppinger, 2022). Due to the research gaps explained above, we lack a focused understanding of how companies can harness CCU in their business models and create and capture economic value from it.

Therefore, *this research aims to increase understanding of CCU business by examining companies' BMIs for CCU and identifying related determinants of economic value capture.* Our first objective is to explore, distinguish, and characterize distinct CCU BMIs, including value proposition, creation and delivery, and capture, in industrial contexts. Therefore, the first research question (RQ) is as follows:

RQ1: What types of BMIs can companies develop to harness CCU?

Second, we zoom in on the economic value capture of the identified CCU BMIs to shed light on the challenging topics of CCU profitability and financial viability. Accordingly, the second RQ is as follows:

RQ2: What are the drivers and determinants of economic value capture of CCU BMIs?

We addressed the research questions with an empirical, qualitative multiple-case study supported by a document analysis. A qualitative thematic analysis was carried out, and BMIs were conceptualized based on a search for patterns of value architecture components and value chain positioning within the empirical cases and document analysis data. The analysis resulted in the identification of 12 types of BMIs across the three interconnected CCU business domains of CO_2 processing, engineering, and system optimization. In the subsequent value determinant analysis, we found that the value capture of these 12 CCU BMIs originates from the four underlying drivers of policy and regulation, technology, market and demand, and business compatibility. Our study provides key contributions to the circular business model literature by exploring carbon circulation business; to the low-carbon and carbon management business literature by offering an in-depth analysis of an important decarbonization pathway; to the circular innovation management literature by analyzing nascent but rapidly developing CCU innovations and carbon circulation with the BMI framing; and to the technically biased CCU literature by strengthening the crucial business perspective. For managers, our study provides clear guidelines on the options available to them to participate in CCU markets and organize the firm's value architecture accordingly, with a focus on optimizing the conditions for economic value capture.

2 Theoretical background

BMIs

A variety of definitions has been applied to the concept of a BMI, including those that regard a BMI as the process of innovating a new business model (e.g., Geissdoerfer et al., 2018; Roome & Louche, 2016) and those that see BMI as the outcome of that process, that is, a newly configured business model (e.g., Bocken et al., 2014; Chesbrough & Rosenbloom, 2002). In this study, we employ the latter view, addressing BMIs as the distinct outcomes of innovation processes, and leave the analysis of these processes for further studies.

The business model literature provides ample options to define and theoretically frame BMIs. BMIs can be studied, for example, as activity systems or classified by a single criterion, but commonly they are analyzed by looking at a given set of elements or components that constitute their value architecture, allowing them to fulfil a customer value proposition in a profitable way (Osterwalder & Pigneur, 2002). In this study, we define a BMI as *a new configuration of value architecture consisting of value proposition, value creation and delivery*, *and value capture*, according to the framework developed by Richardson (2008). Richardson's threefold division of major business model components is clearly defined, is aligned with the popular Business Model Canvas tool (Osterwalder & Pigneur, 2010), and has been frequently applied to the analysis of environmentally sustainable business (Bocken et al., 2014; Geissdoerfer et al., 2018).

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CCU as a key tool of industrial carbon management

The improved management of carbon flows and increased circulation of CO_2 have been widely recognized as crucial elements in the fight against a worsening climate change (e.g., Bataille et al., 2018; Rissman et al., 2020). The specific emission mitigation opportunities of CCU include the decarbonization of fuel-dependent sectors, such as aviation and marine, by replacing fossil fuels with synthetic ones produced from captured CO_2 (International Energy Agency, 2023) and the removal of CO_2 from the atmosphere through the utilization of biogenic or atmospheric CO_2 to produce long-lived products, such as construction materials (Sick et al., 2022). As an important example of current CCU-related ambitions, the EU Commission has recently proposed an industrial carbon management strategy in which CCU is regarded as one of the key pathways, along with capturing CO_2 for storage and removing CO_2 from the atmosphere, to reducing CO_2 emissions in sectors where renewable energy and energy efficiency alone cannot quickly achieve net zero (European Commission, 2024). The Commission has communicated ambitions of capturing up to 450 Mt of CO_2 by 2050 and estimates that around 200 Mt of that amount could be utilized to replace fossil fuels and raw materials in the markets (European Commission, 2024).

The extant academic literature confirms the need for and emerging momentum of CCU and lays out numerous options for the utilization of captured CO_2 (Chauvy & De Weireld, 2020; Mikkelsen et al., 2010). The academic literature on carbon management and CCU innovations to date, however, mostly focuses on techno-economic development (e.g., Chauvy et al., 2020; Zimmermann et al., 2020) and sustainability assessments (e.g., Müller et al., 2020). For business development, which is equally important in ensuring the widespread adoption of these technologies, the extant literature offers only a few early insights.

CCU as business

Overall, most prior research on CCU focuses on technology and policy, rather than business or innovation management, resulting in a lack of focused understanding of business models stemming from CCU. Certain policy-focused papers shed light on the business implications of relevant CCU policy instruments. For example, Zhang et al. (2021) examine the crucial role of government subsidies for CCU investment decisions in China, and Vreys et al. (2019) highlight the importance of the government, industry, and consumers in their scenario development of CCU. Technology- and policy-focused studies provide some insights into CCU business, as business feasibility in this field still largely relies on extensive technology development and significant policy support (Kujanpää et al., 2023).

Research insights regarding BMIs for CCU are, however, scarce and provide little guidance for companies on how to craft value propositions and establish value creation processes while pursuing a profit with CCU solutions. Nonetheless, a handful of studies gives some guidance. Naims (2020) identifies three CCU value chain actors: equipment manufacturers, high-emitting producers, and material and fuel producers. Naims and Eppinger (2022) distinguish four transformation strategies in CCU business, namely, solution providers, intangible value investors, passive observers, and passive sceptics. A couple of studies have touched upon CCU business models using a full chain model approach that includes all the main value chain actors in a single business model. Yao et al. (2018) suggest the vertical integration model, joint venture model, CCS operator model, and CO_2 transporter model as business model options in the Chinese markets. Muslemani et al. (2020) study a similar set of full chain business models in the steel sector, which they name vertical integration, joint venture, independent operator, and transporter models.

As no conceptual academic research on single-actor CCU business models has yet been conducted, current firm-level knowledge relies on sector-specific studies of CCU business cases. Prior studies have examined the business implications of using recovered CO_2 in the construction industry (e.g., Meijssen et al., 2024; Sick et al., 2022), wind power generation (González-Aparicio et al., 2018), and steelworks (Yao et al., 2021), concluding that CCU can form a viable business model in these fields.

3 Methodology

We conducted a qualitative analysis involving an empirical multiple-case study that allowed us to explore, but also conduct a focused analysis of, industrial BMIs (cf. Dubois & Araujo, 2004; Voss et al., 2002). A supporting document analysis not only enabled triangulation, but also added valuable data to the analysis in terms of background and contextual information (Bowen, 2009) as well as descriptions of business cases not included in the empirical case sample.

Purposeful sampling was used to select the nine empirical cases (Patton, 1990). First, we employed high-impact sampling by choosing the cases from particularly CO_2-intensive industries, that is, from the energy, chemicals, and pulp and paper industries. Second, critical case sampling logic was followed by focusing on pioneering cases that are likely to be highly indicative of a near-term scale-up of CCU business in their industry. Third, maximum variation sampling was used because we wanted to attain a comprehensive exploration of CCU BMIs in diverse empirical settings. Therefore, the final sample consisted of three cases that supply CO_2 to the market, three that utilize and convert CO_2 into new products, and three that provide technologies and services to enable CCU processes along the value chain. Table 1 presents and gives short descriptions of the empirical cases. It is notable that CCU BMIs were still at piloting or planning stage in many of the empirical cases due to the newness of the technologies and emergent state of the markets.

For the empirical cases, primary data consisted of semi-structured interviews with high-ranking managers who had a firm vision of CCU business development in their companies. Secondary data consisted of presentations and group discussions, including summaries written up by the researchers. The final datasets for each empirical case are presented in Table 1. In addition to gathering case-specific data, we conducted two expert interviews with the Head of Circular Economy and an RDI manager of an innovation cluster (56 min) and the Chief Advisor of an industry federation (55 min) to further support the analysis.

Table 1 Empirical cases and related datasets

Empirical case	*Short case description*	*Case dataset*
Pulp & Paper Company A	A large multinational producer of wood-based products that is investigating the possibilities of capturing CO_2 from pulp mill flue gases.	• Interview with pulp mill Environment Manager, Development Manager, and Technology Manager (1 h 52 min)

Pulp & Paper Company B	A large multinational producer of wood-based products that is studying various options to capture and further utilize CO_2 emissions from pulp mill flue gases.	• Interview with Vice President of Energy (45 min)
Waste Management Company	A regional Finnish waste management company that produces CO_2 as a by-product of biogas and landfill gas refining and wants to sell that CO_2 to be further utilized.	• Interview with Circular Economy Director and Project Engineer (55 min)
Energy Company	A large energy company operating mainly in the Nordic countries that is piloting the capture and conversion of CO_2 from waste incineration flue gases into high-quality plastics.	• Two interviews with Program Director (66 and 49 min) • Notes from two seminar presentations
Hydrogen Economy Company	A Finnish hydrogen (H_2) and Power-to-X technology company that is about to commence the production of synthetic methane from recycled CO_2 and has plans for a rapid scale-up of green hydrogen and synthetic fuel production.	• Interview with Vice President of Business Development (59 min) • Notes from a seminar presentation
Chemicals Company	A large multinational chemicals company that is considering sourcing captured biogenic CO_2 and converting it with existing by-product green H_2 into synthetic methane.	• Interview with Business Development Director (87 min)
Energy Technology Company	A large global provider of technological solutions for the energy industry that offers multiple carbon capture technologies as part of its portfolio.	• Interview with Strategy Director (59 min) • Notes from two seminar presentations
Mechanical Engineering Company	A small Finnish provider of mechanical engineering consultancy services that is currently looking into business opportunities regarding CCU technologies.	• Interview with Managing Director and Chief Engineer (56 min)
Industrial Project Management Company	A large Finnish provider of industrial project management services that offers system design, project management, and engineering services for Power-to-X and H_2 ecosystems, which often leverage CCU.	• Notes from two seminar presentations and a small group discussion (½ h)

For the complementary document analysis, data were collected following expert consultation and snowballing methods (e.g., Saunders et al., 2019). That is, we leveraged the interviews to identify key forums and organizations producing knowledge on CCU-related business, such as the International Energy Agency, and subsequently searched for relevant reports from the identified bodies for inclusion in the analysis. Only the reports that directly addressed CCU and company-level business were selected for the analysis. Furthermore, we utilized snowballing to search for more documents within the references of those already selected. The interviews were also used to identify relevant policy and legal instruments with evident business implications that could be further investigated in depth within the document analysis. This process led to a final sample of 10 reports and policy documents to be included in the analysis, as shown in Table 2.

Table 2 Document analysis sample

Document code	*Document name**	*Organization***	*Year*	*Short description*
A	CCUS Policies and Business Models: Building a Commercial Market	International Energy Agency	2023	An analysis of current CCUS policies and business models as well as their future developments
B	CCUS in Clean Energy Transitions	International Energy Agency	2020	A scenario analysis of CCUS currently and in the future from the perspective of the clean energy transition
C	Carbon Dioxide Use and Removal: Prospects and Policies	Finnish Government	2023	A government-commissioned report that aims to give an overview of current CCUS and carbon dioxide removal technologies, markets, and policies, with a focus on the situation in Finland
D	A Vision for Carbon Capture, Utilisation and Storage in the EU	Clean Air Task Force	2023	The current state of CCUS in the EU and recommendations for a CCUS Strategy
E	Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry	Material Economics	2019	An in-depth analysis of how heavy industry in the EU could reach net-zero by 2050, including scenario analyses for CCU and CCS
F	Towards an Ambitious Industrial Carbon Management for the EU	European Commission	2024	A communication from the European Commission proposing a strategy for industrial carbon management
G	Net Zero Industry Act	European Commission	2023	A provisionally agreed regulation to strengthen the European manufacturing capacity of net-zero technologies and overcome barriers to scaling up the manufacturing capacity in Europe. Part of the

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				Green Deal Industrial Plan
H	Sustainable Carbon Cycles	European Commission	2021	A communication from the European Commission outlining the ambitions for the industrial capture, use, and storage of carbon as well as for carbon farming and regulating carbon removals
I	Carbon Removal Certification Framework	European Commission	2022	A provisionally agreed regulation proposal to certify permanent carbon removal, carbon storage products, and carbon farming with the aim to incentivize sustainable carbon removals in the EU
J	Directive 2023/2413 (Renewable Energy Directive III)	European Union	2023	The legal framework for the development of clean energy in the EU, which includes targets for the use of CCU-based fuels and rules for their production

* For policy and legal documents, the full official document titles are given in Appendix A
** Full lists of authors, when available, are given in Appendix A

We carried out a qualitative thematic analysis of the data to uncover and characterize the various types of CCU BMIs and identify their economic value capture determinants. All data were coded with the help of Atlas.ti analysis software. A thematic coding scheme was designed to reveal the characteristics and shaping factors of the value proposition, creation and delivery, and value capture of each case firm. Additional code groups addressed, for example, the industries of the focal firm and those of their customers, critical business decisions, and the final products of CCU. The BMIs were identified by searching for patterns regarding value dynamics and the position of the company within the CCU value chain. The economic value capture determinants were synthesized by building on the BMI analysis and clustering the determinants under distinct underlying value capture drivers, such as policy, technology, and markets. To strive for methodological rigor, we applied data triangulation by utilizing multiple types of data sources and researcher triangulation by continuously evaluating and refining the analysis results within the author team.

4 Findings

CCU BMIs

To facilitate the detailed analysis of BMIs, a tentative overview of CCU value chains and the studied cases within these chains is given in Figure 1. In CCU, CO_2 is first captured and then, if needed, transported to be either used directly or converted into a variety of products, many of which are also made using green H_2. Various technologies and system-level services are needed throughout the different CCU value chains. An overview of the empirical cases demonstrates that companies can employ any of these activities as the focal point of their CCU BMIs.

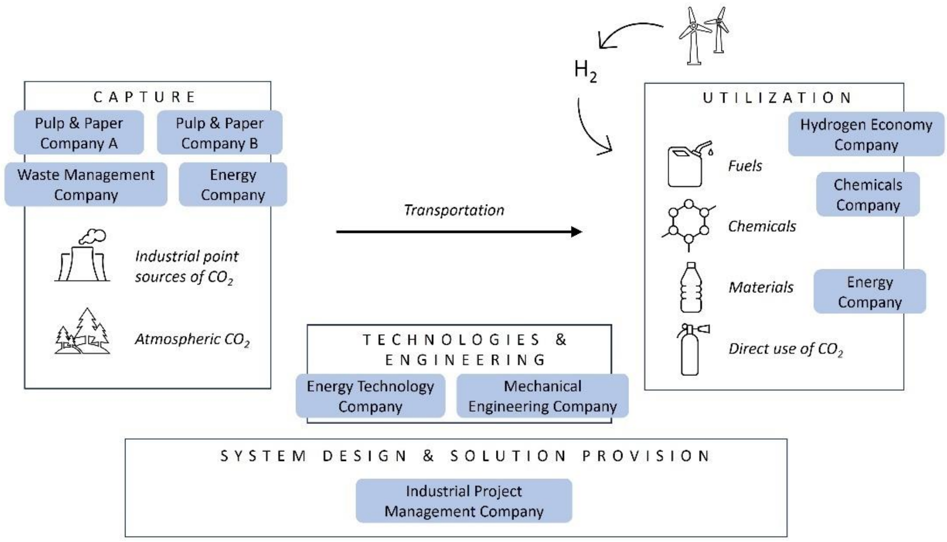

Figure 1 Overview of CCU value chains and empirical cases

A detailed analysis of the empirical cases and document data uncovered 12 distinct but interconnected BMIs, each with a unique value architecture. The identified BMIs are discussed in detail in Table 3, including a brief analysis of the main components of each, namely, value proposition, creation and delivery, and capture. Regarding value capture, the focus is on uncovering the determinants, as per RQ2. Importantly, Table 3 also lists key data examples of each BMI, showing how findings were derived from the empirical cases and the document analysis.

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Table 3 Types of CCU BMIs

BMI	*Short description*	*Data examples (from empirical cases or document analysis)*	*Focal value proposition*	*Logic of value creation and delivery*	*Value capture determinants*
CO_2 Source	Surrender of flue gases or other streams for CO_2 capture against a fee.	○ Pulp & Paper Company A is considering monetizing pulp mill flue gases by allowing external partners to implement CO_2 capture and buy the captured CO_2 for further utilization.	A steady supply of CO_2-containing streams from which the CO_2 can be captured, converted, and utilized, with qualities that match the value chain needs.	The focal firm provides access to their CO_2-containing stream and required facilities. Another actor, who either converts the CO_2 themselves or sells it forward, is responsible for implementing the capture. The focal firm simply provides access to the stream and required facilities.	○ Qualities of the CO_2-containing stream affecting its monetary value: bio- or fossil-based, location, volume, concentration ○ Demand for CO_2: amount, proximity, and volatility ○ Policy and regulation: carbon pricing tools (e.g., emission trading systems) provide monetary incentives
CO_2 Capture & Provision	Capture and sale or further conversion of CO_2 from a given stream. The capture is often outsourced.	○ Pulp & Paper Company B plans to capture biogenic CO_2 from pulp mill flue gases using outsourced but customized technology and either sell it for further conversion into products or engage in the conversion process themselves. ○ Waste Management Company wants to capture and purify the	A steady supply of CO_2 to be converted and utilized either in the downstream value chain or by the focal company, with qualities that	The focal firm implements CO_2 capture (in- or outsourcing) for a stream owned either by itself or another actor. The CO_2 is then sold forward (via a CO_2 transportation	○ CAPEX and OPEX of the chosen capture technology or the cost charged by the technology provider ○ Market price of CO_2 in targeted applications (e.g., in enhanced oil recovery, the CO_2 price follows oil prices and is relatively low)

		CO_2 from its biogas and landfill gas production and convert it either in an integrated process or by selling the CO_2 to conversion partners (a possible target product is methane). ○ Document A lists some companies that capture CO_2 to sell it for different utilization purposes, such as the NWR CO2 Recovery Unit in Canada and Bonanza Bioenergy CCUS in the US. ○ Document C lists multiple companies in Finland planning to capture their CO_2 emissions in the near future, including Helen, Tampereen sähkölaitos, and Finnsementti.	match the value chain needs.	scheme) or further converted by the focal company.	○ Qualities of the CO_2-containing stream affecting cost of capture: volume, CO_2 concentration, impurities ○ Qualities of the captured CO_2 affecting its monetary value: bio- or fossil-based, location, volume, purity ○ Demand for CO_2: amount, proximity, and volatility ○ Policy and regulation: carbon pricing tools (e.g., emission trading systems) or subsidies to implement capture (e.g., carbon contracts for difference) provide monetary incentives
Direct Use of CO_2	Utilization of captured CO_2 without any conversion stage, e.g., in enhanced oil recovery, as a protective gas, carbonation, or greenhouses. Possible to combine with CO_2 capture.	○ Document A stresses that the main application for direct use of CO_2 today is enhanced oil recovery (company examples Enhance Energy and Whitecap Resources in Canada). CO_2 can also be used as a working fluid for other underground applications, including enhanced gas recovery and enhanced water recovery.	Sustainable alternative to traditional natural gas-based CO_2 for industrial applications of pure CO_2.	The focal firm substitutes traditional fossil-based CO_2 in production processes with recycled CO_2, enabling more sustainable production processes (e.g., plant cultivation) or final products	○ Chosen application: volumes, profitability, permanence of CO_2 within the application ○ Price of captured CO_2 compared to price of traditional fossil-based CO_2

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				(e.g., fire extinguishers).	
Intermediates	Production and sale of intermediates (such as methanol) by converting captured CO_2. Possible to combine with CO_2 capture.	○ Hydrogen Economy Company is considering investing in methanol production. ○ Chemicals Company is investigating the possibilities of producing methanol using existing production by-product hydrogen and sourcing biogenic CO_2.	Versatile compounds, such as methanol, urea, or formaldehyde, with low- or zero carbon footprints and the potential to replace fossil-based alternatives, particularly for the chemical industry.	The focal firm sources or captures CO_2 and converts it into versatile compounds together with other necessary raw materials and utilities.	○ Demand and market for the chosen intermediate: volume, versatility of uses, geographical distribution (export potential), market price ○ Downstream uses of the target intermediate: permanence of the end product ○ Demand-shaping policy and regulation: use mandates
Short-Lived Products	Production and sale of short-lived products (particularly synthetic fuels) by converting captured CO_2. Possible to combine with CO_2 capture.	○ Hydrogen Economy Company is ramping up synthetic methane and related green H_2 production in a new dedicated plant. ○ Chemicals Company is considering the production of synthetic methane (possibly also methanol), using existing production by-product H_2 and sourcing biogenic or waste-based CO_2. ○ Document A lists some operational systems, such as synthetic ethanol production, from steelmaking emissions in Belgium by ArcelorMittal and LanzaTech.	Synthetic fuels (and short-lived chemicals) with low- or zero carbon footprints and the potential to replace fossil-based alternatives.	The focal firm sources or captures CO_2 and sources H_2, which is typically needed in the conversion process. H_2 can also be produced by the focal firm (either with dedicated production or as a by-product), which requires it to source the green electricity and water needed	○ Sustainable electricity: stable availability, price level, and volatility ○ Contractual tools: offtake agreements ○ Logistics: optimization to combine CO_2, H_2, and utilities in the production process ○ Demand and market for the chosen product: volume, geographical distribution (export potential), market price ○ Feasible sustainability price premium

		○ Document C lists several companies with commercial-scale synthetic fuel production projects, including Norsk E-Fuel (Norway) and Carbon Recycling International (Iceland, Norway)		in production. CO_2 and H_2 are then converted into short-lived products, which are sold to customers in the transportation and chemical industries, among others.	○ Production-incentivizing policy and regulation: subsidies and carbon pricing tools (e.g., emission trading systems) provide monetary incentives ○ Demand-shaping policy and regulation for fuels: use mandates (e.g., Renewable Energy Directive III), carbon pricing tools (e.g., emission trading systems)
Long-Lived Products	Production and sale of products that store CO_2 at minimum for several decades and can replace fossil alternatives (such as synthetic plastics), typically by converting captured CO_2. Possible to combine with CO_2 capture.	○ Energy Company is piloting high-quality plastic production from self-captured waste-based CO_2 in collaboration with several technology providers. ○ Document C lists several companies with commercial-scale plants to mineralize CO_2 to produce construction materials, including O.C.O Technology (the UK) and Vicat Group (France).	Long-lasting products, such as synthetic plastics or CO_2-cured construction materials, with low or negative carbon footprints, some of which can replace fossil alternatives.	The focal firm sources or captures CO_2 and converts it into long-lived products together with other necessary raw materials and utilities. The products are sold to customers in the chemical and construction industries, among others.	○ Demand and market for the chosen product: volume, geographical distribution (export potential), market price, demand for negative emissions ○ Contractual tools: offtake agreements ○ Feasible sustainability price premium ○ Production-incentivizing policy and regulation: subsidies, carbon pricing tools (e.g., emission trading systems) and ability to sell carbon

					credits provide monetary incentives ○ Demand-shaping policy and regulation: use mandates (e.g., for recycled content)
Process Technologies	Development and provision of technologies for either CO_2 capture or conversion processes, delivered as products or as a service (with the technology provider acting as a project developer).	○ Energy Technology Company is piloting multiple capture technologies, including oxyfuel and calcium looping, to be sold to various industrial customer segments, ranging from technology licensing to delivering integrated solutions. ○ Document A lists multiple commercial capture-as-a-service solutions: Just Catch capture system (by Aker Carbon Capture), CANSOLV capture system (Shell), CyclonCC capture system (Carbon Clean), and 14 others. ○ Documents A, C, D, and E present multiple technology examples being developed for CO_2 capture and conversion targeting different emission-intensive industries.	Technological offerings that decarbonize industrial processes by capturing CO_2 with customer-optimized technology and allow firms to create new types of value by enabling the conversion of CO_2 into various products.	The focal firm develops, manufactures, and sells one or several technologies and derived products for CO_2 processing, i.e., its capture or conversion. Typically, a single company focuses either on capture or conversion technologies. Development and scaling up are often done together with the customers.	○ Required R&D investment and available funding ○ Technology attributes: e.g., capture efficiency, operational cost-efficiency, maintenance need, modularity, scalability ○ Target customer industries: technology fit into existing process, willingness and ability to pay ○ Revenue model: e.g., selling products and additional services, selling as a service, licensing technology ○ Demand-shaping policy and regulation: subsidies (e.g., carbon contracts for difference)
Transportation & Infrastructure	Provision and operation of transportation solutions and	○ Document A lists multiple CO_2 transportation endeavors, including operational CO_2 pipelines (e.g., Alberta Carbon	Logistical solutions that enable a cost-efficient,	The focal firm develops and/or operates CO_2 transportation	○ Contractual tools: long-term capacity contracts

	infrastructure that is required to enable CCU value chains and scale up CCU markets.	Trunk Line of Wolf Midstream in Canada) and regional hubs and open-access transportation networks that can be developed through partnerships (e.g., Porthos hub of Port of Rotterdam Authority, Gasunie, and Energie Beheer) or with strong state support (e.g., Northern Lights hub in Norway). However, most current CO_2 transportation hubs aim for storage instead of utilization. ○ Document D lists repurposed pipelines, road and rail transport, and shipping as the essential future CO_2 transportation methods in the EU, highlighting the cross-industrial business opportunities and need for joint and coordinated development of the transportation network.	continuous, and reliable flow of CO_2 (and H_2) from capture to conversion and onwards to customers.	networks (e.g., pipelines, shipping, trucking) and/or related infrastructure (e.g., H_2 transportation, import and export terminals, liquidation plants, temporary CO_2 and H_2 storage sites), often serving multiple customers within the same system.	○ System optimization: choice of transportation method, intermediate storage needs ○ Policy and regulation: state ownership or state guarantees, subsidies (particularly to develop overcapacity), transport network regulation
Engineering Consultancy	Provision of technology- and process-level design and engineering consultancy for technology manufacturers and various CCU activities.	○ Mechanical Engineering Company is pursuing new consultancy business within CCU technologies and plans to acquire expertise in the field.	Expert services to resolve specific technological issues in value chains and optimize processes.	The focal firm sells expert services to design or customize one or several CCU technology types and/or optimize the performance of related processes.	○ Scope of technology expertise and target customer industries: ability to carry out R&D and willingness to pay ○ Technology readiness level and market presence of target technologies

System Provision	The development or acquisition and provision of various interconnected technologies or processes of the CCUS value chain, possibly on a turnkey basis.	○ Hydrogen Economy Company is bundling technologies from different providers to construct broad production systems. However, in this case, Producer A maintains the ownership of the CO_2 stream and final product. ○ Industrial Project Management Company is integrating various technologies from different providers into overarching value chain packages for their customers.	One-stop-shop for a customer willing to turn CO_2 emissions into valuable products.	The focal firm maps out and bundles together technologies from different providers to provide part- or full-chain CCU architecture optimized to the needs of the customer. The offerings can range from pure technology sales to turnkey solutions.	○ Insourcing/outsourcing of technologies and selection of technology partners ○ Target customer industries: willingness and ability to pay ○ Fit between technologies and customer's CO_2 stream and operations
Project Consultancy	Provision of system-level consultancy regarding, e.g., value chain and concept design, project management, collaboration facilitation, or operational management.	○ Industrial Project Management Company is providing comprehensive system design and project management services for CCU-related value chains, particularly to produce products from H_2 and recycled CO_2.	Services that help customers to, for example, position their CCU activities, identify relevant customer segments, leverage potential synergies, design efficient value chains, and successfully install and implement new CCU processes.	Depending on their service portfolio, the focal firm offers expert consultancy for CCU system-level design and positioning and/or offers management services for large CCU development projects.	○ Scope of service offerings and target customer industries: willingness and ability to pay

Carbon Credit Services	Provision of standardization, certification, registration, and trading platforms for carbon credits within voluntary carbon markets.	○ Document A highlights the role of functional voluntary carbon markets: "In the absence of a compliance market, emitters can sell carbon credits in the voluntary carbon markets based on certified emissions reduced or removed through CCUS." ○ Document C lists multiple platform and service providers for voluntary carbon markets, including Puro.Earth (Finland), Nori (the US), and MoorFutures (Germany). ○ Document F discusses alternative compliance mechanisms for voluntary carbon markets and their implications for business opportunities.	Offerings that enable industrial customers to monetize verifiable carbon removals through carbon credits. Within CCU, potential customers are companies making long-lived products from biogenic or atmospheric CO_2.	The focal firm sells offerings that enable the trade of carbon credits, including, for example, the standardization, certification, or registration of carbon removals or the operation of a digital marketplace.	○ Revenue model (certification fees, credit issuance margin, platform subscriptions, etc.) ○ OPEX: for example, the certification process or maintenance of registries or platforms ○ Marketplace regulation ○ Scope of the marketplace and accepted carbon removal methods

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The first two BMIs, CO_2 Source and CO_2 Capture and Provision, focus on supplying captured CO_2. The former refers only to offering one's CO_2-containing flue gases or similar streams to be utilized for CO_2 capture, whereas the latter includes the capture and purification of CO_2 before subsequent sales or refining. The economic value capture determinants of these models are tied, first, to the characteristics of either the CO_2-containing stream or captured CO_2, such as the origin of the CO_2 and its volume and impurities. The origin of the CO_2 affects its value since regulations such as the EU's Renewable Energy Directive increasingly limit the usage of fossil-based CO_2 in sustainable short-term applications. Impure sources, such as landfill gas, may result in expensive capture, and CO_2 from such sources may not be pure enough to be used in hygiene-sensitive industries, such as food and pharmaceuticals. Capture is one of the costliest operations in the CCU value chain, which means that technology selection and its implementation play important roles in value capture. Finally, policy and regulatory instruments can directly improve the financial feasibility of these BMIs, especially through targeted subsidies and by including more emitters in ambitious emission trading systems.

Second, we identified four BMIs employed by companies that constitute the demand for captured CO_2, namely, Direct Use of CO_2, Intermediates, Short-Lived Products, and Long-Lived Products. Of these, the first is the only one that does not require any kind of conversion: examples of applications are enhanced oil recovery and use as a protective gas in, for example, the food industry. The Short-Lived Products BMI refers to the production of synthetic fuels, in particular, but also of other chemicals from which the CO_2 is set to be released quickly. The Long-Lived Products BMI implies the production of materials such as durable polymers or construction components. The Intermediates BMI refers to the production of chemicals such as methanol, urea, or formaldehyde, which can be further used in the production of a variety of chemicals and materials. Generally, the value capture of these models is heavily affected by the cost of the production process (especially the price of renewable electricity to produce green H_2, when required) and the markets of the chosen target product. Customers' willingness to pay a green premium and sign risk-mitigating contracts, such as offtake agreements, play important roles in determining business feasibility. The Intermediates BMI often has the benefit that the customer segments for the products are more versatile and adjustable. Policy and regulation may directly create demand for the products or make their production more competitive by setting a price for carbon emissions.

Process Technologies, Transportation & Infrastructure, Engineering Consultancy, and System Provision BMIs provide the necessary technologies and novel systems for different CCU value chains. The Process Technologies BMI principally covers the development and provision of capture and conversion technologies, and the Transportation & Infrastructure BMI covers logistical solutions for CO_2 but also for other related resources, such as H_2. The System Provision BMI bundles these technologies into integrated solutions for customers looking to adopt CCU activities, and the Engineering Consultancy BMI provides expert support services for specific technological challenges in technology development and innovation. Policymakers can decisively facilitate the value capture of these models by establishing targeted R&D funding schemes, providing state guarantees, offering monetary incentives for customers to adopt CCU technologies, or directly regulating infrastructure, particularly transport networks.

Finally, the Project Consultancy and Carbon Credit Services BMIs provide essential system- and market-level solutions that help CCU customers to both lower costs and find new sources of revenue. The Project Consultancy BMI may include value chain design, collaboration facilitation, or practical project management services for CCU, whereas the Carbon Credit Services BMI facilitates trade in voluntary carbon markets, enabling companies to monetize verifiable carbon removals created via CCU. Exact value creation and capture dynamics naturally differ between the variants of these BMIs, but the ability to maintain low operational costs and the careful selection of target customer segments seem to be among the key prerequisites for feasible business within these BMIs.

Value capture drivers and determinants in CCU BMIs

A profound analysis of the factors guiding economic value capture within the 12 types of CCU BMIs enabled the identification of 17 determinants and four drivers to which they link. Table 4 presents the value capture determinants with practical examples, grouped under the drivers of policy and regulation, technology, markets and demand, and business compatibility.

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Table 4 Value capture drivers and determinants

Principal driver	*Value capture determinant*	*Identified from*	*Examples*	*Most directly affected BMIs*
Policy and regulation	Carbon pricing	Energy Company, Hydrogen Economy Company, Chemicals Company, Energy Technology Company Documents A, B, C, D, E, F, H, I	Emission trading systems Carbon taxes	CO_2 Source, CO_2 Capture & Provision
	Use mandates	Hydrogen Economy Company, Chemicals Company Documents A, B, C, J	Mixing obligations for fuels Required share of recycled material	Intermediates, Short-Lived Products, Long-Lived Products
	Subsidies and direct support	Pulp & Paper Company B, Chemicals Company, Energy Technology Company Documents A, B, C, D, E, F, G, H, I	Innovation funding Tax credits Carbon contracts for difference State guarantees Public procurement of CCU products Public–private partnerships	Process Technologies, Transportation & Infrastructure, Engineering Consultancy
	Clarity and predictability	Pulp & Paper Company B, Hydrogen Economy Company, Chemicals Company Documents A, B, C, D, E, F.G, H, I	Long-term legal treatment of different CO_2 sources Permitting process speed and transparency	Short-Lived Products, Long-Lived Products, Transportation & Infrastructure

			Transport network regulation development	
Technology	Capital expenses	Pulp & Paper Company A, Pulp & Paper Company B, Waste Management Company, Energy Company, Hydrogen Economy Company, Chemicals Company Documents A, B, C, D, E, F, G, H, I	Availability and price of chosen technologies (correlates with technology readiness level) Need for new plants (e.g., capture plant, intermediate storage sites) Need for machinery investments (e.g., electrolyzer)	CO_2 Capture & Provision, Intermediates, Short-Lived Products, Long-Lived Products, Process Technologies, Transportation & Infrastructure, System Provision
	Energy demand	Pulp & Paper Company A, Pulp & Paper Company B, Energy Company, Energy Technology Company Documents A, B, C, D, E, F, G, H, I	Process energy efficiency (e.g., electrolysis efficiency) Chosen capture technology	CO_2 Capture & Provision, Intermediates, Short-Lived Products, Process Technologies
	Energy availability	Pulp & Paper Company A, Pulp & Paper Company B, Energy Company Documents A, B, C, D, E, G, I	Renewable electricity availability Renewable electricity price level and volatility Grid capacity and strength	Intermediates, Short-Lived Products
	Material efficiency	Energy Company, Hydrogen Economy Company Documents A, B, C, D, E, F, H	CO_2 capture rate Other process efficiencies	CO_2 Capture & Provision, Intermediates, Short-Lived Products, Long-Lived Products, Process Technologies

	Logistics optimization	Pulp & Paper Company B, Energy Company, Hydrogen Economy Company, Chemicals Company Documents A, B, C, D, E, F, H	Proximity of plants in value chain Proximity of markets Chosen transportation methods	CO_2 Capture & Provision, Intermediates, Short-Lived Products, Long-Lived Products, Project Consultancy
	CO_2 quality	Waste Management Company, Chemicals Company, Energy Technology Company Documents A, B, D, E, F	Purity of CO_2	CO_2 Source, CO_2 Capture & Provision, Intermediates, Short-Lived Products, Long-Lived Products
Markets and demand	Willingness to pay added cost	Waste Management Company, Energy Company, Hydrogen Economy Company, Chemicals Company Documents A, B, D, E, F	Level of green price premium Joint investments with customers	CO_2 Capture & Provision, Intermediates, Short-Lived Products, Long-Lived Products, Carbon Credit Services
	Potential revenue models	Pulp & Paper Company A, Energy Company, Hydrogen Economy Company, Energy Technology Company Documents A, B, C, D, H, I	Offtake agreements for CCU-based products Selling technologies via licensing, as products, or with different levels of servitization Long-term capacity contracts or public procurement for CO_2 transportation	CO_2 Source, Short-Lived Products, Long-Lived Products, Process Technologies, Transportation & Infrastructure, System Provision, Carbon Credit Services
	Price of CO_2	Chemicals Company Documents A, B, D, E, F, H	CO_2 price levels for different applications or processes CO_2 price volatilities	CO_2 Source, CO_2 Capture & Provision, Intermediates, Short-Lived Products,

				Long-Lived Products, Direct Use of CO_2
	Demand for negative emissions	Pulp & Paper Company B Documents A, B, C, D, F, G, H, I	Price of carbon credits State of carbon removal market	Long-Lived Products, Carbon Credit Services
Business compatibility	Characteristics of CO_2 source (and subsequently captured CO_2)	Pulp & Paper Company A, Pulp & Paper Company B, Waste Management Company, Energy Company Documents A, B, C, D, E, F, H, I	Type of CO_2 (biogenic, fossil, or mixed) Volume Concentration of CO_2 Location Impurities	CO_2 Source, CO_2 Capture & Provision, Intermediates, Short-Lived Products, Carbon Credit Services
	Capital expenses of adopting CCU	Pulp & Paper Company A, Waste Management Company Documents A, B, C, D, E, F, I	Carbon capture investment depends on type of CO_2 source, existing process, available space, etc.	CO_2 Source, CO_2 Capture & Provision
	Synergies	Pulp & Paper Company B, Chemicals Company, Energy Technology Company Documents A, B, D, F, I	Utility synergies (e.g., recycling energy or water from the existing processes of the plant) Internal demand for CCU products Sector coupling or industrial symbiosis opportunities (e.g., using by-product oxygen from hydrogen production in oxyfuel carbon capture process)	CO_2 Capture & Provision, Intermediates, Short-Lived Products, Long-Lived Products, System Provision, Project Consultancy

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Policy and regulation is the first identified driver of economic value capture. Policymakers may influence the competitiveness of CCU business by applying carbon pricing to increase the cost of traditional fossil-based activities. Regulation may also directly create demand for CCU-based products through use mandates or public procurement. Different subsidy mechanisms and types of public sector involvement can drastically lower the costs and financial risks associated with the establishment of CCU BMIs. Finally, financial risks were also found to be heavily affected by policy predictability and legal clarity, which companies consider carefully before any big investment decisions.

Second, technological development drives multiple determinants of value capture. As many CCU technologies are emergent innovations, technology readiness levels typically set limitations and affect the required investment. The performance of the chosen technologies can lower the operational costs of CCU by, for example, providing high energy and material efficiencies and, in carbon capture, by producing highly pure CO_2. Technological development also drives the regional availability and price of renewable energy, which is a particularly important value capture determinant for the producers of hydrogen-derived products. Firms must consider the available energy mix together with the CO_2 sources, potential markets, and available transportation methods to optimize the locations of various activities in their value chains for maximal value capture.

The third driver was found to originate in the markets. CCU-based products are still generally notably more expensive than their fossil-based, traditional counterparts, so it is crucial for business feasibility that there are customers willing to pay extra, especially when demand is not strongly driven by regulation. In addition to being able to charge a necessary green premium, CCU BMIs may be aided by customers who are willing to be directly involved and invest in CCU development. Most CCU BMIs have multiple alternative revenue models, which should be chosen according to the characteristics of different market segments, such as their willingness to commit to long-term contracts or their need to outsource technology operation.

Finally, for a firm that adopts CCU into its existing operations, compatibility aspects set the conditions for the value capture from CCU. Industry sector, plant location, and characteristics of the CO_2-containing stream define transportation needs, narrow down potential collaborators, and often limit the selection of business-feasible products to be made from the captured CO_2, all of which have implications for costs and revenues. On the other hand, synergies can be found by recycling utilities or by-products of existing processes within CCU to lower operational costs. A producer firm can even identify a certain amount of internal demand for its CCU-based product, which can help to mitigate the market risk.

5 Discussion

To synthesize the results of this study, we developed a framework of CCU BMIs and value capture drivers that presents all the identified BMIs across three business domains as an interconnected system that is externally and internally influenced by the value capture drivers. The framework also demonstrates that entire CCU value chains can be formed from various combinations of the identified BMIs. The framework is presented in Figure 2. The green boxes represent the 12 types of CCU BMIs, whereas the gray areas show the impact of the four value capture drivers.

We found that the 12 types of CCU BMIs are placed within three broader business domains. First, the BMIs whose value creation is based on directly managing flows of CO_2 belong to the *CO_2 processing business domain*. This domain contains the physical supply and demand of CO_2 and derived products. Companies operating in this domain buy, process, and sell CO_2 or CO_2-containing gases, materials, or products, capturing their share of created value in the process. Second, the *engineering business domain* contains the development, production, and provision of the technologies needed to enable individual CCU processes and improve their performance within the CCU value chains. Companies in this domain intervene at specific points of CCU value chains by designing and manufacturing novel products and infrastructure and leveraging their technological expertise to create and capture value. Finally, the *system optimization business domain* encompasses BMIs offering value chain-wide support to make CCU business economically viable. Companies operating in this domain take a system-level approach to their customers' businesses, providing integrated solutions and optimizing their customers' CCU-related costs and revenue models, capturing value for themselves in the process.

We found that the four main value capture drivers affect CCU business through differing dynamics: some drivers are largely beyond the control of the focal firms' business actions, being more exogenous by nature; others depend rather heavily on the focal firms' business actions, being more endogenous. The most exogenous driver was found to be policy and regulation, depicted at the top in Figure 2, since companies often have no choice but to wait to see whether, for example, use mandates of CCU-based products increase or a new carbon capture subsidy scheme is implemented. Technology and market drivers, depicted at the sides of the figure, were found to be partially exo- and partially endogenous. Regarding technology, technological readiness levels and regional energy markets set hard limits for business feasibility, but companies can still influence technological development through R&D investments and by creating demand. Regarding markets, the market pull for any given product is rarely controlled by a single company, but each firm has the freedom to choose which products and markets it targets. Finally, business compatibility, depicted in the middle, was found to be a largely endogenous value capture driver, since the economic viability of CCU within this driver originates from all the actions the company is currently taking. Consequently, the existing baseline business also determines the degree of required transformation if the focal company aspires to fully adopt CCU in its business.

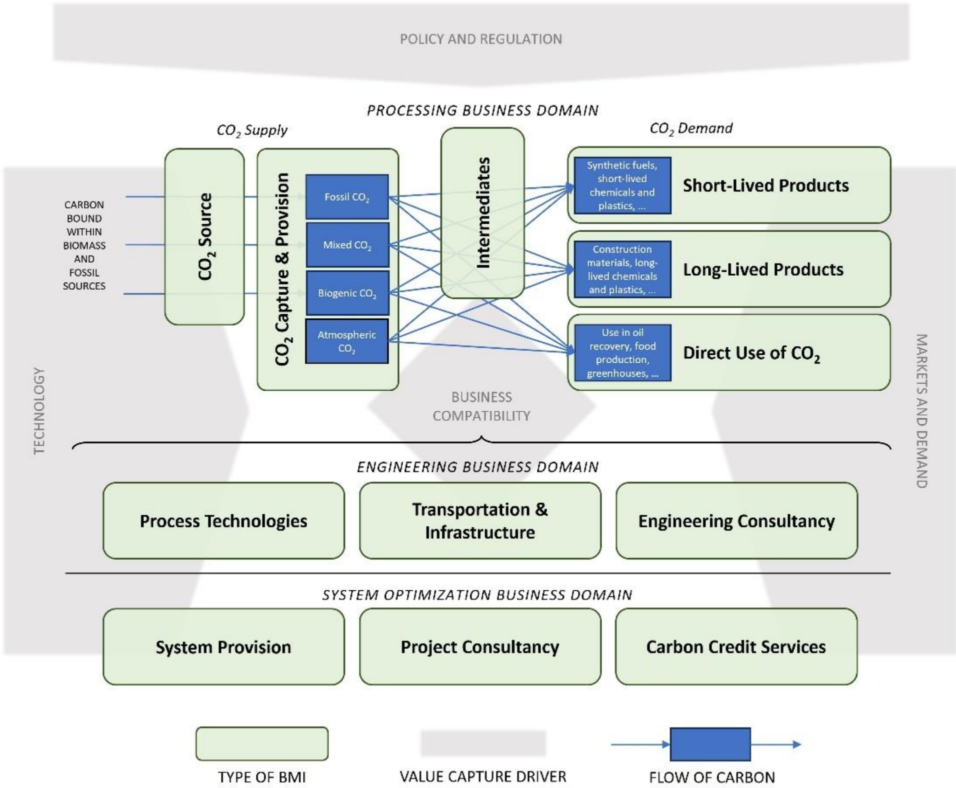

Figure 2 Framework of CCU BMIs and value capture drivers

In summary, the key outcomes of this paper are a comprehensive mapping of 12 types of CCU BMIs, the identification of three broad business domains within CCU, and an analysis of four value capture drivers and their respective value capture determinants. Our BMI analysis shows that companies can exploit diverse opportunities along CCU value chains to create viable businesses. These BMIs are closely connected, and some of them can also be smoothly combined by a single company. Emergent business domains show that companies usually base their value creation and capture from CCU on directly managing and processing the carbon flows, on focusing their efforts on developing well-defined, technologically challenging parts of the CCU value chains, or on optimizing entire CCU value chains through design, integrated solutions, and market development. Finally, we concluded that economic value capture is driven and determined partly by companies' own actions and partly by the surrounding business environment. Business compatibility aspects represent the former, whereas policy and regulation are at the core of the latter. Technology and market drivers partially escape the focal firms' command, but firms still maintain varying degrees of control over how these aspects influence the value capture of their CCU business.

6 Conclusions

Contributions to theory and practice

This study provides important contributions to several research streams. First, we contribute to the circular business model and business model innovation literature by creating a new understanding at the intersection of business model innovation (e.g., Bocken et al., 2014; Geissdoerfer et al., 2018) and CCU technologies, carbon circulation, and net-zero targets (e.g., Chauvy et al., 2020; Naims & Eppinger, 2022) and applying an established business model framework (Richardson, 2008) to the topic. Second, we contribute to the circular innovation management literature (e.g., Durán-Romero et al., 2020; Geissdoerfer et al., 2020) by extending the discussion to cover carbon circulation and outlining how it can be turned into feasible business through CCU BMIs. Third, the study contributes to the technically oriented CCU and carbon management innovation literature (e.g., Huang & Tan, 2014; Zimmermann et al., 2020) by adding the business model perspective that is necessary for the successful commercialization and business development of CCU technologies.

Our cross-industrial study provides technology and business development managers overseeing CCU activities with a crucial understanding of the options available to orchestrate their value proposition, creation, and capture around CCU. The 12 identified BMIs offer managers a clear overview of CCU business, helping them to comprehend the positioning options for their company and understand who their key partners are and what their business models could look like. The findings also guide managers in understanding which factors drive and determine the financial viability of CCU business. In conclusion, this study provides a much-needed structured analysis of business opportunities within CCU, clarifying the potential of this emerging field for business decision-makers.

Limitations and future research

Our study has several limitations. Due to research access, the focus of the study is strongly on Finland and the Nordics. The regional CCU market is characterized by a strong pulp and paper industry presence, leading to large point sources of biogenic CO_2, as well as advanced renewable energy production systems, which could bias the analysis. Moreover, the strong influence of EU policies on CCU business means that some of the results may not be transferable to other institutional contexts. Hence, further studies are needed that focus on different markets and geographical areas. We also acknowledge that, albeit a large empirical dataset was leveraged, certain elements of our results are largely grounded in the supporting document analysis. Therefore, we recommend carrying out further, more specific studies that can, for example, uncover the nuances of alternative revenue models of certain uncovered CCU BMIs or give further information about industry-specific implications of the BMIs and value creation dynamics.

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