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RESEARCH AND ANALYSIS

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Economic aspirations connected to innovations in carbon capture and utilization value chains

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Abstract

International authorities are increasingly recognizing that utilizing the carbon dioxide (CO_2) emissions from various industries can assist strategies for mitigating climate change. In developing novel carbon capture and utilization (CCU) technologies they aspire to contribute to circular economy targets and reduce consumption of fossil-based raw materials. However, the potential economic effects of CCU on industrial value chains remain unclear. Hence, this study investigates the economic expectations placed on those actors currently conducting research and development (R&D) in CCU. The aspired levels of economic performance are identified through a systematic literature review of 19 policy advice reports and 15 scientific papers. Qualitative directed content analysis is conducted, based on an R&D input–output–outcome system. First, we identify three relevant groups of value chain actors by clustering industrial sectors: (a) equipment manufacturers, (b) high-emitting producers, and (c) producers of materials and fuels. Then, we derive a criteria list from the review. Finally, the analysis reveals how CCU innovations are anticipated to impact different industries: Equipment manufacturers could contribute to economic growth. For high-emitting producers, CCU provides one option for "surviving" sustainability transitions. Meanwhile, material and fuel producers need to act as "problem solvers" by offering competitive ways of utilizing CO_2. We conclude by identifying research gaps that should be addressed to better understand the economic and social dimensions of CCU and to increase the chances of such innovations contributing to broader sustainability transformations of industrial and energy systems.

KEYWORDS
carbon capture and utilization, carbon dioxide, industrial ecology, industrial symbiosis, technological innovation, value chains

1 | INTRODUCTION

Most of the materials and products that surround us in our everyday lives are carbon based. Modern standards of living are therefore closely connected to the availability of natural carbon resources such as wood, soil, coal, and oil. In order to conserve these resources for future generations and find more sustainable modes of consumption, an increasing amount of research is looking at ways of reusing and recycling raw materials. Often, such efforts are undertaken to close material loops in line with the vision of transitioning toward a circular economy. Redesigning value chains and reconsidering material use are key elements of this endeavor (Pérez-Fortes, Bocin-Dumitriu, & Tzimas, 2014b; World Economic Forum, 2014). Several processes can contribute to achieving a circular economy, among them utilization of residual materials (Kreikebaum, 2002) and various types of recycling—from high-value, direct material reuse to lower-value thermic recycling (von Stengel, 1999). The utilization of "waste" CO_2

emissions within different industries, through novel carbon capture and utilization (CCU) technologies, can contribute to building a "circular carbon economy" and reduce consumption of fossil-based raw materials (National Academies of Sciences, 2019).

Moreover, political agendas often connect environmental innovations to economic aspirations in order to create "win–win" situations. The UN Sustainable Development Goals exemplify such aspirations to deliver combined environmental and economic (as well as social and other) benefits (UN SDG Knowledge Platform, 2016). According to the organizational literature, "Organizational aspirations are desired performance levels in specific organizational outcomes and have also been called goals and reference points" (Shinkle, 2012). In Ansoff's perspective on strategic management, decision-makers within an organization set aspirations and design actions to address potential deviations from actual performance and are "triggered into operating or strategic change" (Ansoff, 1979). Shinkle (2012) recommends using the concept of aspirations to better understand outcomes for different problems and in particular "social decisions such as environmental sustainability." Based on this understanding of aspirations, the present study investigates the economic aspirations of sustainability innovations to learn about the levels of economic performance desired by the groups of actors presently advancing research and development (R&D) in CCU. From this we aim to derive relevant knowledge for decision-makers in policy and industry on how CCU innovations are anticipated to impact different industries.

2 | BACKGROUND TO CCU

Several industrial processes, such as urea production and carbonated beverages, have traditionally used CO_2 as an input. However, at present, such processes do not consume large amounts of this greenhouse gas. Aresta (2019) estimates that approximately 207 Mt CO_2 is currently used in chemical synthesis. Moreover, most existing applications do not lead to net emission reductions. Lately, chemical researchers and engineers worldwide are seeking opportunities to make environmentally beneficial use of CO_2 in industrial processes. By developing concepts that utilize CO_2 as a carbon source, they attempt to reduce the carbon footprints of materials, chemicals, and transport fuels. A recent National Academies of Sciences (2019) report highlighted interesting technologies for biological or chemical conversion into fuels, fertilizers, polymers, secondary chemicals, or mineral carbonation into carbonates. The variety of possible end products ranges from construction materials to plastics and synthetic fuels. Net emission reductions must be determined specifically for each technology through life cycle assessments (LCA) (von der Assen, Jung, & Bardow, 2013). By 2030, approximately 600 Mt of CO_2 could be used in the production of chemicals and fuels (Aresta, 2019).

Recently, international authorities have recognized that CCU can play a role in the context of larger climate change mitigation strategies (Hepburn et al., 2019). The global Mission Innovation (2017) initiative seeks to advance carbon capture utilization and storage (CCUS). The recent "Mission Possible" report by the Energy Transitions Commission (2018) proposes CCUS as one of the four important technologies to achieve the goals of the Paris Agreement in the six "harder-to-abate" sectors of cement, steel, plastics, heavy road transport, shipping, and aviation.

3 | BRIEF LITERATURE REVIEW OF CCU

A large amount of research into CCU is directed at the chemistry and upscaling of processes (Aresta, 2010; Klankermayer & Leitner, 2015; Peters et al., 2011). Meanwhile, a growing amount of public and private funding worldwide is supporting R&D into CCU (BMBF, 2014; Carbon Capture Journal, 2013; Climate-KIC, 2014; European Commission, 2018; US DOE, n.d.; XPRIZE Foundation, 2018). These endeavors have produced policy reports on CCU, authored by scientific or policy advisors. Moreover, these advances in processes are accompanied by a growing scientific literature on techno-economic assessments (TEA). The vast majority of technologies are still at an early research stage, and only a small number of projects have reached the pilot or demonstration stage; consequently, decision-makers in science, industry, and policy are currently still learning about the long-term potentials and risks of CCU (Hepburn et al., 2019). There is not yet sufficient data to quantify the broader economic effects of CCU. In particular, it remains unclear how CCU may impact industrial value chains. Hence, this study presents a qualitative review of the extant body of policy advice reports and scientific papers, to learn about the economic aspirations associated with CCU.

4 | METHODS

Overall, this study is informed by two levels of analysis: The *organizational* level provides the methodological toolset and definitions, by explaining the innovation system of an individual actor. Moreover, the *meso* level, via actor groups at the sector level, provides aggregate findings on sectoral ambitions for sustainability innovations. All selected approaches are "purpose-driven constructions" (Renn, 2008) that serve to identify the complex value chain structures of CCU innovations and provide insights into their desired causal economic effects.

4.1 | Identifying CCU value chain actors

The first step recommended in any value chain analysis involves mapping relevant activities (Ehrensberger, Opelt, Rubner, & Schmiedeberg, 2000; Tyndall, Gopal, Partsch, & Kamauff, 1998; Volck, 1997). In a value chain map, the output of one activity constitutes an input to the next activity in the chain (von Stengel, 1999). Statistical agencies commonly describe cross-sectoral value chains by deconstructing them down to the industries involved, assuming that individual companies within a given sector pursue similar activities and serve identical purposes (Bach, Buchholz, & Eichler, 2003). The International Standard Industrial Classification of all Economic Activities (ISIC) provides a standard segmentation for sectors (UN DESA, 2008).

The present study constructs such a value chain of economic activities relevant for CCU, including all industrial processes from extracting raw materials to their transformation into consumer products, inspired by the ideal value chain propositions presented by Kannegiesser (2008), Otto (2002), and Schary and Skjøtt-Larsen (1995). To map the value chain, we first identify a list of companies actively involved in CCU R&D, based on their presentations at relevant conferences between 2013 and 2018 (see Supporting Information). We then assign each company on the list one or more ISIC codes based on their core activities and business models presented on their company website (or from reviewing online news sources if the website lacks such information). Consequently, we cluster the resulting list of ISIC codes to define value chain steps at the meso level; these are similar to the value chain propositions mentioned above, but specifically reflect the activities that are necessary to build and connect a cross-sectoral CCU system.

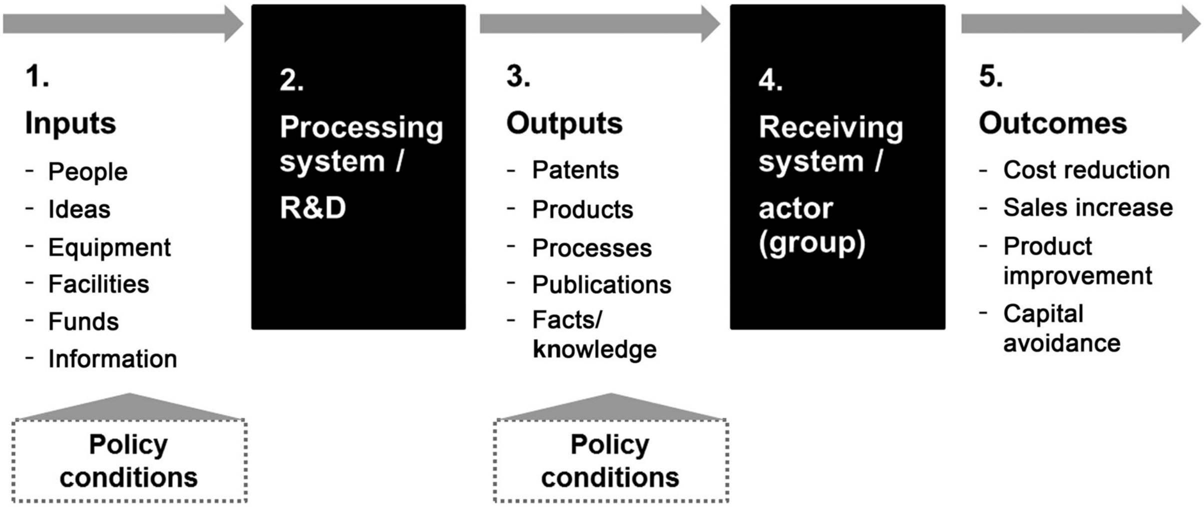
4.2 | Investigating economic aspirations of sustainability innovations

In the organizational literature, aspirations are studied via commitment or performance levels of selected indicators or discrepancies (Shinkle, 2012). In this study, we investigate the economic aspirations of sustainability innovations to learn about the levels of economic performance desired by actor groups in a value chain. These differ from environmental, technical, or social aspirations and are measured in economic criteria. We assume that, at the *micro* or *organizational* level, a typical firm in a given sector is deploying CCU technology and pursuing organizational aspirations such as cost reductions. Meanwhile, at the *meso* level, groups of organizational actors are deploying CCU and pursuing sector-level aspirations such as economic growth. Aspirations are significantly influenced by the dimension of time—through history, path dependencies, and the vision of the respective organization. Furthermore, subjective perceptions of new opportunities are decisive when setting aspirations (Shinkle, 2012). Hence, we consider aspirations not as objective, universal goals but as useful indicators of ambitions for selected actors. These aspirations derive from the review of current policy reports; hence, they do not represent the targets that the groups or individual actors set for themselves, but rather the aspirations that advisors lay out for them. Moreover, we look at the aspiration–performance gap by analyzing scientific papers covering the performance of CCU innovations. Shinkle (2012) suggests that this gap is useful for revealing discrepancies between set aspirations and current performance levels.

4.3 | Defining an evaluation system for sustainability innovations in value chains

The economic success of an innovation is largely unpredictable, and depends on strong externalities and uncertainties (Weissenberger-Eibl, 2002). For the innovator, this can act as a driver of both client value and productivity (Krubasik, 2002). Furthermore, through positive externalities the social value of an innovation can be even greater than the value for the innovating company (Weissenberger-Eibl, 2002). To understand the driving forces within a value chain we need to identify the key variables tailored to our specific empirical setting (Gereffi, Humphrey, & Sturgeon, 2005). In decision-making processes concerning a single innovation, TEAs are helpful in calculating relevant indicators for a specified process according to the particular aim of the decision-making occasion (Zimmermann et al., 2018). To gain insights into the economic expectations toward a broad field of technologies, we first must define a generic system of R&D activities. Hence, we refer to the widely cited concept by Brown and Svenson (1988), which describes an organizational innovation system along the five schematic steps of inputs, processing system, outputs, receiving system, outcomes (Figure 1), and three loops feeding back into the processing system. Since the present aim is not to investigate how technologies work but instead to learn about their aspired economic effects, we treat the R&D activities of the processing system as a black box and also exclude the feedback loops. Instead, we focus on the receiving system, which represents an investigated actor for whom the outcomes can be observed. We identify *inputs*, *outputs*, and *outcomes* as the key evaluation categories requiring detailed examination in the subsequent steps.

In this study, *inputs* encompass human, physical, and financial resources and tools (Adams, Bessant, & Phelps, 2006). In innovation research, *outputs* often measure the innovativeness of a system based on a rigid understanding that focuses, for example, on measuring patents (Blind & Grupp, 1999), new processes or products (Hipp & Grupp, 2005), or tangible and intangible criteria for measuring the innovation itself (Freeman & Soete, 2013). However, the present study investigates the expected effects of innovations. Therefore, we understand outputs as all direct/indirect and tangible/intangible results of the innovating system. Moreover, the innovation research literature does not commonly observe *outcomes*; nevertheless, the concept is central to describing the expected broader economic effects of innovations. Overall, the three categories are similar to those



1. The **inputs** include all raw materials and resources that go into the research and development (R&D) process. They are influenced by given policy conditions.
2. The **processing system** includes all R&D activities that enable the transformation of the inputs into outputs.
3. The **outputs** include all types of results of the processing system such as products and patents. They are influenced by certain policy conditions.
4. The **receiving system** is where the outputs are received by different internal and external actors or actor groups.
5. The **outcomes** are the results that can be observed for the receiving system, defined by Brown and Svenson (1988) as “accomplishments that have value for the organization”, such as product improvements.

FIGURE 1 Research and development as an input–output–outcome system
Source: Adapted from Brown and Svenson (1988, p. 12).

of Grupp (1998), who presents “resource indicators” for R&D costs and investments, “R&D results indicators” for patents and publications, and “progress indicators” for micro- or macro-level effects of the innovation.

Furthermore, the implementation of environmental innovations often depends on a supportive policy framework. Positive economic effects can only occur if the environmental innovation is associated with lower external costs than competing goods and services; this often requires the support of innovation- and environment-focused policies (Rennings, 2000). Consequently, policy conditions strongly influence the evaluation of sustainability-related innovations. Hence, we extend the model of Brown and Svenson (1988) to include policy conditions that directly affect inputs and outputs (Figure 1). Brown and Svenson (1988) proposed their model for assessing R&D performance at the *organizational* level. By extending this, we derive findings at the *meso* level, assuming that the outcomes can be observed for groups of actors within the value chain.

4.4 | Selecting literature for systematic review

Several authorities have commissioned studies to identify or assess various effects of CCU innovations. We reviewed these in detail to identify the economic outcomes anticipated by the diverse groups of authors from science, consultancy, or public authorities. Hence, the review process collected policy reports through extensive and detailed screening of: (a) project websites with a policy scope; (b) websites of active international funding authorities; and (c) studies shared by two international research consortia (see Supporting Information). The sample includes policy reports whose titles reflect a focus on CCU and which cover economic aspects in varying detail. Moreover, all reports were publicly accessible and written in English. The selection criteria result in a sample of 19 reports (see Supporting Information). The sample cannot be assumed to be complete since no extensive database exists for such publications. However, the listed projects gathered comprehensive knowledge and were built on manifold exchanges with experts and stakeholders. Hence, the policy report sample is considered to be representative of current aspirations voiced for CCU technologies. All reports in the sample are science-based policy advice studies that include a literature review and expert workshops, consultations, or reviews. Due to the general paucity of quantitative knowledge on these technologies during their early developmental stages, all reports rely on a combination of both quantitative and qualitative information. Moreover, most reports perform some form of technology assessment, for example, via roadmaps or comparing options. Some include detailed policy analyses, while others aim to provide a technical policy briefing.

Furthermore, we scanned the scientific literature systematically via two comprehensive databases, Scopus and Web of Science, to identify all relevant articles covering economic aspects of CCU. Search criteria: journal articles and full conference papers; written in English; published 1999–2018. Since CCU nomenclature varies, the search parameters included several alternative wordings (conversion, recycling, use, utilization). The following search parameters identified the most relevant article titles: TITLE: ((“econom*)” AND (“CO_2” OR “carbon dioxide”) AND (“use” OR “utili*” OR “conversion” OR “recycling”)). Subsequently, we imported 74 matches from Scopus and 75 from Web of Science into Endnote literature management software; after deleting duplicates, 95 unique articles remained. We then searched this database to eliminate studies on decoupling and those on related but different technologies (i.e., carbon capture and storage [CCS], enhanced oil or gas recovery, biotechnologies, CO_2 capture, or transport only). The remaining 33 papers were checked individually via titles or abstracts to eliminate any with a differing scope. The final sample comprises 15 papers on CCU published between 2008 and 2018 (mostly recent; see Supporting Information).

4.5 | Coding and analyzing the literature

We analyzed the literature sample via directed content analysis, which combines deductive and inductive reasoning (Zhang & Wildemuth, 2009). All the documents were loaded into MAXQDA (VERBI, Germany) content analysis software. The coding strategy used the categories *inputs*, *output*s, and *outcomes* to serve as a deductive structure, with *policy conditions* coded separately. The aims of the content analysis are twofold: to identify relevant criteria for the chosen categories; and to qualitatively evaluate these criteria for different actor groups. We also established codings for the actor groups, to ensure that actor-group-specific information was not overlooked.

First, we performed the content analysis for the *policy reports* by reading through all the documents and coding the relevant text sections. If necessary, we assigned paragraphs multiple codes. Then, we created two matrix structures, summarizing in bullet-point form the inductive findings from the reading. Matrix A gathers all identified criteria and matrix B collects all qualitative evaluations of the criteria for the different actor groups. We filled both matrices in parallel by revising the codings of inputs, outputs, and then outcomes. All the findings were entered into the matrices and assigned either to all actors or the various groups. Subsequently, we screened the policy condition codings and added relevant information to the matrices. Finally, we revised the actor-group-specific codings and added further information to matrix B.

The first result comprises: matrix A, condensed and with all criteria grouped as *list of criteria*. The second result comprises: matrix B, condensed in a *figure of observations* summarizing the qualitative observations (positive, neutral, or negative) for the actor groups.

Second, the content analysis was repeated in MAXQDA for the sample of *scientific papers*. We aim to check whether the scientific literature supports the policy report findings or whether there are potential performance gaps. Hence, we coded the articles using the same categories described above. We then read through the codings and added the new findings to a “*performance*” column in matrix B.

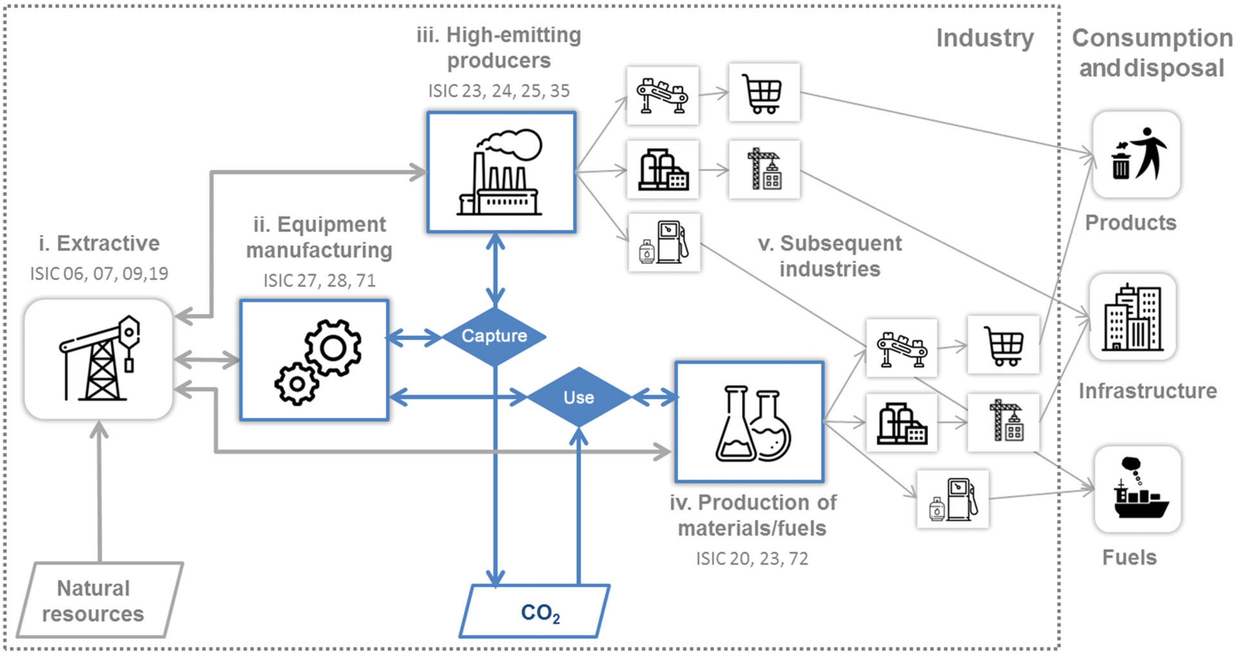
5 | FINDINGS

5.1 | Identified value chain actors in CCU

As a first result Figure 2 depicts the value chain flowchart for CCU according to the American National Standards Institute notation (Chapin, 1970), which is useful for mapping chains at a desired level with process flowchart symbols (Handfield & Nichols, 2002). Key actors include groups ii to iv, which actively contribute to CCU R&D: *Equipment manufacturing* (ii) involves engineering and supplying necessary machinery, plant, and equipment. *High-emitting producers* (iii) includes those industries responsible for significant shares of industrial CO_2 emissions, some of which are particularly difficult to decarbonize (Energy Transitions Commission, 2018). The *producers of materials and fuels* (iv) are developing CO_2 utilization routes. Hence, we look specifically at the economic aspirations of these three groups. We do not investigate the other groups. For analysis purposes, such a simplification of the value chain and the exclusion of less relevant activities can be justified (Volck, 1997). With an increasing number and variety of intersections in real-world value chains it has become difficult to differentiate industries clearly from each other (Bresser, Heuskel, & Nixon, 2000). Individual companies are often active in several sectors and hence are assigned several ISIC codes (UN DESA (2008); Supporting Information). A single actor can thus belong to more than one of the defined value chain groups. In particular, we assign all companies with ISIC code 23 to both groups iii and iv since this industry is a major CO_2 emitter and could also potentially use CO_2 in its production processes. Such overlaps show that single actors can combine different roles and aspirations. As CCU innovations can support industrial symbiosis targets (Bringezu, 2014), the potential synergies between the defined steps are in fact often a desired outcome of the innovation.

5.2 | Identified criteria for economic aspirations of CCU

The input–output–outcome system serves as a deductive structure for identifying criteria mentioned within the literature. Based on this structure, matrix A was revised and all criteria were sorted and categorized. For inputs and outputs we include all relevant financial criteria that can



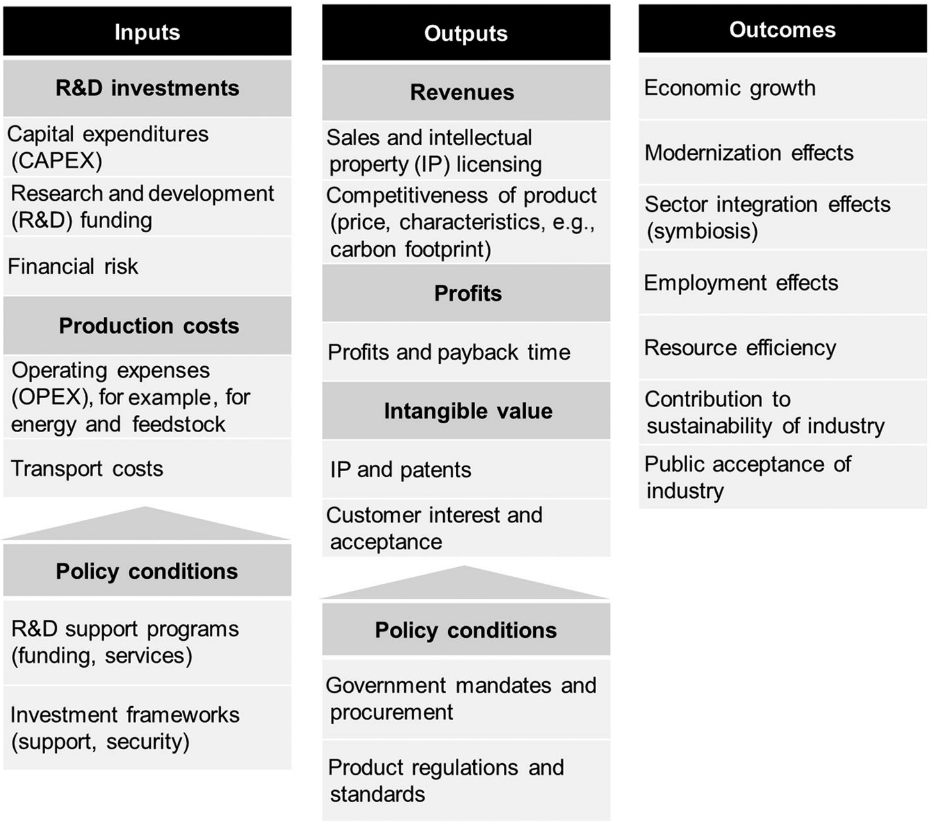
Value chain steps	**Relevant ISIC[a] codes and industry names**
i. **Extractive industry:** all upstream industrial activities, including mining and basic refining of natural resources into raw materials for further processing, for example, the extraction of oil, gas, and minerals from the Earth. Such actors are relevant in the chain as the "conventional"(fossil) source of carbon.	6 Extraction of crude petroleum and natural gas 7 Mining of metal ores 9 Mining support service activities 19 Manufacture of coke and refined petroleum products
ii. Equipment manufacturing: all industrial activities comprising the manufacture of machinery and equipment. Such actors are relevant as potential plant engineers for CO_2 capture and/or CO_2 use and hence play a key role in the innovation process.	27 Manufacture of electrical equipment 28 Manufacture of machinery and equipment n.e.c. 71 Architectural and engineering activities; technical testing and analysis
iii. High-emitting producers: all industrial activities that are responsible for significant CO_2 emissions due to their production processes, for example, fossil-based power generation or large industrial plants for cement, iron, and steel. Such actors are relevant sources of CO_2 and thus play a key role in the innovation process for CO_2 capture, including the necessary purification.	23[b] Manufacture of other non-metallic mineral products 24 Manufacture of basic metals 25 Manufacture of fabricated metal products, except machinery and equipment 35 Electricity, gas, steam, and air conditioning supply
iv. Production of materials and fuels: all industrial activities, including the refining of liquid and gaseous fuels, the chemical industry, and the production of building materials. Such actors are relevant as potential users of CO_2 and hence play a key role in the innovation process for CO_2 utilization. In some cases their business model relies on compensation for using industrial wastes that are processed with CO_2 to form a product, for example, wastewater treatment or waste collection (e.g., ISIC 37, 38).	20 Manufacture of chemicals and chemical products 23[b] Manufacture of other non-metallic mineral products 37 Sewerage 38 Waste collection, treatment, and disposal activities; materials recovery 72 Scientific research and development
v. Subsequent industries: all downstream activities that are not directly involved in CCU innovations, including manufacturing, that is, the large variety of industries that produce consumer goods and services; as well as retail, that is, the various industries selling goods to end customers. These industries are diverse and not actively involved in R&D on CCU; hence they are not investigated.	
vi. Consumption and disposal: the use of the final product by the consumer; its disposal and decomposition at the end-of-life phase.	

NOTES

[a] ISIC = International Standard Industrial Classification of all Economic Activities

[b] We assign ISIC code 23 to the two groups iii and iv because this industry can potentially act in both roles.

FIGURE 2 Value chain flowchart for CCU according to American National Standards Institute notation
Source: Author's analysis of databases of active companies according to UN DESA (2008) and Chapin (1970). The structure is inspired by propositions in Kannegiesser (2008), Otto (2002), and Schary and Skjøtt-Larsen (1995). All icons made by Freepik from www.flaticon.com.



Inputs

R&D investments
- Capital expenditures (CAPEX)
- Research and development (R&D) funding
- Financial risk

Production costs
- Operating expenses (OPEX), for example, for energy and feedstock
- Transport costs

Policy conditions
- R&D support programs (funding, services)
- Investment frameworks (support, security)

Outputs

Revenues
- Sales and intellectual property (IP) licensing
- Competitiveness of product (price, characteristics, e.g., carbon footprint)

Profits
- Profits and payback time

Intangible value
- IP and patents
- Customer interest and acceptance

Policy conditions
- Government mandates and procurement
- Product regulations and standards

Outcomes
- Economic growth
- Modernization effects
- Sector integration effects (symbiosis)
- Employment effects
- Resource efficiency
- Contribution to sustainability of industry
- Public acceptance of industry

FIGURE 3 List of criteria identified in the literature review of policy advice reports
Source: Author's analysis inspired by the structure of Brown and Svenson (1988).

measure cost and income, as well as criteria for intangible value and relevant policy conditions. The outcomes summarize the identified meso-level aspirations. Figure 3 presents the resulting criteria list.

5.3 | Findings from reviewing policy advice reports for the three actor groups

Figure 4 presents the review of the policy advice reports. It differentiates group-specific findings from those that apply to all value chain actors.

On the *input* side all actor groups face high financial risks (Hendriks, Noothout, Zakkour, & Cook, 2013) as CCU R&D has "high upfront investment costs" (Bujnicki et al., 2018). Current policy conditions do not provide investment security for CO_2 capture, for example, through emission allowance cost reductions for captured or used CO_2, unless it is stored according to CCS regulations (Bujnicki et al., 2018; de Bruyn, Croezen, & Jaspers, 2017). Hence, the actors involved require support in funding first-of-a-kind pilot or demonstration plants (BMBF, 2014; Sandalow, Aines, Friedmann, McCormick, & McCoy, 2017).

Regarding *outputs*, all R&D actors aspire to create intangible value, for example, by developing intellectual property (IP) such as patents. Furthermore, the studies reveal the aspiration for CCU to improve the sustainability of actors' products (de Rosbo, Rakotojaona, & de Bucy, 2014; Wilson et al., 2015). However, such claims need to be supported by an LCA (Mennicken, Janz, & Roth, 2016; Sandalow et al., 2017; Schlögl et al., 2018). Improved products are associated with greater customer interest and acceptance, hence, some studies suggest that customers might pay a premium for such products under the right conditions (CarbonNext, 2018; de Bruyn et al., 2017). Other studies mention that technology acceptance can be problematic, but do not evaluate this criteria further (Coddington et al., 2016; Hendriks et al., 2013).

Certain *outcomes* apply to all involved actors: All the studies claim that CCU can contribute to a sustainable transformation of the respective industries (Black, Kabatek, & Zoelle, 2014; BMBF, 2014; Bujnicki et al., 2018; Hendriks et al., 2013; Pérez-Fortes & Tzimas, 2016; Schlögl et al., 2018). Moreover, the scale-up of CCU would require significant investments and structural changes (Bazzanella & Ausfelder, 2017; Bujnicki et al., 2018) and hence lead to modernization of the industry, also called "industrial renaissance" (Wilson et al., 2015). Many studies highlight public acceptance as a prerequisite for deploying CCU (Hendriks et al., 2013; Schlögl et al., 2018; Wilson et al., 2015). Hence, achieving acceptance for cross-sectoral activities is an important aspiration for all involved actors.

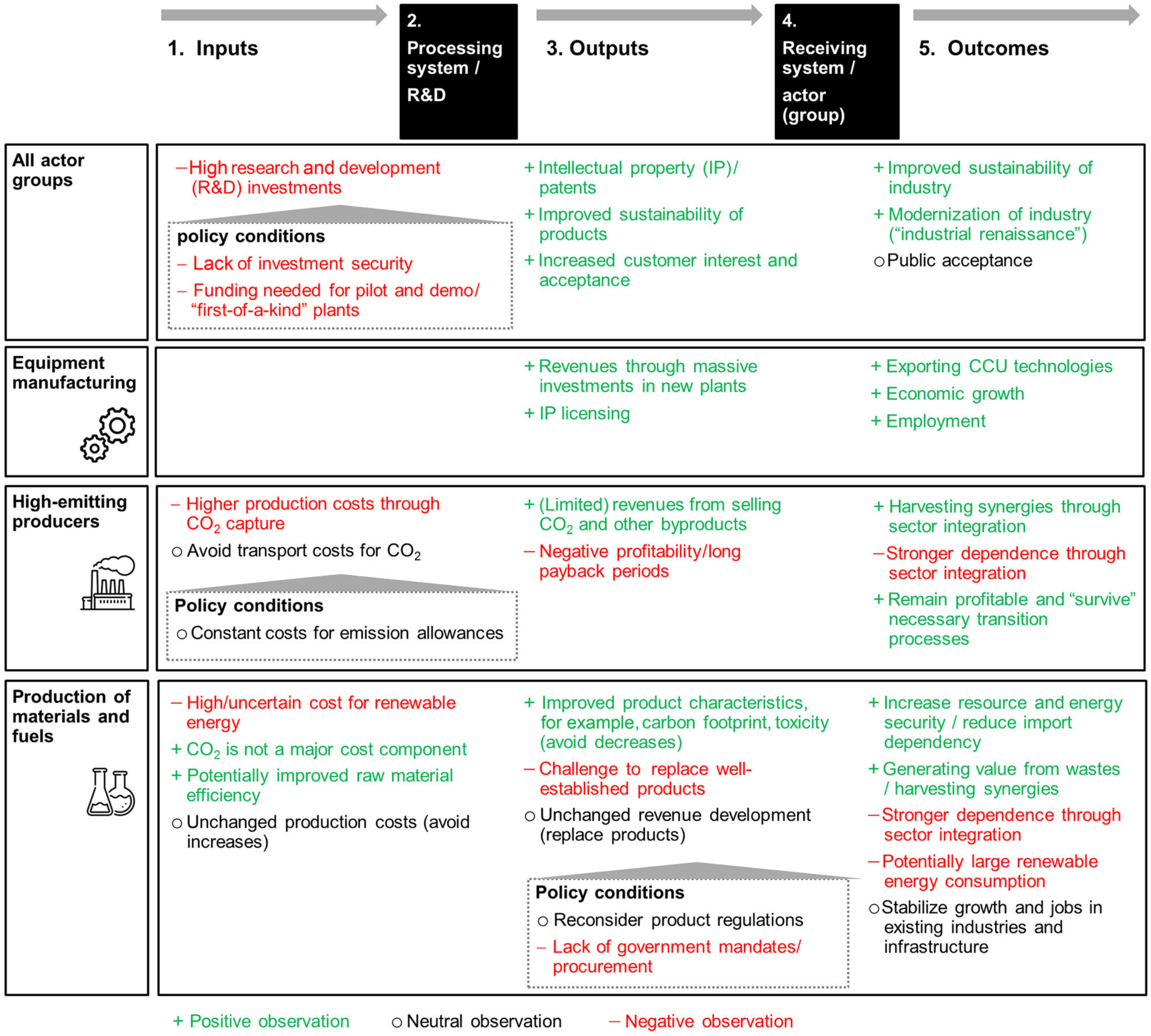


FIGURE 4 Results of reviewing policy advice reports for all value chain actor groups
Source: Author's analysis inspired by the structure of Brown and Svenson (1988). All icons made by Freepik from www.flaticon.com.

5.3.1 | Equipment manufacturing

Overall, the studies give comparatively limited attention (and then only implicitly) to the equipment manufacturing sector. This is surprising, considering the key role of this group in the innovation process and the deployment of machinery for CO_2 capture and/or use. Nevertheless, the following specific aspirations can be derived for these actors.

On the *output* side the aspirations are generally positive. "Very large investments are required and major changes in the current assets are foreseen" (Bazzanella & Ausfelder, 2017). Such potential investments in new CCU plants could provide new revenue streams, IP licensing, and profits for the equipment manufacturing sector.

As future *outcomes*, these actors could be involved in exporting CCU technologies, contributing to economic growth, and providing new employment opportunities (Hendriks et al., 2013; The Royal Society, 2017; US DOE, 2016; Wilson et al., 2015).

5.3.2 | High-emitting producers

Since climate protection threatens the core business models of high-emitting producers they consider all technical options to reduce their CO_2 emissions. Therefore, capture technologies are of interest to this group and qualify in the value chain as a source of CO_2. However, the literature review reveals many challenges for this actor group.

On the *input* side, CO_2 capture increases production costs (Bujnicki et al., 2018; Coddington et al., 2016; Schlögl et al., 2018). CO_2 transport costs depend on the specific set-up and scale. In the absence of large infrastructures such as pipelines (CO_2 Sciences & The Global CO_2 Initiative, 2016) actors will avoid committing to this investment burden, for example, by developing local CCU networks (Bazzanella & Ausfelder, 2017; CarbonNext, 2018). Currently in Europe, CCU is not factored into emission allowance costs, since discussions are still ongoing on potential mechanisms for crediting the new technologies in emission trading schemes (Bujnicki et al., 2018; CarbonNext, 2018). The United States recently introduced a tax credit of $35/metric ton of CO_2 utilized (US DOE, 2016), which is expected to trigger business cases for some "low-hanging fruits" and particularly CCS and enhanced oil recovery (Lucas, 2019).

Regarding *outputs*, high-emitting producers could benefit from limited additional revenues from selling CO_2 or other byproducts in a CCU setting (de Bruyn et al., 2017; Hendriks et al., 2013; Pérez-Fortes & Tzimas, 2016; US DOE, 2016). However, due to the comparatively high investments, the payback periods are long and overall profitability is expected to remain negative compared to conventional production without capture (Bazzanella & Ausfelder, 2017; Coddington et al., 2016; de Bruyn et al., 2017; Hendriks et al., 2013).

When inputs and outputs are shared in industrial clusters, synergies could be enabled according to the targets of industrial symbiosis (Wilson et al., 2015). Hence, a major expected *outcome* is increased sectoral integration (Bujnicki et al., 2018; Mennicken et al., 2016). Different actors would then increasingly depend on each other, which carries certain risks such as balancing production capacities and sharing costs/benefits (Bujnicki et al., 2018; Schlögl et al., 2018). Overall, CCU innovations offer this group the possibility "to survive this transition process and remain in a healthy and profitable condition" (de Bruyn et al., 2017).

5.3.3 | Production of materials and fuels

The majority of the analyzed studies deal with the production of materials and fuel, since this is the essential innovation step and unique to CO_2 utilization. This group encompasses the wide variety of activities involved in refining liquid and gaseous fuels and also the chemical and building materials industries. They are potential users of CO_2 and thus key to the innovation process.

Some technologies require significant *inputs* of renewable energy, particular for producing synthetic fuels. Hence, in those cases, high or uncertain costs for renewable energy hinder the economic viability of their emerging technology (Bazzanella & Ausfelder, 2017; CarbonNext, 2018; Pérez-Fortes & Tzimas, 2016). Despite great variance in the expected cost of CO_2, most studies agree that CO_2 as an input is not a major component of production costs (Bazzanella & Ausfelder, 2017; Bujnicki et al., 2018; CarbonNext, 2018). Overall, ongoing R&D aims to overcome current shortcomings and to reduce or keep production costs constant through raw material efficiencies (Black et al., 2014; Bujnicki et al., 2018; Coddington et al., 2016; de Rosbo et al., 2014; Hendriks et al., 2013). However, many studies forecast higher production costs, which hinder economic viability (Bazzanella & Ausfelder, 2017; Mennicken et al., 2016; Pérez-Fortes & Tzimas, 2016). Nevertheless, Schlögl et al. (2018) state that comparisons with fossil energy carriers neglect future developments and "the service provided by the CCU system."

On the *output* side, product characteristics can often be improved, for example, in terms of carbon footprint or environmental toxicity (de Rosbo et al., 2014; Hendriks et al., 2013). Avoiding deterioration of product characteristics is a central aim of R&D. However, since chemicals, building materials, and fuels are largely commodity goods it can be challenging to replace well-established products with innovative alternatives because markets are often strictly regulated (Coddington et al., 2016; Sandalow et al., 2017; ZEP, 2017). Consequently, no significant effects on revenue development are expected where existing products are substituted (de Rosbo et al., 2014; Pérez-Fortes & Tzimas, 2016). At present, potential producers of CO_2-based products would often experience lower profitability (de Bruyn et al., 2017; Pérez-Fortes & Tzimas, 2016), since few new technologies are yet economically competitive (Bujnicki et al., 2018; de Bruyn et al., 2017). Hence, many agree that future policy frameworks need to allow such products to become profitable (Hendriks et al., 2013; Pérez-Fortes & Tzimas, 2016; Sandalow et al., 2017; Schlögl et al., 2018). As yet, no existing government mandates or public procurement criteria have been implemented to favor CO_2-based products (CarbonNext, 2018). Moreover, product regulations must be revised to enable CCU (CarbonNext, 2018; Sandalow et al., 2017); for example, the European Biofuel Directive was updated to accommodate CCU and since 2018 includes "transport renewable fuels of non-biological origin" (EU Science Hub, 2019). In particular, current building material standards inhibit CO_2 use (Coddington et al., 2016; Sandalow et al., 2017).

With regard to *outcomes*, there are hopes of increasing the resource efficiency of the sector through CCU (Hendriks et al., 2013; Zimmermann & Kant, 2016). While sectoral integration is an important aspiration, material and fuel producers have the task of enabling synergies by generating value from the waste materials of other actors (de Rosbo et al., 2014; Hendriks et al., 2013). Therefore, making use of CO_2 could support resource security (Bujnicki et al., 2018) and, for example, "reduce […] dependence on imported hydrocarbons" (The Royal Society, 2017). Moreover, CCU fuels can store renewable energy, strengthen energy security (Hendriks et al., 2013; Mennicken et al., 2016; Schlögl et al., 2018), and "contribute to the de-fossilization of the energy and transport systems" (Bujnicki et al., 2018). However, large scale-up of CCU could require large amounts of renewable energy (Bujnicki et al., 2018; Hendriks et al., 2013; Pérez-Fortes & Tzimas, 2016). Overall, aspirations are voiced for CCU to stabilize growth and employment in these extant industries and infrastructures compared to other transition scenarios (Bujnicki et al., 2018; Schlögl et al., 2018).

5.4 | Findings from reviewing scientific papers

The review of scientific papers broadly confirms the aspirations identified in the policy reports. As the papers evaluate the current or future performance of one or multiple CCU technologies they provide insights on aspiration–performance gaps and how these may be addressed by decision-makers.

Regarding *inputs* to the production of materials and fuel, the scientific literature largely observes increased production costs through CCU. Many studies measure significant cost increases due to energy or catalyst costs (Christodoulou, Okoroafor, Parry, & Velasquez-Orta, 2017; Dimitriou et al., 2015; Mehleri, Bhave, Shah, Fennell, & MacDowell, 2015). Equally, CO_2 capture requires large investments from high-emitting producers, and further efficiency gains and policy support are needed (Senftle & Carter, 2017). All actors therefore face the remaining challenge of achieving industrial scale-up (Fernandez-Dacosta et al., 2017; Masel et al., 2014). Several studies indicate that future economies of scale could narrow existing performance gaps (Dimitriou et al., 2015; Zhang, Jun, Gao, Kwak, & Park, 2017; Zhang, Jun, Gao, Lee, & Kang, 2015). Many authors recommend overcoming current barriers through continued R&D to improve technological efficiencies (Dimitriou et al., 2015; Pérez-Fortes, Bocin-Dumitriu, & Tzimas, 2014a; Senftle & Carter, 2017). Moreover, some studies indicate that reliable investment policies and emission allowance credits for utilizing CO_2 would benefit the economic viability of such innovations (Mehleri et al., 2015; Zhang et al., 2017). Some studies suggest tailored policy instruments to improve market conditions for CO_2-based products, for example, a landfill tax credit to encourage CO_2 mineralization (Mehleri et al., 2015).

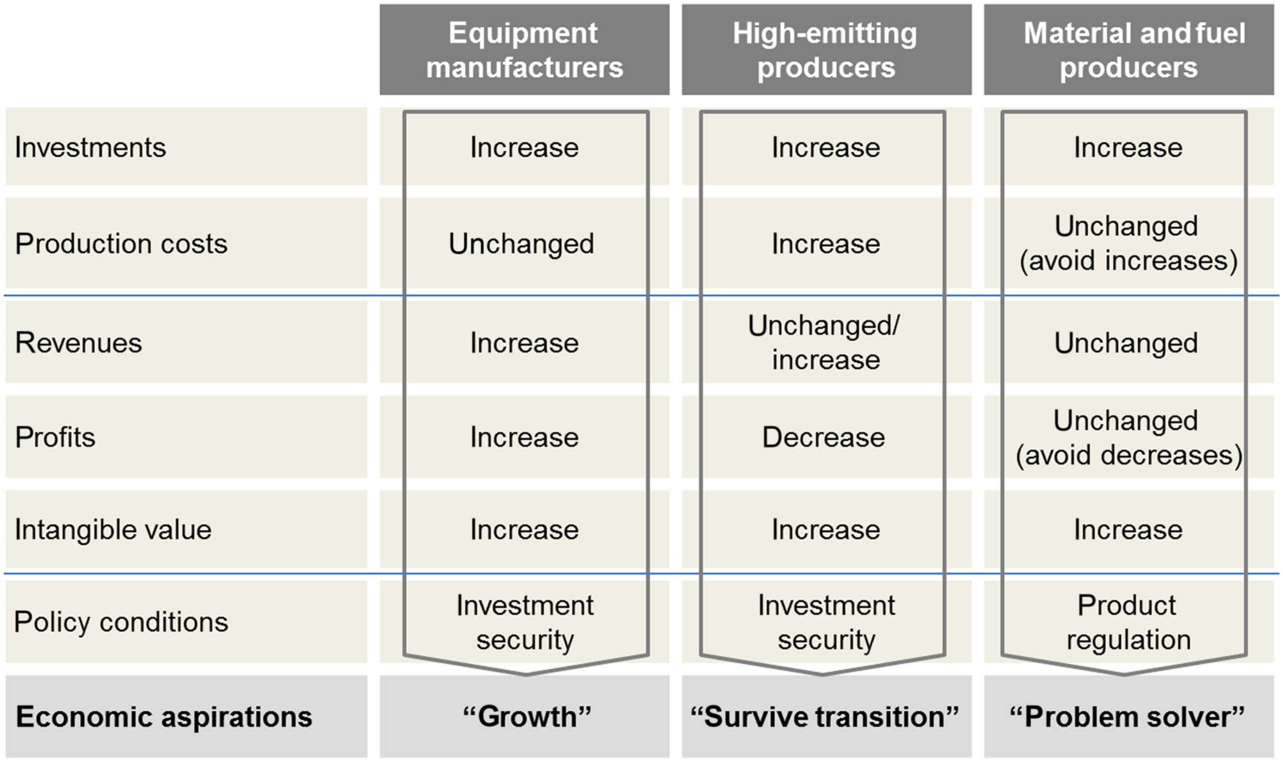
Concerning *outputs*, many authors observe that new materials and fuels have improved product characteristics, particularly reduced environmental impacts (Moats, Miller, & Zmierczak, 2008; Pérez-Fortes et al., 2014a; Santoprete, Wang, & Berni, 2011). At the same time, such products can be compatible with existing supply chains and markets (Dimitriou et al., 2015; Pérez-Fortes et al., 2014b). To develop successful products, Christodoulou et al. (2017) recommend investigating market saturation. Few studies conclude that their investigated technologies are already economically viable (Kim, Ryi, & Lim, 2018; Masel et al., 2014; Putra, Juwari, & Handogo, 2017). Instead, many evaluated technologies cannot compete under current market conditions (Christodoulou et al., 2017; Kuenen, Mengers, Nijmeijer, van der Ham, & Kiss, 2016). Through sensitivity analyses, several studies provide case-specific guidance on how economic performance can be improved (Zhang et al., 2015,2017). None of the scientific studies provide insights on intangible values.

In terms of assessing *outcomes*, several scientific studies highlight the complementarity of CCU to other sustainability measures (Santoprete et al., 2011) and how CCU can reduce costs compared to CCS (Fernandez-Dacosta et al., 2017; Mehleri et al., 2015). Concerning industrial modernization and sectoral integration, Pérez-Fortes et al. (2014b) state that CCU can "advocat[e] tailor-made and local solutions." Santoprete et al. (2011) see the potential for "reorganizing the chemical industry." Moreover, equipment manufacturers could benefit from export opportunities, for example, to regions with low renewable energy production costs or new markets in emerging economies (Pérez-Fortes et al., 2014b).

6 | DISCUSSION

When innovation phenomena are investigated it is necessary to establish a transparent reference system (Dreher, 2013). Since CCU summarizes a broad technology field (National Academies of Sciences, 2019), the object of innovation and its degree of novelty cannot be narrowed down. Neither can a precise time horizon be defined for investigations; instead, all aspirations refer to different or unknown future points in time. On such horizon could be 2030, in line with the UN SDGs (UN SDG Knowledge Platform, 2016). Moreover, the quality of findings is strongly dependent on the reviewed literature. The present sample of *policy reports* encompasses various technological and regional scopes, methods, and assumptions (e.g., technological readiness or plant scale). Some reports build on each other or on the expertise of overlapping authors and advisors. Thus, the current findings are not universally applicable but reflect the informed aspirations of the study authors. These expert estimations indicate how CCU could impact different actors. Moreover, our sample of *scientific papers* over-represents innovations in fuels compared to other products such as chemicals and building materials (see Supporting Information). Since the latter have not yet been as intensely investigated (Sandalow et al., 2017), the present findings might fail to reflect such technologies sufficiently. For example, some innovations in chemicals or building materials may not depend on renewable energy; consequently, the finding that uncertain energy costs hinder economic viability may not apply.

Despite these limitations, the analysis uncovers the economic aspirations currently connected to CCU by the respective authors. While CCU "can and probably will be implemented in industrial clusters" (Fernandez-Dacosta et al., 2017), the findings reveal which industries are likely to benefit from or struggle with such innovations. Furthermore, the findings highlight the different roles of value chain actors in the sustainability transition process (Figure 5): While all groups along the value chain face increased investment costs, all aspire to create intangible value through such innovations. *Equipment manufacturers* are expected to increase their revenues and profits when CCU is deployed. They also aspire to economic growth and employment creation. However, to prove and diffuse new production concepts, they need a policy framework that offers investment security. Meanwhile, *high-emitting producers* face increased production costs through CO_2 capture, hence their central concern is investment security. A major expressed aspiration is that they survive the necessary sustainability transition process through the help of CCU (de Bruyn et al., 2017). In addition, *producers of materials and fuels* face the challenge of finding innovative ways to use CO_2 without increasing their production costs over



	Equipment manufacturers	High-emitting producers	Material and fuel producers
Investments	Increase	Increase	Increase
Production costs	Unchanged	Increase	Unchanged (avoid increases)
Revenues	Increase	Unchanged/ increase	Unchanged
Profits	Increase	Decrease	Unchanged (avoid decreases)
Intangible value	Increase	Increase	Increase
Policy conditions	Investment security	Investment security	Product regulation
Economic aspirations	**"Growth"**	**"Survive transition"**	**"Problem solver"**

FIGURE 5 Summary of results
Source: Author's analysis.

conventional processes. While revenues could remain unchanged, they must work to maintain profitability. Product regulations are a central concern for accommodating their innovative products. Overall, the major aspiration toward this group is that they act as a "problem solver for many other industries" (BMBF, 2014) by offering "CCU as a service to larger production systems" (Bujnicki et al., 2018).

7 | CONCLUSION

This study has shown how CCU innovations involve—and have differing economic impacts on—multiple industries along a value chain. Consequently, such concepts need to be advanced through cross-sectoral R&D consortia in order to better understand the potential synergies and challenges of a specific setting. Funding bodies, policy makers, and administrators should be aware of actors' differing aspirations in order to better design financial and regulatory support when deploying CCU.

We see a research need for further TEAs on novel, CO_2-based materials. Furthermore, we recommend detailed investigations of CCU's potential for industrial symbiosis, in addition to case studies on the roles of subsequent industries. An empirical study could provide evidence of whether the derived aspirations are supported by the industry actors working on CCU concepts. Moreover, insights on the causalities of aspirations would help in developing detailed recommendations on how to deploy CCU to maximize societal benefits. Additionally, the broader social effects of CCU need further study. If all relevant perspectives can be understood at this early stage of development there is greater chance that CCU can successfully contribute to broader sustainability transformations of industrial and energy systems.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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