DOI: https://doi.org/10.1016/j.jclepro.2022.131391

Transformation strategies connected to carbon capture and utilization: A cross-sectoral configurational study

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Abstract

Firms from various industries are investing in carbon capture and utilization (CCU) technologies as part of their circular economy efforts. Hence, managers and policy makers need to develop strategies to create value and “win” sustainability transformations. This study investigates how CCU innovations are connected to economic progress at the firm and industry levels. First, we characterize economic progress from sustainability innovations as a spectrum of combinations of transformation and growth targets, and derive a configurational perspective for such innovations. Consequently, through an empirical study based on 25 in-depth expert interviews with corporate innovation managers, triangulated via additional quantitative and qualitative data, we investigate the causal configurations of R&D activities in CCU that are expected to lead to economic progress, using a fuzzy set qualitative comparative analysis. Our results show a hierarchy of transformation strategies based on investments and value creation which may support policy makers in deciding on appropriate support mechanisms. To enable the emergence of more profitable CCU solutions and facilitate their commercialization, regulators should adapt existing policies to accommodate CCU and consider developing an integrated policy framework. Moreover, managers across industry should develop adaptive strategies for achieving value creation and progress from CCU within changing environments.

Keywords: circular economy; sustainability innovations; CCU; fsQCA; corporate strategies; policy strategies

1. Introduction

The European Commission introduced the Green Deal as a comprehensive action plan towards achieving a climate-neutral and circular economy by 2050. Part of that action plan is to develop carbon capture and utilization (CCU) technologies which capture carbon dioxide (CO_2) from emitting point sources or the ambient air and utilize this as a carbon source in the industrial production of materials, chemicals, or synthetic fuels. High-level international policy studies have concluded that such technologies should be advanced in the context of sustainability strategies (Bujnicki et al., 2018; NAS, 2019). CO_2 utilization and storage concepts are considered important for achieving climate neutrality in particular for dealing with unavoidable industrial emissions and achieving negative emissions (IEA, 2020). Lately, a growing number of sectoral roadmaps of resource and energy intensive industries have outlined their transformation pathways towards climate neutrality and sustainability targets based on a portfolio of technologies, including CCU (Cefic, 2020; Cembureau, 2020; EUROFER, 2019). CCU concepts have been found to be relevant for different sectors, ranging from high-emitting industries that aim to “survive” sustainability transitions such as cement and steel, to equipment manufacturers that see potential for economic growth (Naims, 2020). Hence, R&D is gaining momentum, and companies within various industries are considering deploying CCU. The potential positive environmental outcomes have been studied quite extensively (Kaiser & Bringezu, 2020; Ostovari et al., 2021). Techno-economic studies often accompany CCU development and provide valuable insights on feasibility and necessary improvements (John et al., 2021). However, considering that CCU requires substantial investments in R&D, insights are lacking on how firms should strategically approach CCU innovations with the aim of creating value. Innovation managers from industrial companies that are involved in initiating, advancing, and terminating CCU projects have knowledge and expectations of the costs and value created by such technologies. Hence, we conduct a cross-sectoral empirical investigation with innovation managers working on CCU. The chosen configurational approach investigates causalities and identify patterns for promising strategies.

2. Theory

2.1. Carbon capture and utilization

Carbon capture and utilization encompasses a wide variety of technologies that allow the capture of CO_2 emitted from industrial process or the atmosphere, and subsequently enable this captured CO_2 to be utilized in the production of chemicals, fuels, or building materials. The technologies and potential applications of CCU range from platform chemicals such as methanol to high-performance plastics and cementitious materials (Aresta, 2010; Sanna et al., 2014). Most CCU technologies are still at an early stage of development and only some applications have been piloted. Along with recent increase in targets for a climate-neutral and circular economy, decision makers in policy and industry have acknowledged that CCU will be part of such transformations (EC, 2019; US DOE, 2021). However, the current policy conditions for CCU in Europe are found to be scattered, heterogeneous and in need of future adaptations (Porteron et al., 2019). Life cycle assessments and techno-economic assessments have received increasing attention to ensure the environmental benefits and economic viability of CCU (Sick et al., 2020).

2.2. Sustainability innovations and economic progress

Across economic theories and perspectives there is wide agreement that technical advance increases competitiveness and leads to economic progress. But what does *economic progress* mean exactly? Young (1928) already stated how "the words economic progress, [...] would suggest the pursuit of [...] some way of appraising the results of past and possible future changes in forms of economic organisation and modes of economic activities." However, a much narrower understanding of progress as a synonym for growth from technical advance has prevailed within the economic and innovation literature (Freeman & Soete, 1997). From a neoclassical perspective, Romer (1990) first discussed how technological change induced by research and investments is a driver of macroeconomic growth. From an evolutionary perspective, Freeman (2002) has investigated the contributions of innovation systems to growth at the national level, while the microeconomic effects of innovations, i.e., their impacts on the structure and performance of industries, have been modelled by Dosi (1988) under the assumption that profit-seeking actors aim for an economic innovation benefit. However, innovations in the context of sustainability transitions follow the imperative to reduce an environmental burden via process, product, or behavioral innovation (Rennings, 2000). Hence, their economic impact is not the decisive parameter; instead, various economic outcomes are possible. Often, sustainability innovations are not self-enforcing and require tailored regulatory support to become competitive (Rennings, 2000).

Moreover, the literature agrees that innovation-induced progress is distributed unevenly among firms and industries. Grupp (1998) states that a causal relationship between innovation and progress is observed primarily for firms with R&D-intensive goods and to a lesser extent for others. This is supported by a recent longitudinal study by Sachs (2019), which shows how the U.S. economy is increasingly knowledge-intensive, since over time R&D and intellectual property have grown much faster than gross domestic product. Furthermore, the observed growth is unbalanced between sectors because R&D proves to be a fundamental driver of structural transformation.

The ambitious target of greenhouse gas neutrality set by the European Green Deal implies a significant and disruptive transformation of industrial activities in which sustainability innovations will play a decisive role. The costs and benefits of this transformation will be unequally distributed among market actors. Therefore, a study of economic progress resulting from sustainability innovations must incorporate the variety of expected results from the changes in economic activities. An investigation into three recent European industrial policy strategy documents reveals that growth in productivity, exports and employment remain central targets for economic progress (EC, 2014, 2020a, 2020b). However, growth is not a sufficient element, and transformation strategies have become a key component of progress. According to these observations, we investigate economic progress resulting from sustainability innovations as the spectrum of multiple transformation and growth targets that are unevenly observed across firms.

At the organizational level, the challenge lies in positioning a firm within changing regulatory and market environments. Strategies are needed that align business models with sustainability targets and facilitate necessary innovations without compromising financial targets. Porter (1985) differentiates between strategies of *technology leaders* that pioneer innovations versus those of *technology followers* that wait and learn from the experience of others. Facing industrial transformations, managers today need to make long-term decisions that are less concerned with "*whether*" but more about "*when*" and "*how*" their corporation should invest in particular sustainability technologies. If they seize such moments of change, position and adapt their business successfully, they can shape markets and diffuse their innovation, where the most adaptable innovator is likely to win (Dreher, 2013).

2.3. Configurations of sustainability innovations

The evolutionary innovation literature has well described the configurational nature of technical advance, R&D, and innovations. When Rip and Kemp (1998) define technologies as configurations of artefacts, humans, and procedures "that work" embedded in organizational and societal contexts, they reveal causal structures relevant for guiding technical advances toward desired societal outcomes such as climate change mitigation. Furthermore, Dosi and Nelson (2010) explain how technologies can be viewed as recipes consisting of sequential combinations of physical and cognitive acts for a desired outcome. From an organizational perspective, Grupp (1998) describes the functional interplay between R&D and innovation processes along their typical stages, which are linked by various cognitive but intangible functions of a mathematical, physical, or mental nature. Furthermore, Grupp (1998) embeds this organizational innovation system within economic structures based on evolutionary and institutional innovation theory by detailing several determinants and effects within firms (e.g., strategy, profitability) and beyond the corporate perspective (e.g., growth, policy conditions). Grupp (1998) recommends measuring this interplay with the following indicators:

- *Resource indicators*: all expenditures related to R&D, e.g., personnel, investments.
- *R&D results indicators*: all direct results of the R&D process, e.g., patents, publications.
- *Progress indicators*: the micro- and macroeconomic effects of innovation, e.g., growth, market, trade, productivity developments.

This study employs this configurational innovation system (Fig.1) within a corporate context as a setting for causality analysis. The aim is to observe specific configurations of R&D resources, results, policies, and progress, and to measure these with indicators. The final innovation stages of improvement, diffusion, or disposal highlight the decision-making relevance of this scheme within firms. Policy makers intervene by creating the regulatory framework for this interplay.

(Fig.1)

2.4. Configurational theorizing

This section briefly reviews the innovation literature for configurational relationships within the depicted system, to select main attributes for the empirical study and present the configurational hypothesis in Boolean algebra. The process for configurational theorizing was guided by the heuristics of scoping attributes, linking them and formulating configurations by Furnari et al. (2020).

R&D resources: A determinant condition for the success of innovations is the level of investment. This encompasses all relevant personnel, operating and capital expenses. The literature agrees that investments (Inv) are necessary for economic progress (Prog), since nothing can materialize without investment (Grupp, 1998). Hence, investments are a necessary condition for progress (H1) while the absence of investments is a necessary condition for the absence of progress (H2):

Inv≥Prog (H1)

~Inv≥~Prog (H2)

R&D results: Profitability increase is an important innovation target. Innovations influence corporate profits by impacting costs and revenues. For sustainability innovations, cost savings often stem from improved material or energy efficiencies (Freeman & Soete, 1997). While profitability improvements are not the only condition for achieving economic progress from innovations, they are a dominant condition (Dosi & Nelson, 2010). Hence, investment with increased profitability (Prof) provides a sufficient condition for economic progress (H3):

*Prof*Inv≤Prog* (H3)

Sustainability innovations can facilitate other results that are *intangible* (i.e., not of physical or financial nature), such as patents. Innovations can create intangible value for a firm from different perspectives. Patents aim to protect a firm's future income resulting from an innovation. They are a proven output measure for technological innovation with an empirically verified correlation to corporate market value (Lev, 2001). Customer satisfaction is another useful output measure for organizational, business model, and service innovations (Lev, 2001). Likewise, intangibles often lead to spillover effects that create a "social return enjoyed by society" (Lev, 2001). For sustainability innovations this is a central, intentional element because improving the firm's public perception prolongs its license to operate. While customer and public demands can encourage firms to adopt eco-innovations they are not a sufficient condition for investment decisions (Kesidou & Demirel, 2012). Overall, Lev (2001) finds that R&D investment can transform intangibles into tangible assets and create value or growth for the company if they are sufficiently protected and commercially successful. Hence, we derive that investment with intangible value (IV) provides a sufficient condition for economic progress (H4):

*IV*Inv≤Prog* (H4)

Sustainability innovations often require supporting policy conditions, particularly for internalizing to the firm the formerly externalized costs associated with conventional competitor products (Rennings, 2000). Guerzoni and Raiteri (2015) differentiate technological policies as either supply-side policies including R&D subsidies and tax credits or demand-side policies of public procurement. For technologies in early stages of development, R&D subsidies are particularly important in targeting cost-efficient sustainability solutions (Rennings, 2000) and guiding the direction of technical advance (Freeman & Soete, 1997).Tax credits and public procurement are useful instruments for stimulating implementation. Supporting policies should ideally be monitored to allow for adaptive priority-setting based on the relative performance of alternative technologies (Dreher et al., 2016). While positive and negative externalities of sustainability innovations are often unequally distributed between sectors and regions, policies can intervene and facilitate the attainment of defined targets (Freeman & Soete, 1997). Hence, supporting policies (Pol) combined with investment provides a sufficient condition for economic progress (H5):

*Pol*Inv≤Prog* (H5)

Moreover, if profitability decreases and policies are a barrier, then economic progress cannot be expected. Thus, the combined absence of supporting policies and profitability is expected to be a sufficient condition for the absence of progress (H6):

~Pol~Prof≤~Prog* (H6)

3. Material and methods

3.1. Expert interviews

The empirical study is based on a series of 25 in-depth expert interviews conducted with innovation managers working on CCU innovations within 18 different companies located in Europe (see MethodsX). Most experts represent large, multinational enterprises (MNEs) plus selected small and medium enterprises (SMEs). The experts are employed in manifold sectors covering the industrial value chain (Table 1).

Table 1 Sectoral classification of experts. Sources: Public company data.

Sector code[1]	Sector name[1]	no. of experts[2]
6	Extraction of crude petroleum and natural gas	2
20	Manufacture of chemicals and chemical products	9
23	Manufacture of other non-metallic mineral products	3
24	Manufacture of basic metals	4
28	Manufacture of machinery and equipment n.e.c.	3
29	Manufacture of motor vehicles, trailers, and semi-trailers	2
35	Electricity, gas, steam, and air conditioning supply	1
38	Waste collection, treatment, and disposal activities; materials recovery	1

Notes:

[1] International standard industrial classification (ISIC) of all economic activities of UN DESA (2008).

[2] All 25 experts were assigned to an ISIC sector based on their firm's core activities in terms of revenues.

We conducted the in-depth semi-structured interviews in person, or by video/phone call between 06/2016 and 03/2017. The interviews lasted between one and three hours, and followed a guideline incorporating epistemological and methodological recommendations from Bogner et al. (2009). Moreover, through participatory observations at conferences , combined with desk-based research into the corporations and their activities, the interviews were well prepared for data verification and triangulation (see MethodsX). A significant technological advancement since data collection seems unlikely due to the commonly long timeframes of around ten years from the decision to invest to start of operations (Bazzanella & Ausfelder, 2017).

The interviews examined the experts' knowledge of R&D resources, results, policy conditions, and their expectations for economic progress. Since all interviewees are involved in the advancement of corporate R&D projects, their knowledge of resources and results is of high quality. While those experts from public relations or environmental departments often have more detailed knowledge of policies, even those with an R&D background could reflect on the marketability conditions of their work. The section on economic progress covered the qualitative spectrum of their expectations for achieving growth and transformation goals based on their personal, context-specific experience and beliefs. Despite their subjectivity, all the expectations are shaped within a profit-driven environment with explicit or implicit innovation strategies. Hence, the experts' expectations provide valuable insights on the progress potentials of such innovations. Moreover, analyzing public company data for the experts' firms reveals three groups: (i) CO_2-intensive firms with low R&D intensity, (ii) R&D-intensive firms with low CO_2 intensity, and (iii) firms with medium CO_2 intensity and low or medium R&D intensity (see Fig.2).

(Fig.2)

3.2. Fuzzy set qualitative comparative analysis

Qualitative comparative analysis (QCA) is a well-established field of methods to investigate causal configurations, originally developed and refined by Ragin (Ragin, 1987, 2009). QCA enables causal investigations into social phenomena based on set theory and has found wide application across research fields, including eco-innovations (Chappin et al., 2020; Rabadán et al., 2019). Important advantages compared to conventional methods are that QCA allows for equifinality, i.e., several causal paths to an outcome; and that causality is one-way directional and can be asymmetric (Fiss, 2007). For business research, Misangyi et al. (2017) claim that QCA enables a "neo-configurational perspective" that is particularly promising for certain fields, including studies on expected but unobserved strategy and managerial decision making. Hence, the present study conducts a QCA according to Ragin (2009) and the best practices for strategy and organizational research by Greckhamer et al. (2018) to investigate strategies among firms involved in CCU.

3.3. Data calibration

Data calibration is of paramount importance for the quality of QCA. The present study followed the technique suggested by Basurto and Speer (2012) to transform qualitative interview information into fuzzy sets. The interview data were calibrated as summarized in Table 2 and described in MethodsX. Investments were assessed based on a combined logic of indicator thresholds (size and status of investments, technology readiness level (TRL)). Profitability was assessed based on combinations of the experts' judgments about production costs and revenues. IV was assessed as a continuous fuzzy set with the mean of the indicator groups patents, product & customer value, and public perception. The statements on policies were calibrated to the degree they support or hinder CCU implementation. To calibrate progress, we assessed the expectations concerning growth and transformation. As suggested by De Block and Vis (2019) a cluster analysis assessed the spectrum of combinations for growth and transformation. Fig.3 illustrates the observed clusters and their interpretation, with transformation winners and opportunists who both expect to benefit, and those that do not, including transformation underdogs, pessimists, and impact sceptics. Hence, we calibrated the outcome progress with formulae according to these clusters (see MethodsX), with transformation winners fully in the set, and impact sceptics fully out of the set.

(Fig.3)

Table 2 Overview of calibration of all conditions and outcome. For the detailed calibration of cut-off points and membership score see MethodsX.

Condition/outcome	Measurement indicators	Set type	Calibration
Inv Investments	Degree of investment in CCU measured with a combination of indicators: ▪ Absolute and relative size of investments ▪ Status of investments (active or past) ▪ TRL of activities	Four-value fuzzy set	Major investments/demo plant (1 – fully in) Diverse investments (0.67 – mostly in) Investments in the past (0.33 – mostly out) No investments (0 – fully out)
Prof Profitability	Direction of expected profitability effects measured with a combination of indicators: ▪ Production costs ▪ Revenues ▪ Profitability	Four-value fuzzy set	Profitability increases (1 – fully in) Remains constant (0.67 – mostly in) Ambivalent profitability outlook (0.33 – mostly out) Profitability decreases (0 – fully out)
IV Intangible Value	Degree to which IV is created, measured with a combination of indicators: ▪ Patents submitted or granted ▪ Product image & customer satisfaction ▪ Public relations	Continuous fuzzy set	Significant IV is created (1 – fully in) Some IV is created, small improvement (0.67– mostly in) Unsure / possibility of IV in future (0.33 – mostly out) IV is not created (0 – fully out)
Pol Policy Conditions	Degree to which relevant regulations and policies hinder or support CCU, e.g. ▪ Emission Trading Scheme (ETS) ▪ Renewable Energy Directive (RED) ▪ Fuel Quality Directive (FQD)	Four-value fuzzy set	Policies are largely supportive (1 – fully in) Policies are partially supportive, require updates (0.67– mostly in) Policies are overall unfavorable except in selected/local cases (0.33– mostly out) All relevant policies are unsupportive (0 – fully out)
Prog Progress	Degree of expected progress from CCU, measured with a combination of indicators: ▪ Transformation ▪ Growth	Five-value fuzzy set	Transformation winners (1 – fully in) Transformation opportunists (0.75 – mostly in) Transformation underdogs (0.49 – more out than in) Transformation pessimists (0.25 – mostly out) Impact sceptics (0 – fully out)

4. Results

fs/QCA software was used to analyze the necessary conditions and causal configurations within the sample, thereby identifying promising strategies. The analysis reveals necessary strategic elements and causal combinations to advance CCU innovations.

4.1. Necessity analysis

First, we revisited our configurational theorizing regarding the necessity of investments for achieving progress. Our empirical results confirm investments as a necessary condition for achieving economic progress (H1) with high consistency (0.86) and coverage (0.76):

Inv≥Prog (N1)

Conversely, the results do not indicate that an absence of investment would be associated with lack of progress (H2), due to low consistency (0.41). However, we explain both observations by the nature of our sample, which largely consists of companies that are investing in CCU. The absence of progress would be better investigated in a broader sample of firms. We tested the necessity of the presence and absence of all other conditions for the outcome progress and found that IV is also a necessary condition for achieving economic progress with high consistency (0.81) and coverage (0.80). This finding highlights the underestimated importance of IV and refines H4:

IV≥Prog (N2)

4.2. Configurations for winning strategies

As a second step, we analyzed the truth table in fs/QCA for the presence of the outcome progress (MethodsX):

Prog=f(Inv,Prof,IV,Pol) (T1)

To identify common causal recipes, we deleted all rows of causal combinations in the truth table containing less than two cases. We set the consistency cut-off value at the 75% minimum level suggested by Ragin (2009), which allowed us to include the combinations of causal conditions containing numerous cases. Due to our small sample size and qualitative study design, the observed consistencies of the solutions are sufficiently high with no substantial gap between the solutions' consistency scores. The results in Table 3 present three configurations for winning strategies, which jointly cover 75% of the membership in our dataset at a consistency of 83%. Furthermore, we differentiate between core and peripheral conditions as suggested by Fiss (2011).

Table 3 Configurations for winning strategies.

Causal condition	1 solution providers	2 IV investors	3 passive observers
Inv	●	●	⊗
Prof	⬤		⊗
IV	●	●	●
Pol		⊗	●
Consistency	0.84	0.79	0.81
Raw coverage	0.41	0.51	0.10
Unique coverage	0.16	0.24	0.08
Total coverage		0.75	
Total consistency		0.83	

Notes: ⬤ = present core condition; ● = present peripheral condition; ⊗= absent core condition; ⊗ = absent peripheral condition; blank space = the causal condition may be present or absent

Solution 1 encompasses the group *solution providers*, firms that expect progress from technology-leader strategies as they invest and create value independently of policy conditions:

*Inv*Prof*IV≤Prog* (S2)

Profitability is identified as a core condition from the parsimonious solution with high consistency (0.84). Hence, the solution supports H3 and extends it to H4 by suggesting that profitable investments in CCU bring along IV.

Solution 2 summarizes the group *intangible value investors*, comprising firms that expect progress from technology-leader strategies as they invest to create IV despite unfavorable policy frameworks and independently of profitability:

*Inv*IV*~Pol≤Prog* (S1)

The parsimonious solution identifies policy barriers as a core condition at a consistency below our threshold (0.69). Hence, this solution rather extends H4 by placing it in an unfavorable policy context.

Solution 3 comprises the group *passive observers* as these firms pursue technology-follower strategies, being non-investors that expect progress from a supporting policy environment and IV despite profitability decreases:

~Inv~Prof*IV*Pol≤Prog* (S3)

The parsimonious solution reveals that the absence of investment is the core condition at a sufficient consistency (0.75). This smaller group expects to benefit from adhering to policies and targeting IV despite profitability decreases. Hence, the solution contradicts H5 by revealing that supporting policies for CCU currently do not facilitate investments that monetize.

4.3. Configurations for the absence of winning strategies

Consequently, we analyzed the truth table for the absence of the outcome progress (MethodsX) to identify configurations for impact sceptics:

~Prog=f(Inv,Prod,IV,Pol) (T2)

The consistency scores in our truth table are low except for one combination of causal conditions with high consistency (0.83). Our sample of companies is largely investing in CCU and hence does not well represent the expected absence of progress. Nevertheless, we include *solution 4* (Table 4) as our sufficiently consistent configuration, even though it covers only one case with a coverage of 31%. This group comprises *passive sceptics*, who have an ambivalent transformation outlook and do not anticipate any benefits from CCU. It is observed in the absence of all four conditions, which extends H6 and identifies the absence of IV and investments as core conditions:

~Inv~Prof*~IV*~Pol≤~Prog* (S4)

Table 4 Configurations for the absence of winning strategies.

Causal conditions	4 passive sceptics
Inv	⨂
Prof	⊗
IV	⨂
Pol	⊗
Consistency	0.83
Raw coverage	0.31
Unique coverage	0.31

Notes: ⨂= absent core condition; ⊗ = absent peripheral condition

5. Discussion

To explore our results, we constructed a summary matrix of our four observed transformation strategies based on progress, investment status, and value creation (see Fehler! Verweisquelle konnte nicht gefunden werden.). On the side of the non-investors, we find a hierarchy of passive sceptics and observers with the latter expecting progress; on the side of the investors, we find a hierarchy of value creation between IV investors and solution providers. Moreover, we recognize a potential evolution that suggests that firms adapt their strategies, while regulators adapt framework conditions such that more investors and solutions will emerge in the future. Overall, alongside the *solution providers*, the two other promising strategies both aim at intangible value but are dichotomous in the policy and investment setting; Hence, they complement each other: non-investors or technology followers currently find the policy setting supportive enough for their passive observations, while investors or technology leaders find the current policy setting an impediment to progress. Therefore, overall, our results emphasize the need for regulators to create a policy environment that encourages firms to invest in CCU so that more solutions emerge.

(Fig.5)

In the following discussion, we illustrate the four solutions with quotations from the expert interviews to expand our understanding of explicit and implicit CCU innovation strategies. While the timeframes for technology development from lab to market vary based on technology and market familiarity five to more than 10 years are common in the chemical sector (Miremadi et al., 2014). Bazzanella and Ausfelder (2017) estimate ten years for the technology implementation from the decision to invest to start of operations. Hence, since the interviews, some technologies might have achieved a higher readiness level or selected new installations might have emerged. However, a major scale-up seems unlikely. Moreover, the European policy framework has been sharpened in regard to its climate targets (EC, 2019). Nevertheless, the implementation of relevant policies is still an ongoing process and the environment for firms engaged in CCU has not changed significantly. Thus, the findings are still relevant and useful to guide decision making. We contextualize the findings and propose solution-specific implications for managers and policy makers that encourage value creation from CCU and an evolution within the presented matrix towards value creation and investment. The cases contained in our results reveal that all promising solutions include firms from two or more sectors and differing degrees of R&D and CO_2 intensity. Hence, the identified strategies are not industry-specific. Instead, winning strategies were found for firms of all stages of the value chain.

5.1. Solution providers

Solution providers are proven technology leaders with medium and high R&D intensity. Currently, the CCU business cases in this group are prepared for commercialization, as the following expert describes:

> "Having built our own plants and got them working and profitable, we have a lot more confidence about our own abilities; and we can build and operate if the need arises. [...] The company plans to more than double the number of plants it has [...] in the next five years. It wouldn't be investing all that money if the process wasn't profitable." (E)

With their differing breakthrough CCU technologies, solution providers create tangible value from increased revenues or reduced costs independently of policy conditions. However, our results show how all solutions are also connected to significant intangible value. Anticipated increases in customer satisfaction are a vital element of this innovation strategy. The following two experts explain how the innovativeness of CCU, and the expected progress are perceived as strategic advantages for incumbents in traditional industries:

> "The motivation is on the one hand really the business's own footprint, and on the other hand that there is actually business potential in the area. [...]We [are] in a very consolidated, traditional form of business. [...] There is not much left in terms of innovation. [...]. CCU especially [is] an area where we can actually be innovative again — compared to many other things in our business area, which don't allow that anymore. (R)

> "We have received so many requests for the new [product] that we can never satisfy them. [...] Are people willing to pay more money for it? No. [...] And so suddenly [our industry] is perceived as innovative again. In this respect, CCU was exactly the right thing for the industry." (T)

While the solutions seem to work independently of the observed policy conditions, the firms nevertheless must commit to significant and long-term investments. Hence, the main task for regulators is to create stable framework conditions that encourage investment by solution providers. Funding and support programs for all stages of R&D are necessary to achieve important breakthroughs, as the following expert suggests:

> "We have now found the low-hanging fruit, but the real breakthroughs are still quite low in the TRLs. And public funding is simply the absolute priority, otherwise a company cannot afford it itself unless it is so big that it really has a lot of money that it says, yes, strategically we just want to push it through. So, it's extremely important for society to participate in the development of sustainable technologies of the future." (R)

The adaptation of the firm's strategy to industrial transformations, and specifically CCU, can be a decisive factor for creating value in coming transformation. In the following, an expert explains how, within their firm's strategy, the alignment and comparative evaluation of all innovation activities, have significantly improved decision-making processes:

> "It has been important to first define a uniform strategy for the subject area. In the past we have tended to work opportunistically based on individual funding projects, which meant that it was not possible, for example, to calculate business cases uniformly, because there was no uniform basis of assumption regarding market developments, etc. This is now in place, and it is therefore easier for us to make decisions on this basis for all future things." (Q)

This reinforces earlier findings, that consistent assessments are key to good decision making regarding CCU (Chauvy et al., 2020). Overall, for managers in this group, the main task is to stay committed to achieving scale-up and commercialization of their breakthrough technologies. They aim to enter emerging markets for their solutions and gain experience from first-of-a-kind applications. In line with findings on technology leaders and early mover advantages (e.g., Porter (1985); Dreher (2013)), they should consider expanding and adapting their CCU portfolio based on their first successes. In particular, managers should target a competitive advantage from working closely with customers and other value chain partners to increase the marketability of their products with reduced carbon footprints. Embedding CCU in a strategy that is adaptive to industrial transformations can improve decision making within firms and help firms to prosper in the future.

5.2 Intangible value investors

The diverse group of IV investors shares their ambition to become technology leaders in CCU in their respective fields. Overall, in terms of core conditions, this group finds the current European regulatory system to be a hindrance to CCU deployment. For example, one expert highlights that the firm's global competitors are not subject to EU CO_2 emission regulations:

> "We as [...] industry will be in the middle of it. We are now doing [CCU] projects, [but] the rules on competition are not fair at this moment on the global level." (C)

Moreover, certain regulations hinder the marketability of CCU-based products, e.g., electricity taxes for using renewable energy in CCU applications:

> "If that remains the case, it's not just for us — it's the same for all who are working on these technologies: [...] we'll stop the projects if the politicians tell us that this is just a research topic and that maybe we'll start doing it in practice in twenty years. No one can hold out until then, unless it's as a very small research field on the sidelines." (J)

However, despite unfavorable policy frameworks, several R&D-intensive firms have decided to invest in sustainable products from CCU to create a competitive advantage, as the following expert highlights:

> "Technology is the core of our brand [...] Not at the beginning, but of course at some point you also have to explain to your board of management how this could also contribute to the [firm]'s return [...] At the moment, these are money-burning plants. [...]You try to finance it somehow, but as the framework conditions are today, you will not be able to compensate for it through the customer's willingness to pay[...]. One point must not be forgotten, the competitive advantage for us — who is the first to offer sustainable product options to the customer? [...] from that one they will buy more." (J)

Hence, while engaging in CCU these firms secure technological advances through patents, increase customer satisfaction and public perception. An expert describes how technological leadership in CCU addresses the emerging interest of customers in green products even for standardized goods:

> "The trigger is our intention to bring our CO_2 footprint down. [...] I think, in CCU, the original motivation was really to show advancement over our competitors. I guess that is what our top management likes very much. [...] When we do CCU, people feel that [our product] has become greener. [...] It is a standardized product [...] so, it's only about how the customer sees a product of ours versus the product of a competitor [...] Most of our customers [...] are not really interested in green things. That is changing, in fact, and that is very important to mention. [" (D)

Another expert supports this strategy of creating a competitive advantage from CCU through improving customer proximity and local sourcing. In particular, European firms should aim for the role of technology enablers in transformation scenarios:

> "To create a competitive advantage for us, customer proximity is a motivation; [...], we take what the customer has nearby [...]. Through growth, new structures and value chains will emerge and with them new winners, but also losers will appear on the scene who no longer exist. [...] The winner will be the one who adapts fastest and best; and that will happen locally." (X)

The statements illustrate the potential for policy makers to update specific regulatory conditions within and at the borders of Europe to enable profitable business models with low carbon footprints. While technology leaders are willing to invest initially even under adverse regulatory and market conditions, widespread deployment can only be expected when the spectrum of policy conditions better accommodates CCU in regional and global markets. For example, the EU Renewable Energy Directive II (EU-REDII) has recently been extended to CCU by including "renewable liquid and gaseous transport fuels of non-biological origin, or recycled carbon fuels" (European Parliament and Council, 2018). Moreover, the European Court of Justice has ruled in the Schaefer Kalk case that the monitoring and reporting of CO_2 emissions of the EU-ETS needs to be adapted to accommodate carbonation technologies that use and store CO_2 (CJEU, 2017). These examples show how a variety of policies require tailored adaptations to support CCU. An integrative CCU policy strategy and framework would be an effective means to fill regulative gaps and enable more profitable solutions.

Furthermore, managers who follow a differentiation strategy based on technology leadership are investing in CCU despite unfavorable conditions, because they see significant value created for customers and other stakeholders in addition to gaining important knowledge that may produce tangible value in the future. Hence, a focus among managers in this group should be to steer R&D toward profitable business models, in particular by involving customers in the development. At the same time, they should ensure that R&D efforts are accompanied by tailored marketing measures to direct intangible value into sales channels.

5.3 Passive observers

This small group of two non-investors pursue technology-follower strategies that adopt proven business models of technology leaders at a later stage in time. This strategy explains how they expect to benefit from CCU in the future without yet having invested. One expert highlights a current lack of good technological options as a reason for the firm's passivity:

> "[Our firm] is mainly an operator of manufacturing [equipment…] Sometimes, we do some technologies, but most of the time we see it in partnerships, […our] activities are mainly focused on being a smart user of technologies. […] If we want to target carbon neutrality in 2050, we have to set up a lot of technological ways to succeed. […But] we think that there is no single good option today. Some of the options are somehow more efficient, but […] we have to develop all [of them…]Shareholders and banks […] are increasingly aware of the CO_2 risk. […] Today it is very difficult because there is no business [in CCU]; we do not have a clear prospective business position today." (G)

Moreover, this group finds policies supportive, even if they do not yet facilitate investment. Instead, they anticipate that existing policies such as the EU-ETS and EU-REDII will improve the competitiveness and acceptability of CCU products in the future:

> "[CCU] would add a significant amount to the cost of [our product], which we would be unable to pass on to our customers because the market is very competitive. […] The driver would be just reducing the CO_2 emissions for tax reasons; any intellectual property would be a bonus. […] The technologies […] are quite difficult and you wouldn't want to do this without some support. […]The driver for us to reduce emissions comes from the EU-ETS. Even though […] the price is low, I think the driver is from the perceived cost in the future. […] If the technology had been proven in other industries or in [a competing firm] then we would definitely be more willing to invest. I think that could change soon, so if [others] develop […] and prove the concept." (A)

The main task for these managers is to prepare to engage in CCU as technology followers and to predetermine under what conditions to time their involvement. Hence, even for firms that are not R&D-intensive, all related activities should be anchored in an adaptive strategy that covers paths of industrial transformation and facilitates decision making under changing conditions. At the same time, policy makers should provide necessary guidance by enforcing or strengthening long-term policy instruments that provide reliable investment and marketability outlooks. An integrated CCU policy framework could provide such guidance.

5.4 Passive sceptics

Passive sceptics have the most conservative outlook on progress. The single observed case is neither is convinced by the transformation potential nor expects to benefit from CCU. No opportunities connected to their core business could yet be identified:

> "We are still in this exploration phase, so we haven't made any major conclusions on which route to take. We […] first thought of engaging or exploring the possibilities within the [xy] segment, since we have years of experience with [xy] in our core business; and that's the most natural way to expand our business in the CCU area. But we also see that many of the CCU initiatives, over the last year, have shifted their focus […].[Our] management will be very careful in selecting research areas and commitments,

especially when talking about long-term engagements [...]. If we don't see any opportunities within the next five years, this isn't for us. [...We] are not a technology company, [...] so, basically, in our core business, we buy technology from technology providers. Even if we have research departments, we are not defining ourselves as technology developers, at least not in areas where we have no direct benefit or value from it."

The example illustrates how sceptics are likely to miss out on the potentials that the other groups see. Even if they opt to become CCU technology buyers, managers should reflect on whether to strategically target a technology-follower position as a passive observer. Then, they should start identifying opportunities for creating relevant intangible value from CCU. An adaptive strategy covering relevant innovations could help prioritizing potential activities and identifying trigger points for framework conditions. Moreover, by entering into selected alliances the firm can widen its perspective beyond its core business and learn from others.

Policy makers should ensure that long-term policy goals and instruments are in place for all relevant sectors. Then, over time, more sceptics will become observers, and at some point, might actively engage in sustainability innovations such as CCU.

6. Conclusions

Firms from various sectors advance CCU technologies as part of their sustainability efforts. Facing industrial transformations, managers are in the process of deciding not *whether* but more about *when* and *how* their corporation should invest in which sustainability technologies, including CCU. To benefit from the coming transformations, firms should develop adaptive strategies for creating value in changing environments. Our empirical analysis of the strategies that are in practice connected to CCU has revealed the following implications:

(i) *Solution providers* are proven technology leaders that need to focus on scale-up and commercialization of their CCU innovations. A strategy that is adaptive to industrial transformations can improve corporate decision making. These actors require stable policy conditions that encourage investment and continued R&D to achieve important follow-up breakthroughs.
(ii) *Intangible value investors* pursue technology-leader strategies despite unfavorable policy conditions. Hence, their technologies will only be deployed at larger scale if specific policy conditions are adapted for CCU. Further R&D should seek to involve customers to ensure marketability and be accompanied by tailored marketing efforts.
(iii) *Passive observers* pursue technology-follower strategies and anticipate copying proven CCU business models of technology leaders at a later stage. Hence, managers should plan when and under which conditions to engage and incorporate this within a strategy. Meanwhile, policy makers can provide guidance by enforcing or strengthening long-term policy instruments that provide reliable investment and marketability outlooks.
(iv) *Passive sceptics* are not convinced by the progress potentials of CCU. Nevertheless, to prepare for industrial transformations, managers could target a more strategic technology-follower position by finding intangible value from CCU, introducing a strategy, or entering into selected cooperations beyond their core business.

Overall, the results highlight the need for regulators to improve the policy environment to better encourage firms to invest in CCU so that more solutions emerge. For example, the upcoming revisions and implementation of the EU-ETS and EU-REDII should accommodate the variety of CCU-based solutions to allow reaping the desired environmental benefits. The introduction of an integrated CCU policy framework could help to facilitate the commercialization of more profitable solutions. For example, a European CCU Directive could strategically connect the relevant existing legislations and fill gaps.

This study contributes to the literature by showing how in the context of CCU configurations of corporate R&D activities for sustainability innovations reveal different winning strategies. The presented causal links between R&D resources, results, policy conditions, and economic progress have not yet been investigated at the company level despite the increasing transformation pressures on firms. To enable this analysis, we first had to define progress as a spectrum of combined expected outcomes of growth and transformation, which extends the existing literature.

As more sectors and regions are targeting circularity and climate neutrality, the empirical investigation of the configurations of conditions for expecting progress from sustainability innovations could be tested in other technological settings such as the bio- or hydrogen economy. Additionally, the results highlight the significant role that intangible value can play for firms facing sustainability transitions, a benefit that remains under-represented in the organizational literature. Our results show that IV is a peripheral condition in all solutions for winning the transformation, whereas, conversely, the absence of IV is a core condition for not winning. Hence, the linkage between IV and winning the sustainability transformation is strong overall and warrants follow-up investigations. Moreover, when the European policy environment is shaped more clearly regarding CCU a follow-up study could investigate observable changes. Furthermore, in the long term, an ex-post study of observed company performance data could test and expand the findings. Additionally, sector-specific studies of promising strategies could be useful to accompany industrial sustainability roadmaps. Overall, decision makers should prepare now for the upcoming transformations. The COVID-19 pandemic has accelerated many processes, where instruments for economic recovery are directed towards sustainability targets. Winning strategies are likely to be a piece of this puzzle.

Acknowledgements: We thank Prof. Carsten Dreher and his team and Julia Bartosch at FU Berlin, Barbara Olfe-Kräutlein, Till Strunge, Lorenzo Cremonese at the IASS for their valuable feedback, and Joschka Jahn for supporting the desk research. Moreover, we thank the reviewers and various colleagues at EGOS 2020 and IST 2020 for their helpful comments, Wernerwerke for their work on Fig.1, and Dave Morris for language editing this article.

Funding: This work was funded by the Institute for Advanced Sustainability Studies.

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Figures

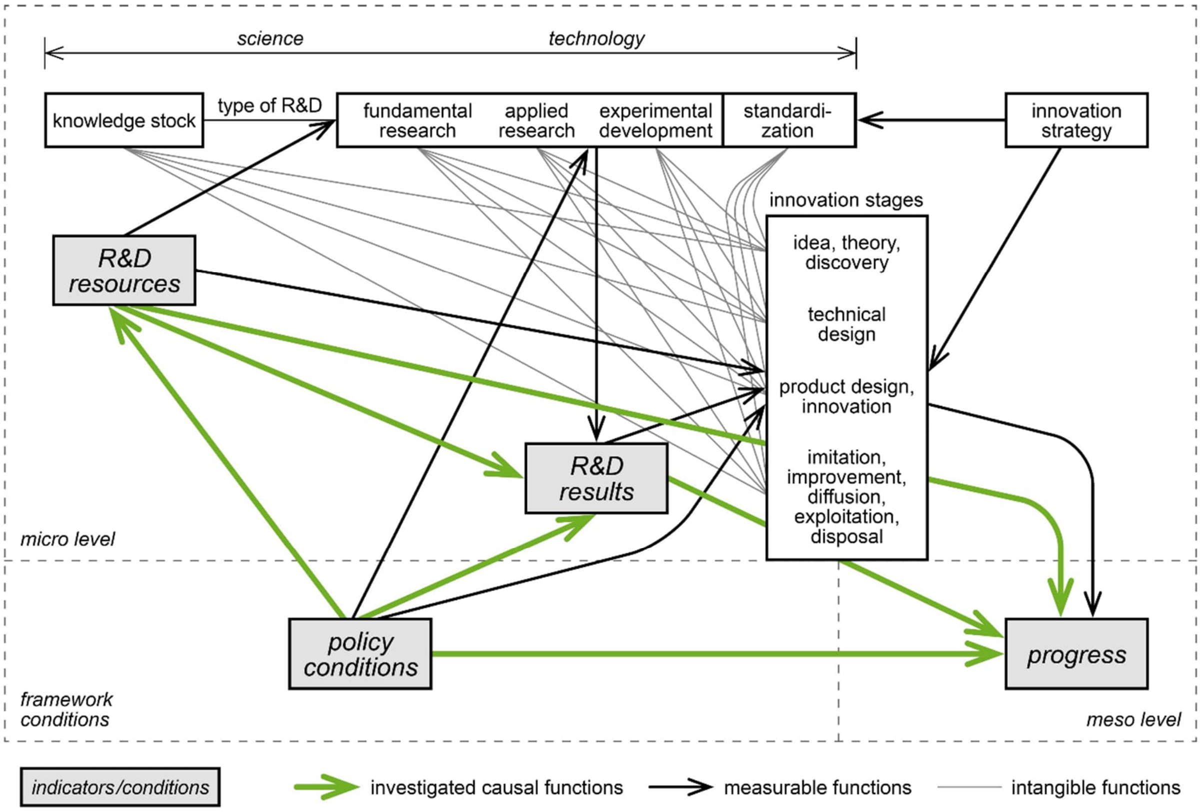

Fig.1 Configurational system of innovations. The functional interplay between R&D, innovation, and framework conditions depicted by Grupp (1998) presents innovation indicators to measure the economics of innovations. This study adds policy conditions to the innovation indicators and displays the investigated causal relationships towards the outcome economic progress. Feedback loops are excluded.

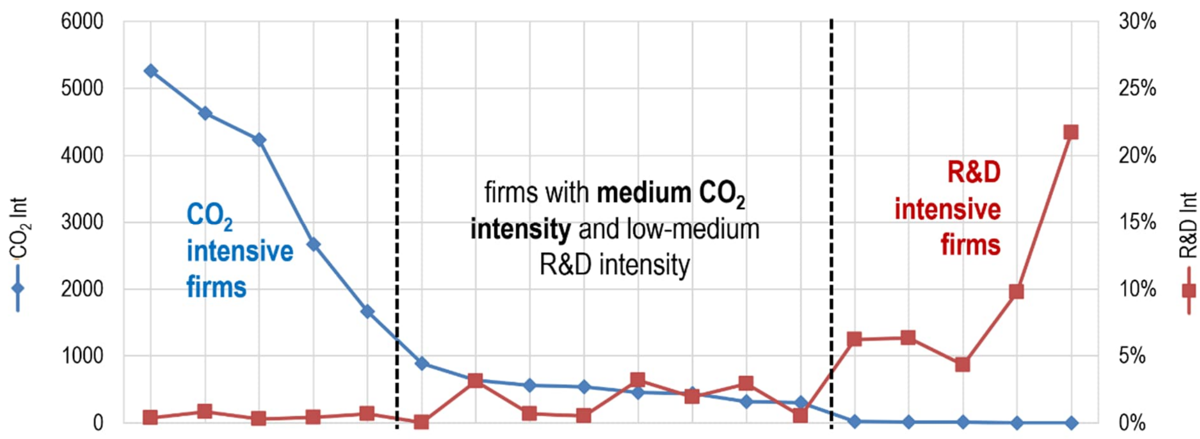

Fig.2 Characterization of experts' firms by CO_2 intensity[1] and R&D intensity[2], Sources: Public company data[3].

Notes:

[1] The CO_2 intensity of the firm is the ratio of CO_2 emissions (including scope 1 and 2) to revenues measured in tCO_2/m US$. This measure is common for ESG stock market index

evaluations. Intervals were classified as *low* when below 300, as *medium* when between 300 and 800, and as *high* when above 800.

2 The R&D intensity of the firm is the ratio of R&D expenses to revenues. Intervals are classified as follows: *low* is below 1%, *medium* is between 1% and 4 %, and *high* is above 4%. This is in line with the classification by the EC (2017) except that the latter defines high R&D intensity as above 5%. In contrast, Grupp (1998) defines high R&D intensity as above 3.5%. Since our sample only contains one firm between 3.5% and 5%, this was categorized as high, and the threshold set to 4%.

3 Data on revenues, R&D expenses, and CO_2 emissions (including scope 1 and 2) is sourced from annual reports for 2017. For one start-up company, financial data for 2017 were unavailable and replaced by data for 2018. For two start-ups, emissions data were unavailable but assumed to be in the low category.

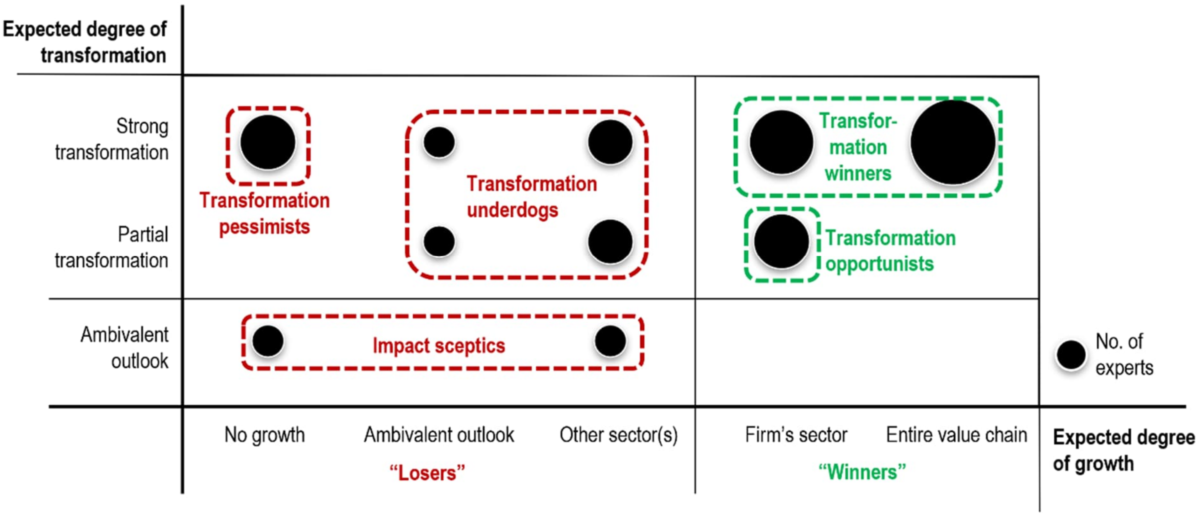

Fig.3 Cluster analysis of economic progress based on expectations of transformation and growth.

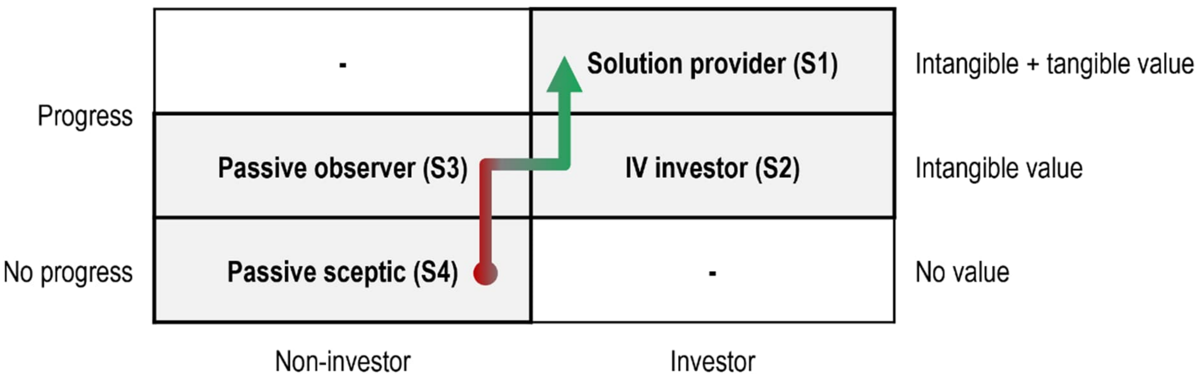

Fig.4 Transformation strategies observed for CCU.