frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 24 September 2024
DOI 10.3389/fenrg.2024.1424865

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OPEN ACCESS

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RECEIVED 28 April 2024
ACCEPTED 10 September 2024
PUBLISHED 24 September 2024

CITATION
Fürst K and Strunge T (2024) Perception of carbon capture and utilization - a framing analysis of German-speaking media.
Front. Energy Res. 12:1424865.
doi: 10.3389/fenrg.2024.1424865

Perception of carbon capture and utilization - a framing analysis of German-speaking media

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Carbon dioxide capture and utilization (CCU) technologies are one building block in Germany's industrial decarbonization strategy. With CCU technologies, carbon dioxide emissions are captured from an industrial point source or the ambient air (direct air capture, DAC) and either used directly as an industrial feedstock or transformed and used as a carbon resource in industry. Despite the potential benefits of CCU in decreasing industrial dependency on fossil fuels and decreasing global CO_2 emissions, robust empirical evidence of the general public opinion and societal acceptance of carbon capture and utilization technologies is lacking. Here, we studied the German-speaking media discourse as a proxy for the public discussion of carbon capture and utilization (CCU) technologies. We show that CCU technologies are overall framed more positively than negatively. Responsible for the optimistic framing are the two dominant media frames: "climate protection-frame" and "benefit-frame," which are mainly used by scientists and policy actors or representatives from the industry sector respectively.

KEYWORDS

CCU, carbon capture and utilization, media analysis, framing, Entman

1 Introduction

In May 2024, the German Ministry for Economic Affairs and Climate Action (BMWK) presented an updated version of the key elements of the German Carbon Management Strategy (CMS) as well as a draft legislative change of the German CCS-law (KSpG) (Bundesministerium für Wirtschaft und Klimaschutz, 2024). The legal amendments shall allow CO_2 capture and transportation to storage facilities as well as utilization sites in the future. We view this as a paradigm shift of the public discourse in Germany. Prior to the development of the CMS, the German government declared its goal to reach CO_2 neutrality by 2045, five years earlier than the European Union's CO_2 neutrality pledge. Yet, the German industry sector is falling short of meeting its decarbonization goals (Bundesministerium für Wirtschaft und Klimaschutz, 2021). One difficulty is that in the so-called hard-to-abate industries, like cement, CO_2 neutrality cannot be reached by means of shifting to renewable energy sources or energy efficiency measures alone as a large share of CO_2 emissions in the cement industry stems from the calcination of limestone (Andrew, 2018; Strunge et al., 2024). Another difficulty lies in other sectors such as the chemical industry which is dependent on carbon-based feedstocks for the production of chemical building blocks or polymers, which are currently sourced mostly from fossil resources like crude oil or natural gas (Kähler et al., 2022; Bachmann et al., 2023). These carbon-based products are used in almost any secondary industry (e.g., food industry, textile industry, pharmaceutical industry). For both hard-to-abate sectors as well as sectors in need of carbon-based feedstock, CO_2 utilization (CCU) technologies can become a vital part for reaching CO_2 neutrality. Through CCU processes, CO_2 is captured and used as a feedstock to produce a product (e.g., low-emission concrete, methanol, formic acid or polymers). Depending on the CCU product and its end-of-life the CO_2 is temporarily or permanently stored (Artz et al., 2018).

Successful implementation of novel technologies requires not only financial and technical feasibility but also societal acceptance (Storrs et al., 2023). Since 2012, several CCS projects in Germany have stalled due to societal opposition. Public protests led to the passing of a national CCS-law, which limited the implementation of CCS-projects to research purposes only and set a deadline to apply for new CCS-projects until 2016, ultimately shutting down all CCS-projects in Germany (Otto et al., 2022; Weber, 2022). This stands in contrast to other European countries, such as Norway or Denmark, which show successful carbon capture and storage projects. With Northern Lights, Norway has recently opened the largest commercial CO_2 transportation and storage site in Europe. This project is supported by the public narrative that CCS is a promising new business field in the face of decreasing fossil fuel demand, while simultaneously allowing Norway to present itself as a frontrunner in climate protection in its foreign policy (Roettereng, 2016).

A comprehensive literature review by Busse and Siebert (2018), in the context of land use policy concluded, that in social sciences several definitions and concepts of social or societal acceptance coexist. It is however important to define the scope of societal acceptance before incorporating the concept in public perception research and concluding policy recommendations from it. Wolf et al. (2023), who research public attitudes towards the German energy transition in a comprehensive public survey, differentiate between socio-political acceptance and local acceptance, they define the two concepts as follows: "The socio-political acceptance indicator measures, among other things, the degree of approval of political goals and specific measures at federal level. Attitudes towards local infrastructure measures among the local citizens affected are included in the local acceptance indicator. "In the context of traditional and non-traditional rural land uses, Williams (2011) wrote that "acceptance in this context describes the process or fact of something being perceived as adequate, valid, or suitable. The opposite of acceptance would be non-acceptance or rejection, whereby rejection linked to an action can lead to active resistance or responses." In the here presented framing analysis of CCU in German-speaking media, we use a similar understanding of acceptance as Wolf et al. and Williams define societal acceptance of CCU technologies as the extent to which a particular technology application or policy is endorsed by society. It involves collective acknowledgment and approval by the majority or significant segments of the population. As an indicator of societal acceptance, one can analyze the public opinion or societal attitudes towards novel (CCUS) technologies. In their analysis of "Risk-benefit perceptions and public acceptance of Carbon Capture and Utilization," Arning et al. (2020) concluded that perceived benefits positively influence public perception and acceptance of carbon capture and utilization, while perceived uncontrollability negatively impacts it. Storrs et al. (2023), showed that negative societal attitudes can lead to project delays or project abandonments. On the contrary, positive attitudes can have a positive impact on the timely implementation of novel technologies (Liu B. et al., 2022). Societal attitudes or public opinion research can encompass public surveys. For example, Linzenich et al. (2019) used an online survey to study laypeople's risk and benefit perception of CCU technologies and products vs. CCS technologies in Germany. In their paper, they argue that the affective (spontaneous) perception of CCU technologies and products impacts the societal acceptance of CCU products and infrastructure that is necessary for CO_2 utilization processes. They concluded that the affective evaluation of CCU was rated significantly more positive than CCS in Germany. However, conducting representative surveys or interviewing laypeople about novel technologies always bears the risk of carrying pseudo-opinions and thus generating unstable results or, if information treatments were provided, yielding biased results (Linzenich and Ziefle, 2021). In a representative study on the public perception of CCU and CCS in Germany, 90% of the respondents indicated that they were not generally proficient in novel technologies. In the case of CCU 50.4% responded that they were "not at all informed" about CCU, 35.9% were "a little informed," 7.1% "good informed" and only 1.7% replied to be "very good informed." In the case of CCS, the numbers are slightly different with 44.8% being "not at all informed," 28.9% "a little informed," 9.4% "good informed" and 2.1% "very good informed" (Wolf et al., 2023). We can interpret these results that while little knowledge on either technology exists in broad society, accessible information of CCU is even scarcer than for CCS. We previously showed that CCU is still mainly discussed within a small circle of experts, scientists, policymakers or business actors working on industrial decarbonization technologies which complicates researching public or societal opinions of CCU technologies (Fürst, 2023). Simultaneously, with more carbon management strategies being announced around the world (e.g., the EU industrial carbon management strategy was published in February 2024, Germany and the Netherlands have announced their respective national carbon management strategies for the same year) we expect an increase of public interest in CCU as well as an increase in academic research on public perception of CCU. A more detailed understanding of the public perception of CCU technologies in German-speaking societies contributes to closing a critical research gap in predicting societal acceptance of CCU technologies, infrastructure, and products.

Due to the aforementioned limitations of public surveys on novel technologies, we approach the public perception of CCU technologies in German-speaking societies by conduction a framing analysis of German-speaking media articles. The media often serves as a primary source of information on technological advancements and can thus shape public opinion (Jiang et al., 2022; Buure et al., 2024). For the framing analysis we applied Entman's Framing concept who has described the effect of framing as a process where certain aspects of a novel technology and its impact on society are emphasized, while other aspects are left out or described less prominently. Hence, the text's subject is being "framed" in a certain way, elevating a technology's benefits to society over its negative impacts for instance. This influences how the content is perceived by the readers (Entman, 1993). Entman developed a concept through which media frames can be isolated from text so that we can systematically analysis the representation of CCU in German-speaking media.

1.1 Introduction to CCU

Carbon dioxide capture and utilization technologies are a group of technologies which all use CO_2 as a feedstock in a reaction. These technologies can take different forms, but commonly consist of three steps: (1) CO_2 capture, (2) CO_2 transformation into a CCU product, (3) use phase of the product. One key distinction between various CCU technologies is the CO_2 source during their capture step, while some incorporate CO_2 capture from ambient air via direct air capture methods or biomass utilization others incorporate capture from industrial point sources (e.g., an existing cement plant). Furthermore, the various CCU technologies differ in the transformation process and the use phase of the product. For example, producing a synthetic fuel (e.g., methanol) from CO_2 requires a significant amount of energy (Milani et al., 2015), as here the combustion reaction from fuel to CO_2 needs to be reversed creating an endothermic reaction. Often this energy is provided via the use of hydrogen as well as elevated temperatures. As another example, in CO_2 mineralization processes CO_2 is reacted with earth-alkaline oxide (e.g., CaCO3) containing minerals to form carbonates (e.g., CaCO3), an exothermic reaction that theoretically could produce heat during the transformation process (Strunge et al., 2022a; Strunge et al., 2022b). These two examples exemplify the large differences CCU technologies can show in their transformation processes. Similarly, different applications can exhibit significant differences in their use-phase. While synthetic fuels in their use phase will be combusted after weeks or months (e.g., when being used in a car), releasing the CO_2 to the atmosphere, carbonates produced via CO_2 mineralization and used in the concrete industry will store CO_2 permanently, as decomposition temperatures of multiple hundreds of degrees Celsius will not be reached during or after the use phase of the concrete (Strunge et al., 2022b). These vast differences in CCU technologies complicate the estimation of the emission reduction potential of such technologies as each technology must be assessed using in-depth life cycle assessments for each technology (e.g., methanol production) and application (e.g., use in diesel cars, use in combined electricity, and heat plants) separately (Cremonese et al., 2022; Langhorst et al., 2022).

To assess the potential of CCU technologies therefore most scholars focused on estimating potential amounts of CO_2 that could be used in each sector (e.g., global potential utilization capacity of CO_2 in concrete blends), rather than potential contributions to countries emission reduction targets. Here, Global CO2 Initiative (2016) estimated that by 2030 up to 7.2 billion tonnes of CO_2 could be used with the biggest sectors being aggregates for concrete production (3.6 billion tonnes), synthetic fuels (2.1 billion tonnes) and concrete (1.4 billion tonnes). Compared to in 2021 estimated 34.9 billion tonnes of CO_2 emitted (Liu Z. et al., 2022). This would lead to a potential of 21% of global emissions that could potentially be used as feedstock CO_2 applications, among which only 5 billion tonnes (14% of global emissions) would actually lead to permanently stored emission. While these estimations don't show the emission reduction potential as the process emissions remain unknown, these studies show that CCU technologies could become an important strategy for emission reduction, but still a significant amount will have to come from other emission reduction strategies. While CCU processes can be used to divert industry from fossil resources (e.g., replacing use of crude oil in the polymer industry (Bachmann et al., 2023), arguably they could also lead to lock-in effects (e.g., a transition from combustion engines to electric vehicles could be prolonged when implementing large scale synthetic fuel production first).

2 Methods

2.1 Literature review

A literature review in this field revealed that for CCU no German-speaking media analysis was found. However, some media analyses on CCS exist. CCS and CCU share a few commonalities (e.g., in both CCU and CCS CO_2 is captured, transported and potentially temporarily stored). For example, Otto et al. (2022) studied the media perception of carbon capture and storage (CCS) in Germany between 1st of January 2000 and 31st of December 2020. The authors identified five main media frames in German speaking newspaper articles on CCS which are: (1) "Clean coal;" (2) "CCS as a climate-change-mitigation option;" (3) "CCS as prolonging fossil-fuel use;" (4) "CCS as a risky technology;" and (5) "CCS as not politically feasible in Germany.". The time comparison showed that while representatives from the energy industry supporting CCS projects disappeared in the media discourse after the discontinuation of planned projects in 2012. In turn, scientists who advocated for the application of CCS technologies outside of fossil-fuel energy industries garnered media attention. Otto et al. concluded that due to the controversial presentation of CCS technology application in Germany, it would be doubtful that CCS technologies will receive public and political support (Otto et al., 2022). Previously, Pietzner et al. (2014) analyzed the media coverage of four (potential) CCS pilot-projects in Germany in North Frisia, Altmark, East Brandenburg and Ketzin. This analysis of regional newspaper articles from 2007 to 2011 showed that over time, the media discourse was dominated by civil society protest movements. In these case studies, both citizen initiatives and energy firms (Vattenfall, RWE) were identified as the central actors in the media discourse (Pietzner et al., 2014).

By breaking down media articles into separate frames, following a coherent analytical framework, this approach helps to make the underlying mechanisms of media framing visible and to derive expectations regarding how the public perception is shaped. The analytical concept of framing analysis is a popular tool in social science research (Benford and Snow, 2000; Scheufele and Tewksbury, 2007). Pivotal studies of qualitative framing analysis on German speaking media exist for the topic of carbon capture and storage (CCS) (Pietzner et al., 2014; Otto et al., 2022). However, a research gap exists in the media analysis of carbon capture and utilization (CCU), which this study aims to address. Through the systematic analysis of media frames, we can gain insights into how different aspects of CCU technologies are discussed, who is represented in the discourse and what frames are dominant. This paper contributes to closing the research gap of public perception research of CCU technologies in Germany by providing insights of an explorative framing analysis of German speaking print and online media. The main research question is "How are CCU technologies discussed in German speaking Print and Online media articles?" The analysis is further guided by the following questions:

- In what contexts are CO_2 utilization technologies mentioned?
- Which CCU technologies are in the foreground?
- What aspects of CCU technologies are viewed positively, negatively?
- Which actors are presented in the media?

These descriptive questions form the basis for the framing analyses with the sequential research question of how CCU technologies are framed in German-speaking media articles.

2.2 Framing approach

As a basis for the qualitative content analysis of the media articles, we applied the framing approach according to Entman (1993).

> *"Framing essentially involves selection and salience. To frame is to select some aspects of a perceived reality and make them more salient in a communicating text, in such a way as to promote a particular problem definition, causal interpretation, moral evaluation, and/or treatment recommendation for the item described."* Entman (1993).

A text consists of multiple frames that influence how the reader perceives the presented information. Framing starts with the selection of certain aspects of a story that are either included in a text or left out. Moreover, some aspects are placed more prominently in a text than others. Entman (1993) further explains that a frame consists of at least two of the following four elements, which we operationalized for our analysis as follows: 1) problem definition: What is the main topic of the text? 2) Causal interpretation: What is the context in which this topic is being represented? 3) Moral evaluation: Is the choice of adjectives and examples more positive or negative? 4) Treatment recommendation: Are policy recommendations provided, i.e., clear regulations necessary.

To organize the text analysis, we used these four frame elements as our main categories. We added three more main categories adapted from our research interest: (A) Is CCU the main theme of the article? (B) What is the geographical realm of the coded text? (C) Which actors/communicators are mentioned in the coded text?

For each pre-defined main category, we inductively developed one or more subcategories, using approximately 20 percent of the text material. Each subcategory was assigned a unique code. Lastly, we coded the total text material following unique coding rules. After this systematic coding process, we used statistics to analyze which categories of at least two different frame elements correlate. Finally, we qualitatively analyzed those text excerpts that showed a high correlation between at least two different frame elements.

2.3 Data collection

For the framing analysis, we first collected German-speaking online and print media articles that covered CCU, in the time period June 2020 - July 2022, by using the software ECHOBOT.

Through the software ECHOBOT we had access to a database with more than 13,000 online media and over one hundred German-language print media. For the collection of relevant media articles, we put together a list of search strings, deducted from our research interest, previous knowledge, which we continued to develop inductively in accordance with the first search results. For this purpose, building on the findings of the first period of investigation, we used the following terms and word combinations:

> "Kohlenstoffkreislauf", "Kohlenstoffabscheidung", "CCU", "CCUS", "CCS", "CO_2 + Nutzung", "CO_2 + Verwertung", "CO_2 + Recycling", "CO_2 + Verwendung", "CO_2 + Kreislauf", "Carbon Capture + Utilization", "Carbon Capture + Utilisation", "Kohlenstoff + Nutzung", "Kohlenstoffdioxid + Nutzung", "Kohlenstoff + Verwertung", "Kohlenstoffdioxid + Verwertung", "Kohlenstoff + Recycling," "Kohlenstoffdioxid + Recycling".

Next, we applied two qualitative selection criteria. First, is the media article thematically relevant? Media articles merely covering CO_2 capture and storage, CCS or DAC were excluded from the dataset. And second, were journalistic quality criteria applied? Press statements or opinion pieces, blog entries, job offers etc., were also excluded.

For the final data set on which we applied the qualitative framing analysis, we selected every other media article for every other month, starting with the first media article on CCU in June 2020, ending with the last media article about CCU in July 2022. The data set consists of free-access media articles only. Ultimately, we conducted a qualitative framing analysis on 125 media articles from different media outlets (distribution of articles by media outlet shown in Supplementary Table S7). 63% of the collected and analyzed media articles were published in so-called special interest media (Supplementary Figure S2). A special interest media we here define as media with a focus on a specific topic, e.g., on environmental or engineering topics. These media outlets serve a specific audience with fundamental knowledge on environmental or energy technologies. 37% of the total dataset were articles from the so-called general interest media, e.g., (regional) daily newspapers that cover a wide range of topics and that are read by a diverse audience with varying educational background and knowledge in the environment or energy technologies. Examples are the Augsburger Allgemeine (regional newspaper), Handelsblatt (national newspaper) but also online platforms like wetter.de The information that CCU is predominantly discussed in special interest media and only little in general-interest media, gives us a first idea that CCU is still a niche topic and not that present in the German public (media) discourse. These findings are in line with the results of the earlier cited representative survey by Wolf et al. (2023). The research methodology is depicted in Figure 1.

2.4 Data collection

We developed a category system based on our guiding questions and on Entman's four frame elements *Problem Definition*, *Causal Interpretation*, *Moral Evaluation* and *Treatment Recommendation* inductively from a subset of the text material. We then added subcategories, according to the text data. For the systematic analysis, we allocated a unique code to each (sub-)category. For

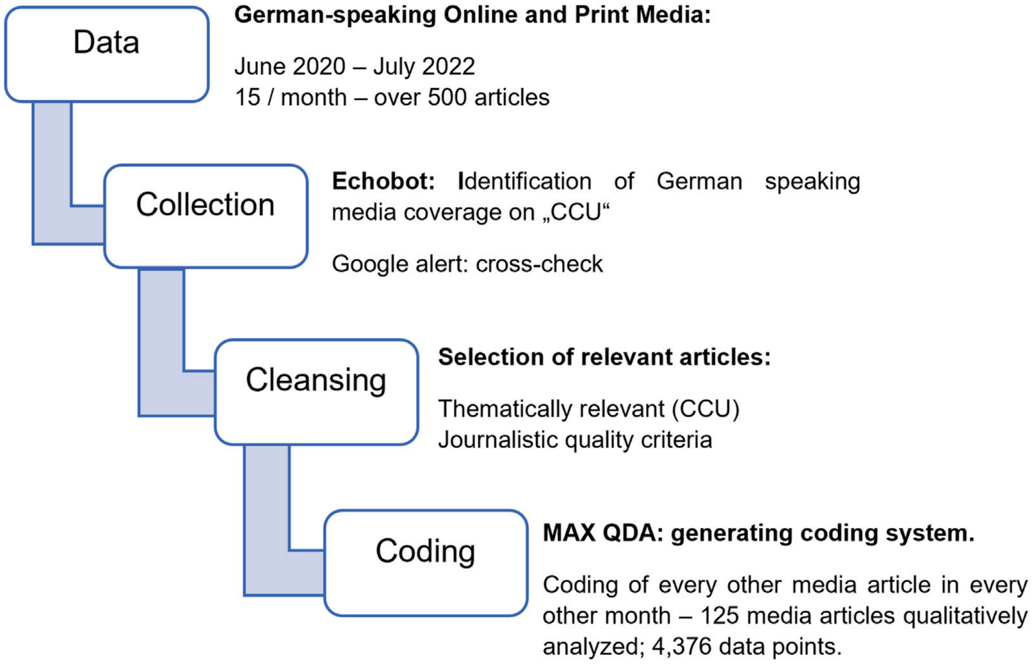

FIGURE 1
Research methodology: Data collection, defining and coding.

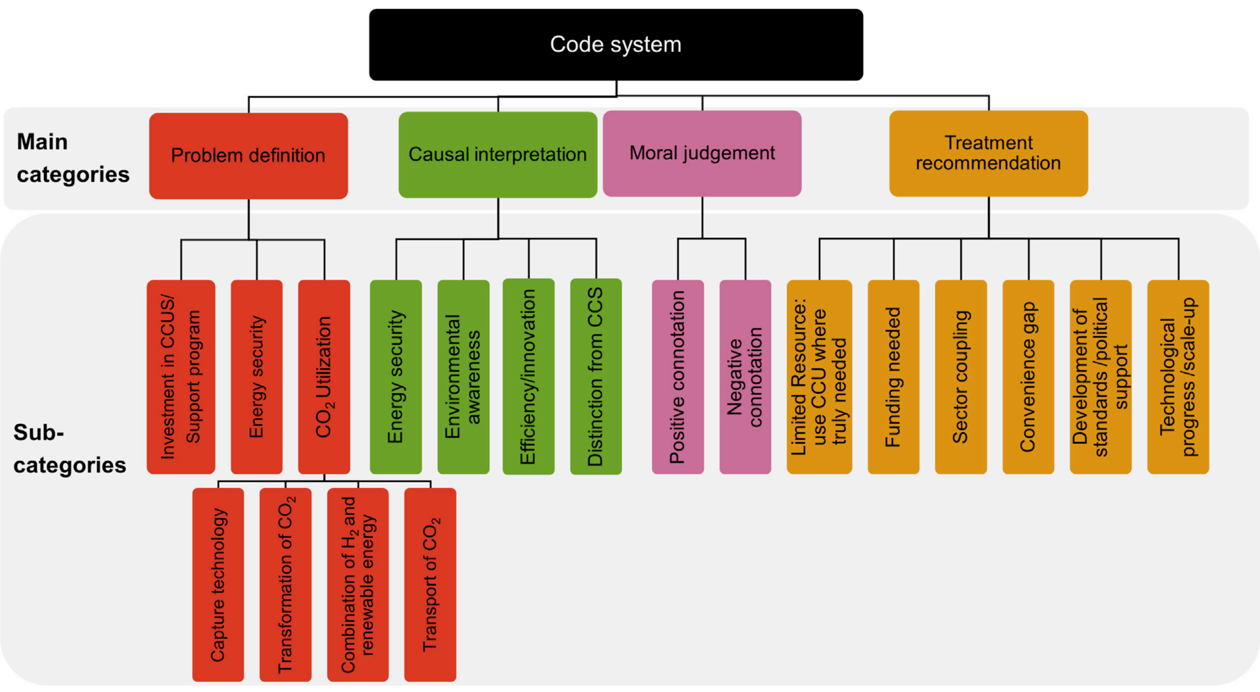

FIGURE 2
Snapshot of the final coding system in MAXQDA with the four frame-categories: 1. Problem definition; 2. Causal interpretation; 3. Moral Evaluation and 4. Treatment Recommendation, including subcategories. Note, some subcategories are further split into more detailed codes. All used codes are shown in Supplementary Figure S1.

each code, we wrote a memo, containing a unique coding rule with examples when to apply this code for a specific text excerpt. This allowed consistency and traceability of the coding process (Supplementary Table S1). Figure 2 displays the final code system.

In the context of the analyzed text, we interpreted the frame element *Problem Definition* as the main theme or context of a coded text passage (e.g., introduction of an innovative CO_2 transformation technology by a leading institution). We identified coded text passages that either discuss specific technologies (subcategory CO_2 utilization) or focused on investments/support for CCU or energy security (subcategories investment in CCU/support program and energy security). Similarly, for the frame *Causal Interpretation* we identified subcategories ranging from environmental awareness to solely distinguishing from CCS (e.g., using CCU when CCS is negatively connotated), which were all selected as subcategories (Figure 2). For the frame element *Moral Evaluation,* we found that most frequently used evaluations were either distinctly positive (e.g., hype for new technology or climate change mitigation) or negative (e.g., a technology might be too costly). Hence, we selected subcategories positive connotation and negative connotation which arguably can be seen as more of a sentiment analysis than true moral evaluation. For the frame element *Treatment Recommendation,* the most subcategories were found ranging from pointing out funding needs (e.g., for the development and deployment of CCU) to pointing out that CCU should only be used, when truly needed due to limited resources (subcategory Limited Resource: use CCU where truly needed).

We conducted the coding-process in two-steps. First, one researcher coded the full data material. A second coder re-coded the more sensitive, technological categories of CO_2 transformation processes. Through cross-checking of the full code-system and coded text material by a third researcher, the plausibility of the analysis was reassured. For the coherent coding process of our data, we used the coding software program MAXQDA. Once the coding process was concluded, we utilized the Code Relations Browser in MAXQDA to examine co-occurrences ($C_{i,j}$) of frame-categories. This measure determines how often two frame-categories or codes (i, j) were coded together in a text passage (k), which was calculated following Equation 1.

$$C_{i,j} = \sum_{k=1}^{n} I\left(A_{i,k} \cap B_{j,k}\right) \tag{1}$$

Here, $C_{i,j}$ is the cell value at row i and column j in the co-occurrence matrix, representing the frequency of co-occurrence of code i and code j. n represents the total number of text passages. $A_{i,k}$ is an indicator function that is 1 if code i is present in passage k, otherwise 0. $B_{j,k}$ is an indicator function that is 1 if code j is present in passage k, otherwise 0 and similarly I represents an indicator function that is 1 if both $A_{i,k}$ and $B_{j,k}$ are 1 (indicating co-occurrence), otherwise 0.

The resulting co-occurrence matrix is for the dataset shown in Supplementary Table S2. High co-occurrence numbers gave us an orientation of which subcategories might constitute a frame. Guided by these first results of automated statistical analysis, we continued with a manual qualitative analysis process. Through this two-step analytical process, we can answer our descriptive research questions of how CCU is framed in the German-speaking print- and online media and further reconstruct three dominant media frames.

3 Results

Answering the research questions formulated in Section 2.1, we present the following descriptive analysis: In general, the main contexts in which CCU technologies were presented in the analyzed articles were either technological innovation/economic products or climate change and industrial decarbonization. This might also be the reason for the more positive sentiments of the CCU media articles: CCU is often presented as an innovative technology that simultaneously fosters economic growth and contributes to reaching Germany's climate goals. The main communicators in the analyzed media articles are representatives from industry and science, followed by policy actors and only a few societal actors (e.g., representatives from NGOs or foundations). We can differentiate between coded text passages that either described different CO_2 sources (industrial point source, biogenic or atmospheric sources), the CO_2 transformation process (e.g., biochemical, electrocatalytic, thermocatalytic, photocatalytic, or mineralization) or the final use of CO_2 (e.g., for e-fuels or ammonia, base chemical, polymers, or final consumer products, like textiles).

We conducted a two-step analysis, initially performing a quantitative assessment of co-occurrences between two sub-categories (Supplementary Table S2). The primary focus of this paper, however, was the second step: a qualitative analysis of text passages with high co-occurrence values for frame reconstruction. This framing analysis revealed three dominant media frames: The "CCU consumer product-frame," the "climate protection-frame" and the "economy benefit-frame." All three dominant frames that we reconstructed from the total dataset contain the *moral evaluation* element "positive connotation." In the following sections (Sections 3.1–3.4) we discuss these dominant frames as well as the actor groups using these frames (i.e., scientists, industry actors, politicians or societal actors).

3.1 "CCU consumer product-frame"

We identified the first media frame that we reconstructed from the dataset as "CCU consumer product-frame." The central framing category (*problem definition*) is "CO_2 utilization_final product/use." This framing element showed a strong correlation with the subcategory "environmental awareness" from the framing element *causal interpretation*, and a "positive" *moral evaluation (correlation is here measured as co-occurrences of two subcategories/ codes).* A slightly weaker correlation also exists between final "product/use" and the *causal interpretation* category "efficiency/ innovation," which is also correlating with a "positive" *moral evaluation*. Figure 3 shows the code map for this frame. It displays an excerpt of the co-occurrence matrix (Supplementary Table S2) only using the subcategories which construct the "CCU consumer product-frame." Connecting lines and their thickness indicate how often these subcategories are used together (i.e., co-occur). In Figure 3, we highlight connections that make up the frame from the qualitative analysis of the coded text passages. This figure aims to provide a visual representation of the via qualitative analysis deducted frame. Note that not all relevant connections coincide with

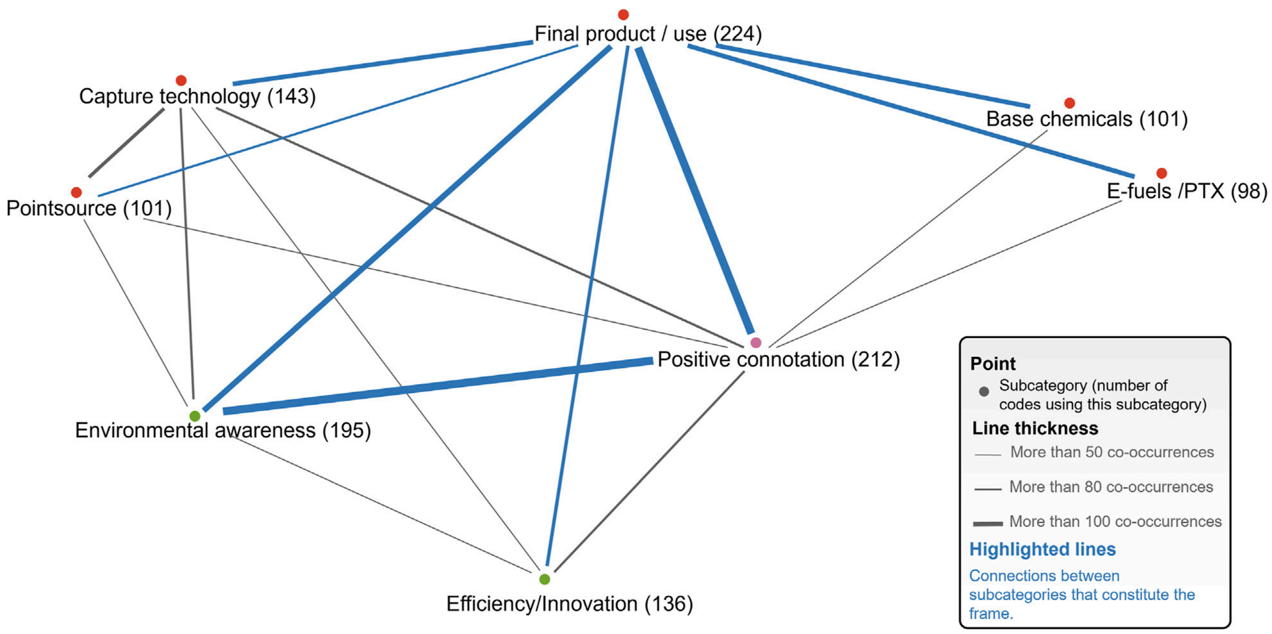

FIGURE 3
Code map of "CCU consumer product-frame." Category colors (red, green, pink dots) according to the code system developed in MAXQDA; with absolute numbers of codes within full dataset (N = 2,664, number of all codes used, shown in Supplementary Table S6). Line width represents the co-occurrences of the two connected subcategories in all coded text passages. Lines connecting subcategories that make up a frame (determined qualitatively) are highlighted in blue. Excerpt of the co-occurrence matrix showing all co-occurrences for the here displayed subcategories is shown in Supplementary Table S3. L.

the line thickness (i.e., quantitative numbers), as the framing analysis is a qualitative analysis.

In text paragraphs where the "CCU consumer product-frame" occurs, often an industrially produced (consumer) product, manufactured with the use of CCU technologies is presented. The majority of the analyzed media articles describe the technical process of CO_2 capture and its use by the chemical industry to produce carbonaceous base chemicals. Special interest media, like *PROCESS* ("*Expert knowledge for chemical engineering and pharmaceutical technology")* or *EUWID Recycling* address an audience with previous knowledge in chemistry or engineering, providing mechanical details on (innovative) CO_2 transformation processes. Described are mostly biochemical or biotechnical processes, followed by mineralization and electrochemical processes.

In the majority of text excerpts where the "CCU product-frame" occurs, the frame element "environmental awareness" provides the interpretational context (*causal interpretation*). Coded are remarks on (inter-)national climate goals, e.g., reducing global warming to 1.5°C or decarbonizing the industry. In other text examples, the context is set by the frame element "efficiency/innovation." Described are for instance novel CO_2 capture and purification technologies that allow for a less energy-intensive process. The overall *moral evaluation* of this frame is positive, emphasizing the "effectiveness" of CCU technologies and the "need for decarbonization". Put together, the "CCU consumer product-frame" presents CCU technologies as an effective solution to producing the much-needed industrial and commercial goods in consistence with reducing CO_2 emissions.

> "CO_2 *is not only a climate killer but can also serve as a raw material for chemicals. In the Celbicon project, researchers have succeeded in producing a dye from the greenhouse gas by means of electrochemical and biotechnological conversion.*" [Translated, original in German, from Goebelbecker (2020)].

In turn, general interest media, e.g., the German daily newspaper *Handelsblatt* or the weather information channel *wetter.de* emphasize final consumer products like textile products manufactured with carbon fibers or plastic containers for cleaning products that can be found in commercial drugstores. These general interest media articles speak to a broader audience and are the minority in the total dataset of German-speaking news articles covering CCU. One article published at wetter.de gives the example of socks for children that are produced with carbon fibers, sourced from CO_2. This example creates a strong image of a harmless technology that can offer an alternative way to produce our daily use products.

> "CO_2 *instead of crude oil as a raw material for elastic, synthetic fabrics - it already exists, for example in socks, yarns or medical textiles.*" [Translated, original in German, from Fuchs and Träger (2022)].

3.2 "Climate protection frame"

The second dominant media frame that we reconstructed is the above displayed "climate protection-frame" (code map for this

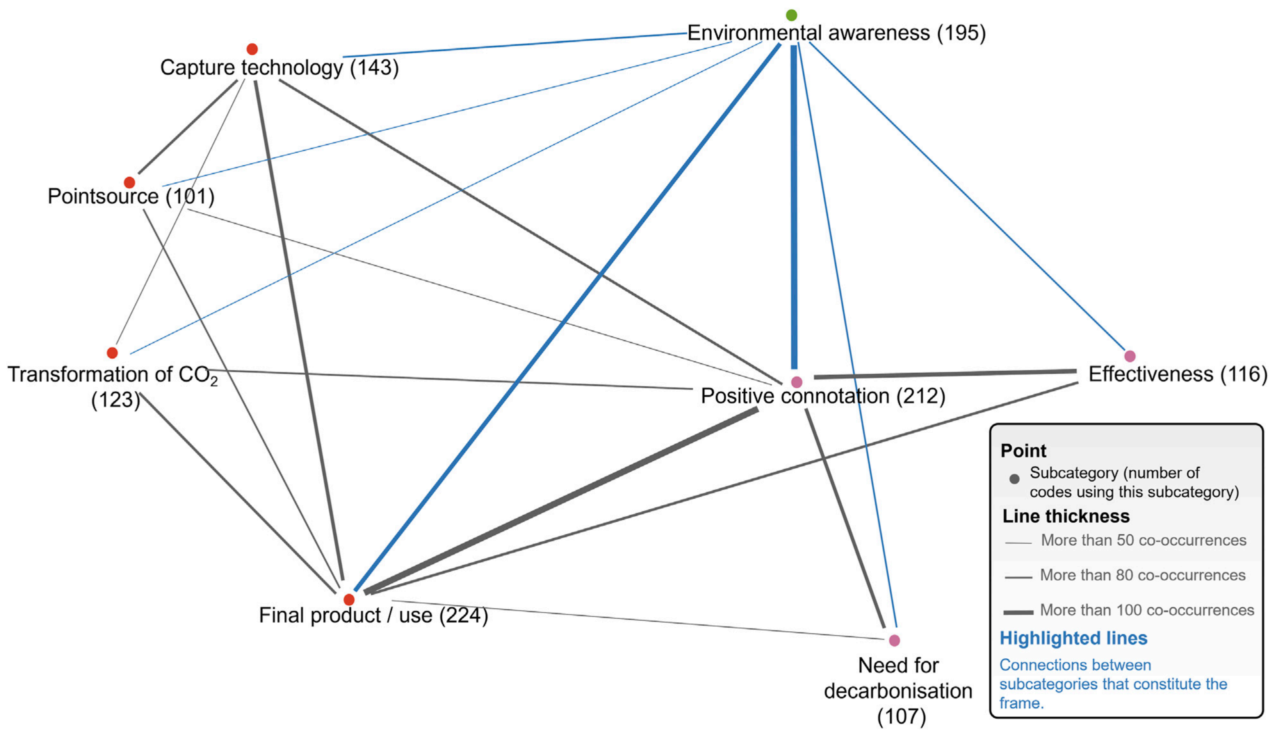

FIGURE 4
Code map of "Climate protection-frame." Category colors (red, green, pink dots) according to the code system developed in MAXQDA; with absolute numbers of coding within full dataset (N = 2,664, number of all codes used, shown in Supplementary Table S6). Line width represents the co-occurrences of the two connected subcategories in all coded text passages. Lines connecting subcategories that make up a frame (determined qualitatively) are highlighted in blue. Excerpt of the co-occurrence matrix showing all co-occurrences for the here displayed subcategories is shown in Supplementary Table S4.

frame is shown in Figure 4). While quantitatively the co-occurrence between the main frame elements ("environmental awareness," "final product/use" and "Need for decarbonization") remains the same as in the "CCU consumer product-frame," the qualitative text analysis shows that the most prominent element here is the *causal interpretation* "Environmental awareness." Respective text passages lead with themes like the anthropogenic climate change, CO_2 emissions, the Paris Agreement or decarbonization goals. While the framing element *causal interpretation* "Environmental awareness" is central in these text paragraphs, CCU products or CO_2 capture, and transformation processes (*problem definition*) is more subordinately presented as means to mitigate CO_2 emissions and climate change. The frame category "Environmental awareness" co-occurs strongly with a "positive" *moral evaluation*. The two sub-categories "effective" and "need for decarbonization" specify the positive evaluation.

> *"One cannot get rid of* CO_2 *emissions in the cement production, however you could capture it and use it as a raw material to make other important products."* [Translated, original in German, from Koisser (2022)].

In contrast to the first media frame "CCU consumer product-frame," the driving element of the "climate protection-frame" is the association of CCU as CO_2 mitigating technologies. Media articles often portray CCU technologies as an effective approach for those industries that cannot easily be decarbonized by other means (e.g., electrification or energy efficiency measures). Against this background, CCU technologies are introduced as an indispensable means to decarbonize the (German) industry. In contrast, limitations of CCU-technologies, e.g., its high-energy consumption and today's limited capacity are rarely mentioned in the coded text passages.

3.3 "Economy benefit frame"

The "economy benefit-frame" is similar to the "climate protection-frame" and they often appear together in one text paragraph (code map for this frame is shown in Figure 5). The main difference in the frame composition lays in the *causal interpretation,* the context in which the usage of CCU technologies is explained. In the "economy benefit-frame," this context is "efficiency gains" or "innovative processes" rather than "Environmental awareness." The "efficiency/innovation" frame element is pivotal to this frame. Also central to this frame are the main topics (*problem definition*) "final product_use" and "Transformation of CO_2." Moreover, the *causal interpretation* "efficiency/innovation" co-occurs with the "positive" *moral evaluation* and thus constitutes another optimistic media frame. However, this last co-occurence is weaker in the "economy benefit-frame" than in the "CCU consumer product-frame" or the "climate protection- frame." We might conclude that while all three dominant media frames inherit a positive evaluation element, the "CCU consumer-product-frame" and the "climate protection-

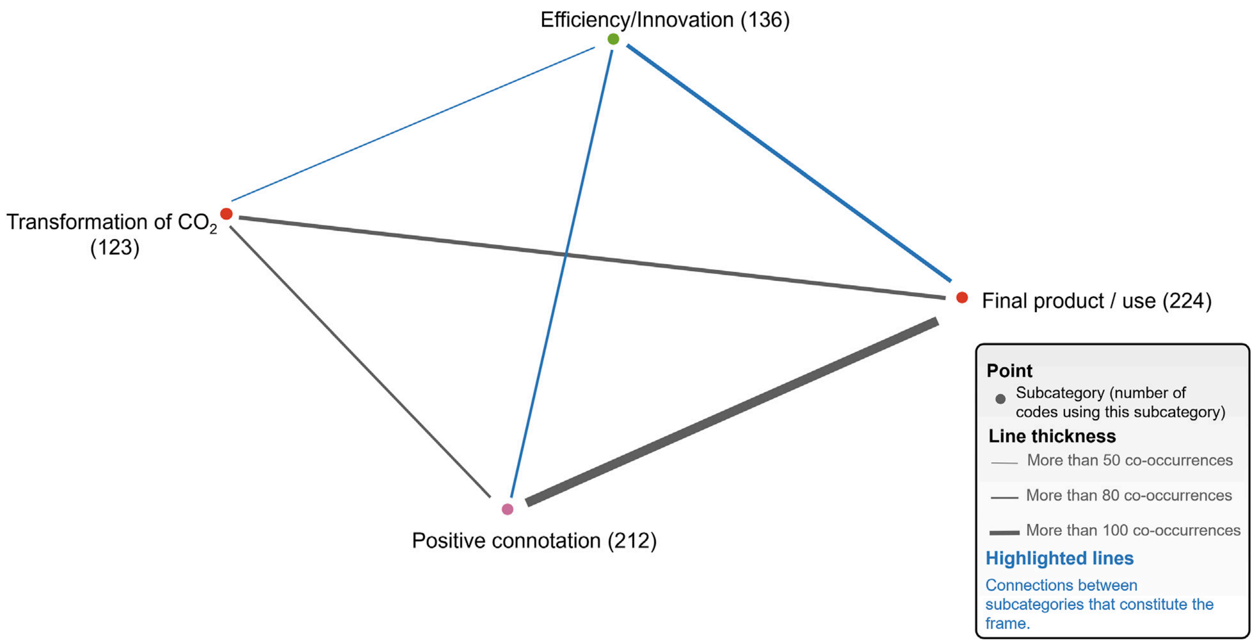

FIGURE 5
Code map of "Economy benefit-frame." Category colors (red, green, pink dots) according to the code system developed in MAXQDA; with absolute numbers of coding within full dataset (N = 2,664, number of all codes used, shown in Supplementary Table S6). Line width represents the co-occurrences of the two connected subcategories in all coded text passages. Lines connecting subcategories that make up a frame (determined qualitatively) are highlighted in blue. Excerpt of the co-occurrence matrix showing all co-occurrences for the here displayed subcategories is shown in Supplementary Table S5.

frame" have a stronger mobilization effect than the "economy benefit-frame."

> "CO_2 *technologies enable the usage of the harmful carbon dioxide as a valuable raw material for sustainable plastics. The process uses chemical catalysts to enable* CO_2 *molecules to react with a conventional raw material. In this way so-called polymers are created in a more sustainable and economically viable way. The* CO_2 *is firmly incorporated in the process."* [Translated, original in German, from PLAS.TV (2021)].

3.4 Communicator/actor groups: relative distribution and usage of frames

In general, societal actors (e.g., representatives of interest groups or NGOs) were least represented in the German-speaking media discussion on CCU technologies. However, in the 44 coded text passages where societal actors appeared, most often the "climate protection-frame" was used, followed by "CCU consumer product-frame" and only on few occasions the "economy benefit-frame" was used.

To approximate how often a frame was used by a certain communicator group we looked at the co-occurrence of communicator code and the code that most independently characterizes the frame (i.e., a code was used in one frame more often than in others). For the "CCU consumer product-frame" this was *final product/use* (Supplementary Table S3), for the "climate protection-frame" this was *environmental awareness* (Supplementary Table S4), for the "economy benefit frame" this was *efficiency/innovation* (Supplementary Table S5). Most often represented as communicators were scientists from universities or other research institutes. In a total of 203 coded text passages, the "CCU consumer product-frame" can be interpreted the most often used frame (117 co-occurrences with *final product/use,* Supplementary Table S2); followed closely by the "climate protection-frame" (112 co-occurrences with *environmental awareness,* Supplementary Table S2) and 62 co-occurrences exist with the frame element *efficiency/innovation*, hinting to the Economy benefit frame.

Business actors (from either established business companies or start-ups) mark the second most dominant group of communicators (164 codings in total, Supplementary Table S2). Similarly, in most text passages which were coded with the *communicator category* "business actors," the media frame "CCU consumer product-frame" can be seen as most often used (101 co-occurrences with *final product/use,* Supplementary Table S2). The second most often used frame in this communicators group is the "economy benefit-frame". With 76 co-occurrences with *final product/use* (Supplementary Table S2) this approximate correlation is higher than the approximate correlation between "economy benefit-frame" and "scientists". On the contrary, with 65 co-occurrences between the frame elements *business actors* and the *environmental awareness* (Supplementary Table S2), hinting to the "climate protection-frame," this correspondence is much lower than the use of the "climate protection-frame" by scientists.

Lastly, policy actors are in general less represented than scientists or business actors in the media discourse on CCU. Moreover, they often appear not alone but in combination with one of the other actor groups. We found 85 "policy actor" codings in total, with the highest co-occurrence (=use of) the "climate protection-frame" (45 co-occurrences with *environmental awareness,* Supplementary Table S2), followed by "CCU consumer product-frame" (42 co-occurrences with *final product/use,* Supplementary Table S2) and lastly the "economy benefit-frame" (30 co-occurrences with *efficiency/innovation,* Supplementary Table S2).

We can summaries that in general actors from the policy realm or society are less present in the German-speaking media discourse on CCU technologies, in comparison to representatives from science or industry. Moreover, policy or societal actors both use the "climate protection-frame" most often. On the contrary, the most often used frame by scientists and business actors is the "CCU consumer product-frame," followed by the "climate protection-frame" for scientists and "economy benefit-frame" for business actors respectively.

4 Discussion

We discovered that two dominant media frames "climate protection-frame" and "CCU consumer product-frame" inherit a strong correlation with the frame category "positive" in *moral evaluation*. This indicates that the overall optimistic medica coverage of CCU technologies in the German speaking media results largely from a framing that CCU technologies are an effective tool to a) reduce CO_2 emissions and thus protect our climate and b) produce industrial or commercial products using a renewable carbon-source and thus decreasing fossil carbon use.

The third dominant media frame that we reconstructed, the "economy benefit frame," also strongly co-occurs with the frame category "positive" in *moral evaluation.* This positive framing may be explained in contrast to CCS technologies, where CO_2 is captured and permanently stored underground. CCU technologies in contrast re-define CO_2 as a valuable resource. By applying this technology not only large amounts of money and energy is invested to fulfill a global goal – reducing CO_2 emissions – but the German industry is also directly benefiting from tapping into a new carbon-resource. Generally speaking, all three dominant media frames embody a benefit frame. With CCU technologies we can protect our climate, continue producing essential industrial and commercial goods and simultaneously foster the German economy. We could indicate from this, that the optimistic framing of CCU technologies in the German-speaking print and online media have a positive impact on its general acceptance. (Linzenich et al., 2019; Olfe-Kraeutlein, 2021; Olfe-Kraeutlein and Krämer, 2022).

Another finding from our media analysis is that scientists and business actors dominate the German-speaking media discourse on CCU technologies. Representatives from policy or society are significantly less present in the analyzed media articles. Meanwhile, the most commonly used media frame is the "CCU consumer product-frame," which is used predominantly by scientists and business actors. The "climate protection-frame" is the second dominant media frame, used especially by scientists and – in comparison to the overall low representation – it is the most often used frame by representatives from the policy realm and society. As for representatives from the business sector, the second most often used frame is the "economy benefit-frame," trumping the "climate protection-frame". In the context of CCU benefits versus limitations it is especially interesting to see that the main actor group utilizing the CCU consumer product frame and the economy benefit frame, are business actors. Industry representatives have a commercial interest in emphasizing the beneficial effects of CCU, like consumers can buy new but climate-friendly products or technological progress in CCU adaptations will benefit the economy. In contrast, little is written about the (economic) limitations of CCU, that many CCU processes can be very energy intensive (often more so than CCS) and hereby costly (Hepburn et al., 2019). Policy actors in turn use the climate protection frame most often – the same frame that is used the least by business actors.

The overall optimistic framing of CCU stands partially in contrast to the actual potential of CCU to mitigate CO_2 emissions (CO_2 Sciences and The Global CO_2 Initiative, 2016). The predominantly positive framing of CCU technologies, caused by the dominant benefit frame, exceeds the potential of CCU as a decarbonization technology. While we will need more and more sustainable carbon sources, e.g., to produce fertilizers, base chemicals or synthetic energy-carriers, the amount of CO_2 that needs to be captured to reach CO_2-neutrality outweighs the amount of CO_2 needed for CCU processes. Moreover, to achieve a long-term climate effect, the captured CO_2 needs to be stored permanently or otherwise, at the end of a product's lifecycle, it will be released into the atmosphere. As a consequence, regulatory frameworks like the EU emission trading system, issues CO_2 certificates only for few CCU processes, where the CO_2 is bound permanently in a product. This is the case for carbonation processes (e.g., production of calcium carbonate or magnesium carbonate) (Strunge et al., 2022b). If however, CO_2 is used to produce synthetic fuels, a small climate effect exists as no additional fossil hydrocarbon is mined to produce synfuel but the CO_2 used for the synfuel is still released into the atmosphere when it is burned. Therefore, to make a production process or product CO_2-neutral, at the end of a product's life cycle, the CO_2 has to be captured again and finally stored permanently. Thus, to reach climate neutrality, we will need both CCU and CCS, each in the amount and fields of application where necessary and most effective. It does not serve the purpose of industrial decarbonisation to distort the potential of CCU by disproportionally highlighting the (economic) benefits of CCU in order to gain societal acceptance and circumvent public opposition for CCU alone. Moreover, if CCU framing benefits from a distinction to CCS, it will make it more difficult to revitalize public discussions on the benefits and limitations of CCS as a decarbonization technology. Although it seems like a good marketing strategy for CCU, it does not benefit the overall goal of industrial decarbonization and climate protection, when CCU is being represented as the "better" technology than CCS. Instead, both technologies will have to play a crucial role in decarbonizing certain industrial processes and should thus be discussed in the public (media) discourse, both with its benefits and limitations.

It will be interesting to see how the media discourse changes, if more policy and societal actors become involved in public discussions. With the announcement of the development of a German carbon management strategy we anticipate that the landscape of communicators will become more heterogenic and business actors inherit relatively less framing power. This could lead to a more balanced media framing of CCU, meaning that the overall positive framing might decrease and a broader discussion on the potential, limitations and role of CCU as a decarbonization strategy emerges.

5 Methodological reflection

This explorative framing analysis provides valuable insights on the question of how CCU technologies are represented (framed) in the German-speaking print- and online media. While we used a two-step analysis where we first quantitatively analyzed co-occurrences between two sub-categories, the main analysis of this paper is the second part, where we qualitatively analyzed those text passages with relatively high values of co-occurring subcategories for the frame reconstruction. Figures 3–5 were included in the results section to guide the reader to understand co-occurrences between different subcategories. However, they are not intended to show statistically significant results. Supplementary Table S2 shows the co-occurrence matrix, with co-occurrence values, on which the figures are based.

The study also comes with its limitations. First, as we have already discussed in the introduction of this paper, the correlation between the media discourse versus the public discourse and societal understanding or acceptance is complex. To understand how media frames affect the public opinion, a follow-up communication study is necessary that researches the impact of the discovered media frames on its audience.

Another limitation of our media analysis is that we could not include media articles behind a paywall. This might has reinforced the imbalance of the largely overrepresented special interest media articles versus general interest media articles in the dataset. However, one could argue that media articles behind a paywall also reach only a pre-selected audience and thus do not resemble the full public/societal discourse.

Following our analysis and discussion of its limitations, further research could cover the developments in the framing of CCU technologies over time. As an external factor, the national carbon management strategy is currently being developed. It would be interesting to see if CCU technologies, which are currently mainly discussed among CCU experts becomes a more publicly debated topic and if yes, how the discourse would change. We would expect the relevancy in the German-speaking news media to increase. As a result of a wider, more informed audience, we could also expect more actors getting involved. This in turn, could change the framing. Moreover, follow-up studies could analyze other news media formats. For the analysis of television, audio or social media on CCU technologies, the developed code system could be used/adopted. Lastly, one could conduct an experiment and analyze how the individual reconstructed media frames affect a German-speaking audience in different ways. The research could also provide empirical data on which role the communicator's function (i.e., business actor, policy actor, scientist, societal actor) play in the media frames impact on its readers.

6 Conclusion

CCU technologies are overall framed more positively than negatively. This is due to the dominant media frames "CCU consumer product-frame," "Climate protection-frame" and "Economy benefit-frame" which share the dominant frame element positive moral evaluation". This positive framing in part outbalances the true potential of CCU technologies as a CO_2 mitigation technology.

CCU technologies are mainly discussed in special interest media, reaffirming previous findings that CCU is still a niche topic and the general public inadequately informed about the potential of this technology. Moreover, the main communicators in the current media discourse on CCU technologies are representatives from science or industry. Societal actors (e.g., representatives of NGOs) mark the least represented actor group in the discourse.

Against the background of current political developments, the German federal ministry for economic affairs and climate action is currently developing a national carbon management strategy, putting the topic CCU back on the political agenda, the composition of actors involved in the media discourse and the topics of CCU that are being publicly debated might change. Consequently, the framing could become more heterogeneous.

7 Policy recommendations

With little coverage of CCU, citizens are less able to inform themselves from diversified sources and independently form their own opinion, thus they are more likely to be persuaded by distorted framing. Consequently, the public attitude towards CCU remains volatile. Continuous support by the public is however necessary to successfully build and operate such long-term infrastructure projects as CCU.

The foremost action public institutions should take is to provide accessible information on CCU technologies. Accessible meaning free in cost as well as easy to consume and understand. Journalists as multiplicators should be trained in covering the novel technology. Moreover, education on CCU and CCS as decarbonization technologies could be included in the formal education system, including capacity building workshops for policy and societal actors. Also, industry representatives should be more transparent about the actual costs and limitations of CCU technologoies, as they too need long-term political and societal support. They could more actively invite citizens to their CCU and CCS sites and proactively provide transparent information not just on the benefits of CCU but also on its limitations, like costs, energy consumptions and short durability of CO_2 storage in a product. Lastly, engineers and political scientists should invest more in interdisciplinary research and science communication. Public research and innovation funding programs could be conditioned to include this.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

KF: Conceptualization, Writing–original draft, Writing–review and editing, Formal Analysis. TS: Conceptualization, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. Kristina Fürst has been funded by the project "CO_2WIN," which was funded by the German Federal Ministry of Education and Research (BMBF), Berlin, Germany (033RC016B). Till Strunge has been funded by the project "Seq-kalz," which was funded by the German Federal Ministry of Education and Research (BMBF), Berlin, Germany (03VP11410).

Acknowledgments

We dearly thank Dr. Sonja Thielges for supporting the analysis and all partners of the "CO_2WIN" project. We acknowledge support by the Open Access Publication Fund of TU Berlin.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2024.1424865/full#supplementary-material

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