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Original research article

Sustainable design of multiscale CO2 electrolysis: A value sensitive design-based approach

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ABSTRACT

The present study utilizes a value sensitive design (VSD) inspired approach to contribute to the design and implementation of CO_2 electrolysis (CO_2E) within the framework of carbon capture and utilization (CCU) technologies, which convert CO_2 into valuable products. The focus of this study is on a low technology readiness level (TRL) technology, yet likely relevant to reach climate neutrality by 2050. We examine the perspectives of stakeholders along the supply chain and proactively identify relevant sustainability-related values and potential conflicts among them. Thus the current work highlights the importance of considering a broad range of stakeholders and their values in the early stages of technological design. The research approach is consisting of various steps inspired by value sensitive design (VSD): identifying relevant values and norms associated with CO2 electrolysis through literature analysis, conducting qualitative interviews with relevant stakeholders to triangulate the results. Subsequently, a value-based alignment network analysis was employed to examine shared values that are central for the design of the technology. The findings indicate that sustainability-related values such as concern for nature, climate change mitigation, the use of renewable energy, critical raw materials, cost, and return on investment, albeit with potential differences in interpretation, are increasingly becoming central considerations in the decision-making processes of individuals, businesses, and governments alike. Based on these findings, specific aspects of technology design, namely scale, location, integration, and synthesized product, that can impact a wide range of identified values, are discussed.

1. Introduction

Anthropogenic greenhouse gas emissions (GHG), resulting mostly from the combustion of fossil fuels, have led to an increase in the concentration of carbon dioxide (CO_2) emissions in the atmosphere and had a warming effect on the climate. The impacts of climate change are now evident worldwide with extended droughts, severe floods, frequent wildfires, and extreme heatwaves, among others. These pose significant threats to humanity, ecosystems, and biodiversity [1]. Various technological options flagged as “green technologies”, promise the mitigation of the impact of economic growth on the environment [2,3] and the achievement of the sustainability goals [2–4]. These technological innovations propose alternative raw materials (vs fossil fuels), better efficiencies, and potentially circular processes, and are considered essential in the fight against climate change. In fact, the majority of the Intergovernmental Panel on Climate Change (IPCC)'s 2 °C scenarios rely on such technological advancements [5]. The list of green technologies is long and includes already commercialized technologies like solar panels, electric vehicles, and batteries, or others that are still in low technology readiness level (TRL) like biomaterials, or carbon capture and utilization (CCU) through CO_2 electrolysis (CO_2E) [6].

Carbon capture and utilization (CCU) technologies use captured CO_2 (from point sources or air) and through thermochemical, electrochemical, or biochemical routes produce building materials, fuels, or chemicals [7]. Carbon dioxide is a thermodynamically stable molecule, which means that significant amounts of energy are needed to promote its reaction. The energy needed for its conversion should come from renewable energy sources to attempt lower CO_2 emission processes than current fossil fuel-based ones. Other environmental and technical barriers include the availability and performance of catalyzers [8,9] and

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high capital and operational costs due to CO_2 feedstock cost (at different purities), catalyzers' costs, energy consumption, and product separation [10]. CO_2-based products can be classified into four categories: (a) direct use in foods and beverages, fire extinguishers, greenhouses, and in the pharmaceutical industry, (b) mineral carbonation and construction materials, (c) fuels production, and (d) chemicals production [11,12]. Each of these products has a different lifetime and only mineral carbonation can be a carbon dioxide removal option (CDR) [13].

Despite the potential to contribute to climate change mitigation and other challenges of current society, as Asveld & Stemerding [14] point out: "*New technologies that emerge under the banner of sustainability bring about new uncertainties.*" Sustainability, commonly defined as "a social development which meets the needs of the present without compromising the ability of future generations to meet their own needs" [15] is a complex issue. Although most will agree that sustainability is desired, there is often a misalignment around technological innovation and practices that can be considered sustainable [16–18]. For example, issues around environmental, social, and economic risks open discussions regarding the need for regulation to avoid potential harm [18]. Thus, engaging a diverse group of stakeholders early in the new technology development process to grasp their values can lead to increased technology acceptance and an appealing product [19–21].

In the present paper, we use value sensitive design (VSD) and a value-based alignment network [22–25] for the case study of CO_2E. The aim of the current work is (i) to discuss the relevant values of multiple stakeholders, (ii) to discuss value alignment, and (iii) to support and guide the design of this technology from an early stage. Particularly in the context of this work, our results provide input to the current modelling effort, at plant and supply chain levels, in the framework of the Dutch-funded projects ""Addressing the multiscale challenge of CO_2 electrochemical reduction" and "Sustainable design of multiscale CO_2 electrochemical conversion".

2. Technology acceptance and moral values in technology adoption

The concept of "technology acceptance" is a descriptive notion with an attitude component that can range from "positive" to "neutral" to "negative", and a behavioral component that can vary between "adoption" to "tolerance" and "resistance" or "rejection" [26]. The debates around technological acceptance are not new in academic and policy-making circles. For instance, the use of information technologies [27], nuclear plants [28], in vitro fertilization [29] and food biotechnology [30] have been widely discussed. The most extended and recent field in the acceptance of technologies concerns renewable energy (RE) installations. This can serve as a valuable reference point, offering insights into the progress and challenges in the broader green technology field and for newer technologies (that rely on RE) that are still under development.

Lack of knowledge transfer and coordination, or institutional lock-ins, are often used as reasons for the failure of green technology innovations to breakthrough [31–34]. These two main arguments rather narrow the understanding of innovation failures to the implication of these specific obstacles, which could be overcome either through marketing methods (e.g., compensations), through adjustments (e.g., different locations), or through external actors that promote knowledge transfer and networking [35–37]. However, little attention has been paid to the conflicting values among different actors or stakeholders within the technology of concern, and the moral reasons that might lead to them.

The initial idea that people are driven by self-interest (the so-called not in my backyard "NIMBY"), or that they are often misinformed and driven solely by unjustified reasons, has been challenged by researchers, who found that opposition to energy projects is driven by more complex values like aesthetics, justness, fairness, and transparency, identity, and pride [31,38–42]. In practice, social acceptance often fails to include moral considerations, while ethical acceptability often follows a normative approach that does not include stakeholders' opinions [43]. Relevant to the case study of the current paper, opposition to RE installations is often a result of a lack of ethical considerations in the design phase that fail to consider the moral values of various stakeholders throughout the design (e.g., [34,44,45]). The present paper contributes to the literature of technology acceptance offering an approach to enhance social acceptance of CO_2E, with a focus on the values of the stakeholders already at an early stage of development of the technology of study.

2.1. Value sensitive design (VSD)

Value sensitive design is an approach that allows for ethical considerations to be studied and included in the early design phase of a technology. The idea of VSD stems from the notion that technological artifacts are not value neutral but are driven and motivated by certain values [46]. A value is often defined in the VSD literature as "*what a person or group of people consider important in life*" [47], p. 2), and the values that guide the design of an artifact today can have multiple future implications on the technology [48]. VSD does not engage only with the different values of various stakeholders, but also with how values can be interpreted differently by different actors [49]. In contrast with values, norms are specific rules, guidelines, or standards that dictate acceptable behavior within a particular context or society [50–52]. Norms are often derived from underlying values [52]. According to some, norms offer a more concrete and context-specific guidance for how individuals or groups should act than values, and thus are relevant descriptors for a VSD approach [53].

VSD was chosen as the foundational theoretical approach in the present study because (i) it can be applied at the early stages of the technology design, (ii) it brings together proactively various considerations of multiple stakeholders, and (iii) it uses terminology from both, the engineering and social science fields and thus, VSD can reinforce communication between engineers and VSD researchers [54]. In fact, through all the research stages of the current paper, there was a close collaboration between the social scientists and the engineers of the project team to support designers in thinking through multiple angles about their process and product design, and to support social scientists with relevant technical information.

VSD employs a tripartite design approach that consists of conceptual, empirical, and technical investigations [47]. The conceptual investigation often includes stakeholder mapping, identification of values (usually through literature review, content analysis, or experience), and how tensions among values can be resolved. Empirical investigation can deploy various exploratory tools like questionnaires, interviews, or scenario planning to validate the values distilled in the conceptual investigation and to solve value tension. The technical investigation attempts to translate the values into design requirements [55]. VSD however does not prescribe specific methods in each phase, giving this way to the scientist the flexibility to choose the most suitable method for the respective context [56].

VSD has been used widely in the literature of artificial intelligence (AI) and robotics (e.g, [38,57]), in the design of various apps [58], drones [59], and cryptocurrencies [60]. However, there is still limited application of the VSD on green technologies or alternative energy or industrial feedstock sources. One example is the work of Oosterlaken [19] on wind farms. The author argues that the use of VSD in the design of windmills and wind parks can help increase the social acceptance of wind energy. Although the author offers a well-developed theoretical approach, they did not test the hypothesis on a real case. Oosterlaken [61] used VSD to analyze the case of shale gas in the Netherlands through an empirical analysis of relevant documents. Despite the in-depth analysis, the authors did not include concrete technologies to exploit shale gas or design recommendations. This gap was filled later by Palmeros Palmeros Parada et al. [62–64] who used the VSD approach for the sustainable design of biorefineries in a complete approach with the use of conceptual, empirical, and technical investigations, leading to case-based design recommendations. Mouter et al. [65] explored the use of VSD in an existing case study, the Groningen gas field. Using available documents and interviews, the authors identified that relevant values were not included in the policy measures like for example, trust and honesty, highlighting the need to use VSD in early, pre-implementation stages. Innovative technologies like smart meters [66] and automated electric vehicles [67] have also been studied through conceptual and empirical VSD approaches.

2.2. Multiscale CO_2 electrolysis (CO_2E) and stakeholders' considerations

Carbon dioxide electrolysis is a CCU technology that uses electricity and heat to convert CO_2 into valuable products. It includes various reactor (cell) configurations, classified according to their type of electrolyte and working temperature [68]. The chemical process is known since 1870, but only recently it has sparked interest in its potential commercialization as the use of waste CO_2 can promote defossilization of industries, a circular economy, and sustainable supply chains [69,70]. The supply chain of CO_2E includes different stages, from the capture of CO_2 either through direct air capture (DAC) or industrial point sources like bioethanol or biomethane plants, iron and steel, cement plants [71] or refineries, to the transportation of CO_2 to the CO_2E plant, the conversion of it into valuable products, and the storage and transport of them to current industries that utilize fossil fuel-based fuels and chemicals (replacement) or to new potential markets [72].

Research applying VSD to green and/or alternative technologies like CCU is scarce. To the best of our knowledge, available research beyond technical considerations usually focuses on the acceptance of CCU, or most likely, of carbon capture and storage (CCS) or of carbon capture, utilization, and storage (CCUS). For example, the recent research of Nielsen et al. [18], used a systematic review to understand how local communities respond to the deployment of CCUS technologies and concluded that issues of transparency, uncertainty, and collaboration are crucial for the acceptance of CCUS. However, as it has been argued elsewhere, the analysis of CCU and CCS as one single concept (CCUS) can be problematic and says little about the specific risks and benefits of carbon utilization [73]. In other cases, the acceptance of CCU is examined through generic lenses without considering a specific utilization method or a specific product [74,75] making it challenging to assess the feasibility, environmental impact, and economic viability of the method and the product(s). A few exceptions focus on specific products, but not on a concrete CO_2 utilization technology, is the work of [76–79]. More concretely, Van Heek et al. (2017) [76] focused on carbon utilization for plastic products. Their research concluded that plastic disposal conditions, saving resources, and health risks were key factors for the acceptance of the product. The results were in line with the research of Arning et al. [77] on building materials, who found that the general impression regarding CCU insulation boards was favorable, as they were recognized for their environmental advantages; however, some slight reservations arose regarding the long-term sustainability and health issues. The authors examined CCU acceptance with a limited set of psychological factors (cognitive and affective risks and benefit perceptions) and concluded that individuals' emotional perceptions of both its risks and benefits particularly concerned environmental and health-related issues.

The current paper proposes the utilization of the VSD approach as the basis to identify the considerations of stakeholders regarding CO_2E implementation and to support and influence the conceptual design of the technology within the framework of the abovementioned projects. This analysis is an initial effort to include issues of distributional, participatory, and intergenerational justice which are often overlooked in the socio-economic analyses [43]. The complementary use of a value alignment network analysis provides a nuanced exploration of the CO2E field, encompassing not only the technological dimensions but also the broader socio-economic, environmental, and ethical factors at play. Through the use of the value alignment network, we can identify values that are central to multiple actors. These pivotal values, if altered, have the potential to influence numerous other values. Drawing on this understanding, we propose preliminary design recommendations.

This method aids in uncovering the intricate network of values and innovation dynamics that shape the trajectory of CO_2 electrolysis, shedding light on the field's challenges and opportunities. The technical project carried out by the engineering team was at the moment of the development of this publication in the early stages of research. On the one hand, there were many uncertainties regarding the potential supply chains and the specific involvement of different stakeholders because a concrete and commercial CO_2ER supply chain does not exist yet. On the other hand, it offered a unique opportunity for VSD researchers and engineers to work hand in hand from the early design phase.

3. Methodology

Due to the nature and purpose of CO_2E, sustainability was chosen as an overarching value of other values following the scheme proposed by [80]. This approach was used to facilitate and organize the discussion on norms and values used in the VSD approach [81]. Based on that, the identified norms were divided into social, economic, environmental, and technological categories. The technological dimension is not commonly used in the sustainability framework. It was first introduced by Iskog [82] to refer to a good quality service during the lifespan of the investment, and it has been amplified by other authors to include aspects like reliability, efficiency, and stability [40].

In the present work, we followed a bottom-up approach complemented with a top-down approach in the identification of norms and values. More concretely, the norms deducted from the relevant literature were used to identify the relevant values which then were used to guide the semi-structured interviews which enriched the norms and led to the design requirements.

The methodological approach we followed was inspired by the tripartite VSD approach, but it does not strictly adhere to each step of the original VSD approach (conceptual, empirical, technical). We acknowledge that the VSD approach is iterative and integrative, as described by Friedman et al. (2006a), and are designed to interact with each other rather than being conducted as independent, standalone, and predefined tasks [83]. The methodology used in the current paper consists of three main steps: First, a literature review to identify the relevant norms (i.e. effective use of rare earth metals) and values (i.e. waste minimization) mentioned in the CCU literature and identification of the relevant stakeholders (conceptual investigations), then a series of interviews were conducted (empirical investigation), and a value network alignment was the last step to identify the most relevant values and how they interact with each other in a systematic way allowing us to provide initial technical recommendations (technical investigation). The following subsections explain further each one of the steps.

Throughout the whole process (qualitative/quantitative, top-down/bottom-up) we established a close working relationship between the social scientists and the engineers to ensure that the technical knowledge was included in the process and to ensure realistic and applicable results.

3.1. Literature review

The purpose of the literature analysis was to identify relevant norms associated with CCU. Although the literature on CCU is still emerging, there are various papers referring to certain aspects of the technology that could be translated into norms. We used Scopus to search for relevant scientific publications using the keywords “CCU”, “CO_2E”, “CDU”, “Carbon utilization.” The search was limited to journals, conference papers, and reports written in English after 2000. It is worth pointing out that a large amount of relevant literature is dated after 2013, with the largest volume of publications appearing after 2019 (see also [84,85]). This is an indication that the CCU field is currently growing, and it is highly dynamic.

3.2. Stakeholder analysis

Stakeholders' values are the central component of VSD as they are elicited and included in the design of the technological process. In practice, this is done by reinforcing technological characteristics that support the identified values and minimize potential harm. Thus, stakeholder identification is an important first step in the VSD approach and the aim of this is to answer the "whose values?" question. To identify the relevant stakeholders, we did a stakeholder mapping based on a life cycle analysis. Various stakeholders that might not be visible in the process were identified using the snowballing sampling? technique according to which, stakeholders identify and suggest other stakeholders they might consider of relevance. Direct stakeholders are those who are directly involved in the CO_2E supply chain in our case study. These are the industries that emit CO_2, the industries with the potential to use CO_2 as feedstock or to consume CO_2-based products, the providers of inputs like renewable energy and water, and companies that offer material and equipment. Indirect stakeholders involve governmental bodies, non-profit organizations, academics, and climate change activists, among others. As suggested by Boucher & Gough [86], because some actors' ethical considerations cannot be included in the research (flora, fauna, future generations), we included actors that position themselves as advocates of these groups like environmental organizations.

It is expected that CO_2E will bring together various stakeholders with common visions, especially after the commercialization of the technology. However, as the technology is still at a low TRL, we chose to interview various stakeholders like technology developers of various cell configurations and possible CO_2E technology adopters as well as different CO_2 users. Fig. 1 presents the relevant stakeholders (direct and indirect) in the various stages of the supply chain from feedstock resources to product consumption and infrastructure and technology providers.

3.3. Interviews

The values identified in the existing literature were validated through a series of qualitative interviews with various stakeholders. Although the open-ended questions were built around the identified values, they remained open enough to allow for other values to emerge. We began the interview with general questions about the organization/role of the interviewee and the perception of sustainability. This was followed by questions on their expectations and potential harms, benefits, and challenges with the use of CO_2E. We did not ask directly about values but extracted the values from the narratives of the interviewed experts (for an exemplary list of the questions, see Appendix A). These interviews allowed us not only to validate the values we identified in the literature review, but also to identify how sustainability-related values can be perceived differently by the various stakeholders [14].

Forty-three interviews were conducted, in person and online, between November 2022 and May 2023. A list of the interviewees can be found in Appendix B. The interviews lasted one hour and at least two members of the group were present. The interviews were transcribed and analyzed using the program, Atlas.ti., with the purpose of coding statements that represented certain norms and values (see Appendix C). To better structure the analysis based on the sustainability pillars, we followed a reflexive approach [88] to leave open space for new values to emerge during the discussions.

3.4. Value alignment network

After the norms and values were identified, a co-occurrence matrix was created using the Jaccard Index, which is expressed as:

$$s = \frac{a}{(a+b+c)}$$

Where a is the count of organizations that have employed both values, the total of a, b, and c signifies the count of organizations that have made references to both concepts and either one or the other of the two. If s equals 1, it implies that both values are consistently used together, as no organization employs one without the other. Conversely, an s value close to 0 suggests infrequent congruent usage of the two values. The alignment between values was visualized on a network in which the size of the edge represents the times this value was mentioned and the width of the Jaccard index value [22,25]. The Jaccard index is used to measure the likeness between two datasets by identifying common and unique elements within them. In the present case this allows us to identify values that were shared (or not) by different actors.

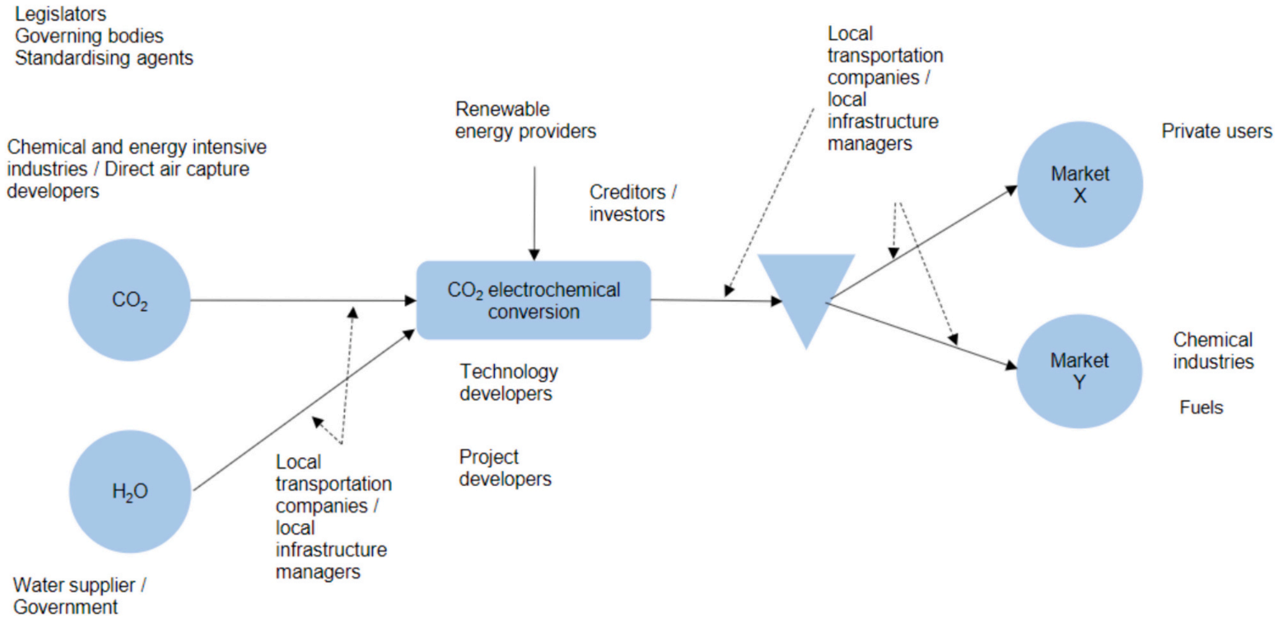

Fig. 1. Simplified map of the main stakeholders that constitute and define the supply chain of CO_2E (after Pérez-Fortes et al. [87] p5).

4. Results

The empirical analysis is split into two sub-sections. First, we discuss the values and norms that emerged from the interviews with the stakeholders and compare them with the ones found in the literature. In the second part, we construct the value alignment network.

4.1. Sustainability values in CO_2E

In the following paragraphs, we present the identified values from the interviews and examples of the norms and statements associated with these values. Overall, the values are similar to the ones identified in the relevant literature (see also Appendix C). The discussion is structured around the four dimensions of sustainability namely environmental, economic, technological and social.

4.1.1. Environmental values

Environmental values refer to a commitment to ensure that the development, deployment, and operation of this technology align with ecological and environmental preservation principles. They encompass a broad set of goals and practices aimed at minimizing the environmental impact of CO_2E throughout its entire lifecycle (Fig. 2).

During the interviews, the values "renewable energy integration", "waste management", "effective use of rare earth metals", "water use", and "land use" were mentioned by almost all the stakeholders. This indicates the need for responsible resource management practices and acknowledges the finite nature of these resources and the need to minimize their negative impacts on the environment. More concretely, the value "use of renewable energy" signifies a dedication to powering the electrolysis process but also the whole supply chain (water treatment facility and transportation of chemicals, for instance) with renewable energy sources, to ensure a minimal carbon footprint and alignment with the overarching sustainability value. For some actors, especially influencers and academics, this was a crucial issue as RE is currently not abundant. However, CO_2 electrolysis technologies should prioritize the use of RE either from the grid or from stand-alone systems. Some actors did not seem to share this concern as they believe that this barrier will soon be overcome: "*But, of course, there is plenty of renewable potential, […] on Earth, we only use a tiny fraction of it today*." [Int.#1] while others highlighted the potential for energy storage. In the assessment of renewable energy sources, and as an alternative to the use of intermittent RE, nuclear energy was brought up by many stakeholders. This seemed to be a point of tension as nuclear energy was rejected as a sustainable option by other stakeholders.

The use of rare earth metals for electrolyzers and water availability were also discussed as important environmental values for the design of the technology. Many stakeholders stressed the need to recycle catalysts whenever possible or to focus on research on substitutes or alternative materials that can perform similar functions as rare earth metals, reducing reliance on these materials when feasible. Others focused on the need for recycling and reusing these materials. As one technology provider mentioned, "*We want to close material loops in the beginning, but also at the end of life. And so, this must mean that […] every electrolyzer has to be decommissioned easily*." [Int.#8]. To reduce the use of water, some project developers point to the use of alternative sources of water like wastewater or desalinized water. For some, water consumption is not a concern. In this aspect, a water provider and treatment company (Int. #32) highlighted that there are ways of recovering and reusing water, increasing water use efficiency. The best way to do so generally depends on the type of water available on-site and many of these processes of recycling and reusing water are still complex and expensive. In contrast, a research/consultant group working on water (Int. #41) stressed that although it is not widely discussed, water is a crucial and potentially limiting resource for electrolysis. This can be attributed to the high energy requirements for practices of water desalination.

The value "climate change mitigation" was another core value for almost all actors. This was expressed mainly by the need to ensure that the technology contributes to emissions reduction and that the final product has a decreased value on CO_2 emissions in the long-time horizon. An NGO spokesperson (Int.#24) mentioned that it is important to know "*what happens to that product and where does the CO_2 then end up*," while a representative from a transportation company questioned "*the*

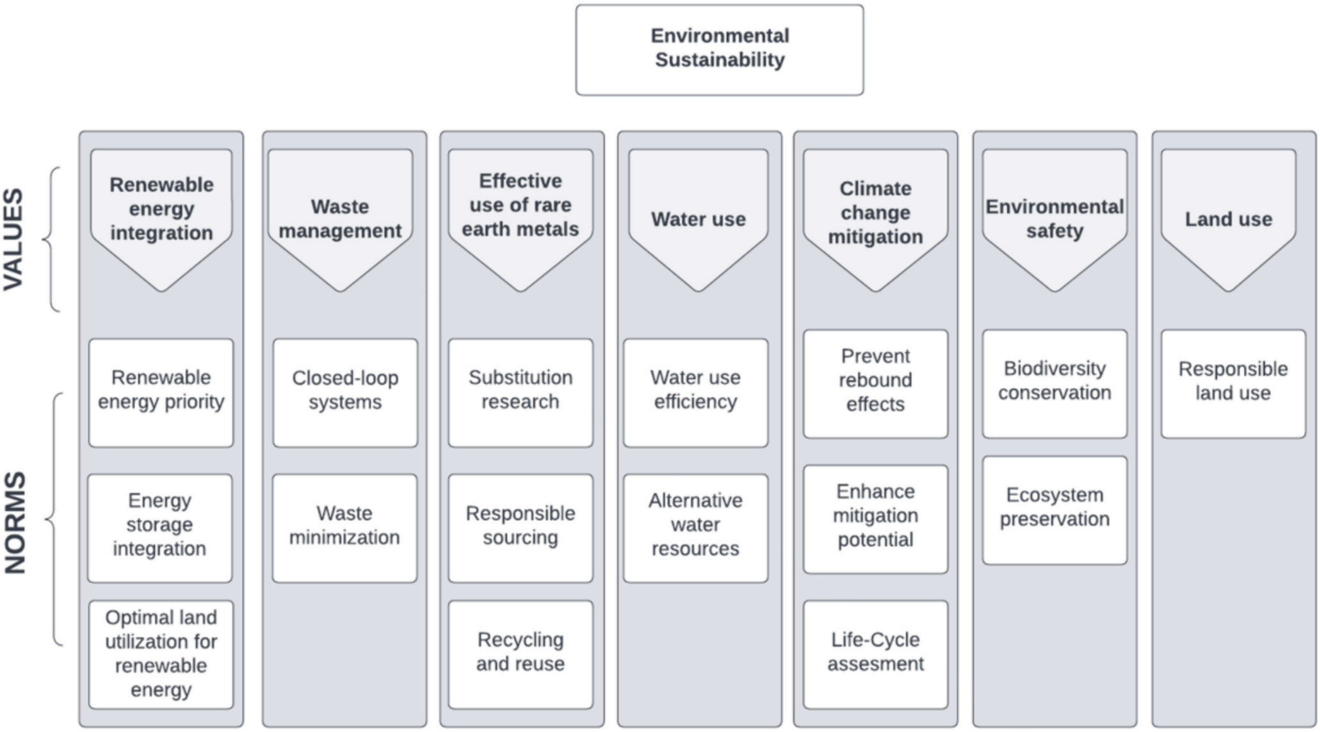

Fig. 2. Environmental norms and values identified through interviews with the stakeholders.

permanency of many CCU options, as the CO_2 is actually released very fast into the air again" (Int. #11). Thus, the need to ensure and demonstrate that these technologies are contributing to climate change mitigation was a key value, pinpointing indeed the importance and need of cradle-to-grave LCA's. Another related norm refers to the source of CO_2, which will have to come from unavoidable process emissions or biogenic sources and should be distinguished from CO_2 emitted from burning fossil fuels. This is related to a concern that many actors expressed around the unintended increase in resource consumption or environmental impact that can result from efforts to improve resource efficiency, a phenomenon known as the rebound effect. As a representative of an NGO (Int. #23) pointed out, there is a danger in "*remunerating an industrial plant for the CO_2 that they capture and then they might just produce more CO_2 because they're getting money for that being captured.*" A similar point of view was the need to ensure that CO_2 electrolysis would not lead to the creation of more products, thereby increasing the overall energy demand.

4.1.2. Economic values

The economic values underpin the financial viability and success of CO_2E, ensuring that it can effectively contribute to carbon reduction goals while remaining competitive, profitable, and accessible (Fig. 3).

On the one hand, the value of "profit and return on investment" was central to many actors, especially investors, startups, and private companies who consider CO_2E and CCU technologies viable only if they can be competitive in the market and bring a reasonable return on investment. As a technology provider mentioned, "*It's all about costs. Finance. Yes, sustainability in terms of having a sustainable company, you need to increase your value*" (Int. #7). More concretely, many of the small-scale/ start-up technology developers highlighted that early and successful efforts in decreasing CO_2 emissions, will make their companies leaders in industrial defossilization, which in turn can increase the chances of receiving funding for demonstration projects. For some stakeholders, like steel and cement manufacturers, this technology is a way to gain competitive advantage, and to avoid emissions taxation resulting from stringent regulations on carbon emissions. Many industry representatives argued that due to the longer investment horizon required to gain a profit, institutional changes and policies are needed to support industrial defossilization. Only two interviewees from the industry mentioned the diversification of income as part of the economic benefits. One of them referred to the need to make a profit from the by-products of the process, while the other one from trading CO_2, which is expected to increase in price. "Ownership" was a central value for multiple actors, with many different interpretations. For some actors, like a representative from the climate change movement, these technologies should be open access and without patents ensuring inclusive access to a diverse range of stakeholders who can participate and benefit from the technology. According to a representative from a non-profit organization, we should ensure that "*the natural monopolies of the infrastructures are not being abused*" (Int. #23). According to other actors (Int. #8, #15, #19), private ownership is inevitable and even desirable if we aim to achieve larger market penetration, as these companies often have in-house expertise.

4.1.3. Technological values

Technological values are mostly centered around the values of "safety", "reliability", "autonomy", "flexibility", "multifunctionality", and "scalability". Although many of these values also have social, economic, and environmental dimensions, we chose to present them in the current category as they are mainly dependent on the performance of the CCU technologies (Fig. 4).

The value of "reliability" was a highly relevant value for most of the actors, especially CO_2 emitters, users, and technology developers. It was expressed in different ways, for example in the need to operate the technology "*without risking interruption in the existing production*" (Int #31) or as the need for "*continuous operation in a stable mode*" (Int. #37). For other actors, issues of "reliability" included the intermittent of RE that can jeopardize continuous production leading to higher costs. This aspect was also brought up in the discussions around "flexibility" with actors calling for more flexible systems that can absorb intermittent renewable energy. For others, the value of "flexibility" was mostly related to the ability to keep using existing industrial installation without having to build new infrastructure that will increase the environmental impact. This seems to be of high priority for the big CO_2 emitters who cannot easily disrupt their continuous production. Additionally, issues of flexibility were also associated with flexibility in the maintenance of the technologies that will allow the technologies to operate while some parts are changed or updated.

The value of "safety" was brought up by about half of the interviewees. Most of them, when asked to elaborate, referred to the general safety requirements of the industrial sites rather than the specifics of the technology. For other actors, safety was not an important issue as "*we have long experience working with these materials*" (Int #34).

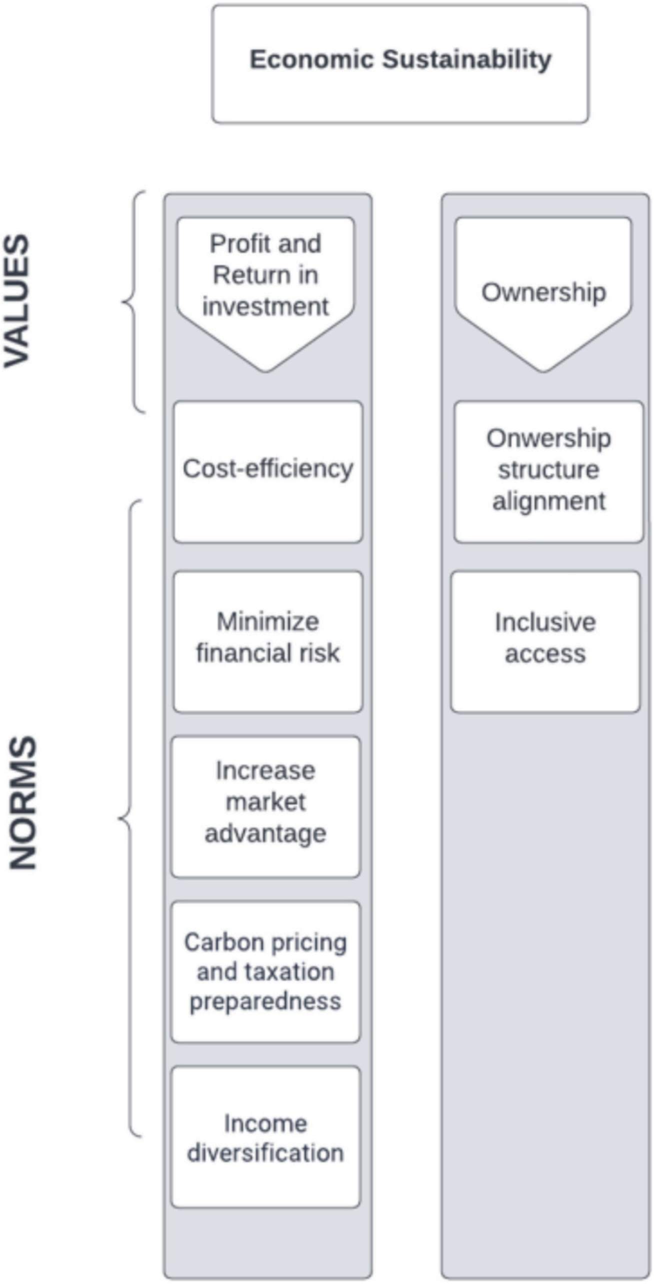

Fig. 3. Economic norms and values identified through interviews with the stakeholders.

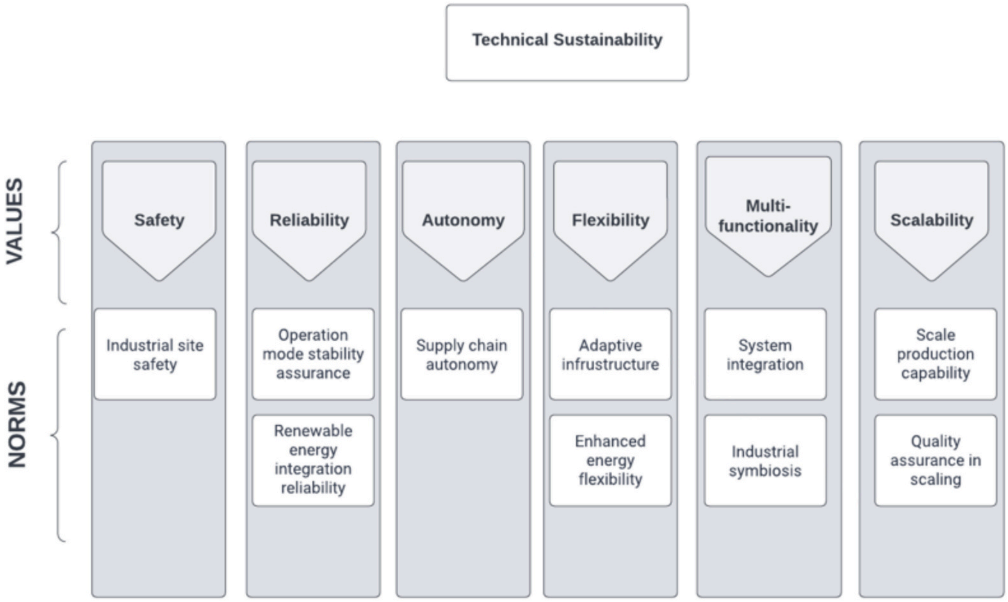

Fig. 4. Technological norms and values identified through interviews with the stakeholders.

This value was also related to cybersecurity attacks mentioned by two interviewees (Int.# 31, 41). "Scalability" to enable large-scale production requires accommodating increased demand efficiently and the need for quality control measures during scaling efforts to ensure that product quality and performance are consistent.

The values "autonomy" and "multifunctionality" were also mentioned by multiple actors, especially technology developers. These values were mostly discussed in relation to system integration which seemed to be a necessary aspect of the CCU technology. In fact, higher system integration seems to reduce the autonomy of the system and increase its multifunctionality. Thus, value tension was observed. Most interviewees seemed to agree that CO_2E would be most efficient if implemented in integrated industrial sites. For some, this was more of an obstacle as it can reduce the autonomy of the system and increase the complexity of the supply chain: "*the problem with all of these technologies is you can't do it alone. You require many partners*" (Int. #9) or because "*they need to be connected, and if one of the two is not in operation, you need to be able to solve that problem*" (Int #3). For others, this is an opportunity to increase multifunctionality: "*Create an industrial symbiosis […], the problem of an industry becomes a solution or an opportunity for another*" (Int. #26) which in turn can decrease investment risk.

4.1.4. *Social values*

Identifying social issues during the early stages of technological development, not yet implemented in a relevant context, can be challenging. Our research unveiled various social values that are related to wider social justice issues (Fig. 5). "Transparency", especially regarding the use of public money that funds CO_2E, was mentioned by certain actors, mostly NGOs and academics. A transparent process that clearly lays out a project's costs and impacts should be readily accessible to the public. According to a project developer (Int #35): "*So I think it's important to really inform the public and there I see a responsibility to also publish and to inform people*". The discussions around the value of "trust" were mostly focused on the trust towards the private sector. As one

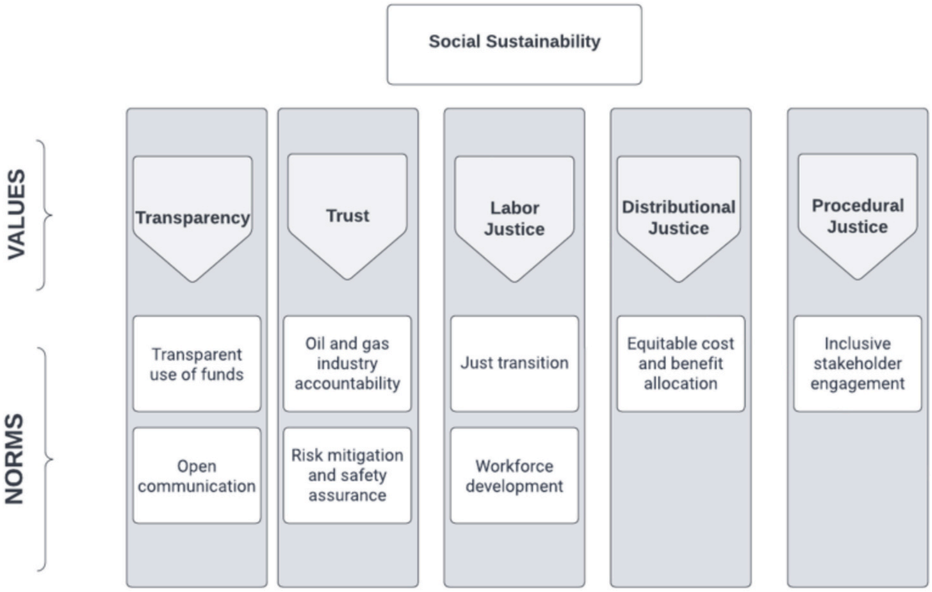

Fig. 5. Social norms and values identified through interviews with the stakeholders.

representative mentioned, this technology is "*connected to the oil and gas industry and no one trusts the oil and gas industry*". This can jeopardize the adoption of the technology and lead to market and regulatory challenges. Acknowledging this concern, requires the need for the oil and gas industry to address this legacy of distrust by taking concrete steps towards a sustainable industry transition. For other actors, "trust" was translated into the need to address concerns around safety and risk mitigation that might arise.

In our research, we identified three interconnected concepts of justice that hold relevance in the context of CO_2 electrolyzers. The most prominent social value related to CO_2E was the need for "labor justice". Various participants mentioned the need to ensure that as we move from fossil-based to defossilized industries, special attention should be given to the human side of the transition, with training and fair labor conditions for workers. The issue of the availability of a skilled workforce was another norm related to the value of "labor justice", as currently there is a lack of available workforce in many areas. This requires strategies for workforce development and capacity building in these regions. Discussions around the value of "participatory justice" were raised by multiple stakeholders throughout the supply chain, especially representatives from non-profit organizations, who highlighted the need to include multiple stakeholders in the design of the technology. The value of "distributional justice" considers the welfare of non-users, who may not directly engage with the innovative technology but could face increased marginalization due to their inability to access it or the consequences of its manufacturing. For CO_2E, this value was mostly expressed through concerns around the impact of the supply chain on local communities, especially those located at the beginning (extraction) and at the end (waste management) of it. These discussions, when brought up by the stakeholders, focused on the installation of RE plants in remote locations where there is cheap and abundant renewable energy and space for large-scale infrastructures, such as in Africa or the Middle East. However, there was only one actor who mentioned the negative social impacts these projects can have on the local communities in these locations. Other aspects of distributional justice raised by the interviewees were the need to ensure that the final products are not significantly more expensive than the fossil-based ones, making them available only to a few, as well as discussions around geo-political conflicts around access to resources.

An overall graphical representation of the number of stakeholders that mention each value is presented in Fig. 6. As seen in the graph, the environmental values were among the most frequently mentioned. This prominence of environmental values in the discussions can be attributed to the pressing global concerns surrounding environmental issues, especially climate change and carbon emissions reduction, which have placed a strong emphasis on environmentally friendly technologies, one of them being CO_2 electrolysis. Beyond its primary goal of reducing greenhouse gas emissions, this technology requires a holistic evaluation encompassing resource management, land use, and responsible material utilization to ensure its alignment with broader environmental objectives. The significant presence of economic values, particularly those related to profit and return on investment, in discussions and research regarding CO_2 electrolysis, underscores the crucial role that financial considerations play in the evaluation and adoption of this technology. CO_2E, while promising in its environmental benefits, must also prove its economic viability to garner support and investment. Stakeholders, including businesses, investors, and policymakers, are keenly interested in the potential returns and financial sustainability of CO_2 electrolysis. Certain values like environmental safety, trust and transparency were mentioned only by a few stakeholders. For environmental safety stakeholders might consider that the inherent nature of CO2 electrochemical reduction, as a clean and sustainable technology, minimizes immediate environmental safety concerns while environmental safety is also inherently considered within the regulatory framework and strict regulatory compliance. The values of trust and transparency might not be seen as a primary concern at these early stages of development, but they might become more relevant as the technology matures and enters practical applications.

4.2. *Exploring values through a value alignment network*

Stakeholders' values come together to shape a dynamic environment characterized by the coexistence of diverse perspectives and objectives. Among these values, there is a convergence with the overarching goal of ecological sustainability, manifested through environmentally responsible practices like efficient water and land use, the adoption of renewable energy sources, and the pursuit of climate change mitigation. Stakeholders prioritizing these values seek to harmonize CO_2E practices with environmentally conscious approaches, reflecting a commitment to reducing ecological footprints. Social values, including distributive and labor justice, intersect with the logic of social sustainability. Stakeholders emphasize equitable resource allocation, fair labor practices, and inclusive engagement, seeking to ensure that CO_2E benefits are distributed fairly across communities and that labor conditions are just

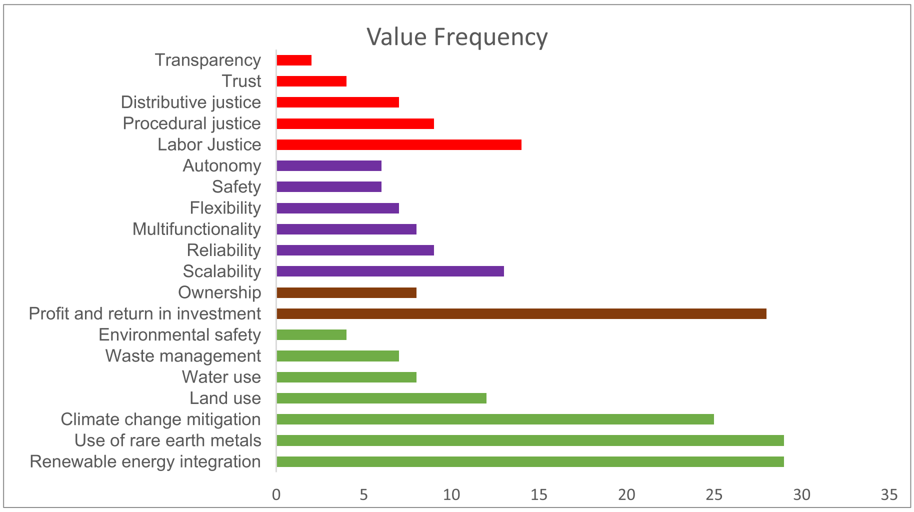

Fig. 6. Number of actors that mention the different values (🟩 environmental, 🟫 economic, 🟪 technical, 🟥 social).

and inclusive. Economic values, such as profit generation and return on investment, resonate with the logic of economic sustainability. Stakeholders with these values emphasize the need for CO_2 electrolysis projects to be financially viable and to yield returns, aligning their interests with long-term economic sustainability objectives. Technical values like autonomy, multifunctionality, and scalability intertwine with the logic of technical feasibility. Stakeholders valuing these attributes seek to optimize the technology's performance, functionality, and adaptability to different contexts, ultimately contributing to its successful implementation.

In Fig. 7 we depict the alignment of values in the context of CO_2E in a way to represent how different values interact and relate to one another. This graph helps identify which values are closely aligned and which may have varying degrees of compatibility or potential conflicts. The width of the line represents the value alignment; it means that the two values were often mentioned in conjunction by the same stakeholder indicating value alignment. The number of actors that referred to a value is represented by the size of the node.

Additionally, one can observe that there is a strong alignment between the environmental values of "RE integration", "use of rare earth metals", "waste management" and "increase climate change mitigation potential". These environmental values serve as the moral and ethical basis for the development of CO2 electrolyzers, motivating efforts to design them with a focus on minimizing environmental harm. Institutions like research centers, industry associations, or governmental bodies which prioritize environmental values are already formulating strategies and policies deeply rooted in these values when approaching technology. A strong alignment exists also between "labor justice" and "profitability". Actors that mentioned the need CO_2E to become a profit-making investment often also referred to the need for a just transition like a scaled workforce and fair salaries to attract the highly paid personnel of the oil industry. Another interesting connection is between the value of "reliability" with "RE integration" and "water use." This can be explained as the stability of the system is expected to be highly dependent on the availability of intermittent sources of RE and of water which in some areas is scarce. The extent and feasibility of desalination are primarily determined by energy use, which accounts for between 30 % to over 50 % of the cost associated with producing water through desalination processes. Additionally, if these processes are to depend on RE electricity issues of reliability due to intermittency but also land use availability might be relevant [89].

The density of the graph represents the proportion of existing links among the edges, compared to the maximum of possible links. A dense graph, like in our case, means that there is a coherent narrative among the stakeholders and serves as an important indicator of the cohesiveness of the values they hold within the context of the emerging technological field.

5. Discussion

Overall, the results of the study indicate that sustainability is an overarching value that drives the development and deployment of CO_2 electrolysis technology. This overarching value encompasses several core values, including environmental, economic, social, and technical values. Stakeholders consistently emphasized the need to minimize environmental impact, emphasizing values such as RE integration, climate change mitigation, efficient resource use (e.g., water, land, rare earth metals), and waste management. Thus, one might assume that these values should guide the design of the technology. Almost all the values identified in the interviews align with the ones identified in the literature which underscores the validity of the research. One important exception is the "durability" of the final product. This was mentioned in previous research examining the attitude of the public towards CCU products [90]. However, recent scientific results suggest that CCU products like concrete can, in fact, be more durable than non CCU-based products [91]. "Health", as a social value identified from the literature related to leakage and toxicity of products, was also not mentioned by any stakeholder, which probably indicates that this technology can be used safely, with minimal risk to both workers and users throughout its operational lifecycle. However, although these values might not seem relevant at this stage this can change as this technology evolves and becomes more integrated into society.

Profit and return on investment emerged as critical economic value. This underscores the importance of ensuring that CO_2E projects are

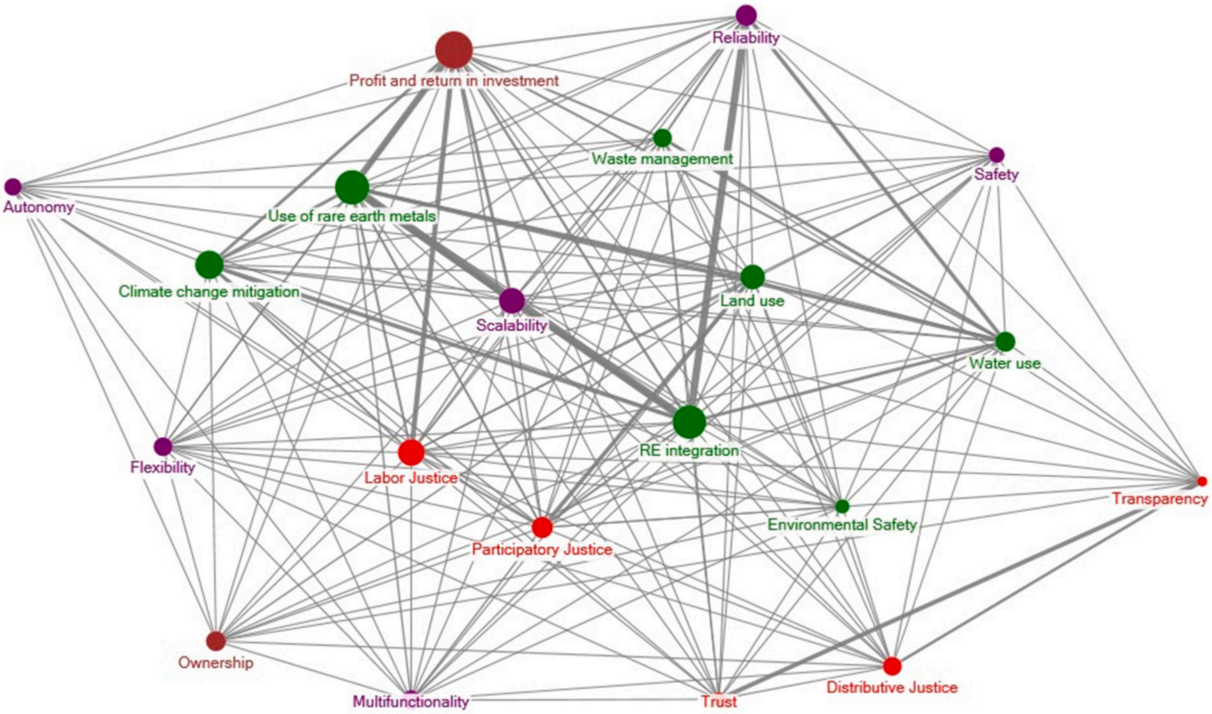

Fig. 7. Network of value alignment. Network metrics: Density: 0.86, Av. Degree: 17.143, Avg. actors:10.3, Total actors: 39.

financially viable. Balancing the environmental responsibility of minimizing carbon emissions and resource use with the economic viability of CO_2 electrolysis projects can be challenging nowadays, for instance, due to a large capital investment. Friedman [48] aptly pointed out that corporate economic objectives can often weaken (other) moral values, such as labor justice or safety. Conflicts between a project's elicited values of promoting democratization in urban planning and the representation of various stakeholder economic perspectives are not uncommon [92]. The personal values of individual designers focused on environmental sustainability, while other interest groups involved prioritized economic development [92]. Similarly, Wedin & Wikman–Svahn [93] also found an imbalance of economic and environmental priorities, with the emphasis typically placed on economic concerns. Our results suggest that when designing and implementing CO_2 electrolysis projects, it is important to focus on achieving a balance between environmental responsibility, which involves minimizing carbon emissions and resource usage, and the economic viability of such projects to avoid tensions.

It is crucial during design and strategic decisions to focus particularly on values that are less central and less interconnected, as this is where conflicts may potentially emerge. Some examples are issues of “trust” and “transparency” which were relevant to a small number of actors and less connected to other values. Other values appear to conflict with each other or hold different meanings for various stakeholders, like “reliability” and “flexibility”, or “autonomy” and “multifunctionality.” Special attention should be given to these values to avoid future value tensions as technology implementers are called to make certain tradeoffs between autonomous or embedded but multifunctional systems. Even though there were only minor instances of conflicting values observed at this early stage it is important to facilitate inclusive dialogue that accommodates a wide range of perspectives during the design phase and to establish and enforce rigorous policies to safeguard against any oversight of ethical considerations.

Values can also reinforce each other [94] and certain values are more aligned and often discussed together. For example, in our case, “labor justice” can increase “labor productivity” and thus, increase profits. Higher efficiency can result in reduced demand for resources and less waste production, which, in turn, can decrease annual costs. This interplay of values, where they can mutually reinforce one another, holds significant importance for designers and engineers because understanding these synergies allows for the creation of more sustainable and economically viable solutions that align with multiple desirable outcomes. The role of indirect stakeholders seems to be important in this regard. Most of them place special emphasis on the environmental and social aspects of technology, highlighting the need to ensure that CO_2E is indeed sustainable in all four dimensions.

5.1. Preliminary design requirements

The centrality of a value in the network (Fig. 7) indicates a value that is used consistently alongside many other values in the discourse. From Fig. 7 we have identified four central values that can influence many other values, i.e., “scalability,” “participatory justice,” “RE integration,” and “labor justice”. Although the design of the present study does not allow us to derive specific design guidelines, there are some initial recommendations that can emerge from these central values.

The “scalability” of the technological application can affect several values. On the environmental aspects, the larger the scale of a technology, the more resources (renewable energy and raw materials) it is likely to consume, resulting in a larger environmental footprint. A bigger plant can generate more waste, which can be harmful to the environment if not properly managed. A larger scale production can also lead to potential rebound effects which can reduce the climate change mitigation potential. This is evident in the literature where most Life Cycle Analyses approaches analyze the environmental impact of CCU as a substitute for current production scales and nor for system expansion [95,96]. Scale up with expansion can also affect the multifunctionality and autonomy of the system [95] as well as the global warming impact [97]. On the other hand, a larger-scale technology can often be more profitable than a smaller one due to economies of scale (even if CO_2 electrolyzers are modular – economies of number, upstream and downstream units benefit economies of scale). On the social aspects, a smaller scale project can increase the benefit to the local population while a larger scale project can offer more employment opportunities and stimulate local economies.

“Renewable energy integration” is key to reducing carbon emissions and enhancing sustainability. Designing CO_2 electrolysis systems to operate flexibly, optimizing operation with renewable solar or wind with a combination of energy and/or material storage, is crucial. Labor justice is also a central value. Labor justice is a vital component of economic sustainability. When workers receive fair compensation and job security, it can have positive economic ripple effects on the industries and areas that rely on this technology. Moreover, labor justice includes empowering workers with the knowledge and skills needed for their roles. In the context of multifunctionality and autonomy, skilled workers play a critical role in operating and maintaining complex systems. The deployment of CO_2 electrolysis technologies often involves a fundamental reconfiguration of industrial landscapes. This transformation may render certain job roles obsolete, particularly in industries with a high carbon footprint. In the pursuit of labor justice, it becomes crucial to address the fate of workers impacted by this transition. Individuals from sectors experiencing decline due to carbon reduction efforts may possess valuable expertise that can be repurposed in the burgeoning field of CO_2 electrolysis.

“Participatory justice” holds a central role in the context of CO_2 electrolysis technology due to its profound impact on various core values associated with the technology. By actively involving diverse stakeholders at the current (early) stage of development, including local communities, workers, and environmental advocates, participatory justice ensures that the decision-making process is inclusive and considers a wide range of perspectives, needs, and concerns. This inclusivity translates into a more comprehensive assessment of the technology's environmental impact. Additionally, by involving local workers and communities in decision-making, the technology can create job opportunities and spur economic development in the regions where it is implemented, contributing to broader economic benefits. Furthermore, participatory justice extends to ethical sourcing in material procurement and transparency. Incorporating participatory and labor justice considerations into the technical design of CO_2E means developing modular and flexible system configurations that can be adapted to local needs and preferences, ensuring that the technology can be efficiently operated by a diverse workforce, and implementing continuous monitoring and feedback mechanisms to respond to community and labor-related concerns throughout the project's lifecycle.

The study also has certain limitations that must be acknowledged. First, the research is based primarily on interviews with EU stakeholders and does not fully incorporate perspectives from the global CO2 electrolysis supply chains and potentially limiting the generalizability of the findings to other regions. Important stakeholders such as the public and future generations are also not represented. Given the novel nature of the technology, there is considerable uncertainty regarding which stakeholders will ultimately be involved and how the supply chain will evolve. Additionally, as the technology develops, the values and priorities of the stakeholders may shift. The dynamic regulatory environment for new technologies also presents a challenge, as future policy changes could significantly impact the technology's adoption and integration.

5.2. Future implications

The utilization of VSD and the establishment of a value alignment network to explore and discuss stakeholder values in the context of low TRL CO_2 electrolysis holds promising implications for the technology's future. This approach enables a thorough understanding of diverse stakeholder values, fostering the integration of ethical and societal considerations into the technology's development. As CO_2 electrolysis advances and matures, this value-driven methodology can guide its design and decision-making processes, ensuring alignment with the ethical, environmental, and social values of stakeholders. Moreover, by facilitating ongoing discussions and collaboration among engineers and social scientists, it can help bridge gaps, address potential conflicts, and lead to more informed, responsible, and inclusive technology development. According to Barnett et al. [98], values are “positioned” within particular social environments, shaped by individuals' experiences, everyday behaviors, and the specific locations and cultural contexts in which these are rooted. As the technology matures a more complete stakeholder identification and a place based or product specific approach might generate a deeper understanding of the unique requirements, challenges, and opportunities in different contexts, ultimately fostering more tailored and effective solutions. Additionally, although our approach allowed us to identify significant values and pinpoint potential future value conflicts it does not provide guidance on how to prioritize or deliberate in such scenarios. Further research should discuss alternative ways to deal with value conflicts once they emerge (see also [99]) and methods like workshops and scenario analysis can lead to more concrete design recommendations.

6. Conclusions

The present study used a VSD based approach to discuss the values of the different stakeholders involved in the CO_2 electrolysis technologies, using sustainability as an overarching value. Our results indicate the complexity behind the design of sustainable technologies, especially for technologies with low TRL due to uncertainties, value tradeoffs and stakeholder expectations. Overall, we observe that the emerging techno-social field of CO_2E is quite stable centering mostly around the environmental and economic values. Although little misalignment was observed among the values, future studies should focus on the new values that will emerge as technology matures and becomes widely implemented. This can lead to new information and experiences that can change people's opinions and beliefs. Additionally, research that includes different socio-cultural environments and more indirect actors like the local population could further enrich the discussion. To this end, VSD can be a useful tool for further analysis.

Engineers designing CO_2E systems should prioritize scalability with a focus on renewable energy integration, ensuring adaptable and environmentally responsible operations without overlooking potential rebound effects. Life Cycle Assessments can shed light on the interrelations between system components, energy sources, and environmental impacts, providing insights for engineers to optimize CO2E systems for long-term sustainability.

Additionally, they must emphasize labor and participatory justice in the design process. To attain this goal, the ease of assembling and integrating individual components or units can provide flexibility and open possibilities for distributed manufacturing, installation, and maintenance. This, in turn, can lead to job creation and economic advantages in multiple areas. Interdependence and uncertainties make decisions complex for technology designers, implementers, and policymakers, who are now called to evaluate how their technologies link to broader sustainability transitions. This demonstrates the intricacy involved in implementing new technologies within an established sociotechnical framework. Ultimately, this research contributes to advancing the field of sustainable energy by emphasizing the importance of considering value systems and institutional dynamics in the design and implementation of technological solutions.

CRediT authorship contribution statement

Marula Tsagkari: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ibo van de Poel:** Writing – review & editing, Supervision, Conceptualization. **Mar Pérez-Fortes:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Examples of guiding questions for the interviews with stakeholders.

1. What is your opinion on CCU technologies? What are the challenges/harms of these technologies?
2. Are you familiar with CO_2 electrochemical conversion?
3. What are your expectations of the growth of this technology? Can it be a viable solution for the future? Under what circumstances?
4. What are some of the most important aspects of the CO_2 electrolysis technology that we need to consider early in the implementation to ensure that is a sustainable technology in the long term?
5. What would be a deal-breaker in the development of CO_2 electrolysis?

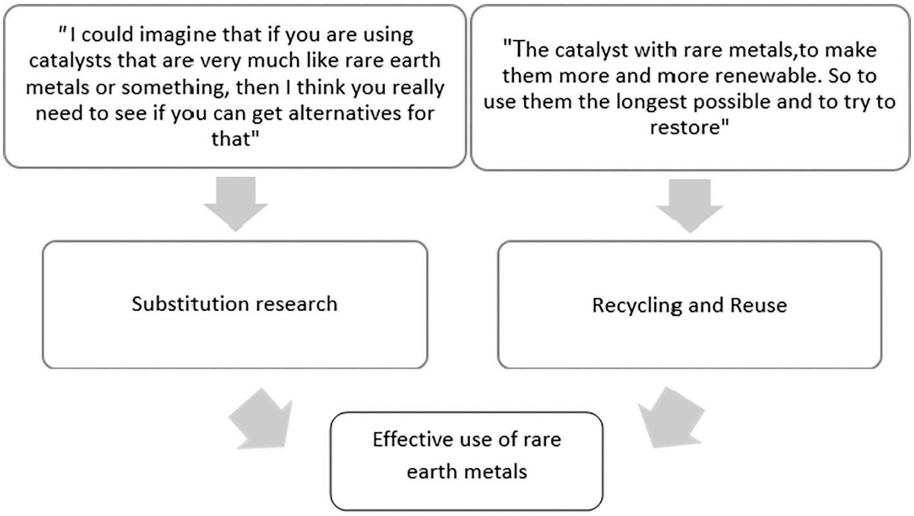
Appendix B

List of the interviewees, their role in the supply chain, and the type of organization they belong to.

Interview number	Role in the supply chain	Stakeholder type	Type of organization	Direct/Indirect involvement in the supply chain
1	Direct Air Capture developers	DAC technology developers	Private company / Start-up	Direct
2	Energy intensive industry (CO_2 emitter)	Cement industry	Association	Direct
3	Energy intensive industry (CO_2 emitter)	Steel industry	Private company (multinational)	Direct
4	Energy intensive industry (CO_2 emitter)	Steel industry	Private company (multinational)	Direct
5	Energy intensive industry (CO2 emitter)	Steel industry	Private company (multinational)	Direct
6	Technology and project developer	Electrolyzer production and application for chemical production	Private company	Direct
7	Technology and project developer	Electrolyzer production and application	Private company	Direct
8	Technology developer	Catalyst producer	Private company	Direct
9	Technology developer	Catalyst producer	University	Direct
10	Transportation	Gas transport/ pipes	Private company	Direct
11	Transportation	CO_2 transport/barge	Private company	Direct
12	Project developer	Landowners and project developers	Private company/start-up	Direct
13	CO_2 user and project developer	Chemical company	Private company/ multinational	Direct
14	Project Developer	Consultancy	Private company/ multinational	Direct
15	Investment agency	Public funds	Private company	Indirect
16	Investment body	Public funds	Public body	Indirect
17	Investment program	Public funds	Consortium	Indirect
18	Renewable energy provider	Auxiliary inputs	Public research organization	Direct
19	Technology developer	Electrosynthesis	Public research organization	Direct
20	Policy maker	Climate Policy advisors- influencer	Private lobbying	Indirect
21	Project developer/ consultant consortium	initiation and facilitation of project development	Public-private innovation program	Direct
22	Environmental movement	Influencer	Movement	Indirect
23	Non-profit organization	Influencer working on CO_2E	International environmental NGO	Indirect
24	Non-profit organization	Influencer working on CO_2E	International and non-profit association	Indirect
25	Investment and policy making	Policy and funding	Public-private funding and innovation program	Indirect
26	Policy making and research	Decarbonization strategies	Public research organization	Indirect
27	Policy making and research	Decarbonization strategies	University	Indirect
28	Research and technology development	Laboratory/large-scale electrolysis for hydrogen	Public research organization	Direct
29	Research and technology development	Laboratory/ Solid Oxide electrolysis	Public research organization	Direct
30	Research and technology development	LT electrolysis and iron and steel	Public research organization	Direct
31	CO_2 user and project developer	Chemical company	Private company	Direct
31	Lobbying	Influencer	Association	Indirect
32	Water provider & treatment	Water treatment for industrial applications	Private company	Direct
33	Engineering consultant	Consultancy	Private company	Indirect
34	Influencer	Training provider	Independent organization	Indirect
35	Project developer	Plant designer	Private company	Direct
36	Technology developer	Electrocatalysis research	Public research organization	Direct
37	Technology developer	Chemistry research and technology design	Private company	Direct
38	Technology and project developer	Electrolysis project	Private company	Direct
39	Renewable energy research	Grid and renewable energy	Research organization	Indirect
40	Water research and consultancy	Water Research institute	Research organization	Indirect
41	Energy intensive industry (CO_2 emitter) and technology developer	Fossil fuel company on way to defossilization	Private company	Direct
42	Energy intensive industry (CO_2 emitter) and technology developer	Fossil fuel company on way to defossilization	Private company	Direct
43	Lobbying	Influencer	International and non-profit association	Indirect

Appendix C

Example of the coding process from interview statements to norms and values using Atlas.ti.



Appendix D

List of relevant values and norms related to CCU, identified from the literature review.

	Values	Norms	Source
Environmental	Use of rare earth metals	Effective use of rare earth metals, reuse and recycling	Ghiat & Al-Ansari, 2021; Gulzar et al., 2020; Ioannou et al., 2022
	Waste management	Effective waste management and reduced waste production	Fraga & Ng, 2015; Ghiat & Al-Ansari, 2021
	Water management	Effective water usage	Ghiat & Al-Ansari, 2021; Ioannou et al., 2022
	Land use	Effective land use and avoidance of land conflicts	Ghiat & Al-Ansari, 2021, Olfe-Kräutlein, 2020
	RE integration	Use of electricity from renewable sources	Cruz et al., 2021; Ioannou et al., 2022; Ravikumar et al., 2020, 2021
	Climate change mitigation	Increase mitigation potential	Arning et al., 2020, 2021; de Kleijne et al., 2022; Ioannou et al., 2022; Mac Dowell et al., 2017; Naims, 2016; Sapart et al., 2022
		Avoid rebound effect-delaying investments in other green technologies- Carbon lock-in	Arning et al., 2020; Cuéllar-Franca & Azapagic, 2015; de Kleijne et al., 2022; Ioannou et al., 2022; Jones et al., 2017; Naims, 2016
	Environmental Safety	Minimize the chance of leakage and pollution	Arning et al., 2019, 2021
Economic	Profit	Increase diversification of income	Ghiat & Al-Ansari, 2021; Patricio et al., 2017
		Return in investment.	Cuéllar-Franca & Azapagic, 2015; Liu et al., 2022; Nyári et al., 2020
	Ownership	government/research institute/university/non-profits organization/state-owned company	Wang et al., 2021
Technological	Safety	Accident prevention during the operation of the technology. Protection from cyber attacks	Al-Yaeeshi & Al-Ansari, 2022; Perdan et al., 2017; Rafiaani et al., 2020
	Reliability	Reduced dependence on intermittent Renewable Energy	Deerberg et al., 2018; Mikulčić et al., 2019; Wevers et al., 2020
		Commercial availability of catalyzers	Masel et al., 2021; Nyári et al., 2020; Wevers et al., 2020
	Autonomy	Development of integrated industries system for onsite conversion of CO_2. Deep integration of the industrial processes	Deerberg et al., 2018; Ghiat & Al-Ansari, 2021; Mikulčić et al., 2019
	Flexibility	Increase the flexibility of the system and integration of variable renewable sources	[100,101]
	Scalability	Implementation at larger scales and/or across a broader range of industries and applications	Aresta, 2019; Faber et al., 2022; Frieden, 2021; Tcvetkov, 2021
	Durability	Final product lifetime	Arning et al., 2019; Linzenich et al., 2019; Ravikumar et al., 2021
	Multifunctionality	Multiple value streams, and multiple catalysts	de Kleijne et al., 2022; Moretti, 2023; Ramirez et al., 2021
Social	Justice	Distributive and participatory	Ioannou et al., 2022; Jones et al., 2017
		Labor justice- fair employee participation	Upham et al., 2022
	Health	Toxicity	Arning et al., 2021; Linzenich et al., 2019
		Carbon leakage from products	Arning et al., 2021; Linzenich et al., 2019
	Trust	Trust in CCU companies and governments	Offermann-van Heek et al., 2018
	Transparency	Clarity and transparency in evaluating carbon dioxide utilization projects, supply chains, risks, and money allocation	Arning et al., 2020; Linzenich et al., 2019; Offermann-van Heek et al., 2018; Rafiaani et al., 2020; M. Wang & Feng, 2019

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