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Original research article

Governing the development of CO_2 electrolysis: How do we give an emerging technology a chance to contribute to a carbon neutral Europe?

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ABSTRACT

Sustainability transition to a climate neutral economy requires the rapid development, testing and scaling of emerging technologies currently in their infancy. Carbon dioxide electrolysis is one such promising emerging technology to produce fossil-free fuels and chemicals for a sustainable chemical industry. This paper investigates enablers and barriers shaping this technology within a European context by combining a technological innovation system (TIS) lens with political economy perspectives. Evidence from over forty semi-structured interviews, policy documents, and an expert consultation workshop reveals a fast-emerging TIS enabled by R&D, legitimisation and advocacy of carbon capture and utilisation as an emission reduction pathway, and complementary technological developments. However, factors such as availability of renewable electricity and carbon dioxide, and a policy bias towards mature technologies to meet urgent emission reduction targets are barriers to its future development. The TIS in this early formative phase, is in a state of flux and vulnerable to shifts in actor strategies, which can result in discontinuities in the learning process. We identify a need for technology-specific policies to support iterative upscaling through long-term projects, encourage niche market formation and strategically manage knowledge. In contrast to the current fit and conform narrative dominated by cost comparison with fossil fuels, we propose a need to empower carbon dioxide electrolysis with a stronger stretch and transform framing by imagining its role in a carbon neutral economy. Our methodology complements existing techno-economic assessments by bringing forth a rich narrative of underlying innovation processes and offers important policy insights for governing emerging technology development.

1. Introduction

Sustainability transition to a climate neutral Europe by 2050 [1] requires reducing greenhouse gas emissions across all economic sectors through improved energy efficiency, modernisation of industries, shift towards greener alternatives and circularity to decrease the consumption of primary materials. Achieving net-zero goals made legally binding by the European Climate Law [2] requires accelerated development, testing and bringing to scale sustainable technologies currently at low technology readiness levels, a process which typically spans decades and is characterised by extreme uncertainties. Carbon dioxide electrolysis (CO_2E) is one such promising emerging technology that can produce fossil-free fuels and chemicals. The CO_2E process involves converting carbon dioxide and water (or steam) through an electrolyzer using renewable electricity and heat to obtain chemicals and fuels. The carbon dioxide can come either from point sources such as emitting industries or from atmospheric air through direct air capture. It can be classified as a carbon capture and utilisation (CCU) technology, which is increasingly being recognised as a climate change mitigation pathway [3–5], or as PtX (power-to-X) technology - an umbrella term referring to conversion technologies that turn (renewable) electricity into potentially carbon-neutral synthetic fuels and chemicals.

Together with many other technologies, CO_2E could play a role in defossilisation of the chemical industry [6–9], which is not easily

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amenable to electrification due to the need for high temperatures and chemical feedstock. It offers a sustainable alternative for structural change of coal-based regions and is one of the technologies being researched for the industrial transformation of the Rhine chemical cluster in Germany [10]. Further, as a process for production of fossil-free fuels plastics, it could greatly contribute to the materials transition and circular economy [11]. CO_2E could also open up new business models, such as the decentralised production of chemicals and fuels, reducing the need for expensive and hazardous transportation in pressurised vessels [12], and unraveling (new) types of infrastructural needs. CO_2E could therefore play a role in sustainability transition, which is understood as the "long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption" [13].

Many fundamental scientific challenges need to be solved before CO_2E can become a viable industrial process [14,15]. A strong conviction of its potential in the chemical industry in the eventual phase-out of fossil fuels, has fueled a great deal of research in this technology in the last decade [16,17]. Alongside experimental research, a host of techno-economic studies have assessed its future potential, [17–20], to name a few]. However, techno-economic models rooted in neoclassical economics do not offer sufficient insights on the underlying socio-technical processes which are evolutionary, contextual and path-dependent [21,22] and shaped by a complex interplay of technological, economic, social and political factors [23,24]. With a focus on the European context, this paper complements the science and engineering literature by bringing in innovation and governance perspectives to bridge this methodological and empirical gap. We explore two research questions: First, what are the current enablers and barriers shaping the evolution of CO_2E to a higher technology readiness level? And second, what kind of policy and governance interventions are further needed to give this technology a chance to play a role in a climate neutral Europe? We explore these questions by integrating a technological innovation systems (TIS) approach [20,26] with political economy perspectives [27]. In doing so, we pay particular attention to key policy objectives, institutions, incentives, and interests strongly influencing this technology.

The TIS is an analytical lens to study the emergence and evolution of new technologies and has been used in many transition studies [28–32]. TIS offers an elaborate framework to study processes for nurturing emerging technologies and has been found particularly useful in informing policies [33]. Given the increasing role of governments in directing transformative change under great geopolitical and other uncertainties [27,34], such as for example issues of energy security, sovereignty and sourcing of critical raw materials needed for a carbon neutral economy, we embed the focal CO_2E TIS in the EU policy landscape. This is also in line with a call by TIS scholars to pay greater attention to the embedding context [35]. Our research draws upon over forty semi-structured interviews, an expert consultation workshop, and policy documents. It contributes to an understanding of the complex socio-technical processes underlying the development and diffusion of CO_2E, outside the scope of techno-economic assessments [21,22].

The rest of the article is structured as follows: Before discussing the theoretical and analytical inspirations for this study, we briefly introduce the technology in Section 2. In Section 3, we draw from a variety of literature streams to discuss the TIS approach, the importance of context and political perspective in TIS evolution, and relevant policy instruments in the governance of emerging technologies. The first two parts of Section 3 informs the methodological approach detailed in Section 4 and our first research question, while the last part guides the second research question. Section 5 presents our analysis of the TIS structure, detailed exploration of functions and overview of enablers and barriers. Section 6 brings together the different elements of the research to discuss the dynamics of TIS with context, the policy implications, and limitations and future research avenues with some concluding remarks in Section 7.

2. Carbon dioxide electrolysis – an overview

While electrolysis of CO_2 alone is also possible, in this paper, we refer to co-electrolysis of CO_2 and H_2O. CO_2E converts CO_2 and water into targeted products using renewable electricity. The electrolysis reaction can take place at high and low temperatures, and electrolysers can be used alone, in tandem with other electrolysers, or in hybrid configurations. Currently, high-temperature solid oxide electrolysis (SOEC) producing syngas is more developed than CO_2E at lower temperatures [12]. Low-temperature CO_2E has its own research and development (R&D) momentum and offers pathways to generate directly, multi-carbon products such as ethylene, ethanol, or acetic acid in convenient and flexible operations [15,36].

There are many technological challenges in the development of CO_2E, both fundamental and related to its upscaling and industrial integration. A key barrier is the performance of electrocatalysts and membranes [36], which need to be developed and tested under commercial conditions [37]. Low efficiencies, formation of carbonates which results in large voltage and CO_2 losses [15], and undesired side reactions and low selectivity in the direct synthesis of multi-carbon products [38] are technological bottlenecks and represent distinct knowledge gaps [39]. Further, there is a need for testing commercial scales of complete electrolysis-based plants under flexible conditions (due to diurnal or seasonal fluctuations in renewable electricity) and considering upstream and downstream units. The capture and transport of CO2 is another technological challenge and research on integrated capture of CO_2 using amines are being explored [40] With carbon dioxide being a highly thermodynamically stable molecule, one of the biggest challenges is the amount of electricity needed for its decomposition, making the availability and price of renewable (or carbon neutral) electricity critical for its techno-economic feasibility [17,19,20]. The CO_2-based product prices compared to other (alternative) routes will have to be competitive for the future adoption of the technology.

A phenomenal amount of research has helped to push the frontiers of knowledge in CO_2E. Fig. 1 illustrates examples of current upscaling initiatives in Europe and indicates that a wide number of products, technology combinations, electrolysis-based architectures, and CO_2 sources are being investigated. Recent research suggests that rather than a one size fits all model, its application will be influenced by contextual factors, with local resources and markets shaping various case studies [41]. While some studies touch upon factors beyond the techno-economic, such as the role of policies [14,42] and alignment of sustainability values in technological design [43] for accelerated development of CO_2E, there is a need to better understand the socio-technical system around it to identify points of policy intervention to accelerate its development. Our study is a step in that direction.

3. Theoretical and analytical foundations

3.1. Evolution of an emerging technology through the TIS approach

The TIS approach builds on the conceptualisation of technological system, defined as a "network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilisation of technology" [44:111]. TIS is characterised by its structural components (technology, actors, networks, and institutions) and system functions [25]. Actors are firms and other organisations that perform innovation activities and pursue deliberate strategies [33]. Institutions are understood as rules of the game and can be both hard ones, such as legislation, incentives and subsidies, or soft ones such as culture and norms. Actors are embedded in and governed by an institutional framework; whereby certain activities are incentivised while others constrained [33]. Networks can be information and knowledge-based or advocacy-based. For a new technology to gain ground, technology

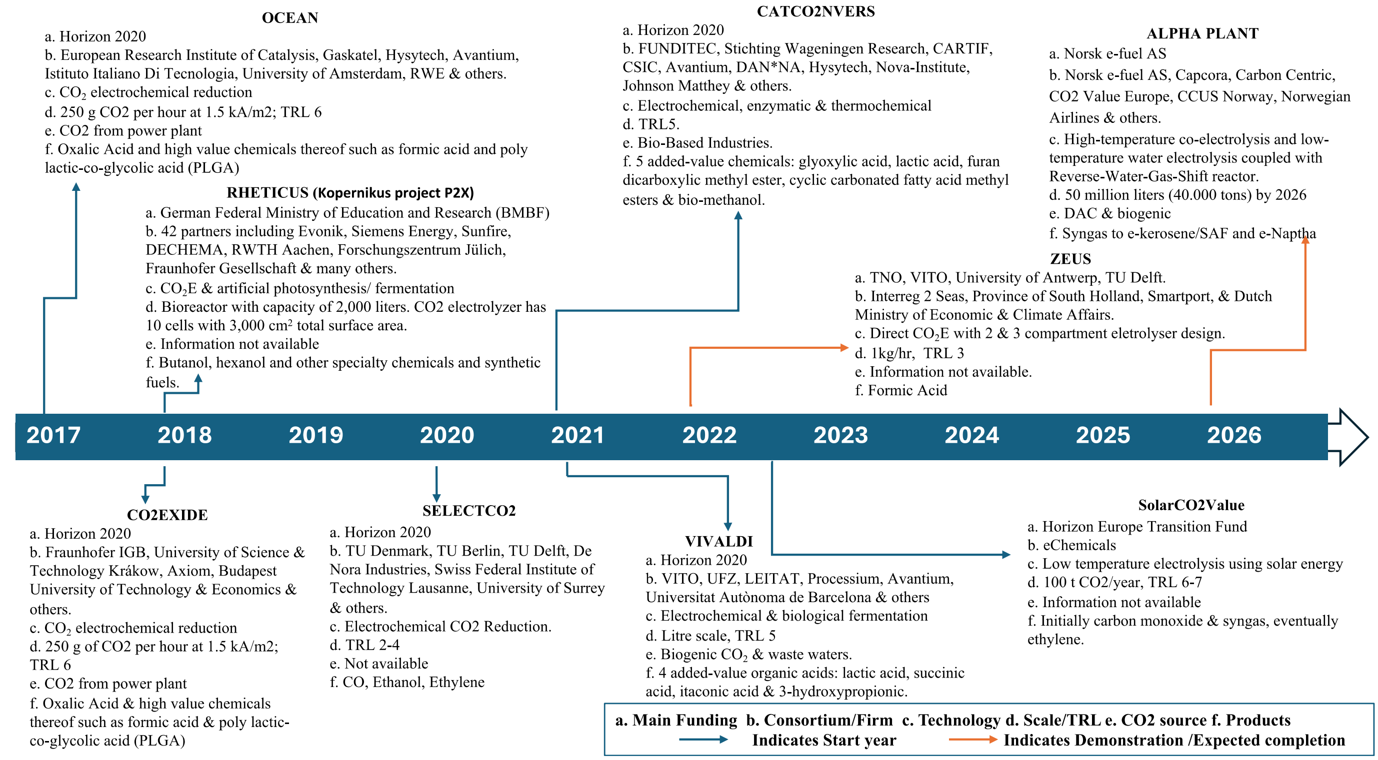

Fig. 1. Examples of upscaling efforts of CO_2 Electrolysis in Europe.
Note: More details in supplementary material.

specific coalitions need to be formed to present a collective voice and engage in political debates [30]. As these networks strengthen, the bargaining power of the emerging industry grows in relation to those with vested interest in entrenched technologies [45].

TIS functions are properties which result from the interaction of actors and institutions [41]. A set of seven functions (Table 1) need to be served for the technology to mature though their importance depends on the maturity of the technology [25,26]. For example, R&D investments and projects illustrated in Fig. 1 are activities strengthening the knowledge development and diffusion function of CO_2E TIS. Some functions such as market formation are barely formed at the formative phase of TIS development. Functions also interact with each other and the context. Contextual interactions, such as that with related TISs, could constrain or accelerate the development of functions [35].

Table 1
TIS Functions.

Function	Indicated by
Knowledge development & diffusion	R&D investments/ projects, joint-projects, conferences, workshops, demonstrations, pilots.
Influence on the direction of search	Anticipation & beliefs of experts, articulation of interest by powerful actors, incentives from taxes, government or industry targets, crises in current business, changes in landscape, regulations, technical bottlenecks.
Creation of legitimacy	Technology promotion by organisations, government, lobby activities, social acceptance, alignment, and compliance.
Entrepreneurial experimentation	New entrants, experiments, diversification by incumbent firms, complementary technologies employed.
Market formation	Experimentation with new applications, niche markets, articulation of demand by potential lead users/ potential customers, stimuli such as regulations, public procurement, and hindrances such as lack of standards.
Resource mobilisation	Extent of mobilising human capital, funding (grants, subsidies, and investments), infrastructure development, changes in complementary technologies etc.
Development of positive externalities	Spill overs due to systemic nature of innovation and diffusion such as changes in pooled labour markets, specialised service providers

Source: Adopted from Bergek et al. [25] and Hekkert et al. [26].

3.2. *A need for contextualising TIS within the policy landscape*

An important and related area critical in shaping socio-technical transition and emerging technologies but which has received less scholarly attention in TIS studies though this is slowly changing are politics and political science perspectives [21,24,46–49]. Technologies emerge in niches which are protected spaces for incubation or a specific application domain for the new technology and are isolated from regime pressures, the latter being a highly stable structure characterised by established technologies, infrastructures, products, expectations, regulations, etc. [24,48,50]. Niches show promising characteristics, but no actual market sales exist [50]. Politics and policies play a powerful role in *defining the landscape, propping up or destabilising regimes, protecting or exposing niches* (original in italics) [24]. For technologies to gain ground, niches need to be empowered, not only through *fit and conform* activities but also *stretch and transform* processes [49,51]. Fit and conform empowerment refers to processes that makes niche innovations competitive within an unchanging environment while stretch and transform aims to empower niches by restructuring the external environment in ways which favour the new technology [51]. For example, the comparison of CO_2E with fossil fuel alternatives based on cost does not take into consideration the social and environmental costs or acknowledge the lengthy learning process which has become internalised in fossil derivatives and is an example of fit and conform narrative [49].

A political perspective is not entirely absent in socio-technical studies rather it remains implicit. As Meadowcroft [24] notes, “behind policy, there is always politics”, and in the TIS approach, policies are considered under institutions which lay the ground rules, therefore steering actor strategies and influencing all system functions. However, as energy transition programmes such as the European Green Deal take a structural perspective to align with broader social and economic goals [52], there is a need to juxtapose the governance of emerging technologies within prevailing policy patterns.

The relationship between politics and the economy within the context of the energy and sustainability transition has been approached by scholars from different dimensions. For example, Kern and Markard [27] draw from international political economy to highlight issues of strong influence of dominant industry actors, diverging national interests, interplay of political developments at various levels, and distributional justice. In a more critical studies tradition, Newell [46] draws upon neoGramscian approach and proposes analysis of the relationship between production, power and world order. That is to examine ownership and access to production, finance and technology needed to enable stretch and transform processes [48]. Others, such as Bridge and Gailing [52] propose a geographically differentiated political economy lens which highlights how transitions are shaped by spatially constituted processes and simultaneously, create new spaces. In their analysis of deployment of CCS in South Africa using TIS approach, Ko et al. [53] examine political economy perspective through interests of powerful actors such as the government and incumbents.

3.3. Governing emerging technologies for sustainability transition

Governance of emerging technologies in a broad sense can be understood as the different modes or institutional rules of coordination among various actors, across multiple levels and the means by which they can be influenced to achieve solutions for collective problems [54,55]. Drawing from the above discussion, the role of policies in governing technology development for sustainability transition to a carbon neutral economy and society is central. However, with increasing contestations and ambiguity even in formulation of policy problems, let alone the direction of travel, means, and expected outcomes [56] within a context of geopolitical uncertainties, makes governance highly challenging for policy makers [34,57]. The conflicting views among diverse actors about the use, production and import of hydrogen [58], a complementary TIS is a case in point. Further, promising emerging technologies may be supported under innovation policies or climate policies. However, their goals are not the same and can even conflict as innovation policy for economic growth and competence building does not necessarily aim for regime shift necessary for transformative change [59]. Policy makers need to listen to a variety of voices and create open spaces for learning and experimentation as well as build competence to make independent critical assessments [60–62] to decide where intervention is needed. Policy makers also need to ensure that the knowledge generated during these processes is widely disseminated [63]. It is important to note that while the role of predictable and stable policies over long term to encourage private investments is critical, niches can also become captured by actors simply enjoying the benefits of protection without any intension of expansion [51]. Within a context of rapidly changing circumstances or moving targets, Kuhlman et al. [55] have proposed a form of tentative governance to combine flexibility with stability.

The process of bringing innovations from lab to market requires a systems approach with multiple interventions or a policy mix [64]. Interventions may include redirection of science and technology policies to allocate resources for R&D, training of specialised workforce, technology demonstration, as well as instruments for market formation such as establishment of standards and subsidies for new industries [25]. However, the Schumpeterian process of creative destruction cannot be accelerated only by supporting niche technologies [51] but also requires regime destabilisation [65]. Therefore, policies such as higher taxes and penalties for entrenched technologies to stretch and transform the external environment, which create incentives for incumbents to invest in niche technologies, are also important. While economy wide destabilisation policies may be high on the political agenda to address short-term emission reduction targets (for example the 2030 target for 55 % emissions under Fit for 55 [66]), technology policies are still needed to develop the advanced technologies needed to meet more stringent abatement targets in the long term [45]. Further, targeted policies may provide a far stronger pull than general carbon pricing measures and may also face less political resistance [67].

4. Methodology

Guided by the above theoretical handles, we investigate the enablers and barriers shaping the evolution of CO_2E by adapting the methodological steps proposed by Bergek et al. [25] for TIS analysis (Fig. 2).

4.1. System boundary

The empirical boundary of our analysis (Fig. 3) is Europe or more precisely the European Union. The focal technological innovation systems and boundaries were identified over several iterations based on the research question and purpose of analysis (a descriptive delineation) [33] and embedded in the EU context. We take into consideration the knowledge field of CO_2E including where it was combined with other technologies. The complementary technological advances in related TISs and their interactions are also considered [25] to the extent possible. This could happen vertically along value chains whereby the focal TIS draws raw materials, components, and services from related TISs such as water electrolysis, electrolysers, renewable electricity, electrical systems as well as direct air capture. Horizontally related TISs are those which draw on or compete for the same inputs and complementary assets or provide similar outputs as the focal TIS. CO_2E and mineralisation could be seen as competing for the same input – CO_2.

It may be important to point out that the boundaries and factors shaping a technology are not limited to nations or regions [25] and there are many external influences. For example, intense technological advancements in CO2E exist outside EU and companies like the Japanese Toshiba, and US based Twelve, a spin off from Stanford University are at the forefront of technology development. Geopolitical occurrences, such as Russian occupation of Ukraine have raised concerns about energy security and sovereignty. Heavy dependence on few countries such as China for supply of materials have led to amendments in renewable energy targets, the adoption of the Critical Raw Materials Act [68], with an objective to reduce external energy dependency more quickly, enhance domestic capacities and improve supply chain resilience. Private investments decisions in EU are also influenced by international developments such as the US Inflation Reduction Act 2022. As CO_2E is still in very early stages of maturity, and a highly energy intense industrial process, the political economy lens is operationalised by taking into consideration the overarching policy direction and actor perception towards this, and key policies for R &D, energy and industry and their potential implications on CO_2E.

4.2. Data collection and analysis

Our data sources include primary data from over 40 semi-structured interviews, complemented with policy documents and an expert consultation workshop. We looked at actors of the full innovation process, starting from fundamental research and applied research, up to a future supply chain actors consisting of carbon dioxide emitters and direct air capture developers to chemicals producers who are also potential users of this technology. Actors have been classified based on their main role within the TIS into nine categories (Fig. 4). An initial group was selected, and additional interviewees were identified using snowballing technique. Interviews were carried out based on informed consent and participant anonymity, in the period November 2022 – September 2023. The interviews were conducted mostly online usually

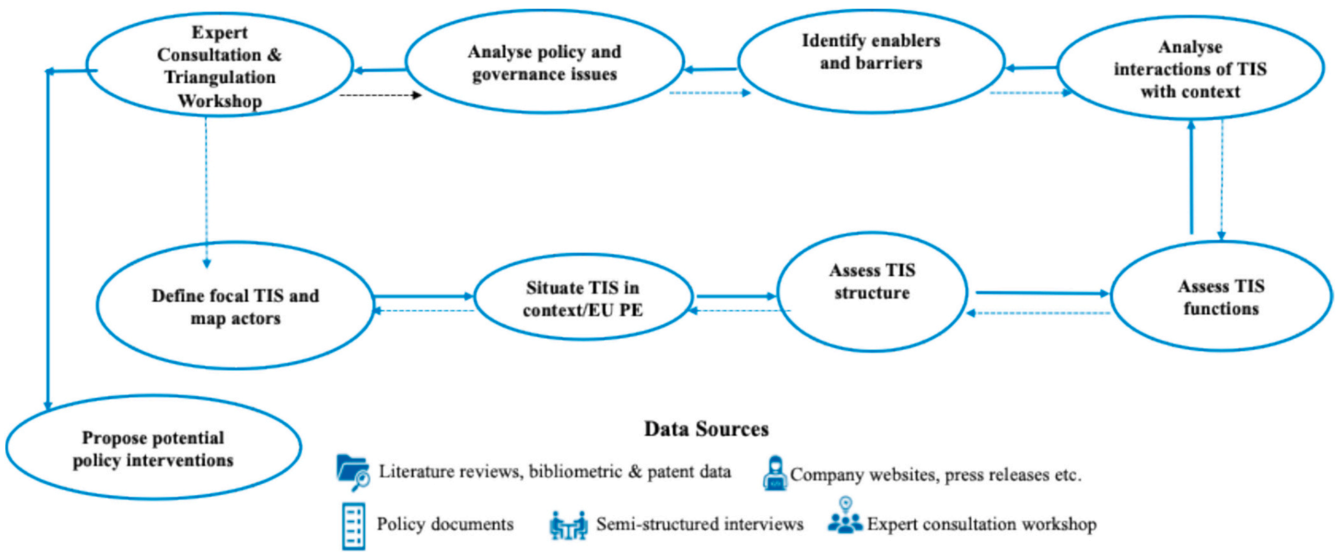

Fig. 2. Overview of methodology.
Source: Adapted from Bergek et al. [25]. Note: Dashed arrows indicate an iterative and non-linear process.

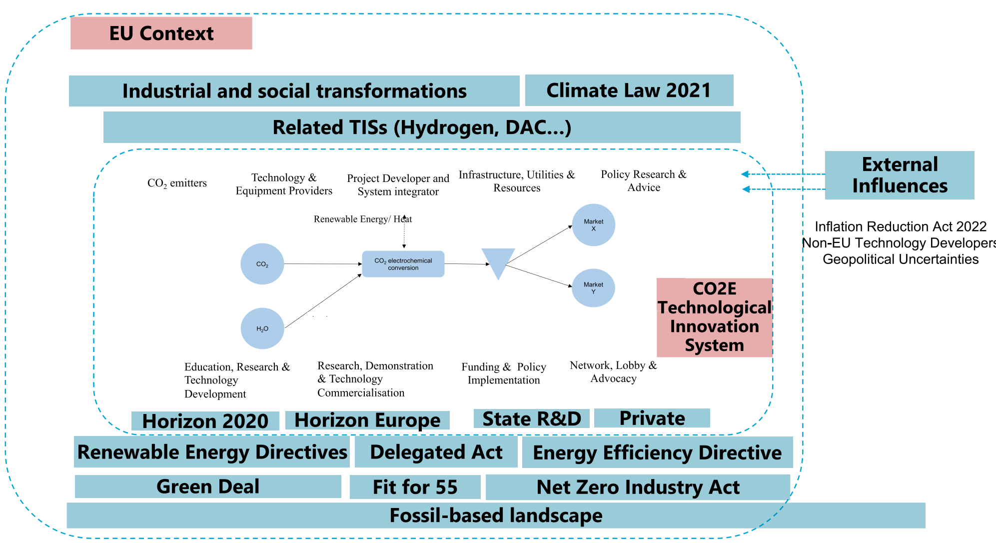

Fig. 3. Visualisation of TIS embedded in EU context.
Note: CO_2E TIS adapted from visualisation of future supply chain by Pérez-Fortes et al. [38].

by two to three project team members, and typically lasted 60 min. For all interviews, we followed a semi-structured interview guide informed by the TIS framework and our research questions. The interview guide was tailored to different actor types and adapted during the research as new information emerged. Transcribed interviews were coded through both deductive (using Atlas.ti) and inductive iterative processes, according to five broad themes and several sub-themes to orgnanise the rich qualitative data for addressing the research questions. These included context (technological, economic, political, social, environmental), TIS structure (actor strategies and expectations, institutions/legislation, network) and functions (seven as per Table. 1), policy (enablers and barriers, governance), and additional factors. An expert workshop was organised to triangulate the initial analysis and draw ideas for policy interventions. The data collection, sources and analysis process are further elaborated in the supplementary material.

5. Findings and analysis

5.1. Structure of technological innovation system: Actors, networks, and institutions

Actors: Several groups of actors are active in the field of CO_2E in Europe. As is expected from an emerging technology at low TRL, CO_2E forms a central element in university research groups, RTOs (Research and Technology Organisations), and start-ups. Examples of active actors can be understood from Fig. 1.

An important technology provider is Avantium, a Dutch company, founded in 2000 and is exploring 100 % plant based recyclable polymers with furandicarboxylic acid (FDCA) as the key building block. Other more recent entries are eChemicles Zrt, a Hungarian start-up which has received European Innovation Council (EIC) transition grant as part of SolarCO2Value project in 2018 and Paris-based Dioxycle. Prominent technology and equipment providers with strength in electrocatalysis, and design, supply, and commissioning of electrolysers include large

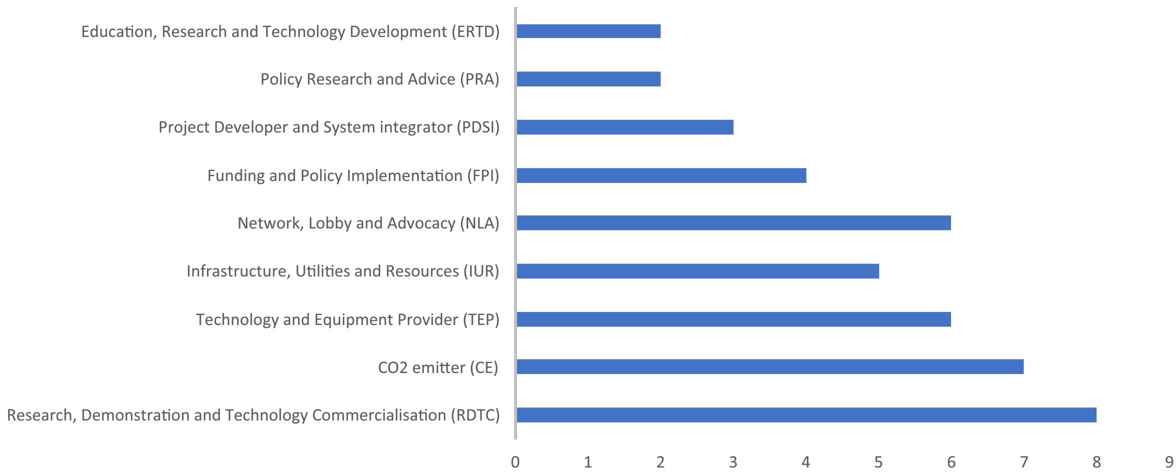

Fig. 4. Interview categories indicating actor roles. Note. Further explanation in supplementary material.

multinationals such as Topsøe and Siemens Energy, but also, smaller but quickly expanding firms like Sunfire. Fig. 5 illustrates the top patent holders in this technology and patenting trends. Fossil fuel companies such as Repsol and Shell also have some initiatives as part of their research portfolio. Project developers and system integrators are not yet active in this technology.

Networks: One of the most important networks is a community of actors brought together by CO_2 Value Europe, a non-profit association with over 70 members promoting and lobbying for CCU technologies to form a part of EU climate portfolio. Consortiums under EU Horizon 2020 form another important network with not only many different stakeholders within each project but also exchange and collaboration between different consortiums.[1] Entities like Avantium, Sunfire, VITO, TNO and the e-Refinery institute at TU Delft, which are involved in many different projects, represent key nodes in these networks.

Institutions: Since the Paris Agreement, a comprehensive institutional framework to achieve net zero and transition to a carbon neutral economy by 2050 is being put into place under the European Green Deal. In Fig. 6 we illustrate some key EU policies and show how the CO_2E TIS (assumed as a low TRL CCU) is guided by multiple policy instruments and their impact is mixed. For example, while policies such as renewable fuels of non-biological origin (RFNBO) defined in the Renewable Energy Directive (RED) legitimise CCU fuels, their production is strictly guided by subsequent amendments such as the Delegated Acts on Additionality [69] putting restrictions. Another example is the impact of the Net-Zero Industry Act [70] which aims to scale up manufacturing of clean technologies, enhance resilience and competitiveness of net-zero technologies, and reduce dependency on concentrated supplies. A subset of strategic net zero technologies (at least TRL 8) has been identified as based on their maturity and ability to contribute to intermediate emission targets leaving out less developed technologies. We discuss more influence of policies later in this section and in Section 6.

5.2. Analysis of TIS functions

5.2.1. Knowledge development and diffusion

The state-of-the-art in CO_2E is still at low TRL and currently there are many fundamental technological challenges which need to be overcome as discussed in Section 2. It also needs to be understood under what conditions the technology and products are sustainable in terms of their carbon footprint through life cycle analysis. Several R&D projects have been funded at EU H2020 Research and Innovation Framework aiming to upscale technologies that have reached at least TRL 3–4 to TRL 5–6 in the short to medium term (Fig. 1). State initiatives [71] and regional level cross-border collaborations such as between Germany and Netherlands [72] also exist. There is a move towards more collaboration and formation of large consortiums. New projects are not individual stand-alone projects, but "part of a bigger ecosystem now and they are looking into everything starting from the CO_2 source, where they are going to supply the energy and where the market is" enhancing their chance of success (RDTC_3). This function is also being enabled by networking organisations aiming to develop links "between some of the CCU technology that are already quite high TRL [...] and others that are much more in lab mode [...] and through collaborations "between academia, start-ups and small and medium sized companies and large companies to work together" (NLA_3).

One of the key governance challenges refers to the management of knowledge and collaborations between actors with different motivations. For example, many projects are working on components of social acceptance, values, governance, policy aspects, and social justice issues around transition. However, these aspects were "not always integrated in the technical development project, but it's more on a separate stream" and bringing all the aspects together is highly challenging (RDTC_1). Secondly, while the need for collaboration from the early stages in "not only designing the facilities but also trying to have suppliers and clients and governmental organisations work together" was viewed as important for success (PSDI_3), companies also need to protect strategic information from competitors. "So compliance and competition law does not allow us to work together on some strategically relevant topics […] for competing companies, it's more difficult to collaborate once you get closer to the implementation stage. So, for me, that's also a policy challenge of working together" (CE_2).

5.2.2. Influences on the direction of search

What was initially primarily academic interest in this technology, "changed drastically after signing of the Paris Agreement" and as "the threat of regulation going through the system becomes more real, interest in this technology, even from large companies has grown" (RDTC_4). Shortages in energy supply due to the war in Ukraine have led to revisions in renewable energy targets in the EU to reduce dependency on Russian oil, and there are strong legislative pressures for net zero transition. All this has manifested in mobilisation of R&D funding in low-carbon technologies including CO_2E. With a move towards electrification of industrial processes, a strong belief in the potential of CO_2E as a relevant technology for the future was expressed across key actor groups. However, there were some differences in the perception of its

[1] For example joint workshops and webinars by projects VIVALDI, CATCO2NVERS and CO2SMOS https://www.vivaldi-h2020.eu/news/vivaldi-co-organises-the-webinar-leading-the-way-in-turning-co2-emissions-into-chemicals/

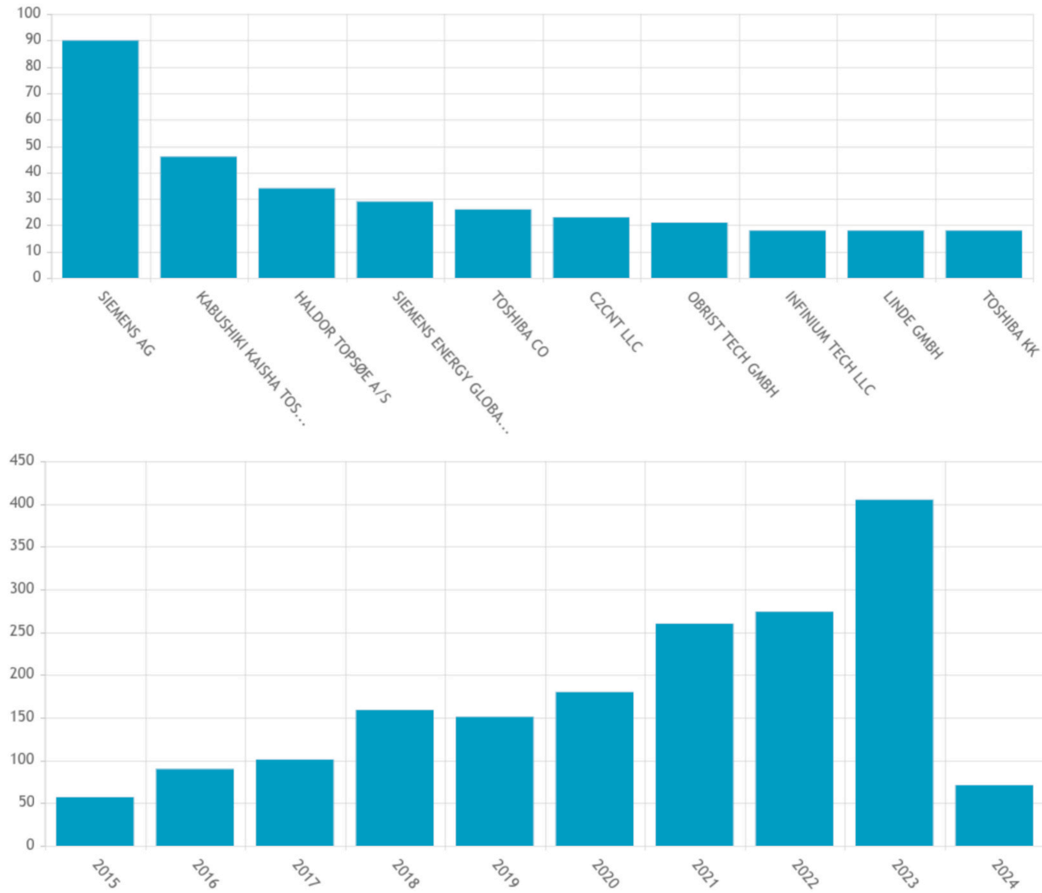

Fig. 5. Patents in CO_2E indicating applicants (above) and publication date (below)
Source: Patentscope, WIPO. Search words: carbon dioxide electrolysis. Date: May 2024.

application and scale. While some actors are convinced that it could be one of the key technologies with a potential to contribute to energy transition at a "global scale", with many advantages over photocatalytic and biological processes in terms of sensitivity and time of reactions, others view it viable over traditional thermochemical pathways only for small scale decentralised operations and particularly suitable for fine chemicals (ERTD_1, RDTC_3, CE_7, CE_6). There is also a degree of caution about too prematurely predicting its sustainability impact. Some pointed out that while electrochemistry is the chemistry of the future, with the current low state-of-art and multiple unresolved fundamental technical challenges; and the enormous quantities of emission reductions that is needed "it is a bit dangerous to really claim" its potential (PSDI_3, TEP_3). Others pointed out that current experiments were largely based on pure CO_2, and industrial flue gases, particularly from steel plants would need "extensive cleaning […] to have pure CO_2 as a feedstock" for electrolysis (CE_1). This makes the process very expensive.

Policy implications on the technology also appear to be mixed. For example, the Renewable Energy Directive (RED) III, where for "the first time Europe is creating mandatory quotas, so saying you absolutely need as a member state to use 1% of the energy in transport from RFNBOs", and failure to do so will result in penalty, are milestone legislations enabling CCU fuels (NLA_3). In EU states with available renewable energy, it offers opportunities for the production of Sustainable Aviation Fuels (SAFs). However, the focus on more mature technologies as strategic net zero technologies could affect low TRL technologies negatively (Fig. 6).

5.2.3. *Creation of legitimacy*

Strong signals of legitimisation were the incorporation of CCU in the 6th Assessment report of the [4] and in the EU Taxonomy [73] as contributing technologies for climate change mitigation and circularity. The Renewable Energy Directives suggesting a move towards renewable fuels of non-biological origin is another strong step towards encouraging CCU based fuels and chemicals. Formation of network and advocacy organisations like CO_2 Value Europe as well as large research group networks specifically around this technology have been important steps. Many of the projects have a component of assessment of societal readiness and public dissemination of knowledge and are also contributing to the creation of legitimacy.

A key issue in the creation of legitimacy is that the general level of public understanding about CCU is currently low and even "many policymakers don't fully understand" (NLA_6, RDTC_7). This need for enhancing collective intelligence also relates to the knowledge development and diffusion function. Another issue is the combined treatment of CCU with CCS, and at times negative public perception of CCS and its association with fossil fuel companies. The philosophes of the emerging CCU technologies and the long-standing CCS are different (industrial symbiosis and circular economy to reduce fossil fuel consumption vis-à-vis a linear approach). Therefore, proponents of CCU identify a need to split the debate between CCU and CCS at the policy level. However, this poses a challenge because of a "huge lobby of CCS at the EU level" (NLA_3).

5.2.4. *Entrepreneurial experimentation*

There is evidence of experimentation as is illustrated in Section 2. Much of this is at the lab scale with few pilot demonstrations and it has not reached where projects are "purely commercial projects since most projects have public funding, […] rather for demonstration purposes" (TEP_2). Despite the interest, the extent of investments from carbon

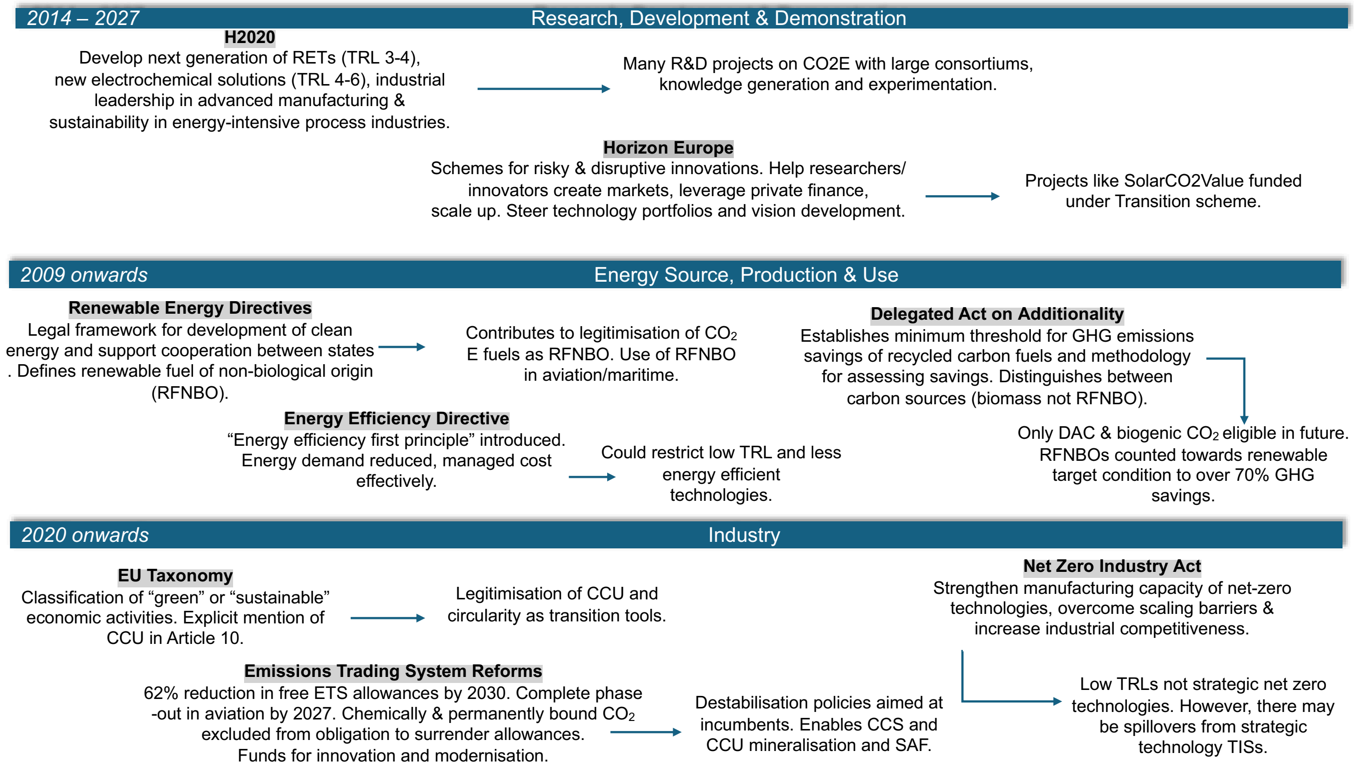

Fig. 6. Key EU policies on R&D, energy and industry, and their potential implication on CO_2E TIS.

dioxide emitters in CO_2E is unclear because as one incumbent actor points out “compared to what others in the outside world are doing, I wouldn't call us a very big player” (CE_6). Therefore, these cannot be identified as real diversification of portfolio into this technology. However, the activities of the carbon emitters and other incumbents could be critical to the advancement of the technology as “it's impossible for a start-up company” to have the resources required to reach the level of scale needed for this technology to have any impact (ERTD_1). .

A systemic challenge identified is the difficulty in demonstrating scaled up versions and funding deep tech projects as “ incentives for those kind of equipment that is not going to have any economic benefit is quite small […] and if we look at Horizon Europe and Innovation Funds, that's the gap that you have to bridge and that's a massive distance still, you know, and that's what we are seeing” (RDTC_7). However, iterative upscaling is a critical part and “super important because […] we are only interested in buying anything from you if you have demonstrated at a certain scale […] Seeing is believing” (ERTD_2). It was pointed out that “in Europe we don't have this culture, […] if you are a small company and if you have a bright idea, especially in deep tech, it is very difficult to find funds” (TEP_3). In contrast, the Inflation Reduction Act, is a “clear statement from the US government that they want to […] sponsor green technologies in a very efficient and simple way”, […], “maybe some of these investment decisions will be shifted towards US, […] you know with the tax benefits granted over there, it's just that a business case is there (NSA_6, TEP_5, TEP_2). Another systemic issue raised was the timeline in the permitting which “makes it very hard to use new technologies quickly because we need to freeze our engineering concept at one point and then have permitting process going on and when it is approved then we can start building. In the meantime, we cannot change the design anymore.” (CE_2). Observations were made that in the EU “you have a good kind of framework, let's say the theory […] we have the definition what it is and so on, but it's true that for the scaling up sometimes it's hard” (NLA_3).

5.2.5. Market formation

As an emerging technology, the market formation function is underdeveloped. Products are expected to be characterised by much higher costs vis-à-vis standard fossil fuel derivatives. A key barrier pointed out is that “there is no CO_2 policy”, and there is not sufficient drive for the big companies to deal with emissions “other than to make themselves feel better” (TEP_1). The current carbon dioxide pricing at less than 100 euros/metric ton and a recent study has pointed out the cost of emissions should be three times more to make a good business case [74] . While varied products from syngas to ethylene and organic chemicals are being investigated (Fig. 2), many commercial actors believe that one of the most promising market segments for electrochemistry is “high value specialty chemicals” where a good business case could be achieved with low volumes (CE_2, CE_6, PDSI_3, RDTC_6, RDTC_4). Niche premium products which could be certified with a green label and involve complex electrochemical conversions difficult to achieve via alternate routes were perceived as important market entry strategy. A keen interest was also expressed for high temperature solid oxide electrolysis which offers for industrial symbiosis using high temperature waste heat. Another key challenge is that, in comparison to energy and fuels, legislations around sustainable chemicals is still emerging. The eventual phase out of fossil fuels post 2050 will require “a whole new suite of materials […] so there's enormous challenges for society, which I think are not well recognised today” (TEP_1) was a concern raised. Interviewees voiced the surprising lack of attention even from NGOs pushing “for more sustainable chemicals to be produced”, the “very, very neglected” lead market development and policy recognition that materials may be “the most important one because you can store carbon in materials” over longer term. This not only includes concrete, “but also in longer living materials like plastics or products that are long there” (NLA_2, NLA_6, RDTC_4).

5.2.6. Resource mobilisation

Significant R&D fundings are dedicated under the Green Deal and

Horizon Europe. Projects under Horizon 2020 have funded CO_2 conversion technologies with the aim of industrial leadership in advanced manufacturing and processing. However, the challenge is to mobilise of resources beyond pure R&D, because as an interviewee points out “if you really want to develop a product, in our case piece of equipment, then you talk about millions” (TEP_3). Though there has been mobilisation of resources in CO_2E, it forms “only a very small part” of big (water electrolysis) projects and the current commercial focus is on water electrolysis (RDTC_6, Personal communication). However, the biggest resource challenge is the availability of renewable electricity and CO_2 within the framework of emerging policy guidelines.

Uncertainties and lack of long-term view were other factors impacting private investment decisions. For example, some stakeholders observed that there is no clarity yet “what we would like the industry to be” and “there's no dot on the horizon for our country […] where do we prioritise our electrons if we have them” calling for conscious decision making around innovation policies as otherwise it “makes it very difficult to make decisions, whether to put your money, […]” (RDTC_4, RDTC_7, FPI_4). Long term vision, clear incentives, and policy consistency “even if it's not necessarily policies that are excessively favourable for the technology, but if you know what the plan is for the next 10-15, 20 years, then you can move forward as a company without that uncertainty” were highlighted to be crucial (ERTD_1, RDTC_7).

5.2.7. Development of positive externalities

The TIS is in a formative stage where strong positive externalities are yet to develop. The main area where a great deal of spillover is expected is from the developments in the closely related TIS of water electrolysis. Technological improvements in DAC is another area which could create positive externalities.

Table 2 offers an overview of the TIS functions analysis.

5.3. Overview of key enablers and barriers

Drawing from the functions analysis, we illustrate in Fig. 7 an overview of the key enablers shaping CO_2E TIS emergence and barriers to its future development. One of the most important enablers has been that many R&D projects have been funded, resulting in capacities across organisations in Europe (A). Experimentation to get desired product(s), many times involving combination of technologies, such as CO_2E with biological fermentation or low temperature water electrolysis and high temperature CO_2E and using real off-gases from industrial sources suggest that the technology is slowly maturing (Fig. 1). There is particular interest in biogenic CO_2 sources, possibly in response to legislations such as the Delegated Act. The boundaries between fundamental and more applied research are not very rigid, with applied research organisations sometimes venturing into more fundamental research and university research trying to understand large-scale industrial from an early stage. All these is contributing greatly to a strong knowledge development and diffusion function and suggests cross-fertilisation of niches contributing to the critical mass of the learning process [50]. Regulations like RNFBO are creating the necessary legitimacy and also enabling the market formation function (B). Formation of network and advocacy organisations like CO_2 Value Europe as well as research networks like the e-Refinery, and dedicated PtX strategies in countries such as Denmark [75], are also contributing to legitimacy. The related technological developments in hydrogen and water electrolysis, which shares a close nexus with CO_2E, with many actors working on both technologies is an important enabler (C).

While destabilisation policies such as the ETF Reforms have stimulated interest in technologies like CO_2E, fossil fuels subsidies and new explorations despite their incompatibility with limiting global warming [76] prolong the status quo (D). Uncertainties in the availability of CO_2 and renewable energy in accordance with regulations at a desired price are enormous constraints (E). The bias towards mature technologies under the Net Zero Industry Act (F) combined with policy uncertainties

Table 2
Overview of CO_2E EU TIS functions analysis.

Function	Enablers	Barriers
Knowledge Development and Diffusion	▪ Intense public R&D investments ▪ Benefits from R&D in related TISs ▪ Systems approach to R&D with close linkages between fundamental and applied research and considering social science perspectives.	▪ Many fundamental technological challenges ▪ Carbon footprint uncertain ▪ Major developments required in complementary technologies ▪ Limited forums specifically dedicated to CCU ▪ Challenges in strategic knowledge management
Influences on the direction of search	▪ Climate policies and net zero targets ▪ Energy policies such as RFNBO ▪ Sovereignty and energy security concerns ▪ Promising for a sustainable chemical industry ▪ Interest from incumbents	▪ Slow changing fossil fuel regime, ▪ Low CO_2 emission price ▪ Bias towards mature technologies to meet net zero commitments ▪ Fundamental technological challenges ▪ Major developments required in DAC ▪ Carbon footprint uncertain ▪ Expensive purification for emissions from steel and cement industries ▪ Over expectations vis-a-vis current state-of-art ▪ Not an immediate commercial focus for incumbent firms
Creation of legitimacy	▪ CCU in 6th IPCC report, EU Taxonomy ▪ Energy policies such as RFNBO ▪ Formation of dedicated CCU advocacy groups	▪ Limited understanding of CCU and association with CCS ▪ Uncertainties around appropriation of investments based on earlier experiences. ▪ No long-term vision and political direction around technology. ▪ Over expectations vis-a-vis current state-of-art
Entrepreneurial Experimentation	▪ Active experimentation in terms of products, processes and technology combinations. ▪ Upscaling efforts in water electrolysis and hydrogen	▪ More upscaling and demonstrations needed ▪ CO_2E a small part of water electrolysis projects. ▪ Innovation system challenges (deeptech funding, permitting processes etc.) ▪ Perceived attractiveness of overseas locations ▪ Bias towards mature technologies to meet net zero commitments ▪ Not sufficient commercial interest.
Market Formation	▪ CCU as RFNBO and in EU Taxonomy	▪ Slow changing fossil fuel regime

(continued on next page)

Table 2 (*continued*)

Function	Enablers	Barriers
	▪ Coupling with related TISs (such as water electrolysis and hydrogen). ▪ Potential for decentralised production and niche high value low volume chemicals. ▪ Potential for non-fossil based ethylene	▪ Current CO_2 emission price/ETS/subsidies, no clear CO_2 policy ▪ Not sufficient commercial interest. ▪ Less attention to sustainable chemicals and materials. ▪ Carbon footprint uncertain.
Resource Mobilisation	▪ Intense public R&D investments ▪ Investments in related TISs (water electrolysis, hydrogen and electrolyser manufacturing).	▪ Limited renewable energy (zero emission electricity) with many competing uses. ▪ Only CO_2 from biogenic and DAC eligible in future ▪ Human resources in electrochemistry ▪ Bias towards mature technologies to meet net zero commitments ▪ CO_2 a small part of water electrolysis projects. ▪ Not sufficient commercial interest. ▪ Policy uncertainties impacting investment decisions
Development of Externalities	▪ Coupling with related TISs (such as water electrolysis and hydrogen).	▪ CO_2 a small part of water electrolysis projects. ▪ Challenges in strategic knowledge management

and characteristics of the European innovation system add further complexity and disincentives for private investments (G-H). The focus on energy with demand side policies for sustainable chemicals and materials still emerging is a barrier impacting the market formation function (I).

6. Discussion

6.1. Dynamics of TIS with context

The evidence shows that despite a vibrant emerging CO_2E TIS, there are many barriers deterring its rapid evolution, particularly affecting the entrepreneurial experimentation, market formation and resource mobilisation functions. Many factors are not specific to the CO_2E TIS but contextual, deeply entrenched and resistant to change. There are three dominant ways in the direction of policies is influencing TIS evolution.

First, a primary focus of climate policies is a shift to renewable energy. Many competing uses of limited renewable electricity and various policies guiding their production and use (as illustrated in Fig. 6) pose a complex environment for an emerging technology. For example, the need to meet the principles of "energy efficiency first" could make it difficult for a low TRL technology which has not yet reached high efficiency levels. Then, while specific contexts may differ and offer unique opportunities, energy intensive CCU/PtX technologies have been projected to be competitive only in countries with more than 3000 h of electricity prices below 10 €/MWh, namely Spain, Portugal, and Cyprus [77]. Further, the availability of CO_2 sources eligible for zero emission (biogenic and DAC) even in 2050 may emerge also as a major constraint. Overall, navigating the availability of two key inputs of CO_2E (energy and CO_2) in line with regulations greatly reduces the degrees of freedom of operation and requires special consideration.

Another policy priority for defossilisation, particularly in industrial processes where electrification is difficult is hydrogen. It is a complementary TIS, with some actors specialising in water electrolysis also invested in CO_2E. For example, Sunfire, which is a technology leader in high temperature syngas production via co-electrolysis in solid oxide electrolyser. In an optimum situation, advancements in water electrolysis could create positive externalities, and CO_2E could piggyback on these developments. This however is not straightforward as green hydrogen production itself is yet to take off as a mainstream industry and fraught with many uncertainties [78]. Further, the policy attention to higher TRL hydrogen, may motivate commercial actors to draw resources away from fledgling technologies such as CO_2E and prioritise on technologies higher on the political agenda. A potential intervention could involve demarcating a larger space for CO_2E within existing water electrolysis programmes to purposefully create coupling between these two technologies as well as incentivise private investments.

Third, sustainability transition is not only linked to climate change mitigation, but also to maintaining industrial competitiveness and economic growth in Europe. Major national programmes such as GroenvermogenNL in The Netherlands also have dual goals of reducing emissions and enhancing competitiveness to ensure future earning power of the country. Policies to support these dual objectives through the use of strategic net-zero technologies under Net Zero Industry Act create a bias towards mature technologies. More disruptive technologies, such as CO_2E which do not contribute to these immediate and short-term policy goals are pushed to the periphery, including in company portfolios.

6.2. Policy implications

While there is a trend towards whole-of-economy approach in transition policies, as identified in innovation literature [45,67], for a carbon-neutral future, there is also a need to create a protective space for emerging technologies like CO_2E through technology specific policies. We identify three points of interventions particularly relevant for the next phase of TIS development within such a policy.

First, enabling a smoother transition from the R&D phase to high TRL through long term projects with iterative upscaling. Although R&D grants are relatively easy to access, funding challenges at high TRL lead to the proverbial "valley of death", dilutes the effectiveness of R&D funding. This has been raised in our interviews but also reported in recent literature [52,56,79]. While R&D projects are usually short term, a protective space over a longer term is needed for experimentation, demonstration, and upscaling to a tangible level of production. An example of a long-term initiative is the Kopernikus Projects in Germany, initiated in 2016. Kopernikus applies dynamic roadmapping to manage uncertainties around technology development, similar to a form of tentative governance proposed by Kuhlman et al. [55].

Second, technologies need to be strengthened through a combination of technology-push and demand pull policies, to stimulate market formation rather than a linear model with only R&D focus [4,67]. Therefore, development of lead niche markets (particularly in sustainable chemicals and materials) which are strategic testing grounds and sources of early revenues [25] and identifying products under public procurement are important interventions. It can be expected that the adoption of standards and regulations for sustainable chemicals, as is happening for fuels, would strengthen market formation.

Third, in line with earlier research by Nemet et al. [63], we also identify a strong need for more strategic management of knowledge development and diffusion. Within this, we point to three important interlinked areas where intervention could create positive externalities and impact several TIS functions. One of this relates to the collaboration between different actors with conflicting interests. Creating mechanisms

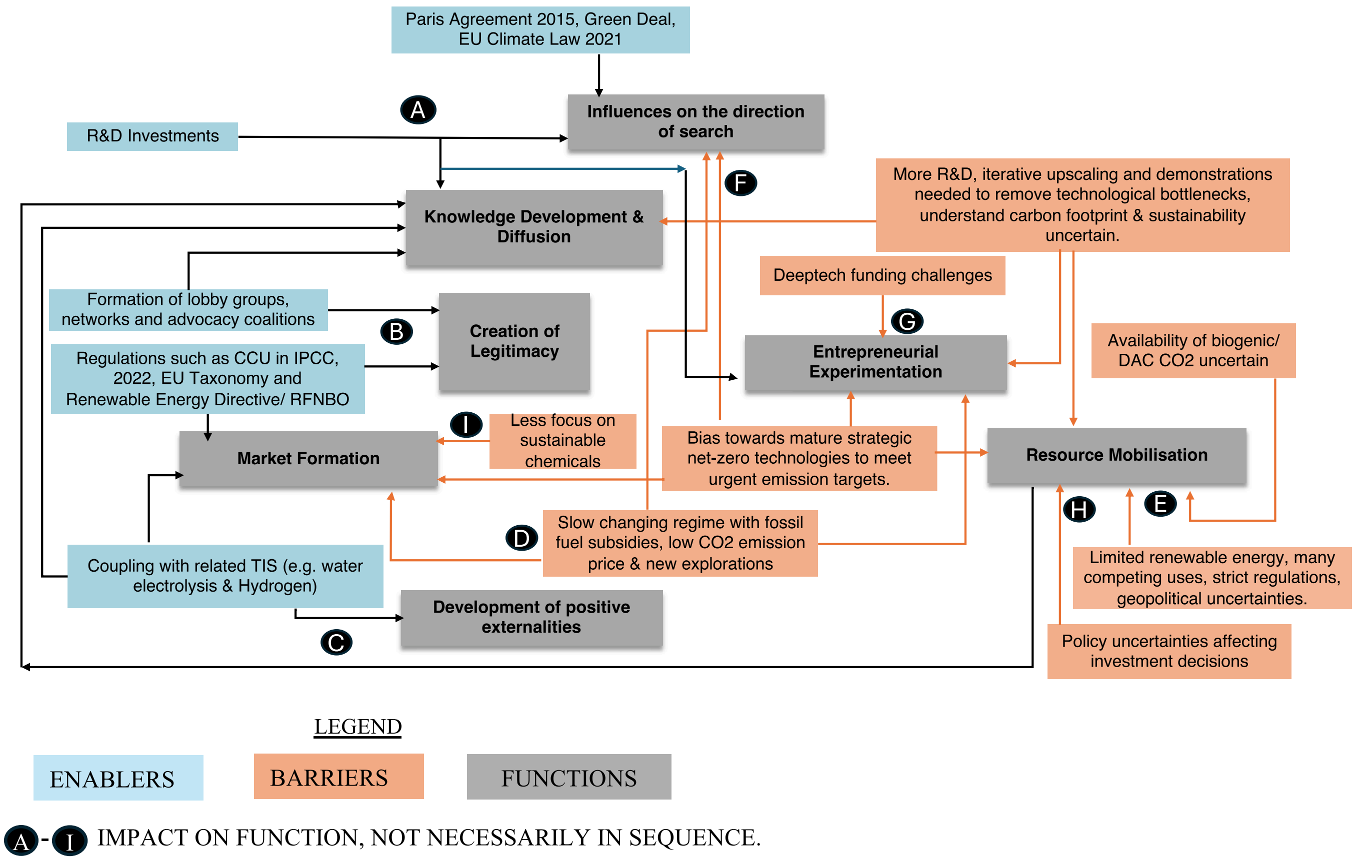

Fig. 7. Enablers and barriers influencing CO_2E TIS evolution in Europe.

to valorise knowledge from public funds for societal benefits and ensuring that knowledge does not get trapped in vulnerable R&D departments of powerful incumbents interested in maintaining the status quo are important areas for policy action. Next, there is a need to enhance collective intelligence around the technology including among policy makers. This is also needed because CCU has typically been associated with CCS, as the initial CO_2 capture part. It is only recently that CCU technologies (or PtX) are being recognised in their own right for their potential to contribute to climate change mitigation. Consequently, not only is little understood about these technologies beyond specialists, their association with at times contested CCS [80,81] may raise questions about legitimacy. Third, there is a need to build consensus around the expectations from the technology from a transformation perceptive (such as future jobs, climate, competitiveness, technology leadership) in a more participative and transparent manner. Soft instruments based on consensus building and information exchange involving a wider group of actors as part of a socio-political process are identified to be especially important in the formative phase of TIS development [60,61,82]. Therefore, the purpose of these open discussions is not solely to enhance collective intelligence and social acceptance, but also in framing and envisioning what the future chemical industry in a carbon neutral Europe would look like and what could be the expected role of CO_2E within these emerging industrial dynamics. This would help shift the currently fit and conform narrative in CO_2E studies (dominated by cost comparison with fossil fuel alternatives) to a stretch and transform vision (aspects of sustainability, carbon neutral society).

6.3. Limitations and future research

This study has several limitations. First, while by combining political economy with TIS approach, we have been able to highlight the interplay between the surrounding environment and internal TIS dynamics, our analysis is straightforward and lacks a more critical perspective. A deeper exploration of relationships between actors with different motivations, and the production and ownership of knowledge and its implications on the technology would be a valuable future research avenue. Second, while sustainability transition involves both production and consumption shifts, we have focused mostly on the former. Future research could look how more responsible consumption based on principles of sufficiency and sobriety could impact the TIS. Third, our analysis is a qualitative exploration embedding the TIS framework within the EU policy context and offers a socio-technical perspective. Interpreting these findings in conjunction with techno-economic assessments would offer a more complete picture and is another future area of research. Fourth, our TIS analysis offers a meso-level perspective at EU level and is not able to consider state level or regional specificities. Future research could look at how CO_2E fits into the broader industrial dynamics, available technological options, resources and transformation goals taking specific cases at the regional and country level. Case studies at state or regional level are important because member states are responding to EU legislations with national transition policies specific to their unique industrial structure and geographic location, whereby the latter determines the sources, availability and use of renewable energy. Therefore, a micro level study would be a valuable extension and particularly relevant for state level policy making. Last, there is a selection bias as many of our interviewees are closely associated with the technology and particularly, users are less represented. Anticipation studies focused on user expectations could inform R&D and is an important future research area.

7. Concluding remarks

A wide arsenal of technologies will be needed in a carbon neutral economy and many disruptive technologies which may contribute to this are currently in their infancy. Our research investigates the evolution of CO_2E, one such emerging technology, by combining TIS approach with political economy perspectives. Our analysis reveals a fast-developing CO_2E TIS in Europe with many dedicated research groups mainly in universities and RTOs, as well as in some firms. Among our interviewees, a strong belief exists in the future potential of this technology as one option in a basket of solutions needed to reduce CO_2 emissions, though the scale and timeline of its adoption are less agreed upon. The TIS is in an early formative phase of development and in a state of flux. At this stage it is vulnerable to shifts in actor strategies, and if key actors decide not to pursue CO_2E development any further, it could cause a discontinuity in the learning process, demotivate other active players and signal disinterest to passive actors [33,45,50].

The TIS is being enabled by many R&D projects, regulations, advocacy, and advances in water electrolysis. Many technological challenges need to be resolved, and its carbon footprint fully understood through lifecycle assessments. However, besides technological challenges, there are many contextual barriers. Overarching policy priority is on one hand meeting CO_2 emission reduction targets made binding by EU Climate Law and enhancing industrial competitiveness and resilience using mature strategic net zero technologies on the other. Wedged between these two policy priorities, emerging technologies like CO_2E which currently do not contribute to these immediate goals face a challenging environment. Combined with a slow changing fossil fuel regime and uncertainties around renewable energy availability, this threatens future TIS development. We illustrate the overwhelmingly critical role of contextual interactions in TIS development, particularly as the technology matures and functions such as market formation, resource mobilisation and positive externalities become important.

It is not that all emerging technologies will be feasible for commercial exploitation. However, their prospects can only be understood through experimentation, demonstrations, and niche-market formation. Neglecting these difficult processes, as innovation scholars have cautioned, in a “quest for cost efficiency in meeting near-term emissions target” will mean that emerging technologies may never see the light of day to contribute to future transition goals [45]. We have discussed the need for technology specific policies to enable these processes through long term projects to support the next phase of CO_2E TIS development. Such directed policies are also easier to implement as their impact on the broader economy is less pronounced than economy-wide policies such as for example carbon price [67] and they can also prevent discontinuity in the learning process [45,50] from shifting government priorities.

Previous techno-economic assessments have mostly looked at price of carbon dioxide emission, renewable energy and electrolysers in the commercialisation of CO_2E, comparing it with traditional fossil fuel alternatives. As Lauber and Jacobson [49] point out in their study on renewable energy in Germany, this kind of fit and conform narrative ignores the social and environmental cost of fossil based derivatives and the extended timeline over which the latter have been developed. Further, such a discourse underplays the unique and superior performance such as biodegradability or recyclability of new materials as compared to conventional alternatives. We have identified a need to empower the TIS with a stronger stretch and transform narrative by imagining the role of CO_2E in a carbon neutral economy and society.

Our research offers a rich narrative of underlying innovation processes and the voice of key actors shaping CO_2E TIS and complements techno-economic assessments with socio-technical perspectives. In this way it contributes to both TIS and technical CO_2E literature as well as evidence for governing emerging technologies for sustainability transition. Though not the primary goal, our methodology also stimulates dialogue and cross-fertilisation of ideas between different actors during the research process.

CRediT authorship contribution statement

Sanghamitra Chakravarty: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Validation. **Hans de Bruijn:** Writing – review & editing, Conceptualization, Investigation, Formal analysis, Validation, Funding acquisition. **Mar Pérez-Fortes:** Writing – review & editing, Investigation, Formal analysis, Validation, Resources, Project administration, Funding acquisition.

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.

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Appendix A. Supplementary material

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Data availability

The authors do not have permission to share data.

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