Master Thesis – Master Sustainable Business and Innovation

Forming Markets for Carbon Dioxide Removal Technologies: The Role and Influence of Voluntary and Compliance Carbon Markets

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0 ABSTRACT

Introduction: Limiting global temperature rise requires carbon dioxide removal (CDR) at large scales. Yet, commercial deployment of CDR technologies is limited and establishing a global CDR market is vital to secure funding for scaling the industry.

Theory: The Technological Innovation Systems (TIS) framework is a theoretical approach to understand socio-technical change, highlighting the importance of technological innovation and the interactions between actors and their networks within an institutional context.

Methodology: This research maps the structure of the TIS at an EU level and analyses the performance of seven TIS functions, with a particular emphasis on market formation [F5] for CDR; an intangible product. This function is expanded by examining two existing carbon market mechanisms, the voluntary and compliance carbon markets, to understand their impact on the development of a market for intangible products. Various CDR actors, including CDR companies, policymakers, networks, experts, journalists, niche market actors, and municipalities, were interviewed and a separate survey was conducted.

Results: The results showed that the CDR TIS is currently in a formative phase, where start-ups are focused on R&D and technology demonstrations, scientific uncertainties exist, and private funding and voluntary demand play a significant role. The TIS is influenced by both soft institutions and hard institutions. While soft institutions are crucial in driving private governance and voluntary demand in the early phase, there is a strong desire for market formation mechanisms governed by hard institutions. Different opinions exist on how to establish compliance carbon markets, indicating a lack of consensus and common understanding in the CDR space.

Discussion: The application of the TIS framework to assess the diffusion CDR technologies in this research emphasises the need to understand the dynamics of market formation for intangible products. The study incorporates the concept of private governance alongside the TIS framework, recognizing its role in the formation of a voluntary market for CDR. Moreover, it emphasizes the importance of fast-moving soft institutions in early market development and the need to synergize different strands of theory for effective industry creation.

Conclusion: The voluntary carbon market, governed by soft institutions, has played a significant role in the early development of the CDR industry. However, compliance market formation mechanisms, governed by hard institutions, are necessary for long-term growth. Overall, a combination of soft and hard institutions is crucial for market formation and diffusion of CDR technologies.

Keywords: Carbon Dioxide Removal, Technological Innovation System, Market formation, Compliance Carbon Market, Voluntary Carbon Market

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1 INTRODUCTION

1.1 PROBLEM STATEMENT

Climate change is widely recognized as a threat to the world, and anthropogenic emissions need to be limited to avoid its largest impacts. Because of the prolonged use of fossil fuels, carbon dioxide (CO_2) has accumulated in our atmosphere, and due to the nature of Earth's biogeochemical processes, this excess of CO_2 has a long residence time and cannot be removed naturally within a time scale of hundreds to thousands of years (IPCC, 2018). Following the Intergovernmental Panel on Climate Change, we must keep global mean temperature rise well below 2°C (IPCC, 2018). To achieve this goal, a major transition to decarbonize production and consumption is underway by switching from fossil fuels to renewable energy sources and curbing negative environmental impacts to reach a netzero target by the year 2050. However, even if these challenging objectives are met, with all fossil-based resources being replaced by renewable counterparts, it will not be enough (Kapnick, 2021; Renforth & Wilcox, 2019). The world will need to actively remove carbon dioxide from the atmosphere on a scale of 10 gigatons of CO_2 annually by 2050 to stay beneath the 2°C goal for global mean temperature change (Figure 1) (Bach et al., 2019; Furhman et al., 2023).

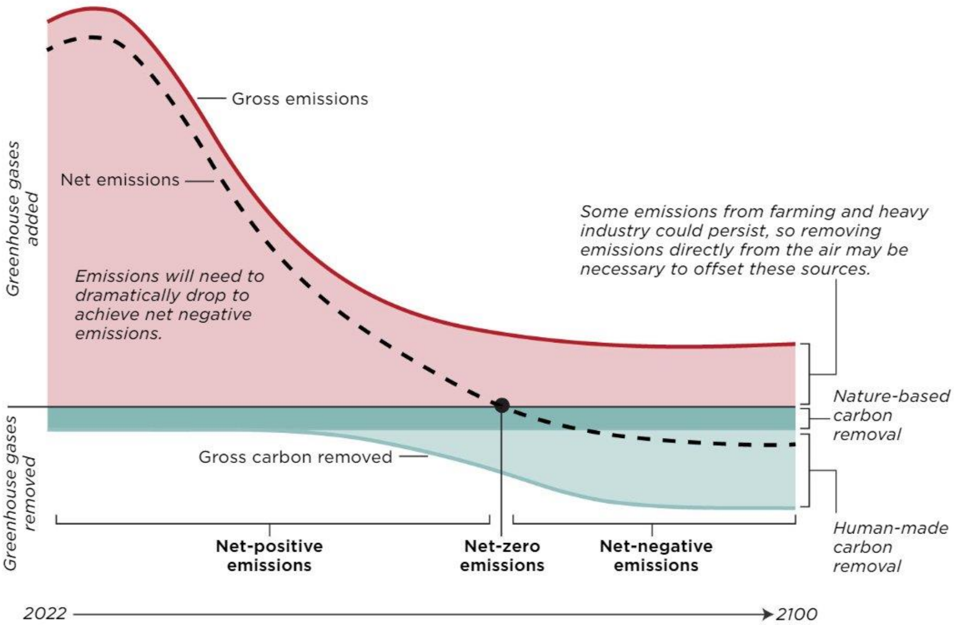

Figure 1: Emission reduction and CDR capacity needed to stay within global goals (IPCC, 2022)

We are therefore forced to tread a path in which we will rely heavily on Carbon Dioxide Removal (CDR), capable of removing CO_2 from the atmosphere at large scales and for the long term (Fajardy et al.,2019; Fuhrman et al., 2019; Fuhrman et al., 2023; Geden, Peters & Scott, 2018; Renforth & Wilcox, 2019).

"The deployment of carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved." (IPCC, 2022, pg. 40)

Unlike Carbon Capture and Storage (CCS) that removes CO_2 from point source smokestacks, CDR focuses on the passive removal of CO_2 that is already in the atmosphere (Fuhrman et al., 2019; IPCC, 2022; Renforth and Wilcox, 2019). Alongside nature-based solutions, like reforestation, various methods exist that use modern, industrial, scalable technologies to remove extant CO_2 from the atmosphere. Unfortunately, as of yet, few technologies have been deployed commercially, let alone at a scale close to that needed to provide a meaningful contribution to climate change (Bach et al., 2019; Fuhrman et al., 2019; Grubb et al., 2022). The industry for CDR may become one of the largest sectors in the world (Renforth and Wilcox, 2019), and various technologies are being developed that can achieve CDR with distinctive use of biological, technological, or chemical processes and reservoirs (IPCC, 2022, pg. 40; Renforth and Wilcox, 2019). However, without a stable revenue stream, the required scale of CDR will not be realized before it's too late (Fajardy et al.,2019). This underlies the importance of forming a legitimate, functioning global market for CDR to provide the financial resources necessary to scale this industry. An understanding of the formation of such a market must also take into account potential interactions between technological, institutional, political, and user-related factors of an innovation.

1.2 THEORY

Innovation Systems is a theoretical framework to understand change in socio-technical systems (Carlsson & Stankiewicz, 1991; Edquist, 2001; Lundvall, 2007; Malerba, 2002; Nelson & Nelson, 2002). Technological innovation is key in socio-technical change, and developing an understanding of the innovation process of any particular technology is essential in ensuring the survival and success of that technology (Bergek et al., 2015; Hekkert et al., 2007). The innovation system framework emphasizes that the system surrounding a particular innovation is the determinant of its processes. In other words, the innovation emerges from the complex interactions between actors and their networks operating within an institutional context (Bergek et al., 2008a,b; Carlsson & Stankiewicz, 1991; Dewald & Truffer, 2011). These complex interactions jointly influence and ultimately determine the rate of diffusion of an innovation (Lundvall, 2007). Although many forms of Innovation Systems exist, this research will focus on Technological Innovation Systems (TIS), which places a technology as the central unit of analysis (Carlsson & Stankiewicz, 1991; Bergek et al., 2008a,b; Hekkert et al, 2007; Hekkert & Negro, 2009).

1.3 RESEARCH SCOPE

The level of aggregation in the technological scope takes an agnostic approach to the nature of CDR technologies, as long as they utilize technological, scalable processes to remove extant carbon dioxide from the atmosphere. Various methods currently exist that either directly or indirectly capture CO_2. Direct Air Capture (DAC) directly captures CO_2 and stores it geologically. Other methods indirectly capture CO_2 either biologically or by chemically accelerating natural processes on earth through a geological, terrestrial, or marine based approach. The geological approach, known as Enhanced Weathering, accelerates chemical weathering reactions in which atmospheric CO_2 is bound for long-term storage (Bach et al., 2019). The terrestrial approach involves the biological process of sequestering CO_2 in biomass and utilizes a technological process for storage, and includes Biochar and Bio-Energy, Carbon Capture and Storage (BECCS). Although closely tied to nature-based CDR, this method is considered a technology because it requires a certain level of technological development to permanently store CO_2 (Fuhrman et al., 2019; Renforth and Wilcox, 2019). The marine based approach is focused on improving or increasing the role of oceans in taking up atmospheric CO_2 either biologically or chemically (Bach et al,. 2019; Renforth and Wilcox, 2019), and is known as Ocean Alkalinity Enhancement or Ocean Carbon Dioxide Removal. Although operationally different, this research considers this broad basket of CDR technologies to fall under one functional TIS for three reasons. First, in an emerging stage, a TIS can share upstream or downstream value chains, where the growth of one technological system could induce growth of a parallel system (Hillman & Sandén , 2008). Second, because this research is focused on the formation of markets for CDR, the results and recommendations that emerge will be applicable to all CDR technologies because they produce a homogenous product. Third, it is highly likely that a broad suite of technologies will be necessary to reach our climate objectives. Therefore, adopting a wider technology-neutral understanding of forming a market for negative emissions will accelerate the potential of CDR to mitigate climate change. The definition of CDR in this research is limited to those processes where previously emitted, or passive atmospheric CO_2, is technologically removed and durably sequestered for a minimum of 100 years. Carbon Capture and Utilization (CCU) and Carbon Capture and Storage (CCS) are excluded from the research, as these technologies are concerned with point source capture of carbon. Although there are some structural overlaps between CCU/CCS and CDR, they are inherently separate innovation systems. Furthermore, nature-based CDR, such as reforestation, afforestation, improved forest management, agroforestry and soil carbon sequestration (IPCC, 2022, pg. 40) are not considered technologies and are intentionally excluded from this research. Figure 2 provides an overview of the taxonomy of the different forms of carbon crediting, highlighting the focus of this research in gold.

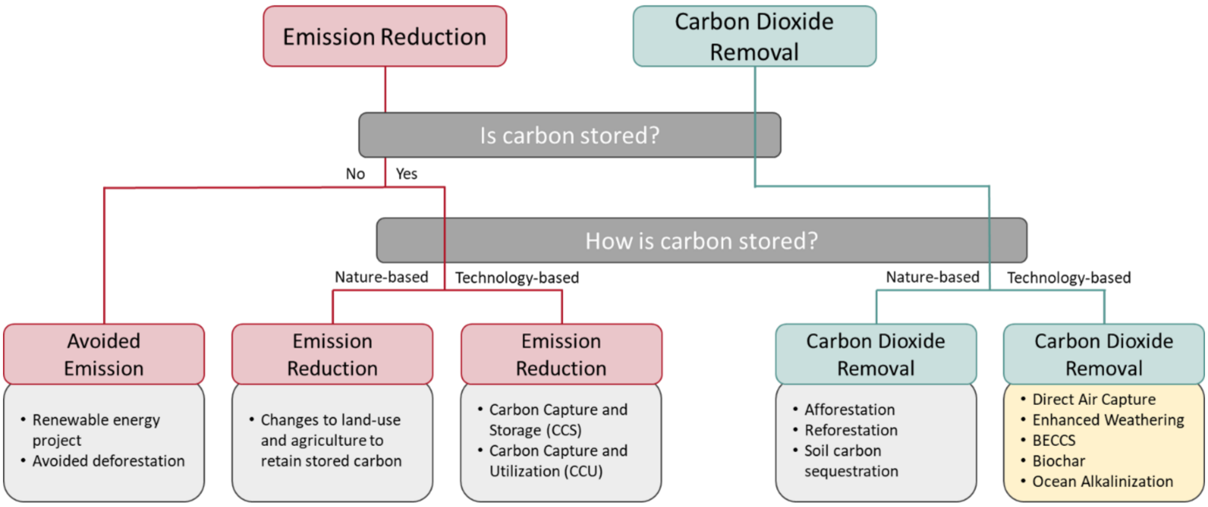

Figure 2: Taxonomy of Carbon Reduction and Removal (adapted from La Hoz Theuer et al., 2021)

The geographic scope of this research is set to encompass the CDR TIS at the EU level. Conventionally, the focus of the TIS approach is on institutions and networks of agents on a national level, as in the studies by Hekkert et al. (2007), Negro et al. (2007), Bergek et al. (2008a), Hillman & Sandén (2008), and Sandén & Hillman (2011). These studies adopted a country-specific focus because of the importance of national institutions for the development and diffusion of the technology and the aim to generate national or local policy recommendations (Wieczorek et al., 2015). However, narrowly focusing on a TIS in a specific country risks overlooking highly relevant transnational influences that significantly contribute to TIS performance (Markard, Hekkert & Jacobsson, 2015; Wieczorek et al., 2015). Since the institutions that govern carbon market mechanisms, like EU Climate Law (European Commission, 2021), are operational on a EU-level, this research will move beyond the traditional national focus and will focus on the CDR TIS at the EU level. Although mapping the TIS in this transnational context will likely diminish the level of detail in the research, the broader perspective will make the results more encompassing. Given the EU-level focus of the research, global institutions like the Paris Agreement (UNFCC, 2015, pg. 9) are intentionally excluded from the research scope.

1.4 RESEARCH AIM & GAP

The aim of this research is to develop an in depth understanding of the innovation system that supports the development and diffusion of CDR technologies in the European Union (EU). This will be done through the lens of a TIS, identifying the structural components and analysing the system's performance by assessing seven system functions. Furthermore, this analysis is extended by expanding one of the seven system functions, market formation, to discover the influence of two existing carbon market mechanisms in the formation of a market for CDR. The use of this framework is unique because TIS studies have generally focused on tangible goods and services, such as renewable energy technologies and electric vehicles (Dewald & Truffer, 2011; Hillman & Sandén , 2008; Ko, Zigan & Liu, 2021; Pohl & Yarime, 2012; Sandén & Hillman, 2011; Suurs & Hekkert, 2009; Wieczorek et al., 2013). Although these studies have offered a comprehensive understanding of the TIS framework in relation to tangible products and sectors, there is a gap in the literature when it comes to intangible products. CDR technologies are tangible technologies that develop and sell an intangible public good and service: reduced emissions and climate change mitigation (Ahonen et al., 2022; Andrew, 2008; *Armstrong* vs. *Winnington*, 2012; Poralla et al., 2021; Tompkins & Eakin, 2012). All people benefit from this public good, leading to the well-known tragedy of the commons, where a finite resource, in this case climate stability, will be exhausted by rational, utility-maximizing individuals rather than conserved for the benefit of all (Ostrom, 1990). Given that the TIS for CDR is in an emerging stage and its principal product (negative emissions) does not follow traditional market mechanisms, such as the sale of vehicles or kilowatt-hours, the process for forming markets is a particularly interesting point of focus. Furthermore, experiences with earlier carbon markets, specifically those governed by the Clean Development Mechanism and Joint Implementation under the Kyoto Protocol, raise major concerns about the environmental integrity of these mechanisms (Allen et al., 2021; Edmonds et al., 2021; La Hoz Theuer, 2019). The intangibility of carbon as a commodity and the negative experiences surrounding carbon market mechanisms makes the formation of a market for CDR inherently challenging (Allen et al., 2021; Edmonds et al., 2021; La Hoz Theuer, 2019; Tompkins & Eakin, 2012). Stimulating demand for innovation is a key part of market formation (Bergek et al., 2008ab; Hekkert, 2007; Hekkert & Negro, 2009), and an understanding of the role of market formation mechanisms in the context intangible products is important (Boon & Edler, 2018; Wesseling & Edquist, 2018).

This research contributes to the understanding of market formation by exploring how market mechanisms form demand-side conditions for an intangible good. To this end, the market formation function of the TIS framework will be expanded by examining two established market mechanisms, the voluntary and compliance carbon market, and determining how their formation mechanisms mobilise demand for emerging CDR technologies. However, this dichotomy of carbon markets reveals a shortcoming of the TIS framework. The dynamics of voluntary market-based instruments can be understood under the concept of private governance, a concept that has not been heavily studied in innovation systems. Although previous TIS studies have considered the influence of environmental standards acting as voluntary market-based instruments (Grösser, 2012; Moy de Vitry, 2013; Ramirez-Gomez et al., 2022; Toivonen et al., 2021), these studies have not broken out the role of a standalone voluntary market mechanism and the influence of private governance. Because private governance plays such an important role in influencing the market for CDR, this study touches briefly upon environmental governance theory to provide a theoretical understanding for the dynamics that govern voluntary markets for sustainable products. This study will aim to answer the following research question:

WHAT ARE THE DRIVERS AND BARRIERS TO THE DEVELOPMENT AND DIFFUSION OF THE CARBON DIOXIDE REMOVAL TECHNOLOGICAL INNOVATION SYSTEM, AND WHAT IS THE ROLE AND INFLUENCE OF THE COMPLIANCE CARBON MARKET AND VOLUNTARY CARBON MARKET?

The research proposal is structured as follows. First, this chapter serves as an introduction to outline the research. Second, the theoretical framework of the Technological Innovation System is described, defining the framework's structural components and the functions that jointly influence the diffusion of an innovation. In this section, the market formation function is expanded by examining two existing carbon market mechanisms to provide an in-depth understanding of the dynamics of this function for intangible products. Additionally, because the concept of private governance has not been studied in innovation systems, the section on voluntary markets is supported by environmental governance theory. The third section contains the methodology of the research, describing in detail the research design and process. The fourth section contains the results, split into the structural and functional analysis. The fifth section contains the discussion, where the theoretical implications are described and limitations are acknowledged. The final section concludes the research by answering the research question, stating managerial recommendations, and providing a key takeaway from the research.

2 THEORY

The following chapter introduces the theoretical framework that serves as the foundation to analyse the results. It introduces TIS framework and expands the market formation function by analysing two existing carbon market mechanisms. Here, the research touches upon environmental governance theory to envelop a theoretical foundation to substantiate the role of private governance in the emergence of the voluntary carbon market.

2.1 INNOVATION SYSTEM FRAMEWORK

Drawing from the evolutionary theory and a system approach, a systems of innovations framework has been developed (Arnold & Bell, 2001; Carlsson & Stankiewicz, 1991; Malerba, 2002; Nelson & Nelson, 2002) in which the emphasis lies on the interaction between a system's structural components (Malerba, 2002). A number of different strands of innovation system concepts have been introduced, including: National Innovation Systems, focusing on economic development as a product of knowledge and learning within the geographical boundaries of a nation (Lundvall, 2007; Nelson & Nelson, 2002); Sectoral Innovation Systems, mainly focusing on firms and arguing that the systems boundaries are based on industry-related factors rather than national factors (Malerba, 2002); and the Technological approach, where system boundaries may vary across techno-industrial sectors (Carlsson & Stankiewicz, 1991).

Carlsson and Stankiewicz (1991) developed the Technological Innovation Systems (TIS) framework to understand the dynamics of an innovation system by analysing its central features, namely economic competence, clustering of resources, and institutional infrastructure. The definition of a TIS, as defined by Carlsson and Stankiewicz (1991, pg. 93):

> *"A technological system is defined as a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology."*

In the modern world, the institutional infrastructure in which an innovation is embedded is hardly determined by geographical or sectoral boundaries. The knowledge base for most technologies originates from various actor networks globally, located in different geographical locations (Carlsson & Stankiewicz, 1991; Hekkert et al., 2007). By taking a specific technology as a starting point, a TIS provides an overview of the dynamics of innovation processes in specific technological fields (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Bergek et al., 2008a).

2.1.1 STRUCTURAL COMPONENTS

A TIS is made up of four structural components: actors, networks, institutions and infrastructure. Actors include all stakeholders that contribute to the development and diffusion of a technology (Bergek et al, 2008b), and can be classified according to their contributing role in the development of a TIS (Suurs & Hekkert, 2012; Wieczorek & Hekkert, 2012). Direct contributors include developers and adopters, like start-ups and large firms. Indirect contributors include governmental organizations, financial organizations, and knowledge institutes that function as regulators, financers, and knowledge developers, respectively (Bergek et al., 2008b; Binz & Truffer, 2017; Wieczorek et al., 2013). The interaction between actors occur through actor networks, and are essential for exchanging knowledge and building a shared set of norms and beliefs (Wieczorek et al., 2013). Initially, entrants to the system are fragmented components of the system. Networks are formed where actors are linked to create learning networks or influence policy through political networks (Bergek et al., 2008b). Political networks are formed when advocacy coalitions compete to influence policy and create legitimacy or resist change counteraction (Bergek et al., 2008b). Especially in an emerging field, the chances of survival improve as the innovation system develops, in which alliances are likely to be more influential and more successful in innovating (Suurs & Hekkert, 2009). Furthermore, Institutions play a crucial role in the dynamics of an innovation system, governing how agents and networks interact with each other (Bergek et al., 2008b; Carlsson & Stankiewicz, 1991; Malerba, 2002; Negro, Alkemade, & Hekkert, 2012; Nelson & Nelson, 2002). They act as mechanisms that can constrain or enable actors to undertake actions related to innovation (Wieczorek et al., 2013). Therefore, technological change is not only the result of disruptive innovation, but also follows policies aimed at inciting change in the socio-technical system (Edquist, 2001; Kivimaa & Kern, 2016; Ko, Zigan & Liu, 2021; Weber & Rohracher, 2012). Effective innovation policies are therefore not only aimed at mobilizing resources for an innovation, but developing powerful institutions that support the TIS as a whole and result in wider change in the socio-technical system (Kivimaa & Kern, 2016; Suurs & Hekkert, 2012). Effective institutions are designed to optimally regulate the interactions between actors and networks, and can take the form of hard and soft institutions (Bergek et al., 2008b; Hillman & Sandén , 2008; Negro, Alkemade, & Hekkert, 2012; Wieczorek & Hekkert, 2012; Wieczorek et al., 2013). Hard institutions include regulatory, legal means to regulate social and market interactions (Binz & Truffer, 2017; Borrás & Edquist, 2013; Kivimaa & Kern, 2016), as well as financial means to form economic incentives and disincentives to support specific activities (Borrás & Edquist, 2013). Soft institutions refer to norms and values embedded in people, organizational routines, or standards (Sandén & Hillman, 2011), and offer non-obligatory and non-coercive agreements, often in the form of private partnerships and standards in transnational private governance (Cashore, 2004; Borrás & Edquist, 2013). Although not binding, these forms of normative institutions incite important public action in terms of innovation and have seen an incremental usage in the 21st century (Bartley, 2007; Borrás & Edquist, 2013; Dingwerth, 2008; Grösser, 2012; Suurs & Hekkert, 2009; van der Loos, Kalfagianni & Biermann, 2018; Vogel, 2008). Finally, Wiczorek and Hekkert (2012) consider infrastructure as an element of an innovation system in the form of three categories: physical, financial and knowledge infrastructure. Examples of these categories include but are not limited to: roads, bridges, machines and buildings as physical infrastructure; expertise, knowledge, and information as knowledge infrastructure; and subsidies, grants, and venture capital as financial infrastructure (Wieczorek & Hekkert, 2012; Wieczorek et al., 2013).

2.1.2 TIS Functions

The structural focus laid out by Carlsson and Stankiewicz (1991) has been extended by focusing on the functioning of innovation systems (Bergek et al., 2008a; Hekkert et al., 2007; Hekkert & Negro, 2009). This has led to studying the emergence of new technologies by assessing the performance of seven key TIS functions (Box 1), identifying factors influencing their performance (Bergek et al., 2008a; Hekkert et al., 2007) and describing the development of a TIS as an interaction of events with positive and negative feedback loops that result in technological change to better identify the systemic issues within a TIS (Bergek et al., 2008a; Hekkert et al., 2007; Hekkert & Negro, 2009). By examining the interactions between the system functions and its structural components, the coupled functional-structural approach can link blocking mechanisms in functions to the presence and capabilities of its structural components (Wieczorek & Hekkert, 2012).

Box 1: The Seven TIS Functions

[F1] Entrepreneurial Activity	Entrepreneurs are necessary to convert novel knowledge into concrete action to create new business opportunities (Hekkert et al., 2007; Hekkert & Negro, 2009), as a TIS without active entrepreneurial experimentation will become stagnant (Bergek et al., 2008a). These actors can take the form of new entrants that have a vision of new business opportunities in new markets, or incumbent companies that diversify their strategy to exploit new opportunities (Hekkert et al, 2007).
[F2] Knowledge Development	The knowledge base of a TIS is at the centre of an innovation process, and is fundamental for its evolution while in turn continuously co-evolves alongside the innovation system (Hekkert et al., 2007; Jeannerat & Kebir, 2016; Lundvall, 2007).
[F3] Knowledge Diffusion	This function describes how knowledge is diffused and assimilated in the system (Bergek et al., 2008). In the structural overlaps between innovation systems, knowledge spillovers occur naturally, where knowledge developed for one technology can be applied in the development of another (Hillman & Sandén , 2008; Sandén & Hillman, 2011).
[F4] Guidance of the Search	Providing incentives for actors to enter the innovation system grants it a certain degree of legitimacy, giving the TIS an advantage by influencing the search in terms of different technologies, applications, markets, or business models (Bergek et al., 2008a; Hekkert & Negro, 2009). The function is driven by the combined effect of industry expectations, regulations and policy, and actor perception (Bergek et al., 2008a).
[F5] Market Formation	Expresses the demand for an innovation, and can be classified into niche, bridging, and mass markets. Markets can enable learning, maintain diversity, encourage trust, create legitimacy, and attract entrepreneurs and investors (Bergek et al., 2008a). The process of valuation and market formation requires proactive social construction processes to attract investment and creating legitimacy (Binz & Truffer 2017; Jeannerat and Kebir, 2016), with a significant breakthrough being delayed until the market formation function is fully developed (Hekkert & Negro, 2009). Markets are therefore embedded in institutional structures and social networks, and a vital role in their formation is played by governments and citizens (Dewald & Truffer, 2011).
[F6] Resource Mobilization	Financial and human resources form a basic input to all activities in an innovation system (Hekkert et al., 2007; Hekkert & Negro, 2009). The mobilization of resources shapes, and is shaped by, the continuous (re)formation of the market, and is the product of interaction between the components (actors, networks, institutions, and infrastructure) of an innovation system (Jeannerat & Kebir, 2016). Resource mobilization is often impeded by uncertainty, often of political nature (Hekkert & Negro, 2009), which results in reluctance of government and private investment (Hekkert & Negro, 2009; Jeannerat & Kebir, 2016).
[F7] Create Legitimacy	To develop well, an emerging technology must become part of, or overthrow, this incumbent regime, which will continuously attempt to resist this force of creative destruction (Hekkert et al., 2007). This implies not only supporting the innovation by putting it on the agenda and lobbying for resources and favourable tax regulations (Hekkert et al., 2007), but simultaneously destabilising existing regimes to create windows of opportunity for emerging innovations (Kivimaa & Kern, 2016) alongside aligning the prevalent institutions to the need of the agents in the emerging TIS (Hekkert & Negro, 2009).

In an emerging TIS, the structural components are often underdeveloped and can structurally overlap with and depend on systems operational in potentially varying industries (Bergek et al., 2008b; Hillman & Sandén , 2008; Sandén & Hillman, 2011). The TIS evolves through this early formative phase by entry of actors, their formation of networks, and alignment of institutions until the interplay of these components materialize into a chain reaction of positive feedback mechanisms called virtuous circles (Bergek et al., 2008a; Hekkert et al., 2007; Hekkert & Negro, 2009). Through virtuous circles, system functions can reinforce each other over time, which is often a fundamental interaction for TIS build-up to occur (Suurs & Hekkert, 2009; Suurs & Hekkert, 2012). However, situations may also develop in which the malpractice of certain functions can slow innovation system growth, raising the term vicious cycles (Hekkert & Negro, 2009). It is apparent that positive interaction between system functions can assist with the maturation of a TIS, with certain patterns being especially important, while negative interactions can form a barrier to diffusion or even lead to the collapse of the innovation system (Hekkert & Negro, 2009).

2.2 Existing Carbon Market Mechanisms

The TIS for CDR is unique as the product generated by these technologies does not follow traditional market mechanisms studied in innovation systems. Therefore, the market formation function of the TIS framework is expanded by analysing the dynamics of two existing market mechanisms for intangible products. This section describes two established carbon market mechanisms to gain insights into their dynamics, to ultimately understand how they can impact the TIS for CDR, and briefly goes into environmental governance theory to create an understanding of the role of private governance in the formation of the voluntary carbon market.

2.2.1 Voluntary Carbon Market

The voluntary carbon market is driven by private governance mechanisms like certification and third-party auditing to set and enforce international standards (Andonova & Sun, 2018; Vogel, 2008). A voluntary carbon offset credit is formed when an private organization creates a project under one of the approved standards, the largest of which are Verra Carbon Standard (VCS) and the Gold Standard (GS) (Andonova & Sun, 2019; Nowak, 2022). Projects are validated and certified by independent non-state organizations, and purchase and sale occurs through organized marketplaces where non-state actors, including corporations, financial institutions, and individuals, can purchase and utilize these offsets as a means of voluntary compensation for their carbon emissions (Nowak, 2022). Current projects are largely made up of emission avoidance and reduction projects, but also include nature-based removal projects (Figure 2) (Ecosystem marketplace, 2020). Emission avoidance and reduction projects are often characterized by the difficulty in measuring additionality, in which the creator of the project must describe a hypothetical world without it (baseline scenario), and assign a value to the greenhouse gas emissions associated with the savings that are additional to that scenario (Lohmann, 2009). These cheap, low quality credits have given rise to negative media attention (Greenfield, 2023), as the actual climate impact of many credits do not reflect the impact they claim to produce (Tamme, 2022b). Although removal credits from afforestation, reforestation and soil enhancement projects are offered and generally preferred in the voluntary carbon market, the volume of avoidance credits circulating the market is an order of magnitude higher than removal credits (Ecosystem Marketplace, 2020, pg. 15).

Because the dynamics of voluntary market-based instruments is not well understood in the innovation system framework, this section is theoretically supported by environmental governance theory to create an understanding of the dynamics of private governance in the formation of the voluntary carbon market. Private governance is a form of rule-making in which non-state actors produce voluntary standards that operate alongside or in conjunction with traditional government regulation (Dingwerth, 2008; van der Loos et al., 2018), and has been instrumental in forming markets for sustainable products (Ramirez-Gomez et al., 2022). Although the impact of these schemes is likely to be limited due to their voluntary nature (Vogel, 2008), this does not necessarily mean that they are trivial, as the relationship between soft and hard institutions is dynamic and social norms may eventually become regulation (Bartley, 2007; Vogel, 2008). The literature of environmental governance recognizes two forces that lead to the emergence of private governance: market forces and political forces (Bartley, 2007; Cashore, 2004; Vogel, 2008). Firstly, market forces lead to private governance because of the increasing societal pressure and scrutiny by transnational actors. Firms attempt to preserve their reputation by developing market-oriented instruments to address environmental concerns (Bartley, 2007; Vogel, 2008). This driver can be recognized in the voluntary carbon market, which address the voluntary demand of organizations looking to offset their company emissions (Nowak, 2022) to protect their reputation in response to pressing environmental concerns (Bartley, 2007; Vogel, 2008). Secondly, political forces result in private governance where certification programs are established to correct social and environmental failures associated with weak public regulations (Andonova & Sun, 2018; Vogel, 2008). Weak governmental regulation in environmental policy indicates that the use of traditional government-led command and control policies have limited effect on complex international problems because globalization has made it difficult for national governments to hold global corporations accountable (Streck, 2004; Vogel, 2008). The complex problems posed by conflicts between states, markets, firms, and society in the context of globalization therefore calls for solutions that result from partnerships between these types of stakeholders (Bartley, 2007; Cashore, 2004; Streck, 2004; Vogel, 2008). This can also be recognized in the voluntary carbon market, which first emerged in parallel with the Kyoto Protocol and the platforms of mandatory regulation that accompanied this treaty (Andonova & Sun, 2019). This internationally defined mechanism provided a platform for the creation of a wide array of public-private partnerships to solve complex global problems (Andonova & Sun, 2018; Streck, 2004). Out of these partnerships, non-state actors developed voluntary certification schemes to support the functioning and creditability of the voluntary market (Andonova & Sun, 2018).

2.2.2 Compliance Carbon Market

An example of a CCM is the European Union Emissions Trading System (EU ETS). Established in 2005, the EU ETS acts as a financial control policy, introducing significant changes through overarching structural reforms in legislation, incorporating high-emitting companies into a cap-and-trade scheme (European Commission, n.d.). This market has developed to form a comprehensive, government driven carbon accounting mechanism for emitting carbon using greenhouse gas certificates, or allowances. A cap is set on the total amount of annual emission that is allowed for a certain installation, which is reduced annually with the aim to decrease emissions in the long run. Within this system, organizations are allowed to trade their allowances with one another. If an organization manages to reduce the emissions of their installation, it may keep the spare allowances to cover future needs or it may sell them to other organizations that are included under EU ETS (European Commission, n.d.). The EU ETS is a form of hard law that uses economic incentives and disincentives to support specific activities (Borrás & Edquist, 2013). Such control policies are often crucial to put pressure on the regime by internalising the environmental costs of carbon emissions and creating a level playing field for innovations to compete (Kivimaa & Kern, 2016). Other carbon pricing instruments, including carbon taxes and emission trading schemes, have emerged globally, including in the United States, China, Korea, and Mexico, and collectively cover approximately 23% of total greenhouse gas emissions (World Bank, 2022). Some schemes have integrated mechanisms in which removal and offset credits are traded to compensate for emissions, like the California cap-and-trade program (La Hoz Theuer et al., 2021; World Bank, 2022). However, such a mechanism has not been integrated into European compliance carbon market mechanisms, like the EU ETS (European Commision, n.d.; La Hoz Theuer, 2021; World Bank, 2022).

3 METHODOLOGY

This research identifies the drivers and barriers to the diffusion of CDR technologies by using the TIS framework. The research starts by mapping the TIS's structural elements, identifying their presence and capabilities. This is followed by a broad analysis of the performance of seven functions to stimulate innovation and contribute to the development of the TIS using indicators found in the literature (Table 1) (Bergek et al., 2008a; Negro, Hekkert, & Smits, 2007; Wieczorek et al., 2013). This analysis was expanded by specifically focusing on the market formation function [F5] and broadening its scope. To expand this function, two existing carbon market mechanisms were examined in detail to gain a comprehensive understanding of the dynamics that drive market formation for intangible products.

3.1 DATA COLLECTION

The data used to conduct the structural analysis was collected through desktop research, and is primarily based on expert and scientific articles. These sources facilitated in developing an understanding of the role of hard and soft institutions, and identifying actors and networks active in the CDR space. Hard institutions were mapped by analysing marco-political frameworks, reading regulations and proposals, and searching for sectoral regulations. Soft institutions were less straightforward to search for, as they are inherently normative and less visible. Actors were searched for using a database of the XPRIZE global competition for carbon removal (XPRIZE, n.d.), while networks where found online through keyword search for relevant NGOs, advocacy organizations, coalitions, and partnerships.

The data used to conduct the functional analysis, including the focus on market formation, came from semi-structured interviews and an anonymous survey (Annex). This twofold empirical data allowed to accurately measure the performance of the seven system functions. The interview was made up of a combination of semi-structured questions that offered the interviewees flexibility when and how to answer questions, while still being able to follow a structure that obtains answers to the research question. This was done using a range of performance indicators to identify strengths and weaknesses of each TIS function (Table 1). These indicators were used in the formulation of the semi-structured interview guides and the questionnaire. Where semi-structured interviews allowed for an in-depth discussion of TIS functioning, the questionnaire made it possible to assess the general TIS functioning among a wider range of actors, using consistent indicators for universal measurement. This allowed for a standardized approach to measuring the functioning of the TIS by minimizing variations in responses, producing reliable and comparable data to draw conclusions from. It showed how stakeholders experienced the CDR industry, and discover where actors, networks, institutions or infrastructure were active, present, and effective. This complemented the insights derived from the in-depth discussions of the semi-structured interviews and added to the comprehensiveness of the results by combining the qualitative depth of the interviews with the quantitative breadth of the survey. Important to mention here is that not all survey respondents were interviewed, and not all interviewed respondents completed the survey. The survey was entirely anonymous, so the researcher would have no way of knowing whether survey respondents were also interview respondents. For this reason, the results from both empirical methods of data are referred to separately rather than in aggregation throughout chapter 4.

Both the interview guide and the survey were structured according to the seven TIS functions and the indicators listed in Table 1. Entrepreneurial activity [F1] was measured by observing the number of new entrants, breadth of CDR technologies, and specialisation along the value chain. Knowledge development [F2] was measured by asking actors in the CDR TIS how knowledge is developed and what type of R&D is engaged in, whether firms have a department for this, and what activities they are working on, and with whom. Knowledge diffusion [F3] was determined by asking actors if they often collaborate in networks with other firms or organizations, and if these collaborations work well, the advantages they bring, and whether they actively share knowledge and expertise transparently. Guidance of the search [F4] was measured by determining the extent to which actors are incentivized to direct their search for climate change mitigation and impact investments towards CDR as a climate solution. The market formation [F5] function was measured with indicators such as market size and phase, its users, and institutions in place to stimulate demand. This research placed a particular focus on the market formation function to identify the systemic problems associated with forming markets for intangible products, such as CDR. Alongside the indicators mentioned, two existing carbon market mechanisms, the voluntary carbon market and compliance carbon market, were included in the analysis to determine how, and in what way, they affect the formation of a market for CDR technologies. The focal point of the research is to discover what the roles of these market mechanisms are in the technological development of CDR: how they fit into the current system, their potential for supporting a market for CDR, and what may need to be adapted to do so. In other words, this research is aimed to determine to what extent both market mechanisms compete with, or are conducive to the formation of a market for CDR. Resource mobilization [F6] was measured by gauging the volume and origin of financial capital and investments. Finally, legitimacy [F7] was measured by determining the level and effectiveness of lobbying and advocacy.

Table 1: TIS Function Performance indicators

		Bergek et al. (2008a)	Negro, Hekkert, & Smits (2007)	Wieczorek et al. (2013)
1	Entrepreneurial activities	- *Number of new entrants, including diversifying established firms* - *Number of different types of applications* - *Breadth of technologies used and the character of the complementary technologies employed.*	- *Project started (+)* - *Project stopped (-)*	- *Number and the type of actors* - *Number and type of experimental projects* - *Actors' involvement in national vs international projects* - *Specialisation along the value chain*
2	Knowledge development	- *Bibliometrics (citations, publications, orientation)* - *Number, size and orientation of R&D projects* - *Number of professors* - *Number of patents* - *Assessments by managers and others* - *Learning curves*	- *R&D projects* - *Investment in R&D* - *Feasibility studies*	- *Number and the type of actors involved in the knowledge development (knowledge institutes vs. industrial parties)* - *Type of knowledge developed (tacit or codified).*
3	Knowledge diffusion		- *Workshops* - *Conferences*	- *Number and type of networks* - *Assess the general accessibility of knowledge.*
4	Guidance of the search	- *Beliefs in growth potential* - *Incentives from factor/product prices, e.g. taxes and prices in the energy sector* - *Extent of regulatory pressures, e.g. regulations on minimum level of adoption ("green" electricity certificates, etc.) and tax regimes* - *Articulation of interest by leading customers.*	- *Positive expectations(+)* - *Regulations by government (+)* - *Negative expectations(-)* - *Expressed deficit of regulations (-)*	- *Type of actors and their activities that influence guidance of the search* - *Impact of informal institutions on the direction of the search (the level of governmental commitment, presence & reliability of policy goals & vision, expressed expectations)* - *Formal institutions (presence & quality of regulatory regimes, policy instruments & permitting procedure).*
5	Market formation	- *Phase the market is in (nursing, bridging, mature)* - *Institutional stimuli for market formation* - *Market size* - *Users & Customer groups* - *Actors' strategies* - *Role of standards and purchasing processes*	- *Specific favourable tax regimes and environmental standards (+)* - *Expressed lack of favourable tax regimes or favourable environmental standards (-)*	- *Size of the market (installed capacity, wind parks consented and planned)* - *Supporting incentives.*
6	Resource mobilization	- *Rising volume of capital* - *Increasing volume of seed and venture capital* - *Changing volume and quality of human resources* - *Changes in complementary assets.*	- *Subsidies, investments (+)* - *Streams allocated to project (+)* - *Lack of subsidies, investments (-)* - *Shortage of streams (-)*	- *Availability of financial resources* - *Availability of competencies and expertise* - *Availability of physical infrastructure*
7	Create legitimacy / Resist change counteraction	- *Legitimacy of the TIS in the eyes of various relevant actors & stakeholders* - *Activities within the system that may increase this legitimacy* - *Influence on demand, legislation and firm behaviour* - *What (or who) influences legitimacy, and how*	- *Support by government, industry (+)* - *Expressed lack of support by government/industry (-)*	- *Level of resistance to technology* - *Perceived level of competition between technologies* - *Extent to which the formal and informal institutions increase legitimacy*

3.2 Sampling strategy

The interviews were conducted with a range of stakeholders active in the CDR TIS. 6 CDR companies, 5 Dutch climate policy makers, 3 Networks of lobbying/advocacy coalitions, 6 CDR Experts, 2 actors on the Voluntary Carbon Market (VCM), 2 Journalists, 1 Niche market actor and 1 Municipality were interviewed, totalling 26 respondents. The CDR companies based in the EU were found and approached using the XPRIZE database (XPRIZE, n.d.). Government officials and policy makers were searched for through desk research by probing national government agencies concerned with climate adaptation. Although not at the forefront of EU climate policy, these respondents were more readily accessible and were assumed to have sufficient knowledge about EU policy making. Experts, Networks, and Journalists were searched for by means of desk research and snowball sampling. The respondent from the niche CDR market platform and the Municipality were found through snowball sampling.

3.3 Data Analysis

Interviews were recorded after consent and transcripts were coded to reduce excess data down to useful information in Nvivo. This method facilitated in finding recurring patterns or themes in the data (Bryman, 2008). The results from the interviews are complemented by the more quantitative results from the questionnaires sent to general CDR actors and interviewees as a follow-up to the interview. Here, descriptive statistics are used to identify strengths and weaknesses in the functions of the CDR TIS.

3.4 Ethical Research

The 26 interviews and questionnaire survey targeting general actors were conducted with ethical practices in mind. Specific measures were implemented, including: obtaining informed consent from research subjects; adhering to data management practices in accordance with GDPR regulations; assigning numerical codes to protect participants' real names and affiliations; documentation of privacy-sensitive information in confidential and protected files; and limitation of access to researcher and supervisor. After transcription of recordings, secure destruction methods were employed to dispose of the data appropriately. All interview participants were sent a consent form prior to their participation. The consent form outlined the purpose and scope of the study, informed participants of their rights and the voluntary nature of their involvement, and emphasized the confidentiality and anonymity of their responses. To proceed with the interview, participants were required to provide signed consent, indicating their understanding and agreement. For the questionnaire survey, survey respondents were presented with terms and conditions that outlined the study's objectives, confidentiality measures, and data usage. Prior to participating, respondents were required to agree to these terms and conditions, indicating their informed consent. To ensure anonymity, both interview and survey respondents remained anonymous in the research findings.

4 RESULTS

4.1 SYSTEM STRUCTURE

The structure of the system is visualised in Figure 2. The following section provides an overview of the structural elements of the CDR TIS, identifying whether they are present and if they are capable of contributing to the growth of the innovation system.

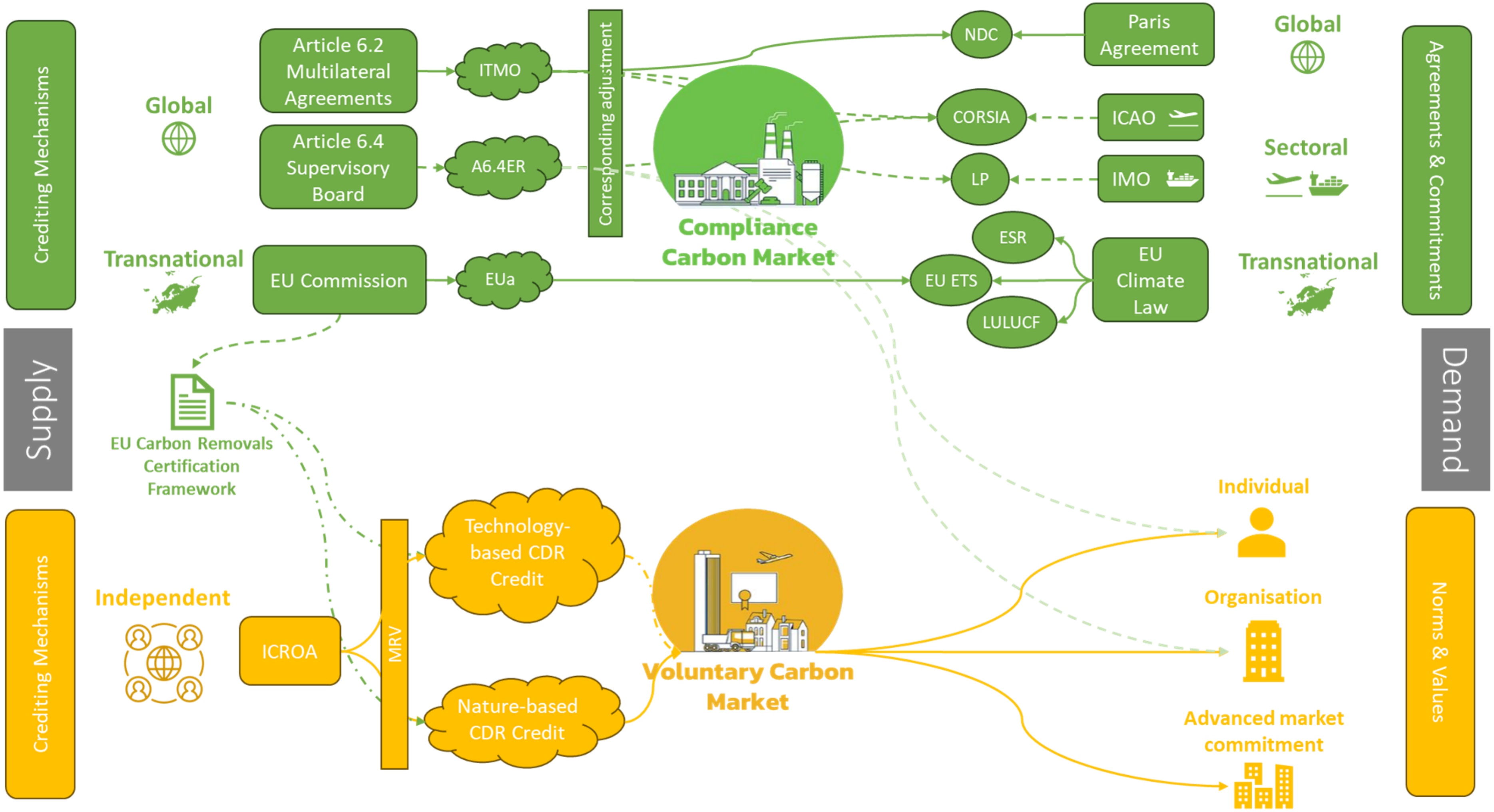

Figure 3: CDR TIS Institutional Structure, where compliance markets are governed by hard institutions (green) and voluntary markets are governed by soft institutions (yellow) (Generated using following sources: Allen et al., 2021; Edmonds et al., 2021; La Hoz Theuer, 2019; Lundberg and Fridahl, 2022; Scott and Geden, 2018; Smith et al., 2013; Tamme, 2022; UK Department for Business, Energy & Industrial Strategy, 2022; World Bank, 2022, pg. 12; Zetterberg, Johnson, & Möllersten, 2021)

4.1.1 Institutions

Institutions govern the dynamics between the components of a TIS, and act as mechanisms that constrain or enable actors to undertake actions related to innovation (Bergek et al., 2008b; Carlsson & Stankiewicz, 1991; Wieczorek et al., 2013). The supply and demand for carbon credits in both markets, driven by their respective institutions, is visualised in Figure 3.

Demand in compliance carbon markets is driven by agreements and commitment reflected in rules, regulations, and legislation sanctioned by governmental regulatory bodies. These can be categorized into three broad categories: global, transnational, and sectoral agreements and commitments. The global and transnational commitments act as macro-political public mitigation targets that do not form the direct incentive for CDR, but act as the driving force for public and private action (Poralla et al., 2021) and inciting change in the socio-technical system (Kivimaa & Kern, 2016; Weber & Rohracher, 2012). Although the Paris Agreement is excluded from this research scope due to an EU-level focus, it may play an important role in the future and is therefore incorporated in Figure 3. The transnational macro-political climate policy of the EU, the EU Climate Law (European Commission, 2021), is supported by regulatory policy instruments that act as pillars, and include the EU ETS, the Effort Sharing Regulation (ESR), and the land use, land-use change, and forestry (LULUCF) Regulation (European Parliament, 2023; Lundberg and Fridahl, 2022; Schenuit et al., 2021). Ultimately, the EU ETS forms the institution that governs the largest compliance carbon market in the world (World Bank, 2022, pg. 18). Sectoral organizations, like the International Civil Aviation Organization's (ICAO) and the International Maritime Organization (IMO) are also in the process of developing agreements and commitments that are aimed at reducing emissions in their respective sector through market based measures (ICAO, 2022; World Bank, 2022, pg. 20). On the supply side, the European Commission issues allowances on an annual basis, decreasing each year at a linear rate (European Commission, n.d.).

Where hard institutions govern a compliance market mechanism based on legal obligations, soft institutions reflect a voluntary market based on social values and norms that reflect the conception of what is preferred or desirable in society (Dhanda, Sarkis, & Dhavale, 2022; Mateo-Marquez et al., 2021). This forms the demand-side conditions for the voluntary carbon market, where norms and values incite voluntary demand and private governance mechanisms facilitate market dynamics (Andonova & Sun, 2018; Borrás & Edquist, 2013; Cashore, 2004; Vogel, 2008) for mitigating climate change by privately trading carbon commodities (Poralla et al., 2021). The voluntary action of compensating for climate impacts has been increasing tremendously over the past years (Tamme, 2022; World Bank, 2022, pg. 33-51; van der Loos, 2018), giving rise to independent market platforms that use private governance to certify and sell carbon credits to form the supply-side of the voluntary carbon market. Recently, alongside the private governance mechanisms of the voluntary market, niche standards and market platforms have emerged that certify, credit, and sell removal credits from distinct CDR technologies, often under their own individual standard and accompanying accounting methodology (Lundberg & Fridahl, 2022; Poralla et al., 2021; Puro Earth, 2021; Tamme & Beck, 2021; Tamme, 2022b). These niche markets are operating to meet the voluntary demand of organizations that wish to purchase high-quality, high-permanence, expensive carbon credits rather than cheap avoidance credits (Scott & Geden, 2018; Smith et al., 2023; UK Department for Business, Energy & Industrial Strategy, 2022; Zetterberg, Johnson, & Möllersten, 2021). Most of these independent market platforms and their crediting mechanisms are endorsed by an overarching organization that promotes best practice across the voluntary carbon market, called (ICROA). Due to the intangible nature of carbon trading, Measurement, Reporting and Verification (MRV) is a necessary and unique component of the CDR TIS structure, used as a private governance mechanism to validate climate impact by maintaining permanence requirements and durability of long-term storage. If done well, MRV can provide harmonised and transparent frameworks for calculation, risk and costs (Poralla et al., 2021), enhancing the legitimacy of CDR technologies as a climate change mitigation method (Poralla et al., 2021; Zetterberg, Johnson, & Möllersten, 2021). However, MRV is often performed and conducted by independent markets and respective crediting mechanisms, which leads to fragmentation of standards and markets, decentralized supervision, and low transparency (National Academics of Sciences, Engineering, and Medicine, 2019; Zetterberg, Johnson, & Möllersten, 2021). Currently, there are no universal scientific standards driven by hard institutions that define the durability of CDR (Smith et al., 2023, pg. 15). However in November 2022 a proposal was accepted called the EU Carbon Removal Certification Framework (CRCF), in which the EU can possibly adopt the role of establishing requirements for carbon accounting (European Commission, 2022).

4.1.2 Actors

Start-up companies are developing CDR technologies in Europe, (Tamme & Beck, 2021), some of which are offering CDR credits on niche market platforms. End users of CDR credits include coalitions of companies making an advanced committed to removal credits to stimulate the market, like the Frontier organization (Microsoft, n.d.). CDR falls outside the current scope of the EU ETS, which exclusively focus on emission allowances (La Hoz Theuer et al., 2021; Tamme, 2022), and CDR technologies are excluded from the methodologies and standards of the voluntary market, which focus more on reduction credits and to a lesser extent on nature-based removals (Figure 2) (Ecosystem Marketplace, 2020, pg. 15; Tamme & Beck, 2021; World Bank, 2022).

4.1.3 Networks

Among the networks in the CDR TIS are numerous partnerships, organisations and foundations present that create and enable mechanisms to scale natural and technological CDR solutions. From global competitions (Extavour, 2021) to non-profits (Carbon Market Watch, 2022), organisations engage in research collaboration, engagement, policy and agenda setting, creating incentives, and connecting supply and demand. Alongside general environmental organisations that reflect on CDR in the broader environmental discussion, there are numerous platforms, hubs, partnerships, and institutes that focus exclusively on CDR technologies, such as Negative Emissions Platform, Puro.Earth, International Carbon Action Partnership, DAC Coalition, and many more. Furthermore, there are some networks that focus on the activities surrounding the formation of a market establishment of trading carbon, aiming to forming high integrity markets to price carbon effectively in order to reach climate goals (Carbon Market Watch, 2022; IETA, 2023). These organisations are largely concerned with working towards a sufficient carbon price on high integrity markets to scale CDR and reach net-zero targets.

4.1.4 Infrastructure

The physical infrastructure needed for some CDR technologies include technology-specific machinery and complementary assets, like pipelines, supply chains, and storage areas (Smith et al., 2023, pg. 59-63). Knowledge infrastructure includes scientific research and certainty of the effectiveness of technologies at removing CO_2, their technology readiness level (TRL), and the intellectual property and patents for technologies (Smith et al., 2023, pg. 16). Financial resources include various venture capital investments (Wilkes, 2023), governmental funds and subsidies from revenues of the EU ETS (European Commission, n.d.), and carbon pricing instruments (World Bank, 2022).

4.2 System Functioning

4.2.1 CDR TIS

92% of survey respondents agreed and strongly agreed that the number of start-ups was increasing over the past years, with the same percentage claiming that CDR technologies and applications have been diversifying [F1]. CDR companies are mostly in a developmental phase, mostly demonstrating their technologies through pilot projects and heavily focused on R&D and scaling. Not one of Companies 1 through 6 was even active in any niche CDR markets yet [F5]. With regards to the development of knowledge [F2], Expert 4 described a recuring pattern of companies concentrated around the strong research universities in Europe. This regional concentration may indicate that CDR TIS's are emerging in technological clusters (Bergek et al., 2008). Companies 2, 3, and 6 confirmed that the fundamental science on which their technology is based comes from universities and research institutes. Furthermore, 85% of survey respondents indicated that academia has significantly contributed to knowledge development over the past decade. Even if most Companies are not direct spinouts, Expert 4 stated that:

"All of the engineered ones [CDR technologies] are based on science that has been published in one way or another… researchers… build a company and develop the technology…. At times, it's entrepreneurs who are looking for a technology to commercialize."

CDR Company maturity ranges from initial research organizations to scale ups, depending on the technology used and the corresponding Technology Readiness Level (TRL). Terrestrial (biomass) CDR methods, like Company 4 and 5, are more developed, already have their own developed R&D department, and are thus focused on later stage activities like fundraising and scaling. CDR with lower TRLs, like DAC and marine CDR (Companies 2, 3 and 6), are still in an R&D phase, working together with universities to further develop their technology before bringing it to market or the attention of financial investment. These respondents stated that their technologies are mainly inhibited by lack of knowledge infrastructure, like academic research and wider confidence that they are effective at removing CO_2, and the science behind quantifying the removals that result from activities [F7]. This was confirmed by Expert 5, stating:

"Very few have deployed anything… biochar… more mature technology… has been scaling up and people are removing carbon now, they need prepurchase or offset agreements... Whereas DAC… most of the companies are still in the lab, very few have built anything… next year… are when the first-of-a-kind facilities get built."

Nevertheless, respondents indicate that these technologies are highly promising. Journalist 2 indicated that DAC has high potential and is expected to scale on an international level [F4] and DAC start-up companies 2 and 3 stated that many groups are active in this space [F1]. This is confirmed in scientific literature, where DAC is expected to deliver significant emissions reductions in the future in the EU [F4] (Tamme & Beck, 2021) and several actors are engaged in efforts to commercialize DAC with multiple pilot and demonstration facilities across Europe [F1] (Smith et al., 2023). Furthermore, company 6, active in marine CDR, mentioned a high level of interest from large corporations [F7]. This is likely due to the importance of oceans in the global carbon cycle (Cooley et al., 2023). However, the respondent indicated that knowledge infrastructure is still undeveloped [F2] and lacks the capabilities to create legitimacy [F7], which corroborates with scientific literature where marine CDR makes up a small portion of CDR patents (Smith et al., 2023).

The Measurement, Reporting, and Verification (MRV) of CDR acts as a private governance mechanism and is a unique component of this TIS, offering a solution to the inherent intangibility of trading carbon as a commodity. Experts 2, 4 and 5, Networks 1 and 3, Journalist 2, and Policy maker 4 stated that MRV plays a key role in ensuring that there are correct protocols for monitoring emissions, robust mechanisms for third party verification of removals, and providing academic certainty that CDR solutions provide the climate benefit they claim to. As Network 3 states:

"Credibility, before we set the industry up, is absolutely essential to the existence of the industry."

There are three separate pathways by which CDR credits are transacted in this stage of the TIS, all of which are exclusively driven by soft institutions and facilitated by private governance and voluntary demand. Firstly, some start-ups, like company 2, are purely focused on developing technologies to offer to buyers rather than individual credits [F1], and are not interested in entering the voluntary carbon market themselves, nor are they planning to enter a potential compliance market in the future [F5]. Company 6 indicated that they are receiving interest and research support from large corporations, like Nestle, in their effort to investigate pathways to compensate for emissions in their supply chain [F1, F7]. The second transaction pathway comprises niche markets that exclusively focus on high-quality credits generated by CDR technologies. Regarding market size, the survey unanimously showed that this market is in a nursing phase [F5]. The third transaction pathway is formed by early buyers that form advanced market commitments to CDR Companies that have not yet started generating CDR credits. These early buyers are organized in coalitions of companies that are collectively committed to buying removal credits before they are produced in order to stimulate the market. Frontier is one of the leading organizations that does this. Network 3, Journalist 2, Experts 4 and 5, and Company 5 all consider Frontier as extremely influential for early development of CDR, with Journalist 2 summarizing:

"I think this whole idea to create an advanced market commitment is brilliant… create a market for something that doesn't exist yet in advance of the top-down policies… big companies with resources and visionary climate strategy I think has been really integral as a step in in that direction."

Taken together, these three pathways have a major influence on the development of the TIS for CDR. Based solely on soft institutions and private governance, the voluntary market dynamics have been integral in laying the foundation of a CDR industry, with Network 1 stating:

"Without voluntary corporate ambitions, this would have never existed."

However, although the financial resources that arise through this pathway have played an important role in the development of CDR technologies, funding is still among the major challenges that CDR companies face [F6]. Funds for carbon removal are mostly derived from pre-purchase agreements and Venture Capital (VC). Journalist 2 described that private funding is more capable of funding the CDR industry in its early stage because it is more flexible and faster than what the government can do at this point. However, as fast as the voluntary CDR market is growing, it is not growing fast enough. To illustrate, the CDR market has seen almost 4 megaton CO_2 purchased, with merely 2% of those purchases actually have being delivered (98% are pre-purchase agreements) (CDR.FYI, n.d.). This amounts to 0.039% of the annual 10 gigaton goal set for 2050 (Fuhrman et al., 2023), which means demand must increase by roughly 2,500 times. This demand is currently largely made up of a handful of buyers able to purchase high quality credits, with very limited producers. As Expert 1 stated:

“You have more marketplaces than buyers… there is no functioning market right now. But if we would have removals included under compliance markets where there's a strong price signal…“

Although effective on the short term, respondents indicated to be sceptical that voluntary action would be enough to grow and sustain the market to the size necessary to reach global goals. Companies 3, 4, and 5; Expert 1, 2, 3, 4, and 5; Networks 1 and 2; and Journalists 1 and 2 all explicitly expressed that the CDR industry would not be able to accelerate without guidance from a top down initiative to grow and sustain the CDR market to the right size. This was confirmed by the survey response where 93% of respondents indicated that governmental support and policies are important (19%), even essential (74%). Many respondents were convinced that targeted policy instruments are much more efficient at supporting and developing larger scale projects, and that private governance and voluntary demand is simply unable to support that large a scale. This is due to the inherent weakness of voluntary mechanisms and private governance: vulnerability (Vogel, 2008). As Expert 4 stated nicely:

“Fundamentally, if demand continues to be voluntary, it is also vulnerable.”

Following this criticism and requirement, the required scale can be reached if hard institutions play a more dominant role, using regulation and universal standards to develop legislation [F4] and increase the legitimacy of the TIS [F7]. Therefore, compliance markets will come to play a key role in scaling CDR to achieve meaningful impact on climate change. To this end, companies are organized into political networks of coalitions and associations that are developing, or lobbying for development of robust compliance mechanisms for CDR [F4, F7]. Political networks will be important in linking the currently fragmented components of the carbon market into one universally recognized system to replace the voluntary mechanism. 87% of survey respondents indicated that these networks were present, and the interview respondents described them as strong and important. Companies 2, 3, 4, 5, and 6 indicated to be a member of a technology-specific network [F1, F3] and described these networks as highly effective in achieving a common understanding. Company 3 stated the following:

“CDR as a broader concept, everyone is engaged. Everyone's talking about it, working to improve it. Because it's a kind of rising tide that lifts all companies.“

Furthermore, these coalitions and trade associations operate with a particular value proposition in mind: policy work and lobbying, with a focus on the European Union [F7]. Network 3 characterized themself as a small Brussels lobbying organization [F7], primarily focused on EU policy frameworks, such as the 2040 targets, the Carbon Removals Certification Framework (CRCF), the net zero Industry framework [F4], and developing a functioning compliance market [F5]. Political networks play an important role in advocating for awareness and lobbying for policy change by addressing strategic political questions on CDR, such as setting targets, producing robust methodologies and standards, and developing protocols for credit ownership. As these market formation mechanisms lead to an emerging compliance market mechanism, the role of private governance and the voluntary market mechanism will become less important, as summed by VCM 2:

“The more instrumented policy, the less room for the voluntary carbon market.”

This understanding has emerged rapidly in recent years according to Expert 4, where advocacy is the first step in getting CDR in a position where it's acknowledged as solution [F4 & F7]. According to 92% of survey respondents, the legitimacy of CDR as a climate change solution has increased over the past years, which is confirmed by Policy maker 1 who stated that the necessity of CDR is becoming increasingly apparent in policy [F4]:

“There is now an understanding of… with that [renewable energy] alone we won't make it. We will need negative emissions to some extent…”

A recurring challenge here is the distinction between reductions and removals, which is mentioned by many respondents as a major awareness gap when it comes to policy making as well as wider public understanding of CDR as a climate change mitigation method [F7]. As stated by Niche market 1:

<u>*Interviewer:*</u>

“… The difference between reduction and removal needs to be clearer. It’s not quite there yet.”

<u>*Niche Market 1:*</u>

“That’s a good understatement.”

Policies for CDR can take many forms and are still very much in a explorative phase [F4]. On a Member State level, Dutch Policy makers 1 and 4 stated they are concerned with national policies, such as governmental research programs, CDR project development, inclusion of CDR in national sustainability reports and climate plans, and financial schemes and instruments for CDR, like tariffs and subsidies. The results from the survey show that respondents are slightly more content with EU-level regulatory pressures than national level regulations. This was consistent with what the interviewees said. Regarding EU-level policy, Expert 2 and Company 2 considered the macro-political EU Climate Law framework to play an important role in setting the broader context for net zero emission targets [F4]. Furthermore, many respondents discussed the fundamental role of the EU in producing clear and universal standards for the CDR industry and supporting MRV. The first signs of this enveloping were recognized by many respondents in the European Commission’s recently developed proposal for the Carbon Removal Certification Framework (CRCF), meant to provide clear guidelines for certification of negative emissions through national CDR policies (European Commission, 2022). This was considered by Experts 1 and 4, Network 3, and Journalist 2 to have the potential to be a key mechanism that can harmonize CDR methodologies and standards on an EU-level and define CDR [F4]. This was confirmed by the survey respondents, where 81% of respondents considered it very important. However, during the interviews, Journalist 1 and Experts 2, 4, and 5 mentioned that the CRCF is far from sufficient in its current state. Expert 4 summarized:

“… ideally, if it's [CRCF] done in a good way… it could become the governing regulatory framework for a compliance market in the future… But It's not there yet… Brussels politics are tricky… this could be a go / no go situation for moving forward. If this is done in a poor way… we might set ourselves up for quite a bumpy road ahead.”

With regards to national CDR policy, market formation mechanisms are largely lacking, with the exception of some counties that do have national frameworks to stimulate CDR [F4]. Experts 2 and 4, along with Journalists 1 and 2 noted that national policies on CDR often follows strategic plans. Pools of CDR technologies often form following presence of industries and availability of resources, where countries tend to favour removal solutions that their country would profit from industrially. For example, Sweden, strong in the paper and pulp industry, has a Bioenergy Carbon Capture and Storage (BECCS) auctioning system and have various BECCS plants, while Switzerland is focused on developing Direct Air Capture (DAC) technologies. When looking at the commitments of different European countries, states are demonstrating varying degrees of commitment towards CDR and negative emissions in general [F4]. Expert 4 mentioned progressive countries such as Switzerland and Denmark have short, mid, and long term plans for negative emissions in the policy schemes. Countries like Norway and Luxembourg have, or are in the process of setting up a feed in tariffs for negative emissions technologies (Clement and Neidl, 2022), while the UK is in the process of developing business models for CDR (UK Department for Business, Energy & Industrial Strategy, 2022). As Journalist 1 stated:

“There are some countries have actually specified specific forms of CDR that they're going to use. Most haven’t still. That's an important step.”

Meanwhile, regulatory instruments and CDR targets in the Netherlands are falling behind [F4]. Policy maker 4 noted that, in comparison, other countries in Europe are a lot more advanced and have strategies, plans, targets, and research budgets for CDR, while the Netherlands is still in an initial phase:

“a developer of DAC technology… successful in the UK tenders… they found their sponsorship… another missed opportunity for the Netherlands… we don’t have anything competitive.”

The only Dutch policy instrument identified for CDR was the Stimulation of Sustainable Energy Production and Climate Transition (SDE++). Although available for a wider variety of sustainable technologies, including CDR, it is allocated on the basis of CO_2 reduction effectivity. Again, the awareness gap arises in which the distinction between reduction and removal is not being made [F7]. Therefore, as confirmed by Policy makers 1 and 2, CDR technologies cannot compete with low-carbon technologies, and therefore will not likely be able to receive subsidies under this existing scheme (F4 & F5):

“Conceptually, it fits. But it would just be outcompeted, not given a chance.” – Policy maker 2

However, CDR is starting to be included on the political agenda in the Netherlands. Policy maker 5 referred to the developments in Dutch politics where the Minister for Climate and Energy answers parliamentary questions on CDR (Jetten, 2023), and Policy maker 4 is part of a working group with Dutch ministries and governmental organizations in which they:

“…often discuss negative emissions and setting up research platforms… thinking about negative emissions in general and working on a strategy on how to achieve negative emissions in the Netherlands. But it's really still in its infancy.”

The limited extent of regulatory pressure, especially in the Netherlands, indicates a failure of national policy to create incentives and pressures that guide the search in the direction of CDR [F4]. The lack of institutional development is clearly marked by respondents as a system failure. Ultimately, this can lead to an obstruction in the formation of the TIS for CDR (Bergek et al., 2008a).

4.2.2 TIS Functional Pattern

Considering the results, the TIS for CDR seems to be in a formative phase because of: high number of entrants; lacking presence and capabilities of knowledge infrastructure; the nursing stage in which the CDR market finds itself; strongly varying prices of methods and technologies; the low volume of CDR currently applied; and the general absence of national and transnational policy, regulation, and incentives for CDR.

Start-ups are developing and demonstrating technologies [F1, F2] and are supported by niche market activities, pre-purchasing agreements and advanced market commitments [F5, F6]. This is driven by the presence of soft institutions that govern private governance and voluntary market mechanisms. Although compliance market mechanisms are widely considered as crucial for CDR TIS functioning, these have been lacking. In their absence, this research shows that private governance mechanisms, driven by soft institutions, have played a crucial role in the early development of the TIS. This governs the voluntary niche market for CDR, driving demand [F5] and providing financial resources [F6], while unique Measuring, Reporting and Verification (MRV) structures develop to overcome the inherent intangibility of CDR and its liability of newness [F7]. Current hard-institutional developments in the TIS are driven by an increasing understanding of the importance of CDR in reaching global climate goals and [F4], and the macro-political EU frameworks that set the broader context for inciting change in the socio-technical system [F4]. On a national level, some countries are establishing compliance market formation mechanisms and are strategically supporting the development of CDR following the presence of strong industries in their countries. However, in general, EU and national policy for CDR is in a developmental phase, with some frameworks emerging that act as the first signs of market formation mechanisms and governmental support for this industry. In response, actors are organizing themselves into industry coalitions and networks with the aim to align definitions on CDR, develop a common understanding and universal industry standards, and lobby for policy change. These networks lobby for policies [F7] aimed at developing powerful institutions that support the TIS as a whole [F4, F6], with the priority of creating a compliance market for CDR [F5], or a mass market, which will result clear expectations for CDR [F4] and subsequent increase in available resources [F6], attracting more entrepreneurs to the CDR industry [F1] (Suurs & Hekkert, 2012). These positive interactions are leading to reinforcing dynamics in the TIS, that give rise to virtuous circles leading to accelerated diffusion of CDR. However, equally important are vicious cycles, where an insufficient activity in one function results in reduced activities in other functions, thereby slowing diffusion of CDR (Hekkert & Negro, 2009). For instance, limited government action with regards to creating policies and targets for CDR [F4] will inhibit the mobilisation of financial resources [F6] to finance development of projects or further research [F2], which will significantly reduce the expectations that CDR will be able to achieve meaningful climate change mitigation [F4].

Although the current functional pattern of the TIS can be considered to match the needs of CDR in this early stage of development, the growth phase will require improvement in certain functions and adjustment to structural components to reach large-scale technology diffusion (Bergek et al., 2008ab). Instrumental to this ambition is that the TIS must at some point reach mass market formation (Bergek et al., 2008a). To this end, this research analyses two existing carbon market mechanisms to determine their potential influence in driving innovation for CDR.

4.3 Learning from existing Market Mechanisms

In this section, the results show how two existing market mechanisms that trade carbon could influence the formation of a market for CDR, looking at what lessons can be learned from the two existing mechanisms to improve the performance of this TIS function.

4.3.1 Voluntary Mechanism

The voluntary carbon market has been extremely effective at creating a market out of nothing in a short amount of time, acting as a precursor to future policy measures. Expert 3 stated:

"the private sector is one step ahead of understanding where technology development is moving and where the market is moving".

This is crucial for early stage development because a TIS cannot develop without institutions that govern the dynamics between actors and networks (Carlsson & Stankiewicz, 1991), and hard institutions are tedious in developing due to long policy making processes. With regards to CDR, this is where opportunities exist. Expert 1 stated that:

"Volunteer markets are really fast… you can try new things, establish methodologies… then you can use these learnings and experience when you're designing compliance…"

Credits that are generated with CDR technologies are currently excluded from the dominant voluntary schemes. According to VCM actors 1 and 2, this is because of relative high prices of technological CDR credits, low TRL and maturity, and general preference for nature-based solutions. Furthermore, respondents in the CDR space were sceptical about the capability of the voluntary carbon market being able to support CDR technologies. Company 2 mentioned:

"I'm not certain that entities like Verra and gold standard are the best positioned to drive success. I think efforts taken by like Puro or these other emerging markets more focused on high quality CDR, I think they are moving faster… especially because they their [voluntary carbon market] reputation precedes them in a negative way… But I definitely think that CDR can and will move into these kinds of verification and certification standards and markets for sure."

The voluntary carbon market is characterised by a lack of regulation and fragmentation of standards and markets, also mocked as resembling the "*Wild West*" by Company 1 and Expert 4. This is confirmed in the scientific literature, where the private governance structures in the voluntary market lack a consistent approach to addressing key issues of MRV, such as permanence, durability, or additionality (Poralla et al., 2021). In the voluntary carbon market, standard setting organisations like Verra and Gold Standard often use their own standards and methodologies to measure reduction or removal, use verification mechanisms prescribed by their own crediting scheme (Poralla et al., 2021; Zetterberg, Johnson, & Möllersten, 2021), and offer subsequent credits on their own distinctive platforms. The result: a global voluntary carbon market offering credits under different standards, generated by diverse methodologies, using different verification mechanisms, and sold via different platforms (Poralla et al., 2021; Zetterberg, Johnson, & Möllersten, 2021). Negative media (Greenfield, 2023) and fear of greenwashing (Gambetta, 2023) undermines the legitimacy of commoditizing carbon and reduces public trust in its capability for climate change mitigation [F7], not to mention the long-term prospects of a functioning market for CDR [F4] (Poralla et al., 2021). To increase legitimacy [F7], the level of societal trust, investor interest and buyers' demand is dependent on the integrity of

MRV accounting principles and strong governance (Ahonen et al., 2022; Cooley et al., 2023; National Academics of Sciences, Engineering, and Medicine, 2019; UK Department for Business, Energy & Industrial Strategy, 2022). The fragmented standards of the voluntary carbon market are not effective at ensuring transparency and achieving trust and legitimacy, as expressed by the respondents. Journalist 2 described them as flawed, and Company 2 and Expert 4 were not convinced that these standards would continue to play an important role in the future carbon market. This lack of trust can form a barrier to the widespread adoption of CDR as a climate change solution. A major challenge for carbon trading in general is the inherent intangibility of carbon as a product, regardless of whether it pertains to avoidance, reduction, or removal. To deal with this uncertainty, MRV is a crucial private governance mechanism to enhance transparency, prevent double counting, and ensure effective and authentic climate impact. This is also acknowledged by respondents as a challenge in the existing voluntary market, with Journalist 2 stating:

"I think we really need a MRV standards body of some sort on the offset market and I think trust is critical and doing it right is critical… the lack of standards for the voluntary carbon market in particular are worrisome… I would identify that as a huge gap right now."

As opposed to carbon offsets, Company 2 describes CDR as having a much higher level of certainty of delivering expected climate benefits. This is the primary benefit of CDR technologies relative to nature-based removal and emission reduction credits: the academic certainty that removals are accurately quantified. Relative to the voluntary market, the quality and certainty of CDR technologies can provide a solution to the uncertainty and lack of transparency. In contrast to the voluntary carbon market, which is driven by price, the CDR market is based on quality and certainty. As Company 2 envisions what the market for CDR:

"… commoditizing this market… should be based on certainty… high permanence, highly measurable opportunities like DAC, those are very close to exact negative emissions… that can actually work towards Net Zero… focusing on commoditization around quality. I can say that for the rest of my life, commoditization around quality."

Therefore, rather than depend on the existing voluntary carbon market, further development of niche markets for CDR technologies will be more effective at developing the industry in this early phase.

The formation of this niche market can use private governance mechanisms that were used to create the voluntary market, like private standards, voluntary demand, MRV, advanced market commitments, and pre-purchasing agreements. However, learning from the fragmentation of the voluntary carbon market, it is important that the CDR TIS builds credibility and transparency through comprehensive, universal MRV mechanisms. EU regulatory oversight could play an important role here by consistently quantifying permanence and additionality, upholding the highest quality of MRV possible, preferably backed by hard institutions, and preventing the emergence of low-quality removal credits and double claiming for activities (Zetterberg, Johnson, & Möllersten, 2021).

4.3.2 Compliance Mechanism

Although the voluntary mechanism is critical to CDR technologies in this early stage, it is heavily unsuited to reach the scale required to stay within global temperature goals. As mentioned, to reach a gigaton scale in the future, CDR will rely on public funding and market formation mechanisms driven by hard institutions to form a European compliance carbon market for CDR. Expert 4 stated:

“We're not gonna get nearly where we need to be without this becoming a compliance market. One way or another, it will have to be regulated by, in Europe the EU. Ideally globally, otherwise it’s just not going to happen.”

Although compliance markets for CDR do not exist yet, the interviewees indicate that this mechanism is imperative for the industry to reach scale. An existing compliance carbon market in Europe is found in the European Union Emissions Trading System (EU ETS). The EU ETS is currently three orders of magnitude larger than the voluntary carbon market. Considering the lack of funding that CDR technologies face to reach necessary scale, incorporating it in a €683 billion yearly market (Chestny, 2022; Tamme, 2022b) may offer a solution to financial troubles. As stated by Expert 2:

“But bear in mind… the size of the EU ETS is like 1000 times bigger than the size of the voluntary market… it’s like it almost doesn't exist compared to what the ETS size is.”

Moreover, the EU ETS is based on a cap-and-trade operation in which the allowances are set to run out. Considering many industries will likely not yet have been able to phase out all fossil carbon use, commonly referred to as hard-to-abate emissions, the incorporation of CDR will offer those companies a method of compensation. As stated by Expert 2 and Expert 5, respectively:

“If you do the math right, after 18 years there will no longer be any EUa’s [allowances] left. So then if you have unavoidable emissions, you have to put CO_2 in the ground somewhere else.”

“It’ll probably be part of the EU ETS. Probably even integrated into… ETS is going to go to zero… there'll be ongoing emissions… then you would have to have carbon removal as part of the system.”

However, this collusion was not endorsed by all respondents. Some respondents are more hesitant to include removals in EU ETS and would rather see CDR in its own scheme. The results from the survey showed mixed results for the potential role of the EU ETS as a platform for CDR. Although 59% agreed that ETS could positively influence a developing market for CDR, 19% was neutral and 22% disagreed. Network 3, Journalist 2, and Expert 2 explicitly referred to the live debate on whether to include CDR in EU ETS. Again, the nuance between reductions and removals is extremely important. As Network 3 states:

“That's a live debate at the moment, and interestingly among members there is not really consensus on that… the ETS today is a tool to reduce emissions. And we as a sector are providing something fundamentally different… we need to be super clear that CDR is not emissions reductions.”

Those opposed to including CDR in EU ETS are convinced that imposing a mechanism where one ton removed compensates for one ton emitted will give rise to a moral hazard, where CDR becomes an excuse to continue using fossil fuels and delay decarbonization. Policy maker 1 describes this as a sensitive political issue:

“… noticeable image problems attached to CDR, giving rise to discussion… you're kind of maintaining the old system… governments are reluctant to address this.”

Company 4 goes on to describe this moral hazard as a barrier to adopting circular business models, keeping the old discourse of fossil fuels in place by resorting to compensation. Avoiding this pitfall is a major challenge for CDR in general. As stated by Journalist 2:

"Avoiding that moral hazard is one of the biggest obstacles. You gotta do it right. You can't have it replace serious reduction."

Even if such a mechanism emerges, Journalist 1 mentions that it could be difficult to limit this mechanism to only those that actually need CDR to offset hard-to-abate emissions. Expert 4 summarizes the complexity of the discussions as follows:

"Yeah, there's a lot of talk about it, I think methodologically, there's still some open questions. So it all boils down to the definition of what residual emissions are… once that is set, and if it's set in a strict enough way, you could theoretically think about including removals in the ETS, post 2030, when there's no free allowances anymore. But that definition is going to be challenged by all voices from all ends, of course, which is understandable… Most importantly, clearly distinguishing avoidance and allowances from removals. Otherwise, this could be an 'easy out' for emitters not to decarbonize completely… the mitigation deterrence argument that a lot of people fear, for good reason. And thus fundamentally halt the deployment of removals."

Rather than depend on an existing compliance market like the EU ETS, Policy makers 1 and 5, Company 3, and Network 3 agreed that a separate scheme, not entirely decoupled from the EU ETS but still in its own framework, would be a better pathway of creating a compliance market for CDR. Learning from the EU ETS, this market could be formed through market formation mechanisms that govern this market, along with market formation mechanisms found in classic TIS studies. These include regulatory oversight, tax incentives, protected niche spaces, public procurement, mandates demonstration zones, funding mechanisms, and subsidies (Hekkert et al., 2007). Some of these market formation mechanisms were explicitly mentioned by respondents as a potential method of creating a compliance market for CDR, with Journalist 2 mentioning public procurement as a market formation mechanism to play a large role in the future of CDR, stating:

"[Public procurement] is the only way in particular that this amount of carbon removal will actually come online and stay online for the long term."

Network 3 went so far as to describe the creation of an entire institution for a European market:

"One of the ideas that I've heard floating around is the idea of this carbon central bank or European Central Bank for Carbon… slightly similar to the way that they use interest rates in the in the European Central Bank for the euro… play with supply and demand of reductions and removals... optimizing prices over time."

However, respondents mentioned that CDR must not become too reliant on government support. Although important for scaling up, Expert 2 described that reliance on purely governmental funding makes the CDR industry vulnerable, and the market as well. Although CDR will likely rely heavily on government funding to scale, it will need also need to demonstrate independent profitability at some point. As Journalist 1 stated:

"From political viability perspective, politicians aren't going to fund an industry if they realize that they're gonna be funding it forever."

Regardless of whether CDR is incorporated into EU ETS or given a separate mechanism, Expert 3 and 4 state that shared definitions and common understanding are key to a compliance market functioning correctly. This is currently undeveloped, as is shown in the results of the survey where more than half of respondents indicate that a shared understanding of objectives and expectations is currently absent. The disagreement between respondents on the implementation of compliance mechanisms demonstrates this as well, indicating a lack of clarity on direction of the CDR industry, where a common understanding is absent with regards to: a clear distinction between reductions and removals; what constitutes as a removal, and how this is quantified to be able to compare projects with different levels of permanence, certainty, additionality, and durability; and what qualifies as a hard-to-abate emission to reduce the risk of moral hazard. Creating robust and universal definitions, methodologies, standards, and guidelines is imperative for including CDR into any compliance mechanism, and MRV plays a key role. As Journalist 2 stated:

"… there is going to be some innovation needed on the MRV side as well, which I think is often not discussed."

4.3.3 CDR MARKET

The formation of a market for an intangible product such as negative emissions is challenging (Andrew, 2008; Tompkins & Eakin, 2012). Looking at both existing market mechanisms shows drivers and barriers to formation of a market for this commodity, and reveals possible synergies.

The voluntary carbon market is governed by soft institutions that drive private governance mechanisms, such as Measuring, Reporting and Verification (MRV), that operate as key verification mechanisms and require institutions to overcome the challenge of intangibility. However, the results show that soft institutions and voluntary markets are not always capable of ensuring credibility and legitimacy of CDR, and rather tend to result in fragmented markets, lack of trust, and reduced legitimacy. If a voluntary niche market for CDR is to develop further, it will require comprehensive, universal MRV mechanisms based on hard institutions that build credibility and transparency in the CDR TIS and ensure legitimacy. If done correctly, MRV can significantly contribute to technological change by introducing robust certification schemes to deal with the issue of intangibility, reduce uncertainty, increase comparability between technologies, create a shared understanding of the direction of the industry, and develop universal guidelines to reduce the risk of moral hazard. Therefore, it is preferably governed by hard rather than soft institutions. Although CDR is operational at negligible scale in the formative phase, the importance of soft institutions for early stage development is indispensable. Almost all interviewed companies and experts explicitly pointed out the critical role of voluntary ambition from the private sector's early buyers, without which, the market for CDR would not have existed. This early development of the CDR TIS as a result of private governance and voluntary demand allows for quicker adoption at a later stage, where CDR technologies can be applied on a larger scale in quicker time. Journalist 2 summarized this nicely by stating:

"I think it's [voluntary carbon market] doing a service to enabling larger scale public procurement or compliance markets because it's hard to make the case to policymakers and constituents alike if those technologies don't exist or the market doesn't exist yet."

This effectively lays the foundation for future compliance markets by developing methodologies, increasing awareness, and ultimately driving innovation faster than policy can. Therefore, the role of the voluntary market mechanism is to support a breeding ground for innovation. Expert 3 stated that:

“What happens in the voluntary market will ultimately have an impact on the compliance markets.”

The compliance carbon market comes with market formation mechanisms that have the potential to create a regulated European market for CDR, capable of reaching scale that can provide meaningful climate change mitigation. Although present, hard institutions are not yet capable of governing a compliance market mechanism for CDR. Furthermore, the threat of a moral hazard in the CCM acts as a barrier that can effectively halt to the diffusion of CDR technologies. Although respondents were unanimous in saying that compliance mechanisms will play a key role in the future, the pathway by which this could best be achieved was hotly debated. Tensions and conflicts are not entirely unknown to the dynamics of an innovation system, and this may indicate that there is not yet a common understanding of which direction the TIS is set to go, confirming the early phase in which the TIS is currently in. At some point, the CDR TIS will require standardization that will lead to lock in. Until then, continued uncertainty will act as a barrier to upscaling (Bergek et al., 2008a). This is not to say that there will be a single standardized mechanism for creating a compliance market for CDR. Expert 5 stated that the CDR industry may need different market formation mechanisms depending on what stage of development it is in:

“… the mechanism that scales it up is not necessarily the mechanism that we need to ramp up… it might be one type of policy mechanism… incentivizing it. But to go from scaling to ramping, that might be a completely different policy instrument.”

A combination of voluntary and compliance forces, working in tandem, can prove essential for the CDR TIS. Advanced market commitment and prepurchase agreements from the private sector are setting the stage for early development in the formative phase, while future outlook of compliance mechanisms can support CDR to take flight in the next decades to enter a growth phase. Expert 3 described this in terms of an expected exponential growth of CDR that follows two phases, very similar to the two TIS phases referred to by Bergek et al., (2008a). The first (formative) phase, governed by soft institutions, uses private governance and advanced market commitments, pre-purchasing agreements, private funding, and VC to mature the industry to prepare it for a second (growth) phase, governed by hard institutions. Here, market formation mechanisms, like tax incentives, mandates, and public procurement, can assist in creating a functioning market for CDR to reach the 10 gigaton scale in 2050 (Fuhrman et al., 2023). In Figure 4, this is visualised as the share of the annual goal that both phases are capable of achieving. In Figure 5, the total capacity of CDR driven by both markets is visualised, where voluntary markets are responsible for initial growth to a certain limit, until they can be relieved by compliance markets that can reach explosive growth. Both Figures 4 and 5 are not based on accurate projections, but are included to visualise expected growth and relative contribution of both market mechanisms, following the qualitative data from the interviews.

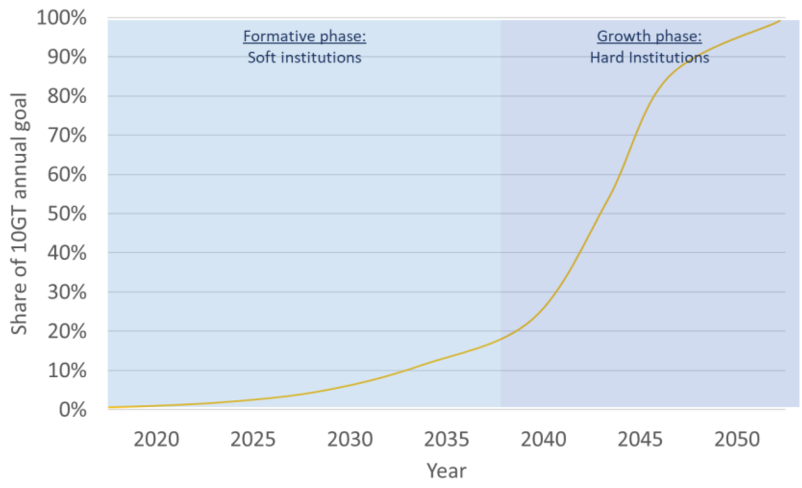

Figure 4: Share of annual 10 GT goal (Fuhrman et al., 2023)

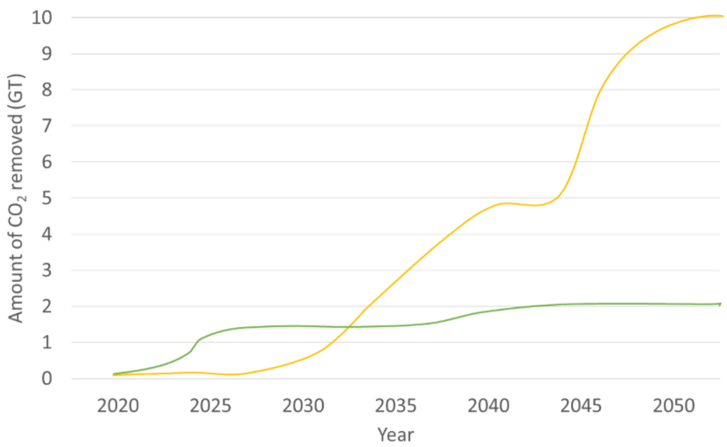

Figure 5: Amount of CO_2 removed with voluntary markets (green) and compliance markets (yellow)

5 DISCUSSION

5.1 THEORETICAL IMPLICATIONS

The TIS framework is used to assess the performance of the innovation system for a basket of CDR technologies and identifies the drivers and barriers for this system to achieve technology diffusion. The inherent challenge of this TIS is that it comprises physical technologies that are developing and selling an intangible public good: Carbon Dioxide Removal. Many TIS studies have offered a comprehensive understanding of the TIS framework in relation to tangible products and sectors, but there is a gap in the literature when it comes to intangible products. Intangible products are inherently hard to market (Tompkins & Eakin, 2012), and an in-depth understanding of demand-side conditions is key to achieve long-term transformative change (Boon & Edler, 2018; Wesseling & Edquist, 2018). By breaking out the distinct roles of voluntary and compliance market mechanisms in forming demand-side conditions, this study develops an understanding of market formation dynamics in the context of intangible goods and contributes to a more comprehensive understanding of the TIS framework's applicability across different product systems. The challenge revealed by the dichotomy of market mechanisms called for the inclusion of environmental governance theory to support the understanding of the role of private governance in the formation of a voluntary market for carbon. The inclusion of environmental governance as a theoretical framework in addition to innovation systems is unique. Although other TIS studies have considered the role of private governance mechanisms such as environmental certificates (ecolabels) and standards (Grösser, 2012; Moy de Vitry, 2013; Toivonen et al., 2021), these deal with tangible products in an established industry in which there are also non-sustainable counterparts. In contrast, private governance plays a much more dominant role this system, as it has led to the formation of a standalone voluntary market mechanism for intangible products. Therefore, this research requires theoretical support from environmental governance alongside the TIS framework to understand the dynamics of private governance in the formation of a voluntary market. This unique approach has allowed to identify the crucial role of soft institutions and private governance in absence of hard institutions and market formation mechanisms. The empirical research shows that although it is likely that soft institutions will play a diminishing role in the long term as hard institutions take over, they play a key supporting role in the emergence of an innovation. This is consistent with Vogel's (2008) understanding of dynamic relationship between soft and hard institutions where soft institutions have the potential to become harder. By identifying the distinct roles soft and hard institutions play in generating demand-side conditions, this research contributes to a better understanding of identifying drivers and barriers to forming markets for intangible products. This understanding is not necessarily limited to intangible products. Swift market formation is important for any TIS, and nascent TISs can profit from fast moving soft institutions for early market development in advance of hard institutions. In this case, the results from this research present an opportunity to expand the application of the TIS framework beyond conventional boundaries of tangible and intangible products and contribute to a more comprehensive understanding of the theory's applicability across different product systems. Moreover, understanding how different types of products operate within the TIS framework may enhance the framework's ability to design and implement effective policy recommendations to accelerate technological change.

Avenues for future research include instances where voluntary mechanisms also play an important role. Up to now, market formation in emerging TISs have focused exclusively on compliance demand-side instruments, like public procurement and demonstration zones (Hekkert, 2007). However, the purchase of tangible sustainable products, like EVs and renewable energy, are often reliant on voluntary ambition of consumers to adopt a more sustainable lifestyle. Private governance is a key concept to behavioural change (Bartley, 2007; Cashore, 2004; Vogel, 2008), and can therefore play an important role in the diffusion of these technologies. In this sense, innovation systems can be complimented by the concept of private governance, which is up until now only embedded in the field of environmental governance. There is a greater need for synergising the application of these strands of theory, as this research has shown that role of fast-moving soft institutions can prove essential in creating an industry from the ground up in time for humanity to reach global temperature goals. A shortcoming of the functional approach in the TIS framework is that it does not pay explicit attention to the dynamics of surrounding contexts (Bergek et al., 2015). Future research could explore how private governance acts as a context structure and interacts with a TIS.

5.2 LIMITATIONS

The TIS for CDR is an early stage of development, with new developments arising continuously. Many key players and frameworks are still yet to emerge in the TIS for CDR. This is inherent to TISs in early phases of development, as networks are often undeveloped and institutions may not yet exist (Bergek et al., 2008a). Ultimately, the adoption of Article 6 will provide a new international context for carbon markets in which the Paris Agreement may play an important role in the formation of an international market for carbon. Therefore, the results from this research may be premature in the international context and the applicability of the results may be limited following the emergence of new actors, networks, institutions, and infrastructure. Furthermore, because CDR addresses a global problem by producing an intangible public good (Ahonen et al., 2022; Andrew, 2008; *Armstrong* vs. *Winnington*, 2012; Poralla et al., 2021; Tompkins & Eakin, 2012), the EU-level scope excludes the influence of international institutions that will likely play an important role in the future of carbon markets. This limitation indicates the need for a comparative analysis across different regions. The impact of other (trans)national and global institutions, such as those in the United States and Article 6 of the Paris Agreement, may play an important role in the diffusion of CDR technologies. Comparative studies can identify similarities, differences, and potential knowledge transfer between regional TISs, enhancing the understanding of the global dynamics of CDR (Hillman & Sandén, 2008).

The research used two separate methods for data collection to increase reliability of data and validity of the results. In total 26 people were interviewed and 37 responses were recorded on the survey. This large, diverse sample of interview respondents enhances the representativeness and generalizability of the findings by reducing biases and including a broad range of perspectives, insights, experience, and expertise, while the survey enhances the depth of the results. By combining these two approaches, this research aimed to generate holistic and comprehensive results to inform the current status of the TIS and accelerate its development. However, a limitation in combining these methods of data collection was that both data sets were not complete in the sense that not all survey respondents were interviewed, and not all interviewees had completed the survey. To avoid double counting, the results from the interviews were analysed separately from the questionnaire rather than being aggregated.

6 CONCLUSION

This study set out to answer the following research question: What are the drivers and barriers to the development and diffusion of the CDR TIS and what is the role and influence of the compliance carbon market and voluntary carbon market? To answer this question, a TIS analysis was conducted by interviewing a wide variety of stakeholders along with a survey among CDR actors.

The functional-structural analysis show that the CDR TIS is in a formative phase, where: start-ups are entering often and are primarily focused on R&D and demonstrating their technologies; knowledge infrastructure in undeveloped, as academic uncertainties exist surrounding capacity, development, and readiness of CDR technologies; private funding, pre-purchase agreements, and venture capital make up the largest part of financial infrastructure for CDR; and national-level CDR policies and frameworks are largely absent and vary considerably across Member States. The voluntary market mechanism drives the early development of the CDR industry has been indispensable in creating an industry from the ground up. Private governance is capable of successfully creating a functioning market within a short time frame, provided that comprehensive Measuring, Reporting and Verification (MRV) mechanisms are present to ensure credibility and transparency. Institutions supporting MRV are essential in establishing legitimacy, building trust, and gaining social acceptance. However, relying solely on soft institutions can result in fragmented markets, lack of trust, and reduced legitimacy. This research showed that the CDR TIS is demonstrating a strong desire for compliance market mechanisms, governed by hard institutions, to reach a scale meaningful for climate change mitigation. To this end, networks and partnerships are active in collaboration, research, and policy-making to establish high-integrity, compliance carbon markets. However, the opinions on how to materialize such a market diverged considerably. This animosity among respondents indicates that a common understanding of CDR, and ideas on where it needs to go, is still heavily undeveloped. The results show that the first signs of these market formation mechanisms are enveloping, where a number of national governments have implemented feed-in tariffs (Norway & Luxembourg), government plans (Denmark & Switzerland), and business models (UK). However, the presence of moral hazard poses a barrier to the diffusion of CDR technologies within a compliance market. Many interviewees expressed that CDR should not replace the need to decarbonize, but must go hand in hand with decarbonization and should not be used as an excuse for companies to continue emitting carbon.

6.1 MANAGERIAL RECOMMENDATIONS

This research was written during an internship at a CDR Company, and therefore provides managerial recommendations in this section. The advice that follows from this research focuses on addressing academic uncertainties, focusing on acquiring funding from private sources, and keeping an eye on market formation mechanisms enveloping for funding opportunities. First, due to low capabilities of knowledge infrastructure, a recommendation that follows from this research is to address the scientific uncertainties surrounding certain CDR technologies. This could include transparency on environmental impacts, communicating the Technology Readiness Level (TRL) to potential investors, and collaborating with knowledge institutes. Second, due to the presence and capabilities of soft institutions in the current phase of the TIS, private sources of funding, such as pre-purchase agreements, advanced commitments, and venture capital form the primary sources for financial infrastructure. However, as reaching scale is dependent on hard institutions, and market formation mechanisms are emerging in the TIS, a strong recommendation that follows from this research is to anticipate for policies and governmental opportunities. Where private funding is sufficient for demonstrative technologies with lower TRLs, public funding and market mechanisms are important for proven technologies with higher TRLs. Political networks are important in establishing these mechanisms, and memberships in these networks could provide key opportunities for CDR Companies looking to scale their technology. Furthermore, it may benefit to focus activity on countries in which CDR technologies have mutual benefits in relation to prevailing industries.

6.2 Take Home Message

The take home message of this research is that the CDR TIS may benefit from a combination of both voluntary and compliance market mechanisms working in tandem. In the current phase, soft institutions play an essential role in driving voluntary demand and forming private governance mechanisms that contribute to forming the foundation of an industry that is too immature for hard institutions. However, hard institutions drive market formation mechanisms and are essential to realize mass markets and contribute to the later growth phase of the TIS. The findings of this research are not limited to the CDR industry, but can be applied to other tangible and intangible product systems. The influence of soft institutions in the formative phase of the CDR TIS contributes to a more comprehensive understanding of TIS functioning across different product systems. This understanding can inform policy recommendations to accelerate technological change and design effective interventions.

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8 Annex

8.1 Interview Guide

0) WELCOME

I would like to talk about CDR. To be clear, with regards to technological scope, the methods of CDR included in this research are those that utilize high-technology and scalable process to mitigate climate change, such as direct air capture, ocean alkalinity enhancement, and biochar. Reforestation, afforestation, improved forest management, agroforestry and soil carbon sequestration are not considered as high-technologies and are intentionally excluded from this research.

a) The purpose of this interview is to gain an in-depth insight into the formation of a carbon market and understand its influence on CDR technologies.
b) What is your background? Experience, education, professional background?
c) Could you describe your company?

1) ENTREPRENEURIAL ACTIVITY

a) Are people testing for new technologies? Do you conduct tests to improve?
b) How are you benefitting from these activities?
c) Are large firms becoming more interested in these technologies?
d) Are you testing markets or public reactions?

2) KNOWLEDGE DEVELOPMENT

a) How do you develop knowledge?
b) What type of R&D do you engage in, do you have a department for this, what activities are you working on?
c) Are you analysing markets, networks, or user behaviours?

3) KNOWLEDGE DIFFUSION

a) Do you often collaborate in networks with other firms parties?
    i) Do they work well? What advantages to they bring? What about universities?
b) How would you describe the networks between actors in CDR? Weak/Strong?
    i) Do you share & have access to knowledge and expertise transparently? Any partnerships?

4) GUIDANCE OF THE SEARCH (SETTING VISIONS AND EXPECTATIONS)

a) How has the EU Climate Law influenced the expectations for CDR?
b) How has Art. 6 of the Paris Agreement influenced the expectations for CDR?
c) How have voluntary organisational compensations influenced the expectations for CDR?
d) How does your national government influence your expectation for CDR?
e) How do you influence the expectations of governments and users for CDR?
f) How does recognizable climate change influence these expectations?

5) MARKET FORMATION

a) Is there currently a functioning market for CDR?
    i) What is inhibiting the commercialization of CDR?
b) How has the demand for CDR developed, and how has it affected the formation of a market for CDR?
    i) What is your target audience?
c) Have you adopted any market entry strategies?
d) How does policy play a role in forming a niche market for CDR? What influence could policy formation have on markets for CDR?
    i) Is there diversity in financial incentives and policy instruments applied in various countries?
e) Has there been a significant breakthrough in the market for CDR?

There are currently two existing carbon market mechanisms. There is a compliance carbon market and a voluntary carbon market. Both are run by different mechanisms, but could be considered to trade a similar commodity.

What could be the role of the voluntary mechanism for CDR?

a) How could CDR fit into the current system?
b) How is the niche market currently functioning?
c) What is the potential of VCM for supporting the formation of a market for CDR?
d) What needs to be adapted for both markets to do so? How does policy play a role in this?
e) What is the role of independent crediting mechanisms like VCS and GS?
    i) What do you expect this to look like or change in the upcoming years?

What could be the role of the compliance mechanism for CDR?

a) How could CDR fit into the current system?
b) Are you familiar with Article 6 of the Paris Agreement? What are your expectations for this?
c) What is the potential of CCM for supporting the formation of a market for CDR?
    i) EU ETS
    ii) CORSIA or NDC
d) What needs to be adapted for it to do so? How does policy play a role in this?

Is it possible that an interplay of both mechanisms may be needed to bring NETs to market?

i) Will the players on these markets compete with each other?
ii) Will the users compete with each other?
iii) Can these separate markets operate conducive to each other?

6) RESOURCE MOBILIZATION

a) Is the level of external funding and investment sufficient to scale your technology?
b) What types of investors are your attracting? What are the priorities of investors?
    i) What are other sources of funding?
c) Is there sufficient availability of human competencies and expertise?
d) Are there complementary assets for you operation being developed?
    i) Think of products, services, infrastructure?
e) **BECCS:** Are there any efforts to improve or build network infrastructure for i.e. BECCS?

7) CREATE LEGITIMACY

a) Do you experience any inertia/resistance to CDR?
b) Have advocacy coalitions been effective in influencing your legitimacy by putting CDR on the agenda or lobbying for resources and favourable tax regimes?
c) Have parties with vested interests been effective in resisting the development of CDR?
d) How do you experience the competitive landscape?

8) FUTURE OUTLOOK

a) What is your outlook for the future? Vision for CDR?
    i) Do you perceive any barriers to the widespread adoption of CDR technologies?
b) To conclude. Thank you for your time and insights. Is there anything you would like to add that we have missed?
    i) What challenges have you faced? What opportunities have you encountered?

8.2 CDR Questionnaire

1 Entrepreneurial activities

a. The number of start-ups in CDR has been increasing over the past years.
   i. Strongly agree
   ii. Agree
   iii. Neutral
   iv. Disagree
   v. Strongly disagree

b. The types of applications and technologies have been diversifying over the past years.
   i. Strong diversification
   ii. Some diversification
   iii. Neutral
   iv. Low diversification
   v. No diversification

c. It is difficult for start-ups to enter the CDR industry.
   i. Strongly agree
   ii. Agree
   iii. Neutral
   iv. Disagree
   v. Strongly disagree

2 Knowledge development

a. The development of knowledge has been increasing over the past years, with the academic world showing increasing interest in CDR.
   i. Strongly agree
   ii. Agree
   iii. Neutral
   iv. Disagree
   v. Strongly disagree

b. The development of knowledge is important at the current stage of CDR.
   i. Highly important.
   ii. Moderately important
   iii. Neutral
   iv. Low importance
   v. Not important at all

3 Knowledge diffusion

a. Is knowledge and expertise transparently shared amongst firms?
   i. Extensive knowledge sharing
   ii. Key knowledge sharing
   iii. Some knowledge sharing
   iv. No knowledge sharing
   v. N/A

b. Are there networks in which knowledge can be shared?
   i. Yes
   ii. No

c. How would you generally characterize CDR firms?

i. Engaged
ii. Individualistic

4 <u>Guidance of the search</u>

a. There are sufficient EU regulatory incentives & pressures that influence the search for climate change mitigation in favour of CDR relative to other technologies, applications, markets, or business models.
   i. Strongly agree
   ii. Agree
   iii. Neutral
   iv. Disagree
   v. Strongly disagree
b. How important do you consider governmental support and policies in forming expectations for CDR?
   i. Essential
   ii. Important
   iii. Low importance
   iv. Not important
c. There is a shared understanding of objectives and expectations for the development of CDR.
   i. Strongly agree
   ii. Agree
   iii. Neutral
   iv. Disagree
   v. Strongly disagree

5 <u>Market formation</u>

a. What phase is the market for CDR currently in?
   i. Nursing phase (early)
   ii. Bridging phase (intermediate)
   iii. Mature phase (late)
b. How big is the demand for CDR currently?
   i. Huge demand
   ii. Reasonable demand
   iii. Low demand
   iv. No demand
c. To what extent do you experience competition with established climate change mitigation methods, other than CDR?
   i. Strong competition
   ii. Some competition
   iii. Low competition
   iv. No competition (fundamentally different product)
d. The EU is supporting and stimulating CDR by actively forming a protected niche market.
   i. Strongly agree
   ii. Agree
   iii. Neutral

    iv. Disagree
    v. Strongly disagree

e. Currently, there are sufficient, legitimate market platforms on which removal credits can be sold.
    i. Strongly agree
    ii. Agree
    iii. Neutral
    iv. Disagree
    v. Strongly disagree

f. The existing voluntary carbon market (Verra Carbon Standard, Gold Standard) mechanism will positively influence the development of a market for CDR technologies.
    i. Strongly agree
    ii. Agree
    iii. Neutral
    iv. Disagree
    v. Strongly disagree

g. The existing compliance carbon market (EU ETS) mechanism will positively influence the development of a market for CDR technologies.
    i. Strongly agree
    ii. Agree
    iii. Neutral
    iv. Disagree
    v. Strongly disagree

6 Resource mobilization

a. CDR has reached a point where is it fully self-capable of attracting investment.
    i. Strongly agree
    ii. Agree
    iii. Neutral
    iv. Disagree
    v. Strongly disagree

b. The volume of investments, subsidies, or resource streams allocated to CDR projects is increasing enough to sustain envisioned growth.
    i. Strongly agree
    ii. Agree
    iii. Neutral
    iv. Disagree
    v. Strongly disagree

c. Because of high levels of political uncertainty, there is reluctance of government and private investment.
    i. Strongly agree
    ii. Agree
    iii. Neutral
    iv. Disagree
    v. Strongly disagree

7 <u>Create legitimacy / Resist change counteraction</u>

a. The legitimacy of CDR has increased in the eyes of relevant stakeholders over the past years.
    i. Strongly agree
    ii. Agree
    iii. Neutral
    iv. Disagree
    v. Strongly disagree

b. CDR is being put high on the political agenda, with increased lobbying for resources, favourable tax regulations, initiatives and proposals.
    i. Strongly agree
    ii. Agree
    iii. Neutral
    iv. Disagree
    v. Strongly disagree

8 Thank you for taking the time to fill out this questionnaire. Please indicate below if you would allow a subsequent request for an in-depth interview to share your insights and perspectives on this topic to further contribute to the quality of this research.
    i. Yes
    ii. No