THE EFFECT OF NEW USER SECTORS ON THE CCS INNOVATION SYSTEM

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Abstract

In most mitigation scenarios compatible with achieving the goals of the Paris Agreement, carbon capture and storage (CCS) develops and diffuses at a very rapid pace over the coming decades. The technology is frequently discussed as a mitigation option in a variety of industries and sectors, including the power sector, the cement industry, and as a tool for negative emissions through direct air capture and/or bioenergy with CCS. Different sectors and industries have distinct requirements, characteristics, and institutional needs which may require significant adaptations to a technology and its innovation system as it is adopted and used in new sectors. In this short paper, we propose using the technological innovation system perspective (TIS) to explore potential innovation challenges and opportunities CCS faces as the technology is adapted to new and different sectors. We argue that developing a socio-technical understanding of CCS innovation will be important, and present preliminary insights from our ongoing case-study on the effect of new user sectors on the Norwegian CCS innovation system. Preliminary findings include that sector changes may have affected the actor composition of the Norwegian CCS TIS, as well as the legitimacy of CCS in Europe. Our research also indicates that being aware of institutional and physical differences between industries – including differences in innovation modes – may be important for the diffusion of CCS going forward.

Keywords: *Technological innovation systems, multi-sector innovation, carbon capture and storage*

1 Introduction

In most mitigation scenarios compatible with achieving the goals of the Paris Agreement, carbon capture and storage (CCS) plays an important role in the global mitigation efforts. In many of these modelled pathways, the global CCS capacity expands from today's capacity of roughly 40 million tons of CO2 captured per year to an industry capturing several billion tons of CO2 per year in a matter of a few decades [1-3]. While possible in modelled pathways and in theory, there are questions about the feasibility of various modelled developments and how these developments can be best achieved [4-6]. It is important to be aware that the models behind most mitigation scenarios include *"oversimplification of social realities, a limited attention for actors and behaviours (struggles, beliefs, strategies), (...) while portraying transitions as emerging smoothly over time"* [7]. Because of this, scholars have called for a better link between the insights from transition and innovation studies and the output of models [7-9], and highlighted a need for "*real-time assessments of the state of a system in transition, including the interactions between the technical, institutional, social, political and normative dimensions of a transition"* [7].

For CCS, the potential discrepancy between current developments and modelled pathways can be implied by looking at the coming decade. Of the over 200 scenarios assessed in the IPCC's Special Report on the 1.5 °C-target (SR1.5), only one avoids CCS this century, and the scale of CCS in the median scenario is 914 million tons of CO2 captured per year (MtCO2/yr) already in 2030 [1]. To put these numbers in perspective, the total capacity of all *planned* and *operating* CCS facilities in 2020 was a bit above 100 MtCO2/yr [3, 10]. Traditionally, CCS facilities have been large-scale projects with long lead times – often around 10 years [11]. If this trend continues, the CCS capacity in 2030 will, to a large extent, be decided over the next few years.

Such rapid growth from early stages of innovation to global industry may present a series of innovation-based challenges. We propose that a *socio-technical* view of innovation can be an important contribution to exploring these challenges. The basis for this short paper is a notion that utilizing insights from innovation and transition studies to explore ongoing CCS developments can help identify potential opportunities, blockages, and barriers which may help or hinder the development and diffusion of CCS. We argue the *technological innovation system perspective* (TIS) is especially fruitful here, since it *"contributes with an analytical framework for understanding the complex nature of the emergence and growth of new industries and a focus on analysing obstacles to this process"* [12]. In this short paper, we focus on how adaptation to new and different user sectors may influence CCS technology and its broader innovation system. As discussed in the theory section of this short paper, adapting to new user sectors can provide a series of challenges (and opportunities) for the development of a technology. Since CCS is frequently discussed in relation to a wide variety of sectors, industries, and use-cases – understanding how interactions with different use sectors may influence the technology and its innovation system could prove crucial at this stage of CCS' innovation journey.

The paper is structured as follows, first we present some theoretical insights into how innovation and transitions studies understand change and technological development. Here we also introduce concepts from the technological innovation systems (TIS) perspective, and how these concepts relate to the introduction of new user sectors into an (existing) innovation system. Finally, we present some preliminary findings from our ongoing longitudinal case study of how new user sectors have influenced the Norwegian CCS innovation system.

2 Theoretical background

2.1 Innovation and transitions as socio-technical processes

Both transition and innovation studies understand change and the development of new technologies as *socio-technical processes* which require and lead to changes in the *socio-technical systems* of society. *Socio-technical systems* can be defined as the networks of actors, institutions, and norms, as well as the infrastructure, knowledge, and material artifacts which compose various societal subsystems [13]. Examples of such systems include the electricity sector and the agro-food sector [14].

Both innovation processes and sustainability transitions can be highly complex and contested and are difficult to steer and control. They are understood as multi-dimensional process, involving a multitude of actors, technologies, considerations, opinions, and include power struggles and discursive struggles between various actors and views [15, 16]. Both the development and diffusion of new (and sustainable) technologies, and the destabilization and change of existing systems are complex long-term process which often take decades to unfold, and which evolve in a non-linear fashion [14, 17]. This puts the insights from these fields in contrast with some of the assumptions of many of the models behind mitigation scenarios, which tend to be characterized by more linear innovation dynamics based on neo-classical economic principles [7, 9, 18, 19].

The technological innovation systems (TIS) perspective, in particular, is argued to be a good framework for identifying the challenges and barriers a technology (and its related innovation system) is facing [13]. While CCS has been analyzed through the lens of TIS before (e.g. [20] and [21], an updated TIS analysis of CCS may provide several valuable insights and a better 'real-time assessment' of the CCS innovation journey. This is especially true when looking at CCS diffusion in sectors other than the power sector, since, as highlighted by Bui et al, *"relative to the power sector, there is a paucity of academic studies of industrial carbon capture"* [22]. The TIS framework is briefly outlined below.

2.2 Technological innovation system

A *technological innovation system* is frequently defined as *"network(s) of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology"* [23]. A core idea in the innovation systems approach is that the innovation and diffusion of technology stems from both individual actors and firms, but also from the broader context – including specific technological characteristics, institutional and economic structures, and various adoption mechanisms [24]. The formative phase of a new technological innovation system involves the entry of firms and organizations, the forming of networks between these actors, and (re-)aligning institutional configurations in line with the new TIS.

If we want to understand how to speed-up the development and diffusion of a technology we must understand what is blocking the current of rate development from going faster [25]. As such, weaknesses in the TIS must be identified. To do this, scholars have developed a *"functions of innovation systems"* approach. This approach introduces a layer of key system functions which are important for a TIS to grow and develop [25, 26]. The functions describe the ongoing developments within a TIS and are considered good indicators of the overall performance of the innovation system [25]. The seven functions are: *1) knowledge development and diffusion, 2) entrepreneurial experimentation, 3) influence on the direction of search, 4) market formation, 5) legitimation, 6) resource mobilization and 7) development of positive externalities* [27].

Simply put, in the TIS framework, the successful diffusion and development of a technology is understood to result from successfully fulfilling all or most of these seven functions. Over the past twenty years the functions approach to analyzing TIS developments has been prominent and fruitful – especially when analyzing the development of sustainable technologies [14, 26, 28]. A benefit to the functions approach is that it allows the analyst to identify *""system failures" or weaknesses, expressed in functional terms"* [27]. The approach can be used to identify the main challenges a TIS is facing, which again may help identify where actors and policymakers should focus their attention, and which policies may prove most suitable [24, 27]. Another benefit to the functions approach is that it allows the study of the dynamics of a TIS and what is driving (and hindering) innovation within the TIS both at a given moment and over time [24, 29]. Taken together, these aspects make the TIS perspective an excellent framework for taking stock of the status of CCS and the potential innovation opportunities and challenges the technology may be facing.

2.3 On innovation as a multi-sectoral process

In later elaborations of the TIS framework, scholars have conceptualized a sectoral configuration of TIS to capture sectoral interdependencies and dynamics related to a focal technology's evolution [30-32]. In this approach, technology is seen as a system consisting of components and sub-components [33, 34] that are applied in and produced by different sectors—upstream, technology-producing and downstream, technology-using sectors

[30, 35].[1] Each sector is inhabited by a population of firms with similar capabilities, and has a particular underlying 'knowledge base' and mode of innovation [36, 37]. Each technology value chain thus involves several heterogeneous sectors whose alignment and complementarities influence the performance of the focal technology [38-40]. A technology value chain approach emphasizes important inter-sectoral dynamics. That each sector differs explains why adaptation is needed [32]. As a technology evolves, its sectoral configuration changes too. Change can happen via changes to subsystems and/or changes in the design hierarchy that coordinates the division of labour between them [41]. This can involve changes to raw materials, knowledge bases, and changes in user sectors [42, 43].

When a technology is introduced into a new user sector it typically requires a good deal of adaptation and innovation and it may lead to "speciation" events, i.e. the creation of a new version or design of the technology which may even entail new technology suppliers and new functionalities [44]. Such changes in the user-sectoral configuration of a technology have historically been important for further deployment and growth in areas such as steam engines and solar PV (ibid). Engagement with new (user) sectors can also influence a technology's innovation system in various ways. Different sectors may have differing institutional needs, pulling a TIS in new and different directions [12]. Incorporation of new user sectors can also open opportunities for market formation, knowledge development, and resource mobilization, as well as changes to the legitimacy of a technology.

These dynamics can be important when analyzing CCS – as the technology has the potential of being utilized in a wide range of sectors and has moved from being primarily discussed in a few sectors (e.g. gas processing, fossil power production) to being discussed as a tool for dealing with residual emission in several sectors (e.g. cement production, steel production, bioenergy, etc.) and for providing options for carbon dioxide removal from the atmosphere (through CCS on bioenergy and/or direct air capture technologies). Some preliminary thoughts on how these changes in user sectors may affect the development of CCS is discussed in coming section(s) of this short paper, but first we will briefly introduce our methods.

3 Methods

To study the effects and dynamics of new user sectors entering the CCS TIS, we perform a longitudinal case study on the Norwegian CCS TIS.

We have analyzed close to 600 newspaper articles from three different Norwegian newspapers/magazines (Aftenposten, Dagens Næringsliv, Teknisk Ukeblad) over the period 2005-2020. This media analysis can be used to inform whether there have been changes to which sectors CCS is discussed in relation to over time. It can also inform changes in some of the seven TIS functions – this includes changes to *legitimacy* over time, tracking number of new (actor) entrants into the TIS (which can inform the *entrepreneurial experimentation* function), as well as developments which may influence the *market formation* and *resource mobilization* functions.

We plan to supplement this analysis with interviews with key actors in the Norwegian CCS TIS, as well as document analysis of various databases and document sources (such as the CLIMIT database of past CLIMIT funded R&D projects). These data sources will be used to inform further changes to the TIS functions, as well as changes to actors and networks included in the Norwegian CCS TIS. Interviews with industry actors is particularly important for informing if/how/why user sector changes have influenced the Norwegian CCS TIS.

4 Preliminary findings

4.1 CCS innovation challenges from a multi-sector TIS perspective

Our preliminary findings show a series of ways user sector changes may influence the development of CCS. These questions and challenges will be elaborated on in coming months, but here we present some preliminary thoughts. We also present some insights from the cement industry as an example of the institutional needs of a sector/industry. In a future (longer) paper, the industrial requirements of the cement industry will be compared with the requirements of other industries.

4.1.1 Adapting to physical and institutional differences

Different sectors and industries may have very different physical characteristics relevant for CCS. Difference in the composition of the flue-gas require adaptation of the various capturing technologies and may influence which capturing technology/solution is best suited for different industries. Similarly, the availability of physical space at facilities will vary across industries. Both of these physical differences can have important implications for the potential of a dominant capturing technology design to emerge. If different technologies/designs end up dominating different industries, this may also affect the potential for cost reduction and learning-by-doing effects across industries and the different capturing technologies. A common assumption is that CCS costs will rapidly decline as the technology diffuses, but if standardization and modularization across industries proves difficult, there is no guarantee that this will be the case for the capture part of CCS – not all technologies decline in cost over time (e.g., nuclear energy), and standardization is an important contributor to rapid cost reductions.

[1] Upstream and downstream sectors are delineated in relation to a particular technology value chain. The focal sector is where the technology is applied, while upstream sectors are those that produce important components and subcomponents of the technology. Note that the focal, downstream sector (in a transition) is viewed as broader than upstream sectors. The main difference is that the former includes users of sector output (e.g. electricity or mobility services) while for the latter, users are based in other sectors. The purpose of this differentiation is to explicate inter-sectoral relationships.

Different sectors and industries may also have very different institutional requirements and traditions. For instance, the cement industry – an industry often seen as a high potential industry for mitigation through CCS – has several characteristics which *could* provide obstacles for CCS diffusion in the sector. Some examples of this are outlined below.

4.1.2 An example of institutional characteristics – the cement industry

The cement industry, generally, has low profit margins and operates in competitive markets. Globally, cement production and cement demand are evenly matched, leaving little space for new entrants. This also means many firms cannot raise the cost of their product without losing market share [45, 46]. The cement industry is capital intensive, and much of the cost is CAPEX. New plants can cost hundreds of millions of dollars, and generally take years to plan and build. However, once a cement plant is built, they can last for several decades, with lifetimes up to 50 years. [45]. These characteristics make it difficult for new entrants to compete with large established firms, and the advantages of scale (supply chain efficiencies etc.) have contributed to high concentration of the industry between a few large actors. [46]. The latter implies fewer opportunities for innovative niche producers, production methods, and products [45]. Long asset lifetimes also mean that radical innovation can lead to major sunk cost. Because of this, the cement industry has historically been rather conservative with regards to innovation, and resource mobilization for innovation has been a challenge for the industry [47]. In addition, current cement supply is sufficient enough to meet cement demand, and with the long lifetime of existing and newly built plants, this leaves little room for new and innovative production facilities.

A further characteristic of the cement industry is the generally short distance between producer and consumer. High transportation costs means producers tend to serve local markets, often limited to a radius of a few hundred kilometers from the production plant [47]. As noted in Victor, Geels [46], “only 3% of global production trades across borders, and that mostly occurs among geographically close neighbours” Victor, Geels [46]. Because of this, the industry is geographically spread out over large areas rather than clustered in regions or specific locals [47].

Taken together, these aspects of the cement industry *could* influence the diffusion of CCS in the industry. For an industry with low-profit margins, including the cost of carbon capture could prove challenging. Due to the long lifetime of facilities, retrofitting of carbon capture may be the only way to introduce CCS to the cement industry in many regions. This could, for instance, limit the available capturing technology options in these regions, since cement producer may focus on technologies which can be easily/quickly retrofit. At the same time, actors in the cement industry are already used to high upfront cost for new facilities, and, as such, might be less daunted by the upfront costs of installing carbon capture.

Many argue a key for further CCS diffusion is the clustering of industrial CO2-sources, since this can reduce cost, and simplify transportation and storage. With a dispersed industry like the cement industry, this could prove a challenge – as it may be difficult connecting the dispersed production sites of the cement industry to the carbon transportation and storage infrastructure required for CCS. However, the dispersed nature (and low trade across boarders) could also be a benefit for the diffusion of CCS in the cement industry. Given the high transportation cost, it may prove harder for cement producers to relocate to new regions if stringent emission taxes/regulations are introduced, potentially lowering the risk of ‘carbon leakage’[2] in the cement industry.

Taken together, the industrial requirements and characteristics of the cement industry highlights why understanding how the CCS TIS can adapt to various industries with completely different institutional characteristics could prove very important if CCS is to diffuse at the rate and scale seen in mitigation scenarios. As CCS enters a variety of new sectors, being aware of how these different industrial requirements and characteristics may affect the CCS innovation system, and how the innovation system should adapt to the different sectors, could prove crucial for the successful diffusion of the technology. Exploring these questions is the aim of our current study.

4.2 Effect of sector changes on the Norwegian CCS TIS

In our current work, we are focusing on understanding how adaptation to new user sectors has influenced the Norwegian CCS TIS over the last fifteen years. To do this we are performing a longitudinal case study on the Norwegian CCS TIS – tracking how the entry of new user sectors has influenced the TIS over time. While our work is still in an early phase and needs to be supplemented with further document analysis and interviews, we present some preliminary results from our media analysis below.

[2] Carbon leakage refers to when an industry or business relocates to a new region or country to avoid stringent emission taxes/regulations in the original region/country.

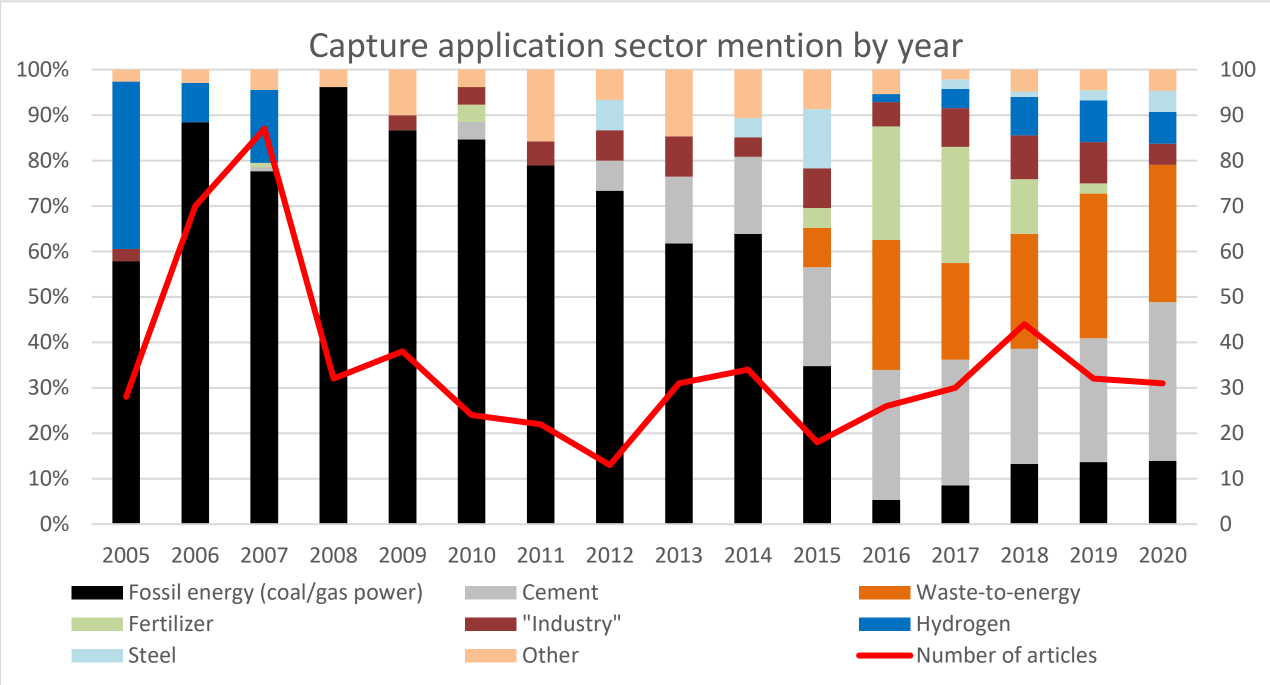

Figure 1: *The figure shows which sectors CO2-capture was discussed in relation to in the newspaper articles by year. The columns show capture application sector mentions as a percentage of all capture application sector mentions that year. The red line shows the total number of articles per year.*

4.2.1 Sector changes

Unsurprisingly, our media analysis shows a significant change in which sectors and industries CO2-capture technologies are discussed in relation to in the Norwegian newspapers over the period 2005-2020. In the period 2005-2012 capture on fossil energy was mentioned in 61-84% of the analyzed articles, while in the period 2015-2020 this number drops to 12-39%.

The move from discussing CO2-capture on fossil energy (primarily gas power) to various other industries is, of course, heavily influenced by the change in focus in the big government funded Norwegian CCS projects. The government focus in the early period of the study (2005-2013/14) was on full-scale CCS in gas power (for instance at Mongstad and Kårstø), while the later period has focused on CO2-capture on cement and waste-to-energy.

While unsurprising, these developments highlight how the Norwegian CCS TIS has moved into new user sectors over the past fifteen years, and, as such, form a good case for studying *how* user sector changes may influence the CCS TIS.

4.2.2 Legitimacy

As an example of how TIS functions may be affected by user sector changes we assessed how the legitimacy of CCS changed over time in the analyzed newspaper articles. While this is only a preliminary analysis of one of the TIS functions, our full analysis will include all TIS functions and include more data sources.

In our analysis of Norwegian newspapers, we find that the legitimacy of CCS in Norwegian news has generally been quite high in the period. The main exception to this is the period between 2010-2013. The flagship government projects on CCS on gas power suffered a series of setbacks, delays, and cancellations in this period, and as such the finding is not surprising. The quick recovery of CCS legitimacy post-2013 is very interesting – and as our analysis moves forward it will be interesting to see if the change is user sectors may have had an effect in *restoring* legitimacy, or if the reduction in legitimacy was primarily a blip linked to the delays/cancellations of flagship projects.

The media analysis in Norway cannot alone support the hypothesis that sector change has influenced the legitimacy of CCS, since CCS has maintained high legitimacy for most of the period. Hints that the hypothesis may still apply to other countries does show up in our media analysis (and in preliminary interviews). An example of this appears in an article, where a representative from WWF in Germany explains how CCS lost legitimacy in Germany because it was linked to coal power, but that WWF Germany now supports CCS on hard-to-abate industrial emissions.

4.2.3 Actor changes

4.3.1 Capture technology developers

Our preliminary analysis shows that a change in user sectors, may have had an effect on the CO2-capture technology developers involved in the Norwegian CCS TIS. Some actors show up as part of the media analysis

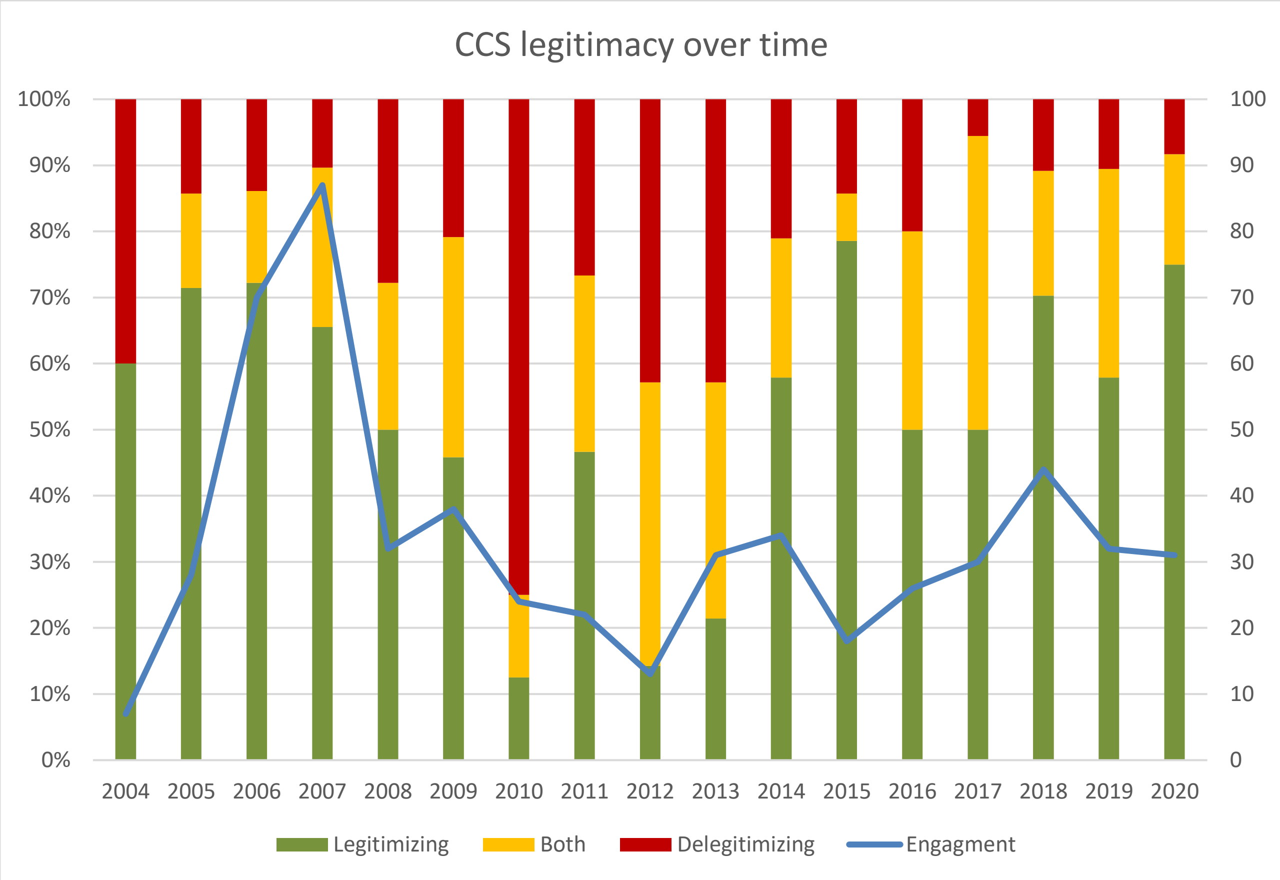

Figure 2: *The columns show the number of articles with legitimizing, delegitimizing, and both legitimizing and delegitimizing storylines per year as a total of all articles with legitmizing or delegitmizing storylines. The blue line shows the total number of articles per year.*

when the focus was on capturing CO2 from fossil power (2005-2014) but disappear as the focus shifts to new sectors. This includes big international actors like Siemens, Alstom, and Mitsubishi Heavy Industries, and the Norwegian company Sargas[3]. In later years, new companies show up in the media analysis – these capture technology companies appear to focus more on applications for CO2-capture other than capture to reduce emissions on fossil power directly. Examples include focus on direct air capture and technologies that combine CO2-capture and hydrogen production. Companies like Shell and Aker have been involved in the Norwegian CCS TIS over the entire period of our analysis and have been involved in capture on both gas power and on the new industries like cement and waste-to-energy. Understanding how these actors (Shell, Aker, Sargas/Capsol) have adapted their technologies and approaches to fit new and different sectors is something we aim to explore further in interviews going forward.

5.0 Final comments

Our preliminary work indicates that new user sectors can have an impact on many parts of the innovation system. These in turn pose new challenges and opportunities for firms and policymakers that we will explore in more depth. As an example, changes in user sectors lead to new opportunities for market formation, resource mobilization, and changes to the legitimacy of the TIS, but may also lead to new challenges when it comes to standardization and adapting to the institutional requirements of new sectors. While the analysis presented here only hints at these effects, we aim to elaborate on the broader effects of user sector changes on the Norwegian CCS TIS going forward.

Acknowledgements

Add acknowledgements here, if needed.

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