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# $CO_2$ capture initiatives: are governments, society, industry and the financial sector ready?

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Abstract (100-120 words)

The deployment of CCUS plants do not match the enormous requirements to meet the $CO_2$ emission reductions fixed during the Paris agreement, and we must ask ourselves what is refraining the technology deployment, especially in light of the recent high $CO_2$ prices. Due to the higher costs than their fossil counterparts, CCU represents a long term solution. In addition to a gigantic scale-up effort even for the most mature CCS technologies, various factors are responsible for the slow roll-out of CCS projects. Luckily, the financial sector and governments are playing their role. Support from the public is however key, and an open communication is required to convert social tolerance into social acceptance.

Keywords: Carbon capture & storage; technology deployment; public support, public acceptance.

Highlights (85 characters per bullets, 3-5 bullets)

- CCS projects roll-out does not match the Paris Agreement requirements
- Support from the financial sector, public and government is key for CCS deployment
- The cost of CCS projects is a major hurdle, and only two CCS techniques are mature
- Social acceptance and public support is key for the successful deployment

Nomenclature

| | |
|---|---|
| BECCS | Bioenergy with Carbon Capture and Storage |
| CCS | Carbon Capture & Storage |
| CCU | Carbon Capture & Utilization |
| EOR | Enhanced Oil Recovery |

## 1. Introduction

Faster than expected ice melting in the Artic seas is opening the door for alternative shorter maritime routes, and investments are pouring in with the potential to reshape maritime transportation [1]. Global warming continues its march fuelled by the continuously increasing anthropogenic $CO_2$ levels with unexpected consequences. Even the tone of the IPCC reports changed from the early 1990s where hope that the climate change could be tackled could be felt, to now where it is simply presented as inevitable, and we need to adapt to it.

CCS is envisioned as the only group of technologies with the potential to decrease $CO_2$ emissions in the 2020-2050 period without requiring a complete redesign of the industries shaping our modern welfare and economies. That is, if the enormous CCS scale-up effort can be achieved on time [2]. CCUS technologies are commonly separated as pre-, post-combustion and oxyfuel technologies, with amine-based capture with the highest TRL of the pre- and post-combustion routes (differing only in that they are applied to either the fuel gas or the gaseous combustion products). We refer to Osman et al. [3] for an exhaustive review of the recent advances in CCUS technologies, including their advantages and disadvantages, status of development, required improvements, geographical distribution of demonstration projects, etc. CCU might also play a key role, most probably heavily incentivised due to the higher costs of CCU-obtained products compared to their conventional fossil fuel-based counterparts [4, 5], as high as 2 to 8 times for ammonia and methanol [6, 7], and up to 20 times for aviation fuels [8]. CCU also involves low sequestered amounts compared to CCS, and CCS projects are more advanced than CCU in Europe [9]. CCU could however help in solving some of the hard-to-abate emissions from the cement industry. Supplementary cementitious materials (SCM) from the mineralisation of the inevitable CO2 emissions from the production of cement might represent an easy business case [5], as their valorisation could yield profit of up to 32 € per tonne of cement [10]. In general, CCU most probably represents a solution for the long term, and the urgency to act favours CCS in the short term.

The capacities of current commercial deployment of large scale CCS still represents a small fraction of what is needed to comply with the Paris Agreement (a combined 40 Mtpa from 18 projects). At least, additional projects are announced amounting to 60 Mtpa in Europe (Figure 1) [11]. What is refraining their full commercial deployment at scales matching the needs of our current societies? In particular, what is exactly needed from the three societal actors (society, industry and the government) to finally meet the promise of CCS?

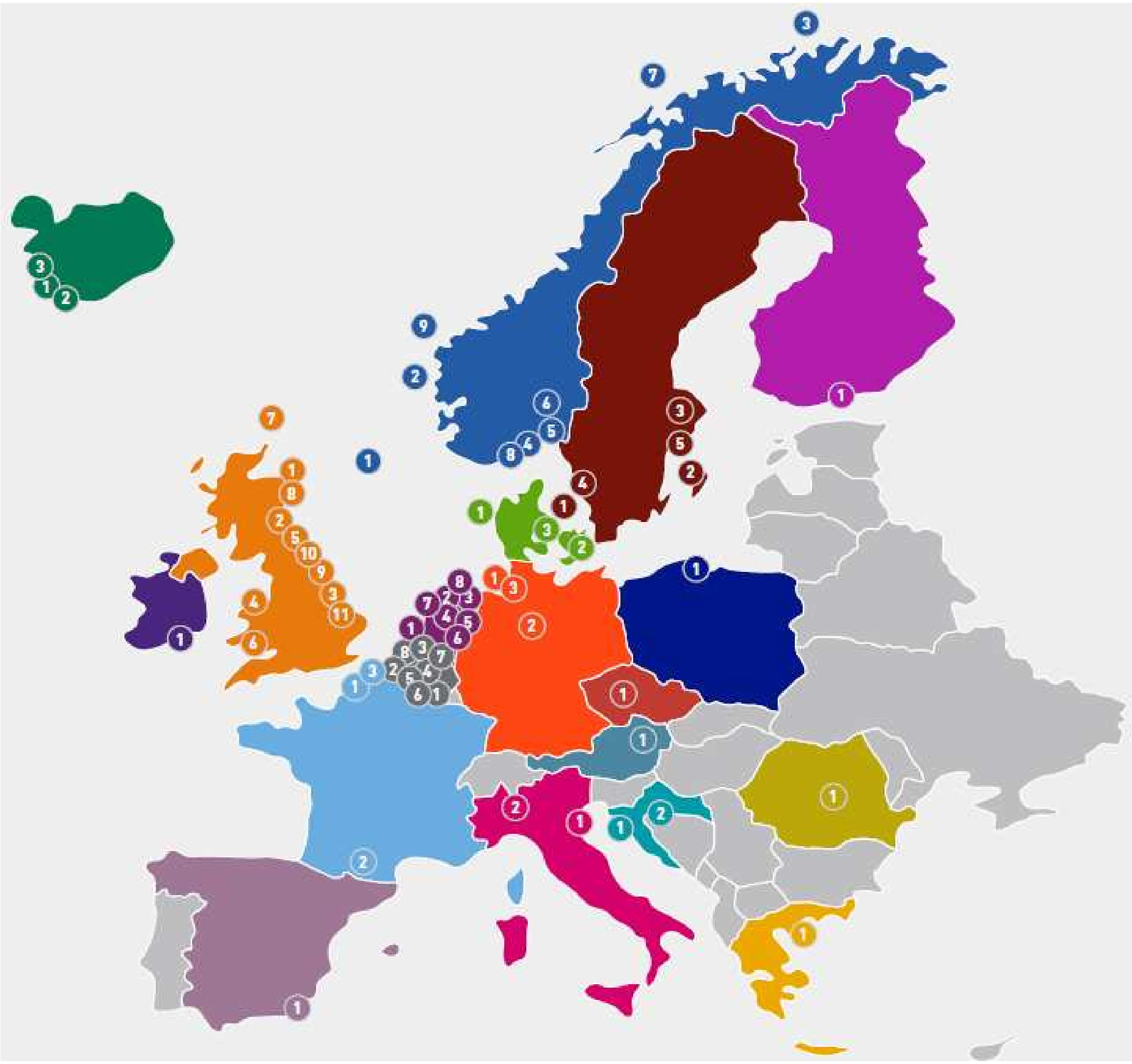

*Figure 1: Overview of the 65 existing and planned CCUS projects in Europe, amounting to 60 Mtpa. Details of the 65 projects can be found from [11].*

## 2. Industry and the financial sector

EOR drove the initial boom of CCS (almost 80% of the CCUS plants of the 1970-2020 period). However, the potential revenues from EOR are not able to transform what is ultimately a net cost into a sounded business decision. Oil prices of 85 USD per bbl were estimated in 2017 to act as the catalyst to Gt-scale CCS project [12], i.e. less than the current prices [13]. Still, CCS is not yet been deployed to a sufficient scale. In addition to the highly variable regional storage capacity estimates, non-technical factors have to be tackled such as regulations, public acceptance, property, and financing [2]. The financial sector seems however ready to back-up clean technologies, with record amounts invested in climate technology innovations. Still, the financial sector might be more conservative to avoid the unfulfilled promise of the 2006-2012 climate tech mini boom [6]. This is critical for success as even EOR requires significant upfront capital investment that take several years to generate a positive cash flow, and a decade to achieve return on investment [14]. However, even when all the conditions seems to be in place, public incentivisation is key, as revealed by the absence of CCUS projects in Wyoming, despite extensive laws covering the requirements for CCS retrofitting, the rules for sequestration, as well as ownership and long-term liability of the stored carbon [15].

The costs of CCS is a major hurdles: CAPEX of up to 110 € per tonne of $CO_2$, and variable costs amounting to up to 80 €/tonne $CO_2$ [16]. Carbon prices are climbing in the EU, averaging 84 €/tonne since the beginning of 2022, thus reaching close to breakeven and potentially converting planned CCS projects in profitable business cases in the near future. Lange [17] estimated that reaching the goals of the Paris Agreement would require increased $CO_2$ prices of 100 USD per tonne to increase the cost of oil, energy and fossil $H_2$ enough to incentivise the renewable transition. CCS project developers however require that the price of $CO_2$ remains high for the duration of projects (via most probably legislation). The high costs of CCS (capture, purification and potentially transport) and a lack of supporting regulation, coupled to the security of the availability of the $CO_2$ feedstock represent major risks. $CO_2$ emissions might be reduced during the course of CCS project due to more efficient process being developed precisely to reduce $CO_2$ emissions.

The immaturity of the market explains the slow roll-out of CCS projects [18]. Mature CCS solutions (amines and sorbents) are very limited, with still more limited innovations being tested. Additionally, the CCS economics is based on the assumption that there will be no place in a competitive future for high $CO_2$ emitting industries, assuming that major sectors of the industry will be carbon constrained, such that high investment and operational costs are inevitable. Will this be the case? The recent invasion of Russia in Ukraine is forcing countries like Germany, the Netherlands and Austria to revert to coal power. Lowering CAPEX and OPEX via either improvements of current technologies, technology innovations, and lower energy requirements for either existing or upcoming technologies should be one of the primary focus [19].

Technical uncertainties for permanent $CO_2$ storage also needs to be removed, e.g., the effect of the injection dynamics on the effective storage volume without unplanned reemissions [20]. This uncertainty could refrain the confidence of CCS projects developers: Fortunately the required risk assessment expertise related to high exploration uncertainties is probably only found in the oil and gas industry.

CCS projects developers must also pay attention to 1) selecting the appropriate capture technology with the $CO_2$ concentration, 2) matching geographically and in size the $CO_2$ source and sinks [16, 21], and 3) ensuring the availability of low cost renewable energy and hydrogen in the case of CCU [22]. In addition, a CCS “culture” (experience and expertise) must emerge for this sector to finally develop, i.e. versus mere EOR operations where $CO_2$ reemissions are unavoidable [20]. Geographically matching $CO_2$ sources and sinks might create competition among storage sites by favouring already explored sites where the uncertainty in the injection dynamics is low.

For CCS to take-off, difficult to decarbonize industry sectors (e.g. steel) must also join the effort. Again, while China represent the largest crude steel producer worldwide (44% in 2015), the Chinese steel sector does not seems to recognise the urgent need to lower $CO_2$ emissions, and up to now, there are no steel CCS plants in that region of the world [23]. This is also probably due to the lack of an enforceable legal framework, insufficient information for the operationalization of projects, weak market stimulus, and a lack of financial subsidies [24]. For this reason, the Asian Development Bank is fostering the use of the "Carbon Readiness" concept for new plants at the early plant design stage to plan for the eventual retrofitting to CCS in their operating lifetime at minimal economic penalty.

## 3. Society

The majority of the population has little technical knowledge of CCS [25]. Nevertheless, actors from the civil society have the power to block CCS projects, based on either real or perceived risks related to safety issues and human health, especially related to potential leakage from underground storage (e.g. CO2 reemissions in the form of "blowouts" from below the surface), even though they are considered as unlikely [16, 26], or negligible in the case of mineralisation [21]. Opposing groups can in that way put projects on hold by requesting additional risk analysis, and drive local politicians to change their initial support.

Social acceptance is a complex question where different factors comes at interplay: the source of biomass feedstock for BECCS [27] receives better acceptance than CCS from fossil-fuel power generation plants. Interestingly, while Asia (and India) will likely be where most of the CCS projects need to be implemented (assuming the availability of suitable storage sites), there is limited awareness, support, policy and incentives for CCS in China [21, 27]. Fostering acceptability is key at every stage of the development of CCS projects, especially for large scale projects. Saito et al. [25] however argued that due to the Chinese political system, fostering CCS acceptance "maybe less required". In general however, the active promotion of CCS is key for social acceptance, including the assurance that leakage detection and management strategies (already part of regulations for offshore storage projects) will be present [26].

CCS also suffers from its perceived end-of-pipe solution as allowing the persistence of the fossil fuel-based modern economy. For social acceptance (or better, social tolerance [16]), CCS projects should be sold as a transition solution towards the availability of truly decarbonised and electrified fuels. In addition, the emphasis on the economic benefits is required to foster acceptance, especially for the populations living nearby of CCS projects: social acceptance of CCS declines with the closeness of projects [25, 28].

4. Government

Besides their roles in the legal aspects (e.g. permits, liability, obligations related to the closure of CCS sites, $CO_2$ storage permits), governments can truly drive the deployment of the CCS sector by either stimulating (via financial incentives) or imposing (via reduction targets) projects. It would be simply impossible to implement the current CCS projects without financial support from governments as the cost of CCS projects can be staggering [29]. However, governments are generally playing their role, and hopefully the lessons learned from the 2006-2012 mini climate boom are still in their minds. In particular, the fact that they took too long to include low TRL technologies in their legislations. Interestingly, as few technologies are ready to contribute to the Net Zero Emissions by 2050 from the IEA, the European Commission acknowledge the need to scale-up and implement demonstration plants, and its innovation fund is the most important in the world [6].

In addition to financial incentives, policies that establish the price of CO2 are required, and uncertainties at this level could compromise the roll-out of CCS projects [30]. On the contrary, carbon taxes (e.g. European Emission Trading System) have no effect, and only touch the most carbon-intensive industries, opening the opportunities of cheaper emissions than capture [30]. Other factors which are seen as key for the deployment of large scale CCS projects include CO2 storage regulations: CO2 content for storage, liability, and the transfer of responsibilities [30].

The success of CCS in the US is the result of the combination of flexible environment laws (to match the specificity of CCS projects), funding and tax credits, as well as active promotion of CCS [29]. For Canada, it is due to the alignment of the federal and provincial regulatory framework, combined to adequate funding. In Europe, where Norway is clearly pioneering, the success is based on the presence of the world largest CCS test centre, extensive public funding program, government plans for full scale demonstration projects, active participation of research institutes and universities in the design of CCS infrastructure [18].

In the case where there is not sufficient low risk storage spaces for all potential projects, local governments might have to prioritize who gets access. Should they favour fossil fuel-based power plants, or the steel, cement and chemical sectors with limited “de-fossilised” alternative approaches [20]?

3. Conclusions

In light of the recent increases of $CO_2$ prices and the urgency for carbon capture, combined to the readiness of the financial sector to support the clean techs, it appears that we should soon see the roll-out of CCS projects. A favourable business case must be backed however by the stability of the $CO_2$ price, as well as legislations and incentivisation. This favourable business case will first apply to technically favourable projects (“low hanging fruits”), i.e., where concentrated streams of $CO_2$ are to be captured, e.g., industrial processes like ammonia plants (as opposed to direct air capture), and where there is a match between the $CO_2$ sources and sinks (e.g., Norther Europe, and the U.S.A.). Industrial actors leading those upcoming projects will then benefit from this emerging market by gaining this up to now lacking CCS “culture”, allowing them to rise as the key players in the field. The first to risk might be those dominating this emerging giga-scale market. That is of course, if the incentivization is sufficient to cover for the high OPEX and CAPEX, and to ensure that it remains so for the entire duration of the new projects.

To avoid repeating the errors of the past, an open-discussion with the general public is required. Social tolerance must be converted to social acceptance, highlighting the economic benefits for local populations. Luckily, the stars are getting aligned and governments are gradually passing the required laws and incentivisation required to wrap up the business case. Hopefully, we will re-read this articles in 30 years with emotion that the job has been done, and only minor deviations from our analysis were required for the successful full deployment of the critically required CCS projects.

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