Exploring attributes of global CCS projects and the key factors to their accomplishment based on the CCUS project database

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Abstract. In recent decades, the serious excessive level of carbon emissions has become the worthiest of human consideration to alleviate the problem. The negative impacts of carbon emissions on human beings involve a variety of aspects, such as sea level rise, deforestation, air pollution, global warming, etc. Any one of these issues could cause serious negative impacts on human society. In a large number of relevant studies, Carbon Capture and Storage (CCS) programs are considered to be the most promising and effective approach. The carbon produced during production is captured and transported to rock formations deep underground where it is centrally stored. There are nearly 300 CCS plants in operation around the world that demonstrate the feasibility of such projects. However, one relevant question is whether the project is costly and has barriers to deploy at a scale. We gathered a comprehensive list of large-scale CCS projects globally by utilizing the CCUS Projects Database. We then conducted a comparative analysis of these projects across various categories of project status, ensuring comparability by standardizing cost and extraction figures for each project. We found that the cost of Capture and Storage Projects is the highest, followed by just Capture Projects and just Storage Projects. These plants predominantly exist in developed regions: the U.S. hosts the most, then Europe, parts of Australia, with fewer plants scattered globally. Based on detailed project-specific information, we found that that the two most common reasons for suspended or closed plants are high costs without sufficient financial support and the impact of government agencies' permissions and regulation. As such, improvement in the capital market and more policy support would be crucial for the deployment and operation of Carbon Capture and Storage projects.

Keywords: carbon capture and storage, regulation support, environmental-friendly

1. Introduction

Carbon capture and storage (CCS) is an increasingly important topic for this century. As climate change is heading to a more severe phase, the human society faces the pressing demand to limit temperature to 2 or 1.5 degree. As such, more understanding and implementation knowledge in carbon removal is crucial. The great harm of carbon emissions has been recognized and seen by everyone around the world, and both public and private sectors are actively looking for solutions from the perspective of CCS. For example, Lefvert et al studied the road of transformation and the implementation of CCS for Sweden [1], and identified that both CCS for fossil CO2 and bio-energy with carbon capture and storage (BECCS) would be further developed with a focus on BECCS. BECCS technology is considered an overlooked near-term opportunity to generate CO2 removal and low-carbon hydrogen [2]. As such, we examine existing and planned CCS projects globally to provide an important view in the decarbonization pathways.

Scientists have conducted various analyses and reviews to understand whether the current state of CCS technology has full capabilities of widespread use [3, 4], and deeper insight in which public resistance to onshore storage and the assumed policy impact of changes in carbon transportation costs are not the most important issues in undertaking CCS projects, when the real story is that storage site type issues appear to have a greater impact of CCS technology [5].

One main challenge for the broad deployment of CCS is public acceptance associated with a broad set of socioeconomic factors. Wennersten et al demonstrated that for today's era, in the circumstances that all countries are developing science and technology to protect the environment [6], the main obstacle to large-scale implementation of CCS is not technology, but economic and social. The penetration rate of CCS is so low that ordinary people in many countries and regions have not heard of or understood the CCS project. As a result of that, the main challenge for CCS will be to gain widespread public acceptance. Based on the current situation where the Internet is severely developed, it is not difficult to popularize the basic content of the CCS project to the public. However, It's not an easy mission. The technology opaqueness and the unsettled discussions in the scientific community further hinders public acceptance. For example, plenty literature has examined and discussed the uncertainties in thermophysical properties on the design and operation of components and processes involved in CO_2 capture, conditioning, transport and storage, as reviewed by Tan et al [7]. These technical discussions have made it difficult for public to evaluate the readiness of CCS. Bruhn also suggested that another important point is that the popularization of CCS technology to the public should also include details of how to distinguish the difference between CCS (Carbon Capture and Storage) and CCU (Carbon Capture and Utilization) [8]. Carbon capture and utilization is a necessary strategy for reducing atmospheric carbon dioxide levels and has the ability to stop global temperatures from rising. The idea is that this technology can remove carbon dioxide from the atmosphere, which can then be reused or stored permanently. Carbon capture and storage is also a very effective way to reduce carbon emissions, involving three steps: capturing carbon produced during industrialization, transporting it, and finally storing it deep underground. Comparing the difference, CCU offers novel solutions to utilize carbon dioxide as a raw material, which helps to replace fossil fuels and chemicals and even produce entirely new products like "food without fields". CCS technologies on the other hand help create net negative greenhouse gas emissions [9].

In addition to challenges in public acceptance, CCS projects are both highly localized and capital intensive. Despite that the technology is now complete, the capture and storage are dependent on local geological conditions, and cost of capturing and storing carbon has been constantly high. For example, Selosse conducted a modelling analysis and found that the type of storage site having a large impact [10], and the cost of transport would not influence the penetration of the technology but the choice of site. However, limited onshore storage would still largely influence the penetration of CCS technology because storing carbon offshore would cause a significantly higher cost. As such, here I conduct this research using CCS project specific data to analyze the impacts of local conditions and costs on the implementation of CCS technology.

2. Methodology

2.1. Data sources

We obtained the list of large-scale CCS projects worldwide from the CCUS Projects Database (https://www.iea.org/data-and-statistics/data-product/ccus-projects-database).

Founded in 1991, the remit of the GHG TCP is to evaluate options and assess the progress of carbon capture and storage, and other technologies that can reduce greenhouse gas emissions derived from the use of fossil fuels, biomass and waste. The aim of the TCP is to help accelerate energy technology innovation by ensuring that stakeholders from both the public and private sectors share knowledge, work collaboratively and, where appropriate, pool resources to deliver integrated and cost-effective solutions.

2.2. Data transformation

For the convenience of further research, we transformed the cost of every project all to current US dollars. Specifically, we obtained exchange rate between US Dollar and Canadian Dollar, Austrian Dollar, Euros, Japanese Yen, Norwegian Kroner, British Pound, Chinese Yuan, Danish Krone and Brazilian Real from HSBC (https://www.currencyzone.hsbc.com/?cid=HBEU%3APW%3AFXSEARCH22%3AP1%3AGBM%3AL14%3AGO%20%3AXTR%3A14%3AXX%3A13%3A1122%3A672%3AFXSearch22_FX_Google_PPC_Exact%20_foreign%20currency%20exchange%20rates&gclid=EAIaIQobChMIquXhncKV_wIVzGtMCh1ihg5jEAAYAiAAEgKFt_D_BwE&gclsrc=aw.ds&ccyFrom=GBP&ccyTo=USD&range=month&amount=20&lng=en-GB). Also, the same unit of cost is ensured. In addition, the amounts being sequestered, transported, and stored are based on different units. We transformed all of these amount to tonnes per day. Specifically, the transformation from MW (Megawatt), B/D (Barrels per day), CF (Cubic foot) to tonnes per day follow the below rules:

•From MW to tonnes per day: we used the CO2 emission rate of 884.2 lb per MW (https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references#:~:text=Home%20electricity%20use&text=The%20national%20average%20carbon%20dioxide,EIA%202020b%3B%20EPA%202021). Assuming 1 lb is equivalent to 0.0004535924 ton, we multiplied the number of MW by 884.2 and by 0.0004535824.

•For B/D to tonnes per day: based on Ordos Basin Project (Project ID 43), we assumed that the capturing rate of CO2 is 85% with 400kg CO2/barrel of oil. As a result, we use the original date multiply 400/1000 and times 0.85.

•For CF to tonnes per day: Based on Project summary, plan to capture 900,000 metric ton of CO2 per year, transform to tonnes per day.

and based on Ordos Basin Project (Project ID 43)) to help make all data to transform into T/D (Tones per day), the product of the origin size or capture amount and the transformation coefficient would calculate the quantity of carbon each program transformed with the same unit (T/D) guaranteed.

2.3. Results and Discussion

Status of capture, storage, and capture and storage plants

Most of the CCS projects are either existing, or have been under development or planned. From Figure 1 which is the Summary of status of plants, the Capture and storage plants that have been cancelled appear to have the highest level of costs, which raises our suspicion that the high cost could have led to projects being cancelled. We observe that among the “in development” and “planned” Capture, Storage, and Capture and Storage plants, about half have the highest level of costs. This is to say, current and future development of CCS have increasing project costs, which could be a key factor for the successful implementation of these projects.

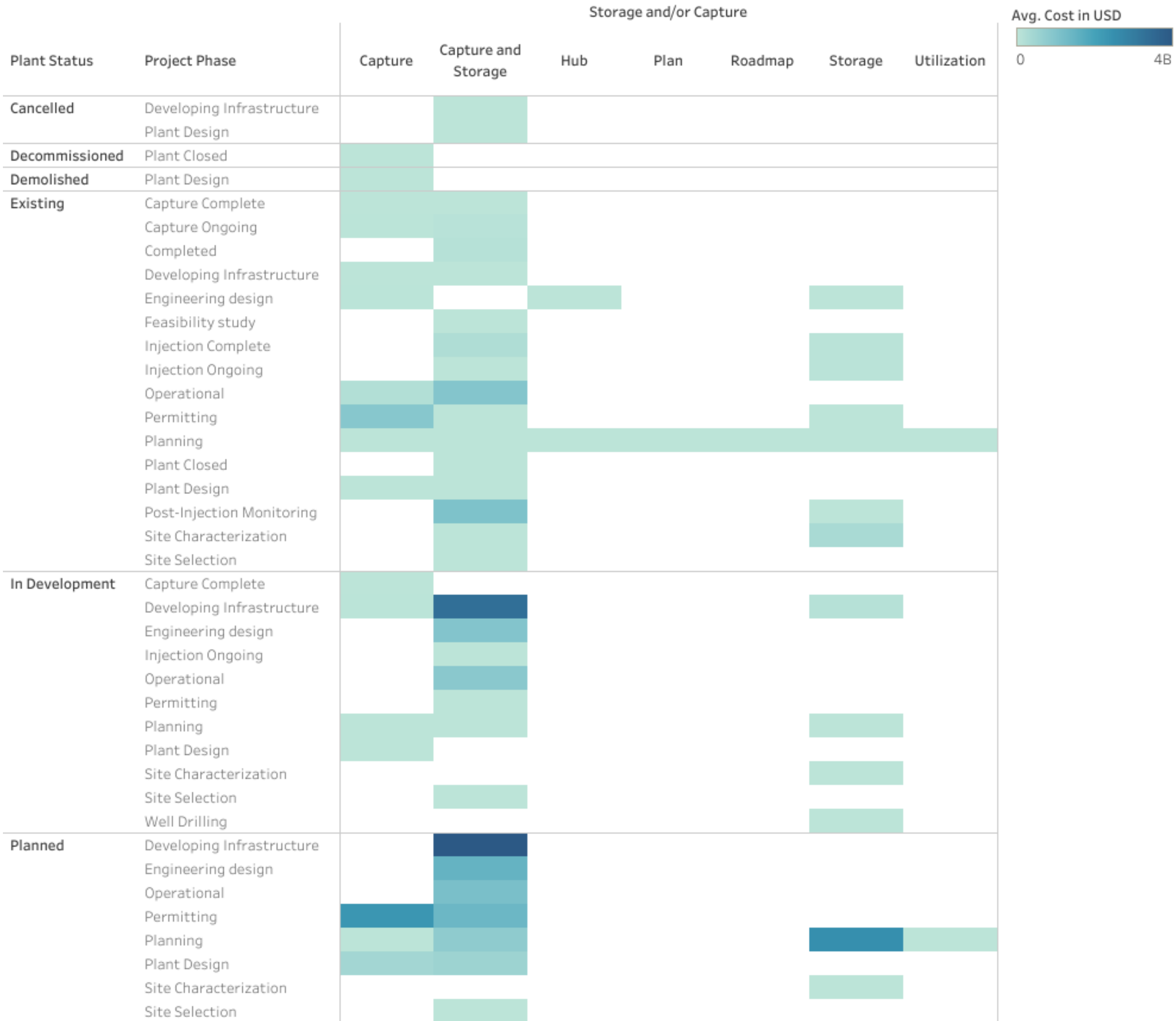

Figure 1. Summary of types of CCS project by status of plant and projects. Colour gradient indicates the average cost of CCS projects in each category

2.4. Cost of CCS projects

Within the total cost of the projects, data from Figure 2 describes that Capture and storage (CS) projects have the highest cost, with the largest projects costing 30 to 40 billion USD. Capture projects has the second-highest cost, where the largest costs lie between 2-3 billion USD. Storage projects themselves are a lot less costly, with most cost hundreds to a thousand million USD, and an extremely small part exceed the interval.

DOI: 10.54254/2755-2721/61/20240922

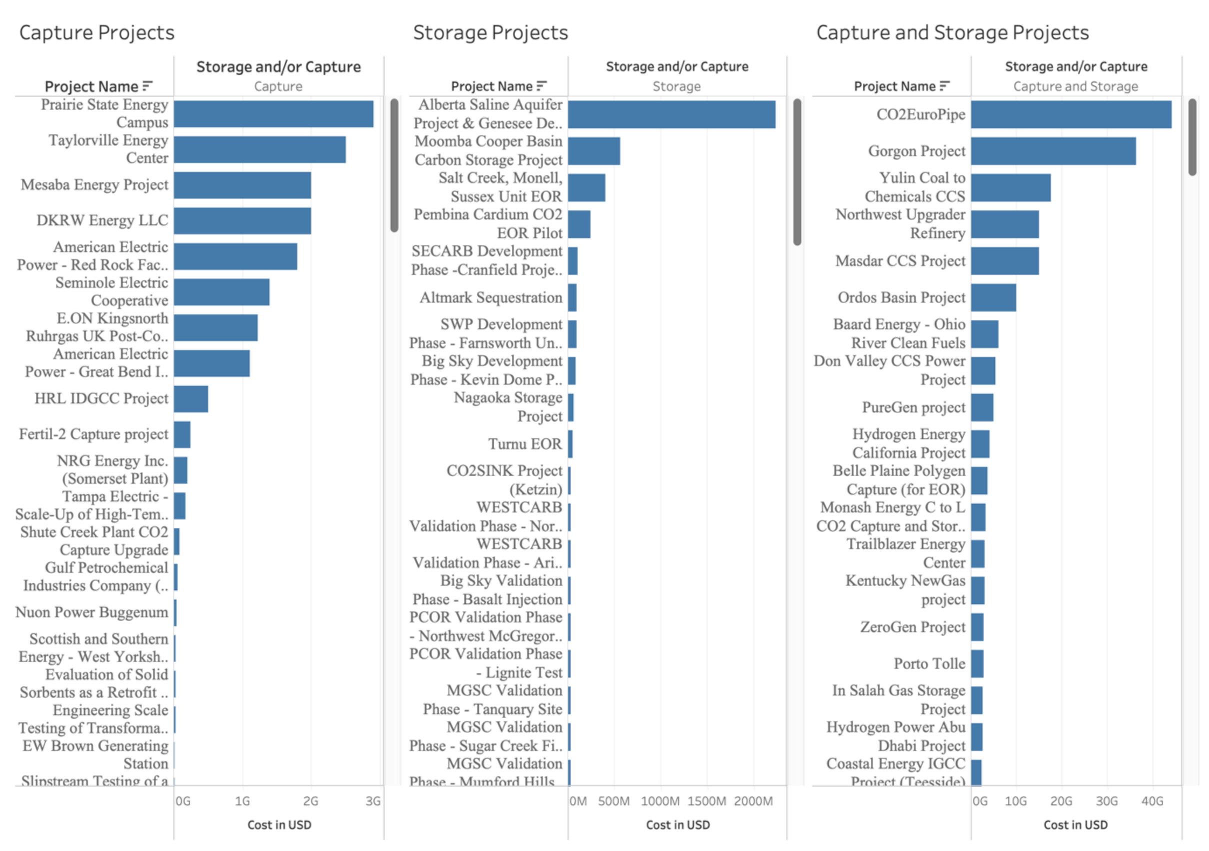

Figure 2. Lists of global carbon capture (left), carbon storage (middle) and carbon capture and storage (right) projects ranked by cost. The size of bubbles indicate the level of cost.

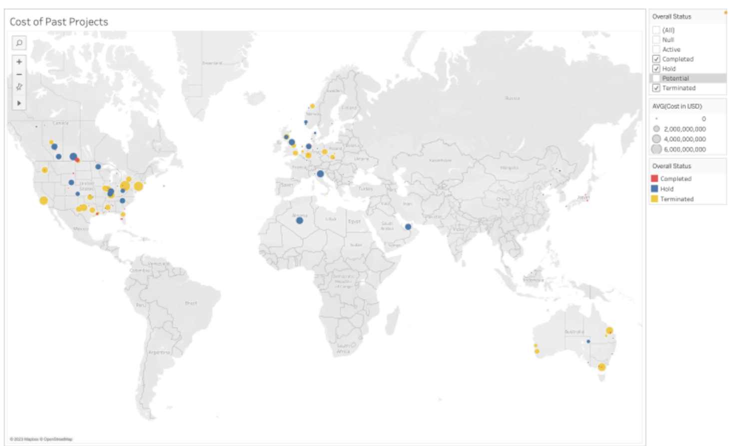

Figure 3. Distribution of completed, terminated, and on hold CCS projects worldwide

Figure 3 shows the geographical distribution of existing projects, that are either completed, on hold, or terminated and lists of global carbon capture (left), carbon storage (middle) and carbon capture and storage (right) projects ranked by cost at the same time. The size of bubbles indicates the level of cost. Results from Figure 3 indicate two major outcomes. First, projects that have been terminated (in yellow) show higher cost on average than those that are on hold (in blue). Both terminated and hold projects show higher cost than completed projects (red). The distribution of projects is relatively concentrated in

DOI: 10.54254/2755-2721/61/20240922

North America and Europe, with fewer projects in Australia and only a few small CCS projects in Africa, Asia, and South America.

3. Discussion

A series of factors are required to the succeed of a project. The most important factor for the success of Carbon Capture and Storage projects is whether they are economically viable. The cost of ccs projects is severely high that some CCS plants will be shut down or suspended due to lack of funding. Of course, in addition to the cost factor, public recognition and the government's policy support are also very influential. Whether the task is accepted by the public will directly affect the corresponding regulations, including carbon reduction targets, etc., such as ccs projects, large-scale factories must get government policy support if they want to succeed.

From our analysis, among the projects that are on hold or terminated, we found several common reasons which are divided into two categories. The first one is the most common one, which is issues caused by finance and profits. More specifically, uncertainty of the economic value of CO2 reduction blurs the economic return of such projects.; The carbon sales market and emission reduction price are insufficient to support the continuation of the project. On the cost side, issues related with lack of funding can be a hurdle, and the price is too expensive to meet the sequestration and storage demand for some projects on hold etc. In addition, for plants that remove CO2 as a byproduct in a gas plant, the low price of nature gas could also put the project to cease; Another important reason of unsuccessful projects is government regulation, such as the suspension of a ccs plant in Mecklenburg-Vorpommern because of a lack of political backing. In addition to that there are a number of projects because the air permit application, pre-approval for permit denied, unknown climate policy, legislation issues on these grounds have been forced to end.

In addition, injecting CCS to reservoirs still faces technical challenges and can cause damages of the site when not implemented successfully. When compressing, injecting or transporting CO2, the factors that have a significant impact on ccs projects include pressure and temperature. The critical points between gas, liquid, and supercritical phases are 31.1 degrees Celsius and 73.8 bara, three different phases with very different properties and often sharp transitions, so it is likely that these pressure and temperature boundaries will be crossed during transport, injection, and storage. This is especially true for offshore storage. For example, to store offshore, CO2 usually needs to be heated to a critical degree before injection, and many offshore storage sites does not have the heating facility, such that CO2 needs to be heated when onshore [11]. As such, successful offshore CCS projects need to meet several criteria. For example, depleted gas reservoirs suitable for CO2 injection usually needs to locate close to offshore compression facilities to reduce the cost of heating pipelines so that they can provide higher pressure later in production. In addition, they need to have a large storage space (a reservoir with a large volume of water) to ensure the high cost of additional heating [11]. In summary, there is still a lot of uncertainties and unknown in the technical development of CCS implementation, especially for offshore storage. Successful deployment of CCS relies on continuous breakthrough in development, as well as stable financial outlooks and economy of scale.

4. Conclusion

In conclusion, Carbon Capture and Storage projects are of great importance to human's task of environmental protection. While they add significantly to the effectiveness of reducing emissions and is already feasible, there are still a lot of challenges for the deployment at a scale. In order to study the reasons why CCS projects have not been promoted in an exaggerated way in the past decades, we obtained data for the existing and planned projects from the CCUS Projects Database. We first standardized the cost of each project and extracted data to ensure comparability, because the standards of units in different regions are very different, leading to incomparability of information. Then, through the comparative analysis and data collection of factories currently suspended or closed, we found that the two main challenges it faces are high cost with insufficient financial support, and restrictions from the governments. Both of them to some extent affect the normal operation of carbon capture and storage

DOI: 10.54254/2755-2721/61/20240922

plants. It is clear that CCS projects are mainly located in economically developed regions, with the United States having the most projects, followed by Europe and some coastal areas of Australia. Smaller scale CCS facilities are more widely distributed, which in fact shows that CCS projects need a certain cost to operate and capital is likely an important factor in the further deployment and successful implementation of these projects.

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