Insights into CCS Deployment: Trends in Geographic and Technological Clustering

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Overview

Limited progress in climate change mitigation has highlighted the need for large-scale carbon dioxide removal (CDR) to help meet the emission reduction targets set by the Paris Agreement (IPCC, 2018). Although much of the current climate policy focuses on reducing emissions, it is increasingly recognized that CDR, especially Negative Emissions Technologies (NET), is an essential complement to these efforts (Minx, Lamb et al. 2018). The development of carbon management strategies at national level in different countries as well as at EU level, the development of the EU's framework for the certification of carbon dioxide removals under the CRCF framework and the development of negative emission strategies show the increase in attention for the topic at the political level. Although deployment of Carbon Capture and Storage (CCS) technologies globally has accelerated, with a total of 50 projects globally and 51 Mt CO_2 being captured annualy it is nowhere close to where it needs to be (Global CCS Institute, 2024). While CCS is recognized as a critical solution for reducing industrial CO_2 emissions, detailed studies examining the global distribution and clustering of projects remain limited. Most studies in this area have either focused on specific countries as case studies (Ozkhan et al., 2022; Sun, X et al., 2021) or have conducted analyses that included a focus on utizlization technologies (Popielak et al., 2024, Wang, 2024). These studies, however, often lack a comprehensive global perspective on the distribution and deployment of CCS projects especially regarding projects that are currently in development or planning stages as they predominantly regard operational facilities. Hence, this study aims to address this gap by analyzing CCS projects in different project phases (operational, in construction, in development, announced) using data from the Global CCS Institute's CO_2RE Database[2]. Specifically, it examines geographic hotspots, technological attributes, deployment stages and project capacities to uncover spatial and operational patterns. By identifying spatial and operational patterns in CCS deployment, this study reveals regional specializations and technological preferences, providing insights e.g. into the distribution of large-scale vs. small-scale facilities and operational or early-stage projects as well as the role of transport infrastructure development. The findings present valuable insights into the understanding of the development of global CCS deployment, which can offer guidance for policymakers in shaping effective regulations and incentives for accelerating CCS adoption. Additionally, this highlights areas for future research, particularly in regions with underdeveloped CCS infrastructure or policy developments in hotspot regions.

Methods

In this study we analyze the global distribution of commercial Carbon Capture and Storage (CCS) projects, including transport projects, that are operational, in development, in construction or announced, their capture technologies, storage methods and annual capture capacities. Using data from the Global CCS Institute's CO_2RE Database (as of July 2024), the analysis aims to identify regional hotspots and classify commercial CCS projects into distinct clusters. The methodology involves three key steps:

1. **Data Collection and Preprocessing**: The dataset includes 870 projects across various development stages—operational, in construction, in development, and announced. Key attributes such as geographic location, capture capacity, development stage, capture technology, and storage method are included. The dataset is cleaned to address inconsistencies in spelling, wording, and formatting, ensuring a standardized structure. Missing values for critical variables are supplemented through publicly available sources, where feasible. Projects with unavailable or inapplicable variables are excluded from specific analyses but retained in the dataset. For the analysis, only commercial CCS facilities categorized as "Capture," "Storage", "Transport" or "Vertically Integrated" are included, excluding test and research facilities. Moreover, projects focused on enhanced oil recovery (EOR) are excluded from the analysis as their main aim is not the permanent storage of CO_2. Additionally, the process of injecting CO_2 in EOR often results in its eventual release back into the atmosphere, which contradicts the objective of long-term carbon sequestration.For the cluster analysis categorical variables such as development stage are one-hot encoded, and continuous variables like capture capacity are scaled to standardize their influence.
2. **Hotspot Identification**: The global distribution of CCS projects is analyzed to identify regions with the highest density of projects across different development stages. Descriptive statistics are employed to categorize projects by technology, industry, transport method, storage method, and capacity, providing insights into regional trends. Heatmaps generated using Python visualize geographic concentrations of CCS

facilities, highlighting key "hotspots" such as North America and Europe. These hotspots are defined by the number of projects and cumulative capture capacity, offering a macro-level view of global CCS deployment.

3. **Cluster Analysis:** A k-means clustering algorithm is applied to group CCS projects based on attributes such as location, project capacity, and development stage, as this algorithm is well suited for multivariate datasets and allows for analysis of regional, technological and project characteristics efficiently. The optimal number of clusters is determined using the inflection point of the within-cluster sum of squares (WCSS) curve. Silhouette analysis is used to validate the quality of the identified clusters, ensuring their robustness and interpretability.

Results

A first analysis reveals significant geographic clustering of commercial CCS projects, with Europe and Asia as dominant regions. Initial results indicate that planned projects (announced, in development, or under construction) in Europe are primarily focused on CO_2 storage in deep saline formations. While post-combustion capture currently is the dominant technology, the number of pre-combustion capture technology projects is increasing. Moreover, the analysis grouped commercial CCS facilities into clusters based on capture capacity, capture technology, transport methods, storage methods, and geographic location. Thefindings of this initial analysis underscore regional CCS specializations and varying project scales, reflecting the evolving focus and maturity of global CCS deployment.

Conclusions

In this study we analyse the global distribution of commercial CCS facilities and transport projects based on geographic location, capture capacity, technology type, transport method, storage method and other attributes, excluding test and research facilities as well as projects designated for EOR. These trends linked with other factors such as geological attributes reflect regional priorities and infrastructure capabilities as well as a development in capture technologies and storage preferences emerging in Asia and Europe in newly planned projects. This reflects regional differences in policy incentives, research priorities, and the integration of CCS into broader climate strategies and suggests the positive effect of policy support for CCS projects as hotspots in Norway and the United Kingdom emerge. Moreover, it indicates the importance of transport infrastructure and political frameworks as well as regional and cross-industry cooperation in the creation of CCS hubs as shared infrastructure and public funding increase attractiveness for creation of CCS projects in terms of investment costs and scalability.

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