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A Bibliometric Analysis of Carbon Capture and Storage Research

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MASTER THESIS

May 2021

Abstract

Purpose of the study: The purpose of this thesis is to identify the relevant research, its focus, development, and most influential contributions concerning the capture, transportation, and storage of carbon dioxide.

Methodology: The research was conducted by using a bibliometric analysis to investigate the 92 publications in the research field from 2006-2020. The bibliometric analysis used citation, co-citation, bibliographic coupling, and co-occurrence techniques, as well as a text mining analysis was performed to substantiate the bibliometric analysis.

Findings: The study reveals that the research field of carbon capture and storage is growing and maturing. Given the small number of influential documents and that the documents are only relatively connected provides significant room for further development. Many organizations and researchers have contributed to the research field, but only a few influential and productive players make a noticeable difference.

Research implications and limitations: The analysis revealed that there are several implications for the research. The study was limited due to the sample extracted from the Web of Science. Some documents may exist in other databases such as Scopus or google scholar. Time is also a limitation in this study. The period selected for data collection (2006-2020) is relatively new, and the documents published at the end of the period have not had enough time to be widely cited.

Contribution: This study extends the approach to explore the research development and gaps through a bibliometric analysis. The research and publications performance of individuals and institutions may help to stimulate and benefit the research regarding the topic. At the same time as it identifies the future research areas for carbon capture and storage.

Keywords: Carbon Capture and Storage, CCS, Shipping, Bibliometric, analysis, Meta-analysis, Citation, Co-Citation, Text Mining, Vos Viewer.

Acknowledgment

This master thesis is the concluding work of my studies to obtain a Master of Science degree in maritime management at the University of South-Eastern Norway. It has been a great experience that has provided me with educational and personal enrichment.

I would first like to express my sincere gratitude to my advisor, associate professor Umar Burki, for the continuous support and patience, and immense knowledge. He has guided me in the right direction whenever he thought I needed it.

Finally, I must express my very profound gratitude to my parents and my partner, Amalie for providing me with support and continuous encouragement.

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1 Introduction

Climate change is one of the many issues of this century, and a changing focus toward mitigation and adaption has made it a very central topic. Scientists nowadays mostly agree on the fact that climate change really occurs and that it is a problem we need to solve. There is a need to reduce global greenhouse gas emissions substantially to avoid the most adverse impacts of climate change, such as rising global temperature and sea levels, more extreme weather, etc. (European Energy Agency, 2017).

One of the primary reasons to why climate changes are happening is due to the large amounts of greenhouse gases that are released into the atmosphere as a result of the many human activities worldwide. United Nations Framework Convention on Climate Change (2021) states there is a direct relationship between global average temperatures and greenhouse gas concentrations in the atmosphere. The key to solve the climate change problem is to be found in decreasing the amount of emissions released into the atmosphere and reducing the current concentration of carbon dioxide (UNFCCC, 2021).

The increasing focus on climate change has initiated a gradual move towards traditional mitigation measures such as new sources of renewable energy sources and increased energy efficiency. Additionally, it has encouraged the development of new prosseses such as Carbon capture and storage (CCS). CCS is the abbreviation for carbon capture and storage and refers to a process that limits the amount of CO2 emitted to the atmosphere by capturing the CO2 and transporting it to the storage facilities where it can be stored safely in, for example, underground geological formations (Ministry of Petroleum and Energy, 2020). The technical excellence of individual components that represented CCS is characterized differently, as some of the technology is still in the developing phase while other is commonly used in different markets. Carbon capture and storage can be an essential measure to reduce CO2 emissions by preventing a large amount of CO2 from entering the atmosphere, and by reducing the levels of CO2 already emitted into the atmosphere.

The United Nations took the first step towards a greener future already in 1994, when they put the United Nations Framework Convention on Climate Change into force. The objective of this convention is the "…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system…" (UNFCCC, 1992). Some years later, in 1997, the Kyoto protocol was established to operationalize the convention's objective. The Kyoto protocol can be considered an extension of the UNFCCC and shares more or less the same mission as the convention: To stabilize atmospheric concentrations of greenhouse gases at a level that will prevent dangerous interference with the climate system (UNFCCC, 2008). The protocol was criticized because it only applied to developed countries and not major emitting countries like China. It was questioned around how much-developed countries can offset their emissions while developing countries continued to emit greenhouse gases. The fact that two of the most CO2 emitting countries, China and the USA, did not participate was one reason why many people considered the Kyoto protocol to be ineffective.

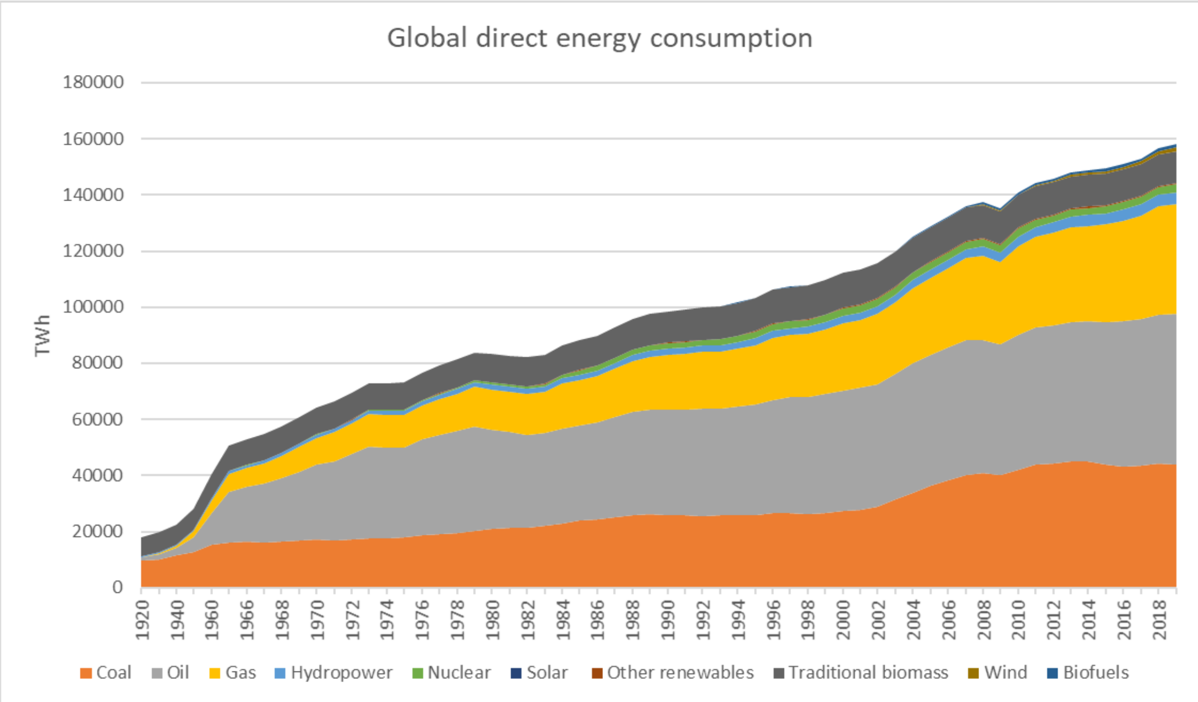
This initiated the construction of the Paris Agreement that was set out to improve upon and replace the Kyoto Protocol (Britannica, 2021). The Paris agreement is an international treaty on climate change, with the goal of limiting global warming to well below 2, preferably to 1.5 degrees celsius (Britannica, 2021). To accomplish this does the agreement aim to substantially reduce global greenhouse gas emissions. The agreement includes commitments from all major emitting countries to cut their climate pollution and assist developing nations in their climate mitigation and adaptation efforts (Denchak, 2021). The treaty provides a framework for the transparent monitoring, reporting, and ratcheting up of countries' individual and collective climate goals (Denchak, 2021). The treaty is designed to increase ambition over time and make countries submit climate pledges every five years, ensuring that net-zero emissions are reached within 2050 (Yeo, 2016).

Reaching the targets of the Paris Agreement can be challenging due to the economic growth and a rising global population. Economic growth and the increasing population have caused a steady increase in energy demand since the 1950s, and it is forecasted that this increase will continue (International Energy Agency, 2020). Globally the use of energy represents by far the largest source of greenhouse gas emissions from human activities (European Environment Agency, 2017).

The growth in environmentally friendly sources such as hydropower, solar power, wind power, wave power, geothermal energy, etc., has given us more environmentally friendly energy alternatives, but our society still heavily dependent on fossil fuels which cover 84% of the world's energy consumption (Rapier, 2020). A shifting focus toward more sustainable alternatives has a positive effect, but the problem is that the global energy demand is increasing faster than the supply of green energy sources (Stevens, 2019). This gap in energy demand is therefore covered by different fossil fuel sources and makes it hard to deal with the impact they have on the climate.

The global energy sector is expected to meet the rising demand and provide a low-carbon future to meet the climate goals. Carbon capture and storage can be one of the solutions to deal with the gap in energy demand covered by fossil fuels. If CCS become widespread the fossil fuels could continue to provide much of the worlds energy supply, at the same time as a minimal amount of greenhouse gases are released into the atmosphere.

Figure 1 – Global Direct Energy Consumption



Data retrieved from Our world in data, u.d.

Successful commercialisation of carbon capture and storage will be important to fossil fuel-dependent economies, finding it easier to comply with stringent greenhouse gas reduction targets. Carbon capture and storage will have a positive impact on the climate obligations set by the Paris Agreement. To achieve the goal for climate obligation imposed by the Paris Agreement, the participating countries must be climate neutral within 2050, but the target to reduce emissions by at least 55% by 2030 calls for rapid deployment of carbon capture and storage.

1.1 Research question

Based on the importance and rapid development of CCS, my thesis will explore the research development and gaps through a bibliometric analysis. To my knowledge there has never been conducted a bibliometric analysis on the research field, and I will through this master thesis seek to evaluate the research and publications performance of individuals and institutions. This may help to stimulate and benefit the research regarding the topic in the future.

Research question (RQ) 1 and 2 helps address the external characteristics of the published documents. RQ 3 and 4 targets the internal characteristics, while RQ 5 aims to identify the future research areas.

RQ 1. How are publications placed in time?

RQ 2. How are publications concentrated to specific researchers, journals, documents, organizations, and countries?

RQ 3. Which publications are the most cited?

RQ 4. What have been the focus areas regarding carbon capture and storage?

RQ 5. What are the future research areas?

1.2 Outline of the thesis

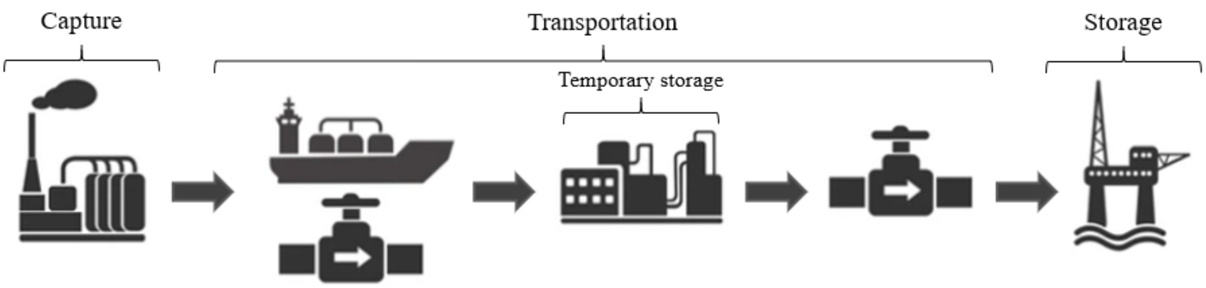
The master thesis is organized as followed. Chapter 2 gives a brief introduction and defines carbon capture and storage. Chapter 3 outline the research method and the data collection process. Chapter 4 presents the analysis and the results. Chapter 5 identifies correlations, patterns, and relationships among the data and outlines the limitations and suggestions for further research. Chapter 6 highlights the keypoints of the study.

The next chapter will provide an introduction to carbon capture and storage. The first section attempts to define carbon capture and storage. The second, third, and fourth describe the carbon capture and storage supply chain, while the last section gives a brief description of the capacity.

2 Defining carbon capture and storage

The global Carbon Capture and Storage institute (2020) divides CCS into three major steps, where the first step is to capture CO2 at the source of emission. The second step involves compressing the CO2 for transportation. The CO2 is then transported via ship or pipeline from the capture sites to a temporary storage site before the CO2 gets transported by pipeline to the permanent storage facilities. The third step is to inject it deep into a rock formation at a carefully selected and safe site, where it is permanently stored.

Figure 2 – Carbon Capture and Storage



The technology of carbon capture and storage has been applied in a different industry since 1972 when several natural-gas processing plants in the Val Verde area of Texas began employing carbon capture to supply CO2 for enhanced oil recovery (EOR) operations (Global CCS Institute, 2020). The basic idea of CCS – capturing CO2 and preventing it from being released into the atmosphere – has been present for decades. However, the different industries have been very slow to adopt the technology. Which challenges and barriers that have slowed down the adoption of the technology are hard to tell, but there has most likely been a combination of economic, technological, and political barriers.

The fear of leakages has been a widely discussed topic within the field. Fluede & Alcade (2020) has ask an important question: Who should pay to fix the storage site if CO2 starts to leak out? The storage site is supposed to contain the injected carbon for thousand to millions of years, but a company operating it may only exist for a few decades. Other economic uncertainties like the upfront cost needed to build CCS infrastructure and the cost of operating them have made it challenging to adopt the technology (Flude & Alcade, 2020).

A shifting focus toward climate change has made CCS more relevant in the last decades. Capturing CO2 released from burning fossil fuels can prevent large amounts from being released into the atmosphere. CCS is recognized as a key proven technology in reducing greenhouse gas emissions worldwide (Global CCS Institute, 2020). Advancing the technologies needed to capture and store CO_2 is a sensible strategy to reduce the levels of greenhouse gases – gases that bring us ever closer to dangerous interference with Earth's climate system (Stephens & Zwaan, 2005). This has made it a discussed topic in the research environment.

Various researchers and organizations have attempted to describe CCS, and table 1, holds a collection of some of the different descriptions of CCS. Many of the definitions are built on the fundamental understanding of CCS and divide it into three distinct steps. At the same time, others do describe it as a way of reducing greenhouse gas emissions.

Table 1 – Describing carbon capture and storage (CCS)

Description	**Studies**
"CCS involves capturing CO_2 from a fossil fuel power station, removing the CO_2 chemically, and then permanently storing the captured CO_2 underground in depleted oil wells."	(William & Craig, 2020)
"CCS is a process where waste carbon dioxide (CO_2) is captured from large industrial plants, transported in pipelines or ships and deposited (e.g. in an underground geological formation) so it will not enter the atmosphere."	(NCCS, 2020)
"CCS consists of three major parts: capture of CO_2 from a large stationary source (e.g., coal-fired power plant), transport to a storage site (e.g., by pipeline), and storage (e.g., injection into a saline aquifer). The goal of CCS is to reduce anthropogenic carbon emissions by storing CO_2 in the subsurface instead of emitting it into the atmosphere."	(Bandilla, 2020)
"CCS is being considered as a way of reducing the rate of increase of atmospheric CO_2 concentrations due to combustion of fossil fuels for energy production and other industrial processes"	(Loisy, et al., 2013)
"CCS is a series of technologies and processes designed to help mitigate climate change. Capturing waste CO_2 from industrial processes, transporting it in concentrated form and injecting it deep underground."	(SINTEF, 2020)

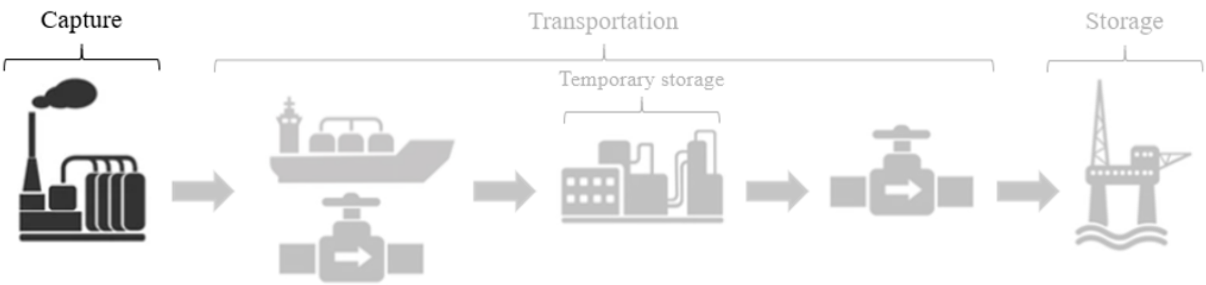
Among the descriptions presented in Table 1 does four out of five descriptions include language related to climate mitigation. CCS is essential for reducing the rate of increase in CO_2 released into the atmosphere (Loisy, et al., 2013). Climate mitigation is a fundamental factor for CCS's evolution, and there would not be any need for CCS unless we had a climate crisis threatening our society. Four of the five descriptions also include carbon capture, which is the first part of the CCS chain. Carbon capture descriptions refer to capture of CO2 from "power stations," "large industrial plants," and "large stationary sources" from the industrial processes, which are all related to fossil fuels.

Another characteristic that influences the descriptions is the transport, which is an essential step to transport the CO2 from the "carbon-rich sources" to the storage sites. The last characteristic that is influencing the descriptions is the storage part. Based on the explanations above, a good description of CCS covers the four characteristics of climate mitigation, capture, transport, and storage. Climate mitigations represent why the topic is relevant, and the capture, transport, and storage represent the CCS chain, and why it is needed to be successfully implemented.

2.1 CO2 capture

The capture part is the first step in the CCS chain and involves the separation of CO2 from other gases emitted. The CO2 is captured from sources with high levels of CO2 emissions, which in the first phase will be natural gas and coal, together with "other industries" such as the cement, steel, and waste industries (SINTEF, 2019).

Figure 3 – CO2 Capture



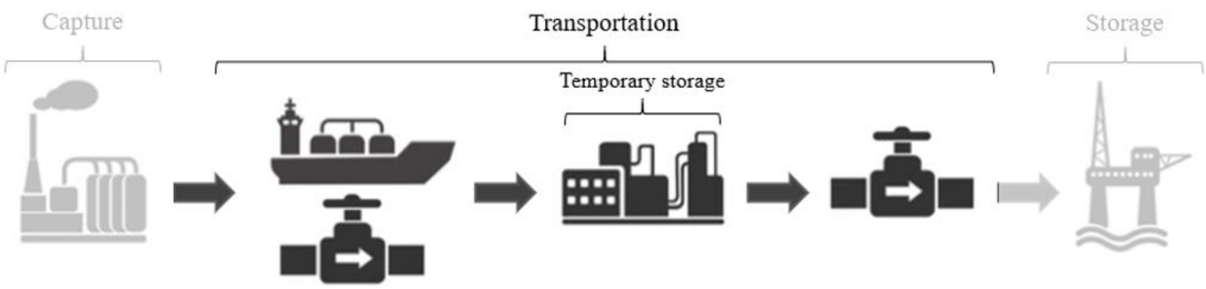
The two main methods for capturing CO2 are via absorption technology or BIO-CCS. The absorption technology uses chemicals that bind to the CO2 before reaching the chimney (SINTEF, 2019). This means that industries such as the steel industry, fertilizer producers, and cement factories, can theoretically reduce their CO2 emissions to zero (SINTEF, 2019). The second method, BIO-CCS, is used to extract CO2 from the atmosphere and can be used in the biological waste industry. BIO-CCS reduces the amount of CO2 released from the natural biological cycle, thereby reducing the amount of CO2 existing in the atmosphere.

2.2 CO2 Transportation

After the carbon dioxide is captured, it must be transported to the storage site, and this can be done either by pipeline or with vessels as liquid bulk. Both options are available as both technologies are in use today. Transporting liquified CO2 by ship has been done for over 30 years, and the first dedicated CO2 tanker was launched in 1988 (Yara, 2016). The transportation demand for CO2 has mainly been requested from the food and beverage industry, but CCS provides new areas for CO2 shipping. The industrial gas supplier Nippon Gases owns four liquid CO2 tankers, and the Linde group owns one liquid CO2 tanker, which is all operated by Larvik Shipping AS. To Larvik Shipping's knowledge, these five vessels is the only vessels that are transporting CO2 in the world. The shipping company IM Skaugen has six ships in their fleet which are registered to carry CO2, but their standard cargo is LPG, and it is not clear if the ships have been used for transportation of CO2 (Brownsort, 2015). The transportation demand for CO2 is now mainly requested for food-graded CO2, but the concept of transporting CO2 is transferable and can thereby also be applied to industrial CO2. This makes the idea very relevant for CCS.

There will most likely be a combination of pipelines and vessels based on transport distance and transport volumes for CCS. A fixed annual capacity would more likely use pipeline transport on shorter distances, while transportation via ship is a better alternative for longer distances (Roussanaly, Jakobsen, Hognes, & Brunsvold, 2013).

Figure 4 – CO2 Transportation

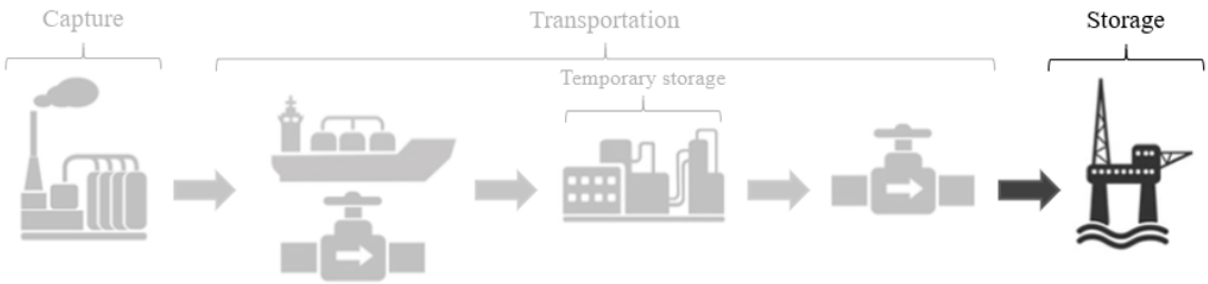


Carbon capture, transportation, and storage infrastructure require big initial investments that carry financial risk due to the uncertainties on volumes of CO2 to be transported in the future. Therefore, it is reasonable to believe that the infrastructure will be deployed step by step. Transporting CO2 with vessels could be used initially, while pipeline networks would be deployed later as the projects develop (Roussanaly, Jakobsen, Hognes, & Brunsvold, 2013). Transportation via ships also brings the flexibility to load CO2 from several capture sites. The flexibility and lower cost make it a favourable solution to transport CO2 from the capture sites and temporary storage facilities. At the same time as the transportation from the temporary storage facilities and to the storage site would prefer pipelines because of the fixed volumes.

2.3 CO2 Storage

The last step in the CCS chain is to safely store the CO2 in underground geological formations. The storage locations can either be onshore, in depleted oil and gas reservoirs, un-minable coal seams, and deep saline aquifers, or they can be transported offshore and injected deep into the ground. Deep saline aquifers seem to be the most promising solution based on the storage capacity and the risk for leakages (Bellona, 2015). It is estimated that there is a tiny chance of physical leakages if the geological formations are chosen with care (Osman-Elasha & Pipatti, 2018). However, there is a significantly higher chance of leakages in geological formations such as oil reservoirs and coal seams if the exploitation or mining activities in these fields continue after CO2 storage (Osman-Elasha & Pipatti, 2018). Geological storage of CO2 uses the same forces and processes that have trapped oil and gas underneath the Earth’s surface for millions of years (Global CCS Institute, 2020). It is hard to estimate the total storage capacity, but the geological storage resources for CO2 appear more than sufficient to meet global requirements under any net-zero emissions scenario (Global CCS Institute, 2020).

Figure 5 – CO2 Storage



This is a widespread explanation of how carbon capture and storage can be executed. Among all the different CCS projects does many of them do it differently with various solutions and modifications. But the most general approach includes these three steps.

2.4 Estimated capacity

Global geological storage capacity for CO2 is many times larger than what is required for CCS to play its full role in supporting the achievement of net-zero emissions under any scenario (Global CCS Institute, 2020). The global CCS institute (2020) estimates a need for approximately 5634 Mt of CO2 that needs to be captured annually within 2050 to follow up on the United Nations energy-related sustainable development goals for emissions, energy access, and air quality goals. Today, it is approximately 65 commercial CCS facilities, where 26 are operating (Global CCS Institute, 2020). These operating CCS facilities can capture and store permanently 40 Mt of CO2 every year (Global CCS Institute, 2020). 40 Mt of CO2 annually is equivalent to 0,71 % of what is needed to reach the net zero-emission in 2050. To accomplish the goal of net zero-emission in 2050, we must therefore have a tremendous growth in the field of CCS in the years to come. Even though 2050 may seem to be far in the future, the Paris Agreement have its first milestone in 2030, with its objective to reduce at least 55% in greenhouse gas emissions compared to 1990 levels. To reach these climate targets in a cost-efficient and sustainable way, there is a need to support early deployment and establish the foundation for CCS during this decade (ZEP, 2020). This makes it an interesting topic to study through a bibliometric analysis; the research that has already been conducted can be evaluated and new future research areas can be identified.

The next chapter describes the applied research methodology in order to answer the research question of this thesis. The first section introduces the research methodology, while the second part describes the search results and refinement.

3 Research methodology and initial data statistics

3.1 Research methodology

The goal for undertaking a bibliometric review of the published literature is to map and evaluate the available literature, and through this identify gaps and highlight the boundaries of knowledge (Tranfield, Denyer, & Smart, 2003). Conducting a bibliometric citation analysis can be considered as a meta-review of the selected literature. Bibliometric citation analysis provides a visualization of the academic research written on the select field of interest, and is a set of mathematical and statistical methods that offers several opportunities to support research (Bazm, Kalantar, & Mirzaei, 2016). A bibliometric analysis outlines the connection among articles for a particular field of interest, based on citations, authors, keywords, etc. By analysing which authors and papers that are cited frequently, the technique goes beyond simple counting of publications to an analysis of which authors and publications that have “value” to other researchers (Pasadeos, Phelps, & Kim, 1998). This approach examines the evolution of research domains, including topics and authors, based on social, intellectual, and conceptual structures (Donthu, Kumar, & Pattnaik, 2020). The bibliometric analysis in this thesis can be considered as the fundamental analysing method, and to substantiate the bibliometric analysis, a text mining analysis will also be conducted.

The bibliometric methods and text mining technique were performed by analysing annual publication outputs, publications distribution by country and institution, the authorship productivity, and collaboration pattern to provide an overview of the evolvement and development. The bibliometric analysis part used citation, co-citation, bibliographic coupling, and co-occurrence as the type of analysis. The citation analysis is performed to measure the influence of the selected units (documents, sources, authors, organizations, and countries). The citations establish the foundation for the importance of the unit, and the more a unit is cited, the more influential it has been in the research field. This is based on the assumption that authors cite documents they consider important for their work (Zupic & Cater, 2015).

The co-citation analysis uses citations to offer insight into the research topics and trends evaluated over time from different perspectives. A co-citation is defined by the frequency where two units are cited together (Small, 1973). Co-citations analysis helps to investigate how the units are related to each other. The more two units are cited together, the more substantial is the possibility that their content is related (Zupic & Cater, 2015). Bibliographic coupling is very similar to co-citations analysis. The difference is that bibliographic coupling uses the number of references shared by two documents instead of citations to measure the similarity between them.

Co-occurrence, also referred to as co-word analysis, is a content analysis technique that uses the keywords in documents to establish relationships and build a conceptual structure within the research field (Zupic & Cater, 2015). The co-word analysis is based on the same assumptions as the co-citations analysis: Keywords that frequently occur together are closely related. A series of such analyses conducted in different periods can trace the changes and better understand how the research field has evolved over time (Zupic & Cater, 2015).

This master thesis does also use a text mining analysis to substantiate the bibliometric analysis. Text mining allows us to utilize the large amount of unstructured data that makes it possible to analyze the content of the published papers and investigate their structural aspects. The text mining analysis is done through Vos Viewer, which creates a term map based on the data from the abstracts of the published papers. The term map is based on co-occurrences, and each term is valued with a relevance score. Terms with a high relevance score tend to represent specific topics covered by the text data. In contrast, terms with a low relevance score will tend to be of a general nature and thereby not be representative of any specific topic (van Eck & Waltman, 2010).

The academic database the Web of Science was used to collect the data sample for the bibliometric analysis. The Web of science is the world's most extensive publisher-neutral citation index and research intelligence platform, and the data sample retrieved from the Web of science is based on keywords related to the field. The keywords used in this thesis are elaborated in section 3.2.

To analyze the data sample from the selected keywords, Vos Viewer was used. VOSviewer is a software tool constructed for creating, visualizing, and exploring bibliometric maps of science (van Eck & Waltman, 2010). Vos Viewer provides the ability to develop various network maps in a two-dimensional way which allows us to analyze the findings. The network maps are constructed so that the distance between two items can be interpreted as an indication of the relatedness of the items. In general, the smaller the distance between two terms, the stronger the terms are related to each other. This makes it possible to investigate the relationship between keywords, authors, journals, etc., and visualize how the different factors influence each other.

3.2 The search results and refinement

To try to cover all possibilities the Keywords used for data collection included “Shipping” and “Carbon capture and storage or CCS”. The initial search terms alone are extensive, and each search term produced a lot of results in the Web of Science. Choosing two broad search terms gives us a better chance of completely covering the field before gradually narrowing it down and removing papers that are not relevant. The keywords “Shipping” and “Carbon capture and storage or CCS” gave all a lot of results, and to get a better understanding of the CCS field and how it is related to the shipping industry they were therefore combined. After combining the two keywords, the number of results was reduced to 112 published documents.

Table 2 – The initial search results

Search Keywords	Search results (no. of papers)
Shipping	61,063
Carbon capture and storage OR CCS	21,191
Shipping AND Carbon capture and storage OR CCS	112
After inclusion criteria	108
Removed non relevant papers	92

The initial search resulted in 112 published papers, but to further specify the data set some inclusion criteria was selected. These inclusion criteria are presented in figure 6 below. The first inclusion criteria restricted the published documents to be published in English. It was necessary to have all the documents in the same language to conduct the analysis.

Figure 6 – Search log

TOPIC: (Shipping) AND TOPIC: (Carbon capture and storage OR CCS)

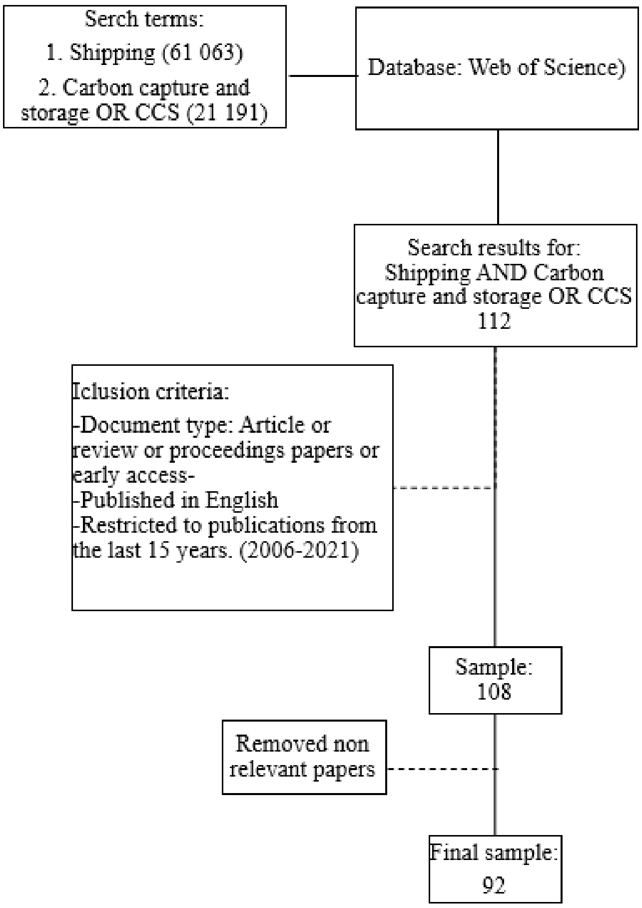
Refined by: DOCUMENT TYPES: (ARTICLE OR REVIEW OR PROCEEDINGS PAPER OR EARLY ACCESS) AND LANGUAGES: (ENGLISH)

Timespan: 2006-2021. Indexes: SCI-EXPANDED, SSCI, A&HCI, ESCI.

The second inclusion criteria restricted the data set to only include documents categorized as articles, reviews, proceedings papers, or early access. The third inclusion criteria defined the period for the collection of data, and the time frame was decided to be 15 years – containing a timespan from 2006 to 2020. The inclusion criteria reduced the number of published documents from 112 down to 108.

After removing those documents that did not meet the inclusion criteria, it was necessary to manually go through the data collection and review the abstracts of the papers. By manually screening through the data collection, another 16 documents were excluded from the sample.

Figure 7 – Search tree



The documents that were excluded from the sample did not have any relevance to carbon capture and storage. CCS is an abbreviation for carbon capture and storage, but it is also referred to as "counter-current simulation," "California current system," and "cargo containment system." These were manually excluded, and the final data sample was left with 92 published documents. The flow chart displays how the initial search was narrowed down to the final data sample.

The next chapter will utilize the final data sample by analyzing how the publication trend, journals, authors, articles, organizations, countries, keywords, and terms have influenced the selected research field.

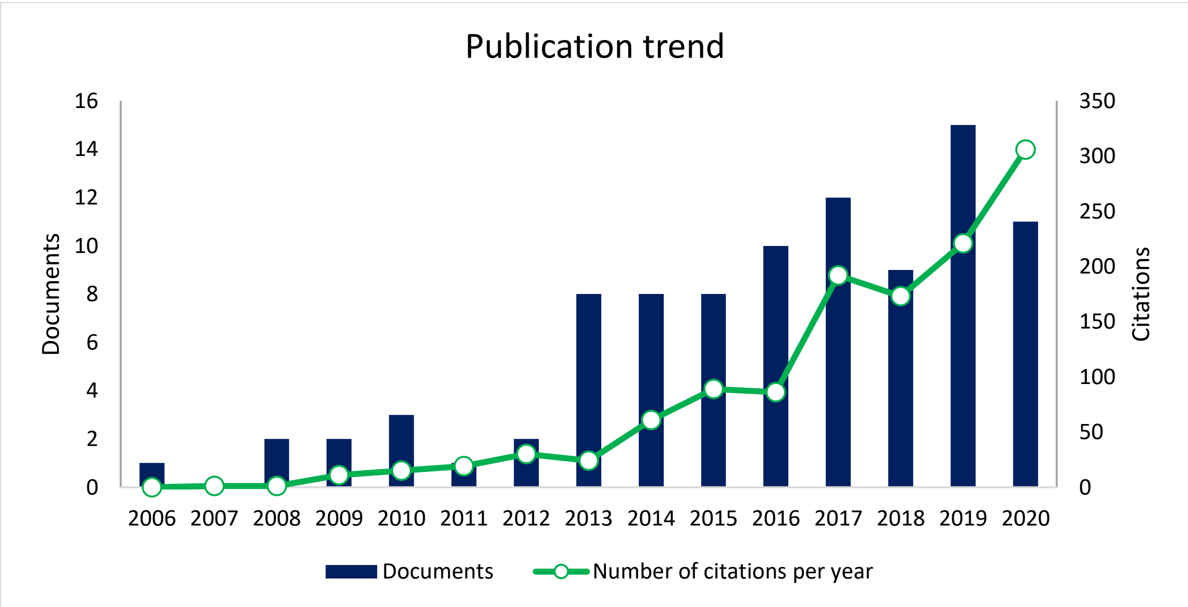
4 Analysis and results

4.1 The publication trend

The publication trend portrays a general direction of how the field is developing. The publication trend data is retrieved from the analyze result function in Web of Science. This function allows us to separate the number of publications and citations into each specific year, making it possible to analyze how the field has evolved. Figure 8 shows the number of published papers from the year 2006-2020. The green line represents the number of times a document is cited each year and is combined with values on the vertical axis on the right side. The number of published papers is presented with bars with the values on the left vertical axis.

A total of 92 published papers were distributed within the time frame of 2006-2020. Within the same time fram where The 92 published papers were cited a total of 1324 times of 954 citing articles. The citing articles are the number of articles that have cited one or more published papers in the citation report. The number of publications correlates with the number of citations: When the number of publications increase, so does the number of citations. There has been a significant increase in the number of publications and citations over the last years. Figure 8 displays the correlation between the publications and citations.

Figure 8 – The Publication trend



Approximately 87% of all the papers published in the field are written within the last eight years. Eight years is a relatively short time compared to the time to build the infrastructure needed to make CCS possible. The number of citations is often used as indicators of the acceptance or importance of published work in the research community (Dimensions, 2019). The number of citations has the last five years increased from around 100 citations per year to over 300 citations per year, and indicates that the field is growing. A growing number of citations may represent an increasing acceptance of the field, which is vital for successful implementation of CCS. The increasing development of academic research on carbon capture and storage and shipping combined may indicate the expanding scope of the industry.

4.2 Leading journals

The final data sample with 92 published papers is divided into 58 journals in total. Table 3 below displays the productivity of the top three publishing journals. The reason for choosing the top three leading journals and not five, is because the following five journals on the list have all contributed with three documents in the given period. To gather the information in table 3, I used the analysis result function in the Web of Science.

Many of the journals have only published one or two, while others have made more substantial contributions. The top three contributing journals have supplied approximately 41% of the published material, and there is especially one journal that stands out. The International Journal of Greenhouse Gas Control is clearly the most productive within the field, and did alone contribute with 27% of the published papers. The International Journal of Greenhouse Gas Control primarily focuses on carbon capture, cransport, utilization & storage, so it is not unexpected that this journal has been the most productive within the field of CCS.

Table 3 – The Top three publishing journals contributing to the field of Shipping and CCS.

Source	Publication year															
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
IJGGC[1]					1	1		4	2	4	3	4	2	2	2	25
AE[2]				2				1	1		1	1	1	1		8
E[3]									1	1				1	2	5
Other	1	0	2	0	2	0	2	3	4	3	6	7	6	11	7	54
Total	1	0	2	2	3	1	2	8	8	8	10	12	9	15	11	92

[1] IJGGC = International Journal of Greenhouse Gas Control. [2] AE = Applied energy. [3] E = Energies

Applied Energy covers a broader topic and focuses on the optimal use of energy resources, analysis and optimization of energy processes, mitigation of environmental pollutants, and sustainable energy systems (Yan, 2020). Energies is a journal that publishes studies within the general field of energy supply, conversion, dispatch, and final use. Typical characteristics for them all are energy efficiency, utilization, and climate mitigation, which are all relatable to the research field of CCS.

The high level of productivity among the top journals gives them a valuable opportunity to shape the research field. The number of publications per journal indicates the importance of the journals within the field, but it is not sufficient to measure the impact and influence the journals have.

Vos Viewer, provides total citations (TC), and total link strength (TLS). TC represents the total number of citations, e.g., counting how many times an article has been cited by another. A citation is a link between two items where one item cites the other. The number of citations represents the acceptance or importance of published work and can be a measure to see how much it has impacted the field. TLS indicates the number of links an item has with other items and the total strength of the links of an item with other items (van Eck & Waltman, 2010). E.g., it is based on the number of links and the strength of those links. Each link has a strength that is represented by a positive numerical value, and the higher this value is, the stronger are the links (van Eck & Waltman, 2010). The strength of a link is in this case based on the number of citations each journal has in common.

The citation journals analysis was first generated by using a benchmark of minimum two documents per journal in Vos Viewer. This provided a threshold of 13 results of journals that have published two or more papers. This means that among the 58 journals it is 45 journals that have only published one document, giving us an indication that some few big players dominate the field.

Table 4 – Top five cited Journals

Source	Documents	TC	TLS
International Journal of Greenhouse Gas Control	25	423	74
Applied Energy	8	190	18
Energy Conversion and Management	3	170	9
Chemical Engineering Research & Design	3	81	27
Energy	3	51	7

To further investigate the number of citations to analyze how influential the top journals have been, I changed the benchmark from a minimum of two documents per journal to only one. This was done to make sure that no journal was excluded due to the requirement of documents. This provided the same results as with a minimum of two papers per journal, and I decided to go with a benchmark of two papers per journal.

Table 4 above displays the five most cited journals. The top five influential journals is based on the TC. The International Journal of Greenhouse Gas Control was the most dominating within the field and had the highest TLS and TC. It has been cited 423 times, and the next on the list is Applied Energy with 190 citations. The International Journal of Greenhouse Gas control has twice as many citations as Applied Energy, but this can also have a connection with the number of publications per journal (25 vs 8).

Investigating the average citations per publication gives us another picture. If doing so, the Energy Conversion and Management (56,67) is the leading on average citations per publication, followed by Chemical Engineering Research & Design (27,00), Applied Energy (23,75), Energy (17), and last among the five, the International Journal of Greenhous Gas Control (16,92). Despite having the least average citations per publication, it is clear that The International Journal of Greenhous Gas Control has been the most influential.

Figure 9 – Citation network: Journal

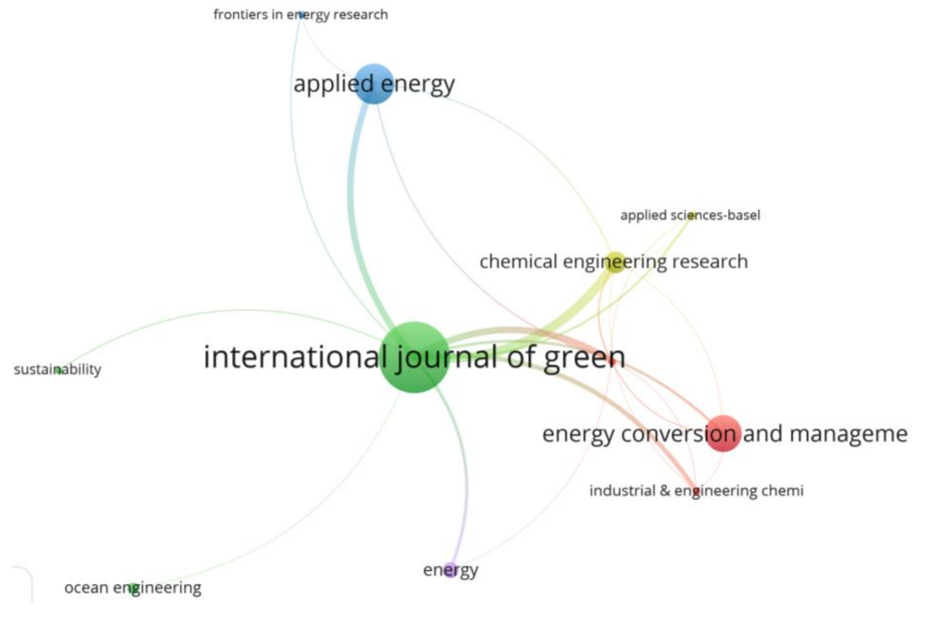
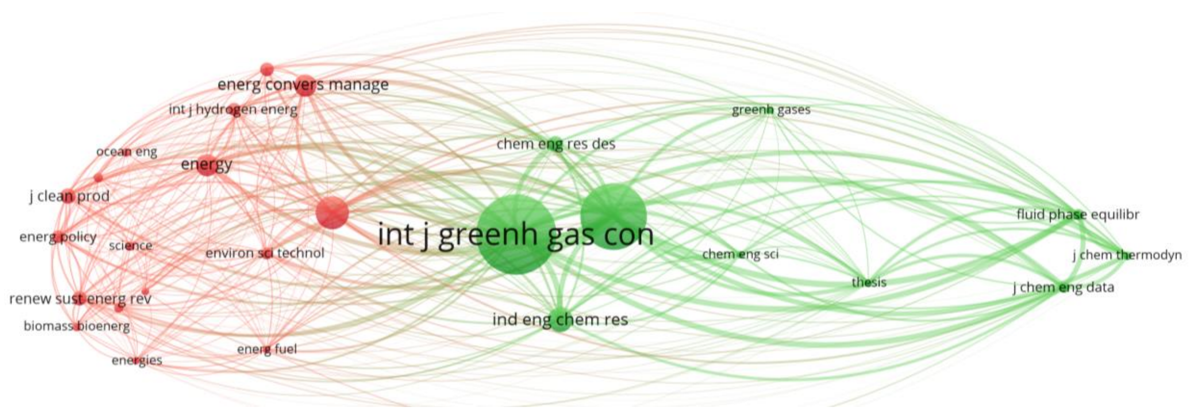


Figure 9 is a visualization of the citation network. The size of the circles is related to how many citations the journal has, and the lines between the different journals together represent links. The thickness of a link displays how strong the connection between the two journals is. The International Journal of Greenhous Gas Control is displayed as a major journal within the field. It has a TLS of 74, and figure 9 makes it possible to visualize how links are connected to other journals. The journal is linked, to some degree, to all the other 13 journals, and it has especially strong connections with Chemical Engineering Research & Design (TLS=27) and Applied Energy (TLS=18).

The two most productive journals (International Journal of Greenhouse Gas Control and Applied Energy) accounted for 36% of the total publications. This can indicate a narrowness of publication distribution and concentrated interest in CCS research from the same journals. The two most productive journals have been central when it comes to influencing the field of CCS. The third most publishing journal from table 4, Energies, has not been one of the dominating journals shaping the field, based on only being the number ninth most cited journal with 16 citations.

Today's published research is an extension of earlier published works, creating linkages between the papers or journals. These linkages between papers make it possible to apply co-citation analysis. Co-citation involves classifying the scientific literature of papers that correspond to specific problems. The co-citation analysis we apply here uses the cited sources, e.g. Journals, as the unit of analysis. This analysis examines the source titles extracted from the raw reference strings, and is used as the unit of analysis. Journal 1 and 2 is co-cited if both Journal 1 and 2 are cited by journal 3. The benchmark for the co-citation analysis was set to a minimum number of 20 citations of a source with full counting. This resulted in 27 journals that met the threshold.

Figure 10 – Co-citation network: Journal



The co-citation analysis counts the number of times two journal titles were jointly cited in later publications. This journal analysis created a total of 33 574 linkages between the journals. The journal with the highest number of linkages was the International Journal of Greenhous Gas Control (12 941), followed by Energy Proceed (12 611). It has been shown that other journals often cite journals that are likely to be more related and focused on a similar subject area (Hjørland, 2013).

4.3 Author influence

Over the last year there has been an increase in the number of authors contributing to research concerning the CCS field. There was a total of 287 authors that contributed to the 92 published papers. The objective of this analysis is to identify the most influential authors within the field. I decided not to make any limitations on the number of documents per author, to make sure to include the most influential author independent of their productivity.

Four of the authors were represented under different names, and to merge the variants of their names together, I used a thesaurus file in Vos Viewer. A thesaurus file is a text file with two columns, a “label” column, and a “replace by” column, as displayed in table 5. Every line in the thesaurus file specifies a name (label) and an alternative name (replace by). The terms that occur in the label column is to be replaced by the alternative term in the replace by column. For example Aspelund A. is replaced and merged with Aspelund, Audun.

Table 5 – Merged authors

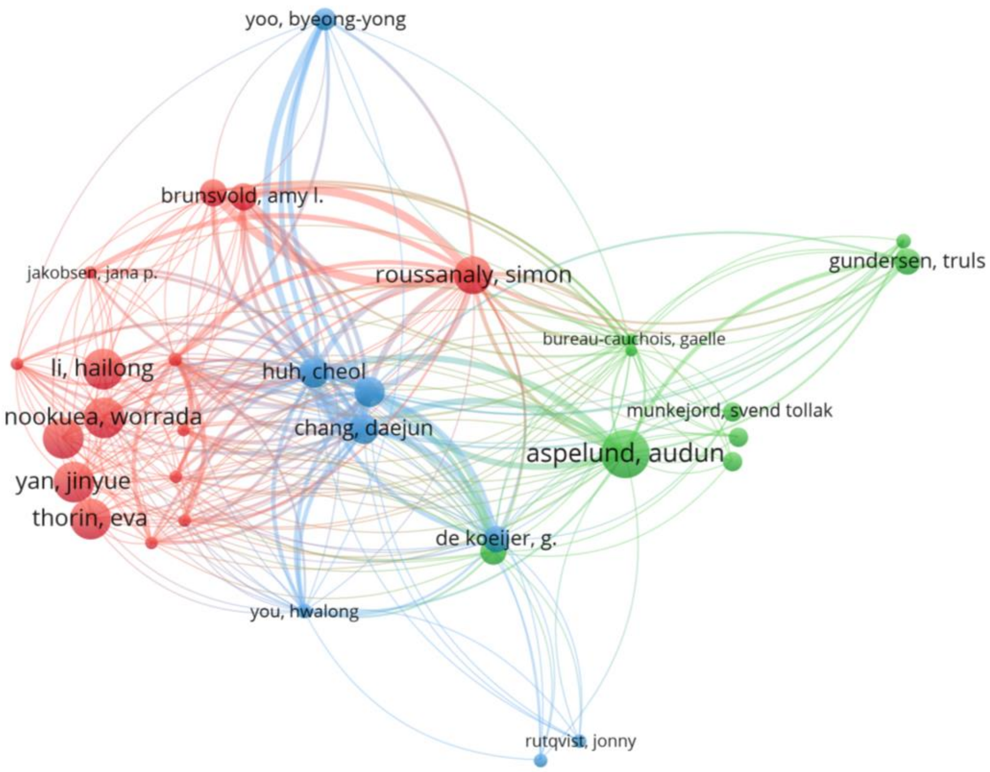
Label	Replace by
Aspelund, A.	Aspelund, Audun
Brunsvold, Amy	Brunsvold, Amy l.
Hognes, Erik H.	Hognes, Erik S.
Jackson, Steve	Jackson, Steven

Table 6 identifies the 15 most cited authors and is mostly dominated by collaboration. Among the top six, five of the authors, Li, Nookuea, Tan, Thorin, and Yan are related to a partnership on a published document. Other authors like Chang, Huh, and Seo has collaborated on all 6 of their papers published. Huh has published one more document than the other two authors, but that document has zero citations in the Web of Science collection. Bergmo, Grimstad, and Lindeberg have also collaborated on the one document that they have published. The paper they have published together is called “Simultaneous CO2 injection and water production to optimize aquifer storage capacity”. They have been influential in the field with 82 citations, but the TLS is still 0. The TLS is calculated based on the number of linkages. A link is a connection or a relation between two items, which means that the document they have published does not have any connection to the other documents. The lack of linkages can indicate an immaturity of the storage field that they have investigated.

Table 6 – Top 15 cited authors

Author	Documents	TC	TLS
Aspelund, Audun	3	154	50
Li, Hailong	1	126	18
Nookuea, Worrada	1	126	18
Tan, Yuting	1	126	18
Thorin, Eva	1	126	18
Yan, Jinyue	1	126	18
Roussanaly, Simon	6	116	86
Chang, Daejun	6	88	104
Huh, Cheol	7	88	115
Seo, Youngkyun	6	88	104
Bergmo, Per Eirik S.	1	82	0
Grimstad, Alv-Arne	1	82	0
Lindeberg, Erik	1	82	0
Brunsvold, Amy L.	3	81	37
Hognes, Erik S.	2	79	37

Figure 11 – Author citation network



The author citation network in figure 11 is narrowed down from 287 authors by using a benchmark of minimum 30 citations per author. This resulted in 44 authors, but since some of the authors did have 0 TLS the larges set of connected authors was 32. For example

Bergmo, Grimstad, and Lindeberg would have been a central author in the visualization map, but because they have a TLS of 0 and thereby no linkages with the other authors, they were not included in the author citation network.

It is also easy to identify the collaboration in the citation map. Authors such as Li, Nookuea Tan, Thorin, and Yan are located in the same area and the citation map is thus showing us that they are closely related. The authors with the highest TLS, Huh (115), Chang (104), and Seo (104), are located in the middle of the map and have strong connections to the other authors. The high TLS of these three authors can thereby indicate that they have a leading role in the research field.

4.4 Leading articles

The top five leading articles in Table 7 are retrieved from a citation analysis with no minimum number of citations set as a benchmark. The document by Tan (2016) is the most cited document with 126 citations, and the document is a review paper published in the journal Energy Conversion and Management in the middle of 2016. On average the document has been cited 21 times each year. Comparing the average citations per year with the other top-cited papers shows that Tan (2016) has been an influential paper. No other documents have over ten citations on average per year, and the second-highest is Munkejord (2016) which is also a review paper.

Table 7 – Top five leading articles

Document	Author	TC	TLS
Property impacts on Carbon Capture and Storage (CCS) processes	Tan (2016)	126	6
Simultaneous CO2 injection and water production to optimise aquifer storage capacity	Bergmo (2011)	82	0
Ship transport of CO2 – Technical solutions and analysis of costs, energy utilization, exergy efficiency and CO2 emissions	Aspelund (2006)	77	27
CO2 transport: Data and models – A review	Munkejord (2016)	54	3
Benchmarking of CO2 transport technologies: Part II – Offshore pipeline and shipping to an offshore site	Roussanaly (2014)	44	12

Table 7 displays that there is no correspondence between the TLS and TC. Bergmo (2011), the second most cited paper, has 82 citations and 0 in TLS. The links attribute indicates the number of citations a given paper has with another paper. Bergamo (2011) can still be considered an essential contribution to the CCS field in terms of TC, but the low TLS can indicate that it could be one of few papers that focuses on the storage part.

The top five leading article covers various areas within the field. Tan (2016) is a technical article that covers much of the CCS chain: It reviews the impact of uncertainty in thermos-physical properties on the design and operation of components and processes involved in CO2 capture, conditioning, transport, and storage (Tan, 2016). Bergmo (2011) investigate how the storage sites for CO2 can be optimized and exploited to their full potential. Aspelund (2006) covers the transport of CO2 with vessels as a flexible and effective transport system. Munkejord (2016) considers data and models for CO2 transport, and this article focuses on the phase equilibria, density, speed of sound, and viscosity. Thermal conductivity is also reviewed, togheter with property models. Aspelund (2006) on the other hand, focuses more on technical solutions related to the analysis of cost. Roussanaly (2014) considers the technical, costs, and climate impact characteristics of pipeline and shipping transport. At the same time as he uses the infrastructure to benchmark offshore pipeline and CO2 shipping to an offshore site.

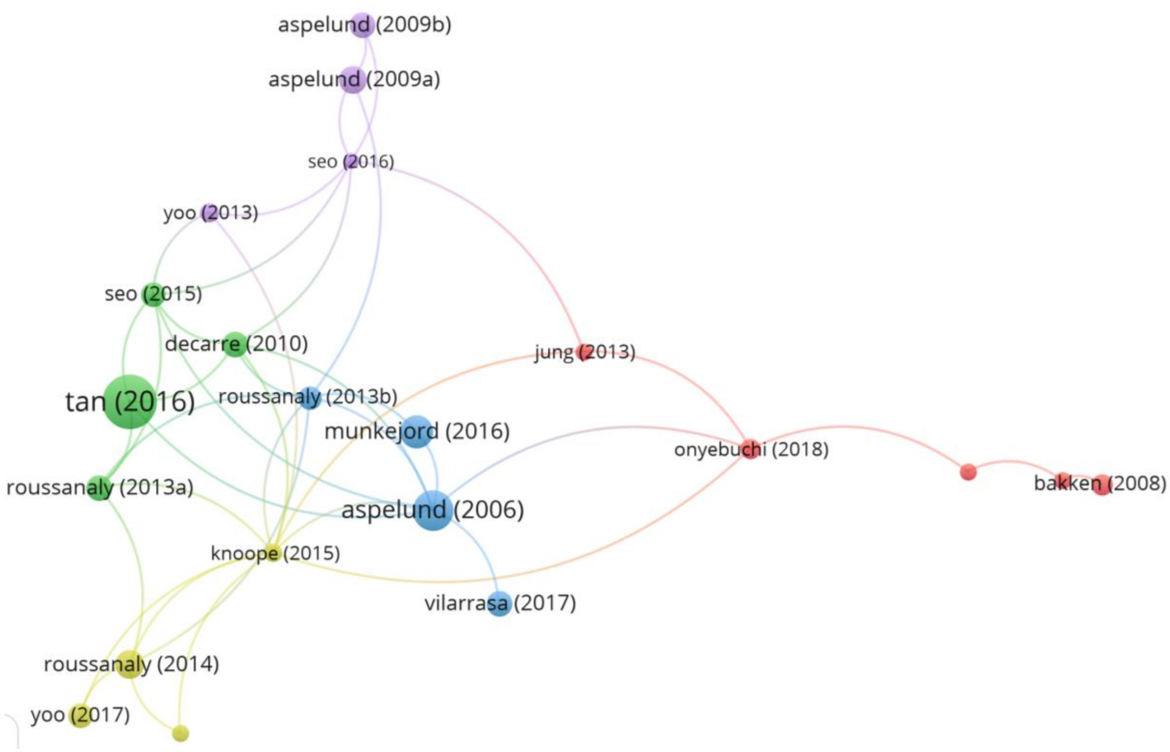
It is interesting to see the various focus areas among the top five cited articles. Three of the articles are related to the transport of CO2. One article focuses on the storage part, and the other one is a comprehensive review covering the whole CCS chain. Among the top five articles there is no published papers that focus on the capture part directly, apart from when Tan (2016) reviews the CCS process. There could be various reasons for this: It could be that the capture part is very new, or that the articles written about carbon capture have not been that influential.

Conducting a network analysis can be useful to see how the articles are related to each other. Restricting the benchmark for a network analysis to a minimum of 15 citations per article provided a network of 27 items. The problem is the same as the one in the author's influence. And six of the items are not related with any linkages to the main network cluster. One of these articles is Bergmo (2011), which is considered the second most cited published paper.

To further investigate the network, it was necessary to exclude the six articles that had a 0 TLS. This provided the most extensive possible set of connected items, with a network analysis consisting of 21 published papers divided on 14 different authors.

The papers are categorized by color cluster-based papers that share the same characteristics. The red cluster investigates the cost estimation and optimization regarding CCS, and the green cluster is a combination between CCS and transport. The blue cluster is characterized by ship and pipeline transport, while the yellow cluster explores the infrastructure regarding transport and onshore storage sites. At last, the purple cluster examines the CCS chain and its infrastructure.

Figure 12 – Network analysis: article



4.5 Leading organizations

The contribution of different organizations and institutions was analyzed according to their number of citations. There were 105 organizations or institutions that had any relation to one of the 92 published papers. These 105 institutions have produced academic works impacting the direction of CCS research. To obtain an overview of the leading organizations, I used a benchmark for a minimum one documents per organization and no citation criteria. Table 8 gives us an overview of the leading organizations within the field and aims to identify productivity and influence.

In total, 105 organizations have contributed to the research field, and the top five leading organizations, based on the number of publications, contributed with 43% of the documents published. In other words, have the other 100 organizations contributed with 57%

of the documents published. This clearly indicates that few very productive organizations dominate the field. It is essential to distinguish between productive and influential organizations. Seoul National University has been the most productive organization with 12 published documents but is only the number ninth influential organization in terms of citations (TC=66). This gives us an average number of citations per document of 5,5 citations.

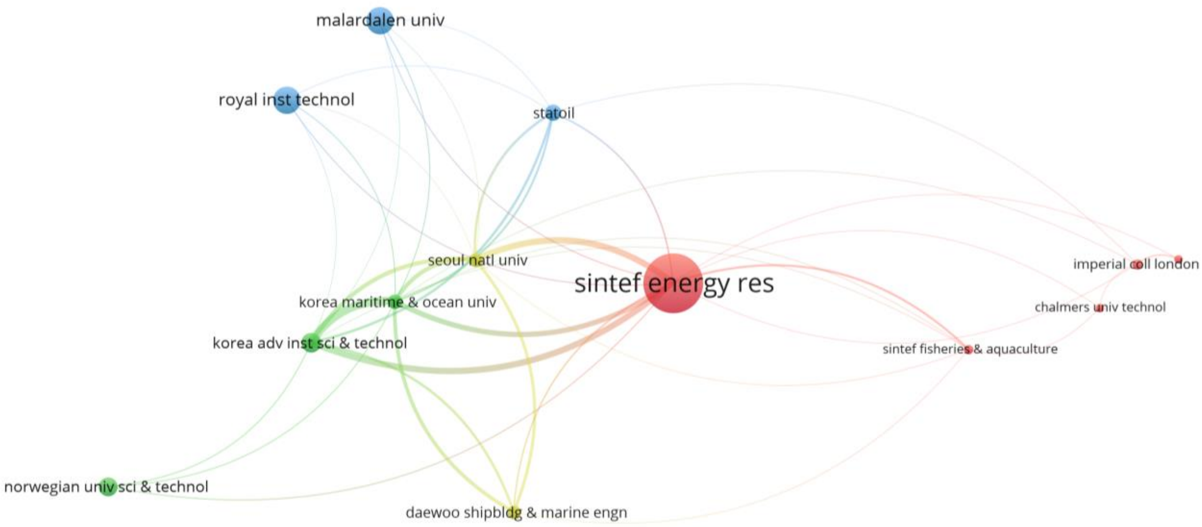
Table 8 – Top ten leading organizations

Organization	Documents	TC	TLS
SINTEF Energy Research	11	277	130
Malardalen University	1	126	13
Royal Institute of Technology	1	126	13
Korea Advanced Institute of Science and Technology	7	92	107
Norwegian University of Science and Technology	3	86	9
SINTEF Petroleum Research	1	82	0
Statoil	1	77	47
Korea Maritime and Ocean University	7	70	104
Seoul National University	12	66	109
Daewoo Shipbuilding & Marine Engineering	3	65	40

SINTEF Energy Research is one of the most influential and productive organizations in the field as assessed by the number of publications, TC and TLS. The following two organizations, Malardalen University and Royal Institute of Technology have only published one document: a collaboration between the institutions. Malardalen University and Royal Institute of Technology have not been productive in publishing documents, but they have still been very influential within the research field. The following group among the top ten leading organizations does all have a TS between 50 and 100. The top ten leading organizations are dominated by two Scandinavian countries (Norway and Sweden) and South Korea.

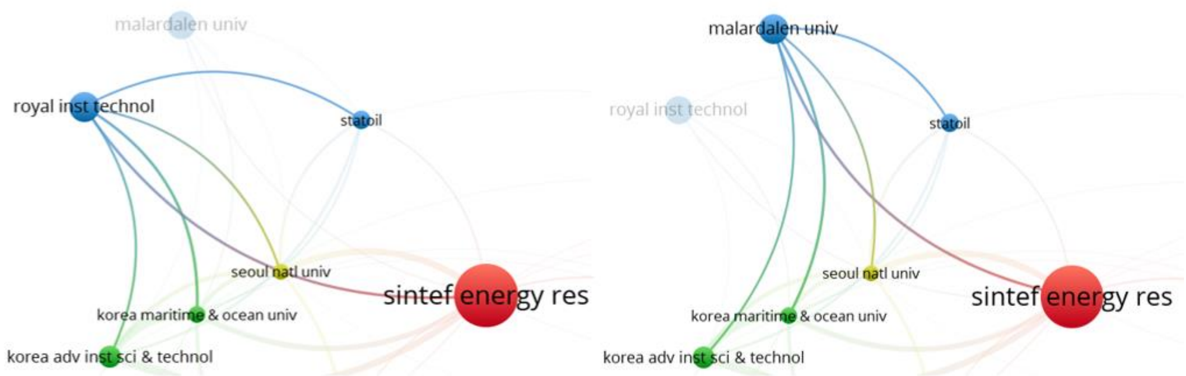
SINTEF Petroleum Research is not a part of the network analysis because the organizations have no direct connection with the other organization (TLS=0). The network analysis in figure 12 gives us a visualization that corresponds to table 8. The size of the circles represents how frequently an organization is cited.As shown in figure 12, many organizations group together with organizations that originated from the same countries. The South Korean organizations (Korea Advanced Institute of Science and Technology, Korea Maritime and Ocean University, Seoul National University, and Daewoo Shipbuilding & Marine Engineering) are all closely grouped together except from Daewoo Shipbuilding & Marine Engineering that is placed below the others.

Figure 12 – Leading organizations network



The thickness of the lines attaching Daewoo Shipbuilding & Marine Engineering to the other Korean institutions still shows a strong connection. The two Swedish organizations Malardalen University and Royal Institute of Technology, are also clustered together. There is no link between these two organizations because they collaborated on the same published document. It can be observed that the institutes tend to collaborate more with those within the same country than international counterparts.

Figure 13 – Specified organization network



The lines between the leading organizations are significantly thicker than the others and show a strong connection. One exception is Malardalen University and Royal Institute of Technology, as shown in figure 13. The two organizations link to the same organizations and could maybe have been viewed as one unit. The network analysis only compares the 13 most influential organizations, and the lines between the organizations would have been much thicker if we would do the analysis with several units. This indicates that productive and influential organizations tend to have more academic cooperation with similar organizations.

4.6 Geographical dispersion

To create a worldwide picture of the research concerning CCS and shipping, I will in this section investigate the published papers based on their country origin. To include all the contributing countries, I did not use any restrictions based on the number of published articles and no minimum citations.

Table 9 – Contribution based on their geographical dispersion.

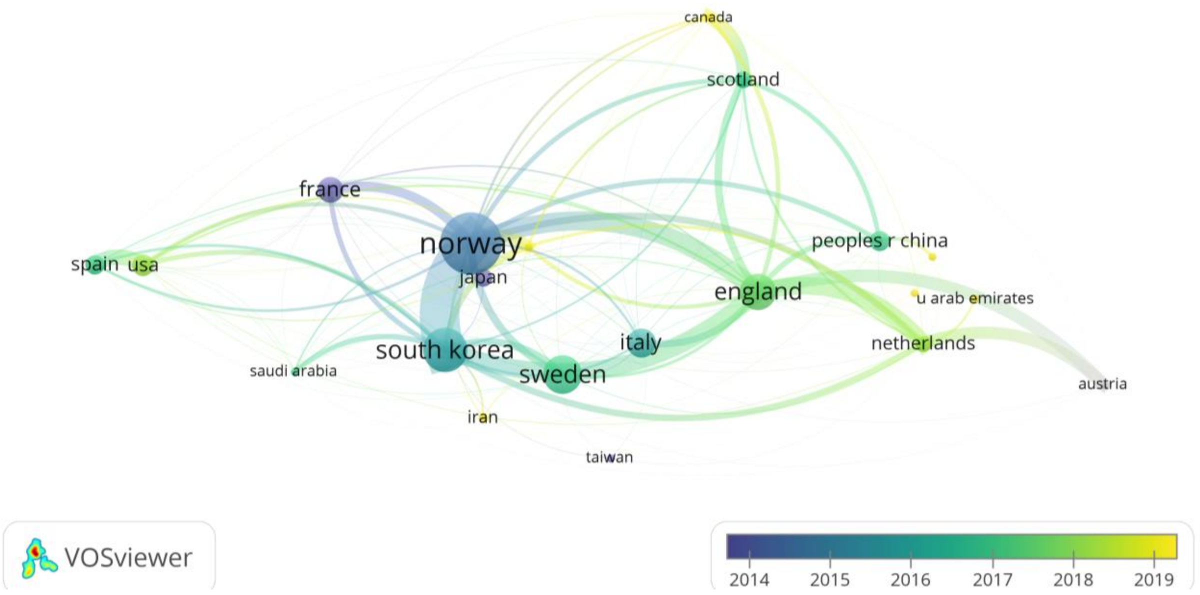
Country	Documents	TC	TLS
Norway	21	478	78
South Korea	25	224	83
Sweden	5	167	16
England	13	142	35
Italy	8	88	7
France	2	67	30
USA	4	47	7
Peoples Republic of China	5	39	7
Spain	1	36	3
Japan	3	29	1
Scotland	5	28	15
Netherlands	5	26	23
Australia	1	8	0
Iran	1	8	3
Singapore	1	4	2
United Arab Emirates	1	4	2
Germany	4	2	10
Taiwan	2	2	0
Austria	1	1	1
Saudi Arabia	1	1	7
Canada	1	0	5
Switzerland	1	0	1

The countries are related to the organizations that published the paper and do not consider the nationality of the researcher who writes the article. This could be considered a limitation for the geographical dispersion, but I believe it will still create a sufficient overview of the published research. Because the country relates to the organization or institution that published the document, collaborations between organizations will not be considered. For example, we know chapter 4.5 that Malardalen University (Sweden) and Royal Institute of

Technology (Sweden) collaborated on a paper, but these will be considered as two documents. Table 9 does therefore show a higher number of published documents (111). This will eventually not influence the TC because Malardalen University and Royal Institute of Technology each had 126 citations, and Sweden is only reported with 167 TC.

South Korea and Norway have both been very productive countries, publishing 25 and 21 documents. This also reflects the TC and TLS. Norway can be considered as the most influential country with 476 TC, followed by South Korea with 224 TC. The same two countries have the most cited linkages among the countries with TLS of 78 and 83.

Figure 14 – Bibliographic coupling: Countries



A bibliographic coupling analysis was carried out to investigate further how the countries' linkages and connections relate. The geographical dispersion is created by bibliographic coupling in Vos Viewer. Bibliographic coupling is referred to as a single item of reference shared by two documents, and is defined as a unit of coupling between them (Jarneving, 2007). A bibliographic coupling occurs in this case when two countries reference a common third work in their link and is a link between two items that both cite the same document. The bibliographic coupling network displays 21 of the 22 countriesm because Australia is not included in this visualization map due to a TLS of 0. The colored timeline is automatically set to 2014 -2020 and gives a visualization of when the countries have the most published documents on average. The size of the nodes is proportional to the contributing degree of each country based on their citations. There is shown relatively thick connections between the most dominating countries.

The map also shows that it is a very new research field, as no country have an average publication year before 2010; it is France that has the “earliest” average publication year with 2011. The most influential countries are South Korea and Norway, which have an average publication year of 2016 and 2015. It appears that many countries have gotten their eyes up for CCS in the later years as 70% of the countries have an average publication year of 2017 or later.

To make it easier to visualize which countries may be key players, I also created a visualization map. The visualization map is created with the 3D map function in excel, and the data is retrieved from the Web of Science and processed in excel. The red circle on the map represents which city has published a paper, and the size of a circle represents how many document the city have published. The visualization map correlates very well with the data in table 9: Norway and South Korea are the two most productive countries, followed by England and Italy.

Figure 15 – Visualization map based on published papers.

The geographical dispersion indicates that research is being conducted all over the globe, but there are still only developed countries that are conducting research. CCS is a very complex topic that can be very capital intensive, making it reserved for the rich, highly developed countries. Many of the leading countries already have competence and technology that can be transferred from other industries to CCS, with Europe as the leading continent for research. It is also the only continent with a small transport network for CO2 transport by vessels, and this kind of competence and tecknology is valuable as it can be transferred to the CCS field. I believe that there also will be a connection between where the storage sites are located and the countries conducting research: To select and qualify a geological storage site for safe storage will be essential, and storage capacity may be a limited resource regionally (Bergmo, Grimstad, & Lindeberg, 2011). Geological storage of CO2 uses the same forces and processes that have trapped oil, gas, and other hydrocarbons in the Earth's subsurface for millions of years (Global CCS Institute, 2020). The storage site is therefore narrowed down to regions with old oil reservoirs, and the two leading countries of the commercialization of CO2 storage resources are Norway and Australia. Still, countries such as the USA, China, Canada, and many others are estimated to have large undiscovered suitable storage facilities (Global CCS Institute, 2020).

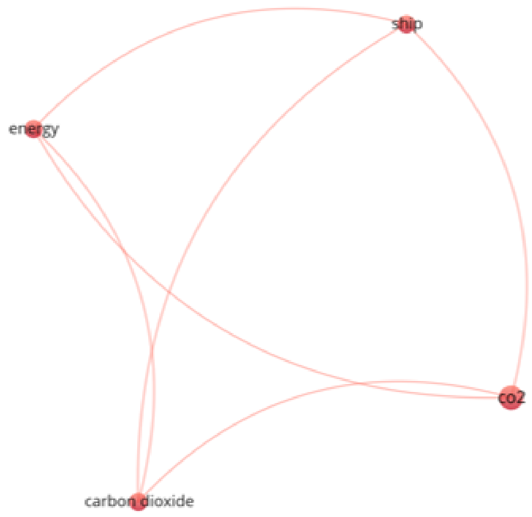
4.7 Keyword analysis

This section will investigate the field and the development of research regarding CCS and Shipping through a keyword analysis. A keyword analysis investigates how frequently a keyword occurs within the set of data. The analysis is conducted by using a co-occurrence analysis, with all the keywords used. The co-occurrence analysis investigates the number of documents that occur together, which determines the keywords' relatedness.

The last decade witnessed a rapid development of the research concerning CCS and shipping. The selected timeframe 2006-2020 was divided into three periods with a five-year interval to investigate the rapid development. Each of the intervals presented all the research that is published within the given period, and the periods are analyzed by using co-occurrence analysis with all the keywords. The co-occurrence analysis creates a network that shows the relatedness of items based on the number of documents that occur together. Each of the visualization networks uses a benchmark of a minimum of three occurrences for the items, which means that each keyword needs to occur three or more times to appear in the network visualization.

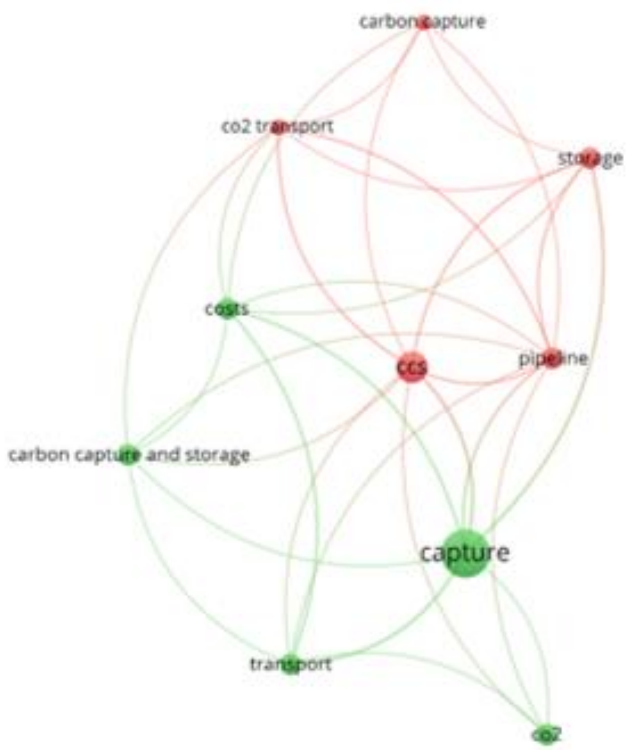
Figure 16 on the next page represents the first period and does only consist of eight papers. This figure displays all the research published within 2006-2010. Figure 16 is very lean, and among the 50 keywords related to the documents, only four keywords met the met the criterias, and occurred three or more times. These four keywords are related with six linkages.

Figure 16 – Keyword analysis 2006-2010



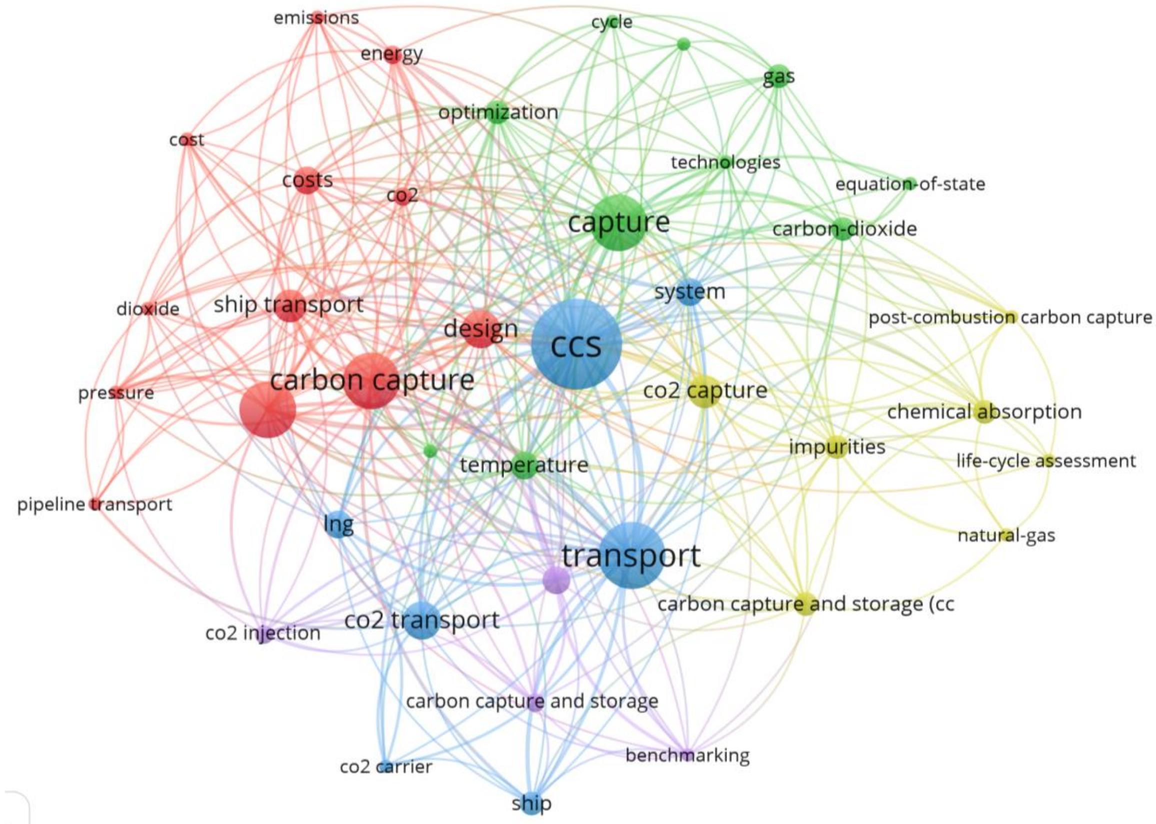
The next period 2011-2015, is visualized in figure 17 below and consisted of 27 papers. Among these was a total of 173 keywords and ten keywords that met the criteria. A significant increase compared to the first period.

Figure 17 – Keyword analysis 2011-2015



The last period from 2016 to 2020 presented in figure 18 on the next page shows an explosion in the number of published papers (27), keywords (431), and keywords that med the criteria(40). It was produced 315 linkages among the 40 keywords in figure 18.

Figure 18 – Keyword analysis 2016-2020



Comparing the three figures makes it easy to see that much of the research has been conducted in the later years and that the research field is very new. It is interesting to see how some of the most central keywords have evolved over time. For example, the transport keyword no was to be found in figure 17, occurs three times in figure 18, and it is the second most occurred keyword in figure 18 with 14 times. Figure 17 displays many relevant CCS keywords – this can indicate that it started to be a focus area in the period 2011-2015. Figure 18 shows many of the same keywords, but it seems like the topics have gone more in-depth and more thoroughly explored. This can imply that the researchers have started to examine more sophisticated research questions related to the topic.

The following keyword analysis views the whole period as one (2006-2020) and is also based on a co-occurrence analysis based on all the keywords. The benchmark for the analysis was set to a minimum number of three occurrences of a keyword, which resulted in 52 keywords that met the threshold. Among the 52 keywords there were four keywords manually excluded due to low relevance in the visualization map.

Table 10 – Excluded keywords

Excluded keywords	Occurrences	TLS
Benchmarking	5	23
Model	4	20
System	7	32
Systems	5	16

After excluding the keywords with low relevance, it was still necessary to improve the visualization map. The keyword referring to the CCS was found in three different variants. "Carbon Capture and Storage," "Carbon Capture and Storage (CCS)," and "CCS." The various authors use different words to describe the same topic and to give a better understanding and visualization of the keywords some of the keywords was merged.

Table 11 – Merged keywords

Label	Replace by
Capture	Carbon Capture
Carbon-Dioxide Capture	Carbon Capture
Co2 Capture	Carbon Capture
Dioxide Capture	Carbon Capture
Carbon Capture and Storage (Ccs)	Carbon Capture and Storage
CCS	Carbon Capture and Storage
Carbon-Dioxide	Carbon Dioxide
Co2	Carbon Dioxide
Dioxide	Carbon Dioxide
Costs	Cost
Co2 Liquefaction	Liquefaction
LNG	Liquefied Natural-Gas
Natural-Gas	Liquefied Natural-Gas
Pipeline Transport	Pipeline
Shipping	Ship Transport

To merge different variants of keywords together I did again use a thesaurus file in Vos Viewer. I decided to use "carbon capture and storage" as the main word representing both "carbon capture and storage (CCS)" and "CCS". Table 11 displays all the words that have been merged.

Table 12 displays the ten most occurred keywords, and it can appear to be a strong correlation between the number of occurrences and the TLS. The most frequent occurred keyword is "carbon capture," which has occurred 46 times with a TLS of 166. The high level of occurrences and TLS, indicates that “carbon capture” is a very central keyword with significant influence in the field. The second most occurred keyword is “carbon capture and storage,” with 39 occurrences and TLS of 147. The top ten occurred keywords can be considered as conceptual building blocks for the research.

Table 12 – Ten most occurred keywords

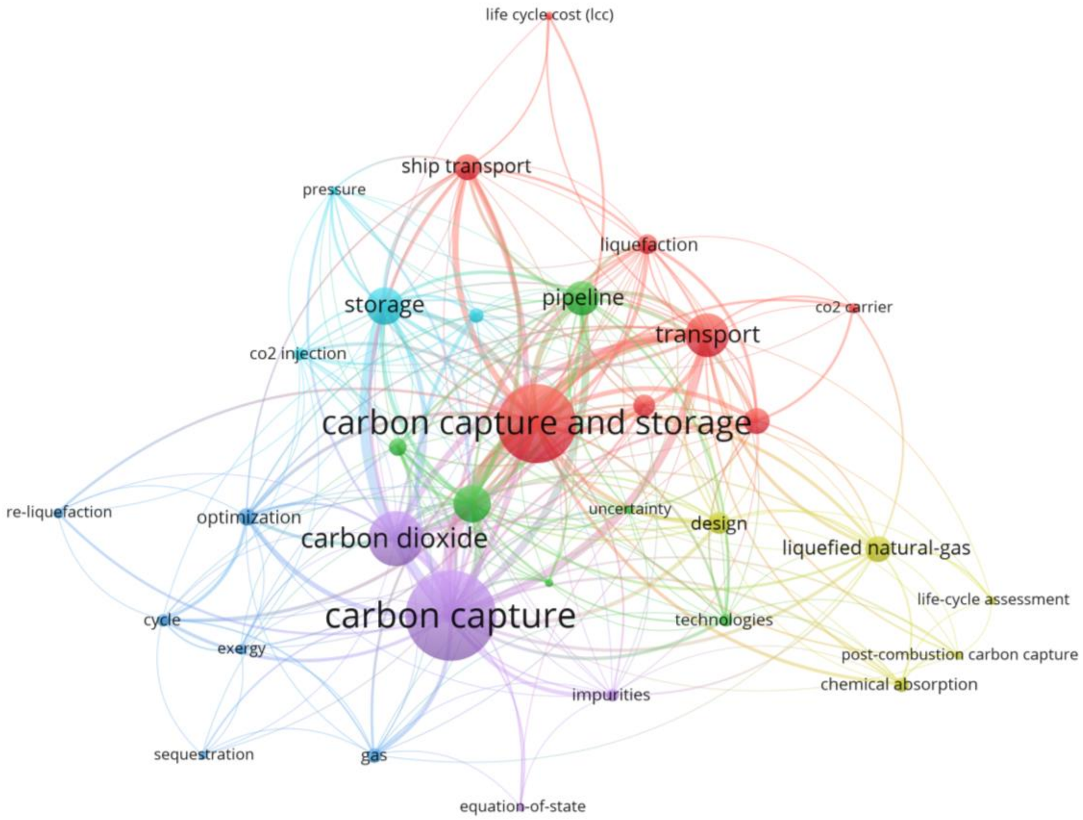
Keywords	Occurrences	TLS
Carbon Capture	46	166
Carbon Capture and Storage	39	147
Carbon Dioxide	26	85
Transport	20	91
Cost	17	78
Storage	17	69
Pipeline	15	64
Co2 Transport	11	40
Liquefied Natural-Gas	11	34
Ship Transport	11	50

Among the keywords found in table 12, almost every keyword is directly connected to the carbon capture and storage chain, except for “liquefied natural gas” and “cost.” LNG is considered an essential contributor to global energy consumption and is expected to be central for reducing greenhouse gas emissions (Arizmendi-Sanchez & Eastwood, 2018). It is a cleaner fossil fuel that can be a good alternative to other more traditional fossil fuels such as coal and oil. LNG liquefaction plants still produce a significant proportion of the total CO2 emissions of the LNG supply chain, and LNG plants may provide the potential for decarbonization via carbon capture and storage implementation (Arizmendi-Sanchez & Eastwood, 2018). The keyword “cost” has occurred 17 times with a TLS of 78. The keyword may relate to the high capital investment required to develop a CCS value chain, such as capture plant, transportation, injection, storage facility, and operating costs. Like other technologies that are expensive in the beginning, researchers expect the price of capturing and storing CO2 to fall as the technology will become more efficient and cheaper (SINTEF, 2019).

A pool of 574 keywords drawn from 92 papers displays the visualization map of the 33 most frequently occurred keywords that have occurred a minimum of three times or more. After merging, some of the keywords that had similar meanings like “carbon Capture,” “Carbon Capture and Storage,” and “Carbon Dioxide”, have gotten an even stronger position in the visualization map; they are located in the middle of the network visualization map, showing that they are some of the most frequently occurred keywords.

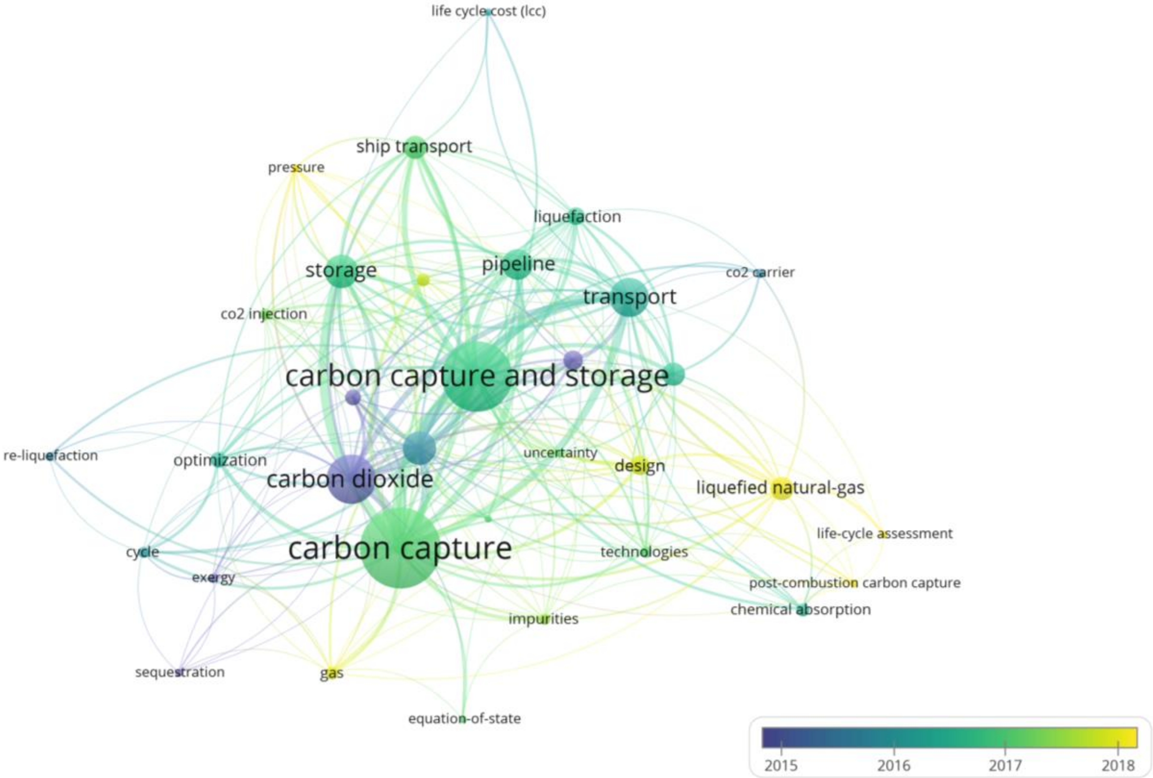
“Carbon Capture,” “Carbon Capture and Storage,” and “Carbon Dioxide” are nested together relatively close with solid linkages, which stipulates that they have a high degree of relatedness to each other. This is as expected, because they are the most frequent occurred keywords fundamental to the carbon capture and storage chain.

Figure 18 – Keyword network



The overlay visualization map is identical to the network visualization except for the color on the nodes. The color on the nodes is connected to the average publication year for the keyword. All the keywords have an average publication year of 2014 to 2018, and the timeline is therefore set automatically to the range of this years to give the best possible visualization. The data collection period stretched from 2006 to 2020, and of the 33 most occurred keywords have an average publication year between 2014 and 2018. This again pinpoints that this is a very new research field, and indicates a shifting focus towards the topic, with most of the research being published in recent years.

Figure 19 – Overlay keyword network



4.8 Data mining and research clusters

The collection used for data mining through Vos Viewer consists of terms from the titles and abstracts of the 92 publications in 2006-2020. It was used a binary counting method, meaning that only the presence or the absence of a term in a document mattered. The number of occurrences of a term in a document was not considered. Out of the 3129 terms, it was 108 terms that met the benchmark and occurred five times or more.

Table 13 – Manually excluded terms

Excluded terms					
Account	Development	Factor	Order	Solution	Work
Addition	Effect	Impact	Paper	Source	Year
Application	Efficiency	Influence	Part	Study	Case Study
Availability	Concept	Model	Point	Term	Analysis
Boil	Condition	Number	Review	Time	Scenario
Case	Consideration	Option	Simulation	Use	Comparison

Among the 108 terms were some keywords that did not provide any value to the analysis, and it was therefore necessary to perform a data cleaning. Table 13 displays the terms that were manually removed. The purpose of conducting a manually data cleaning is to exclude terms and merge terms with the same meaning. This process excludes so-called ‘general terms’, which is terms that provide very little information and influence the usefulness of a map – the usefulness of a map tends to increase when these terms are excluded.

Further on, it was necessary to also merge some of the terms that had a similar meaning. To combine different variants of terms I did create a thesaurus file. For example, did “Carbon capture,” “capture,” and “CO2 Capture” all occur in the original data file. These three words all have the same meaning, and I did therefore choose to keep the “carbon capture” as the primary term and replaced “capture” and “CO2 capture” with this term. All the terms that fall under the column “replaced by” are replaced by terms already present in the original file. This was useful not only for merging synonyms, but also for correcting spelling differences and merging abbreviated terms with full terms. For example, did the term “Enhanced Oil Recovery” and its abbreviation “EOR” appear as two different words.

Table 14 – Merged terms

Label	Replace by	Label	Replace by
Capture	Carbon Capture	Co2 Emission	Emission
Co2 Capture	Carbon Capture	EOR	Enhanced Oil Recovery
Co2	Carbon Dioxide	Pipeline Transport	Pipeline
Injection	Co2 Injection	Bar	Pressure
Co2 Liquefaction	Liquefaction	Area	Region
Liquefaction Process	Liquefaction	Degrees C	Temperature
Co2 Shipping	Co2 Transport	Carrier	Vessel
Transportation	Transport	Co2 Carrier	Co2 Vessel
Long Distance	Distance	Ship	Vessel
Range	Distance	Ship Transportation	Shipping

After the exclusion and merging of similar terms, the total number of terms was reduced to 53 terms that met the threshold. This was further reduced to 32 terms due to Vos Viewer's default settings that select the 60 % most relevant terms. Terms with a high relevance score tend to represent specific topics covered by the text data. In contrast, terms with a low relevance score tend to be of a general nature and tend not to be representative of any specific topic (van Eck & Waltman, 2010). By excluding terms with a low relevance score general terms are filtered out, and the focus shifts to more specific and more informative terms.

Table 15 – Text mining terms

Term	TO	RS	Term	TO	RS
Hydrogen	6	2,8519	Co2 Vessel	7	0,6995
Electricity	8	2,1676	Performance	16	0,6986
Large Scale	5	1,8844	Future	8	0,6909
LNG	8	1,7135	Technology	31	0,6664
Investment	6	1,5733	Energy	19	0,6534
Scale	5	1,4688	Region	13	0,6422
Greenhouse Gase	5	1,3978	Co2 Transport	13	0,5755
Atmosphere	7	1,3908	Capacity	17	0,5643
Fuel	15	1,3719	Challenge	12	0,5309
Uncertainty	9	1,3516	Optimization	11	0,521
Enhanced Oil Recovery	9	1,226	Global Warming	7	0,5153
Safety	5	1,2001	Power	11	0,414
Storage Tank	8	1,0928	Storage Site	12	0,4088
Operation	11	1,0749	Liquefaction	19	0,3843
Co2 Injection	10	0,8581	Temperature	27	0,3669
Tank	9	0,7179	Sequestration	14	0,3262

TO = Total occurrences, RS = Relevance Score

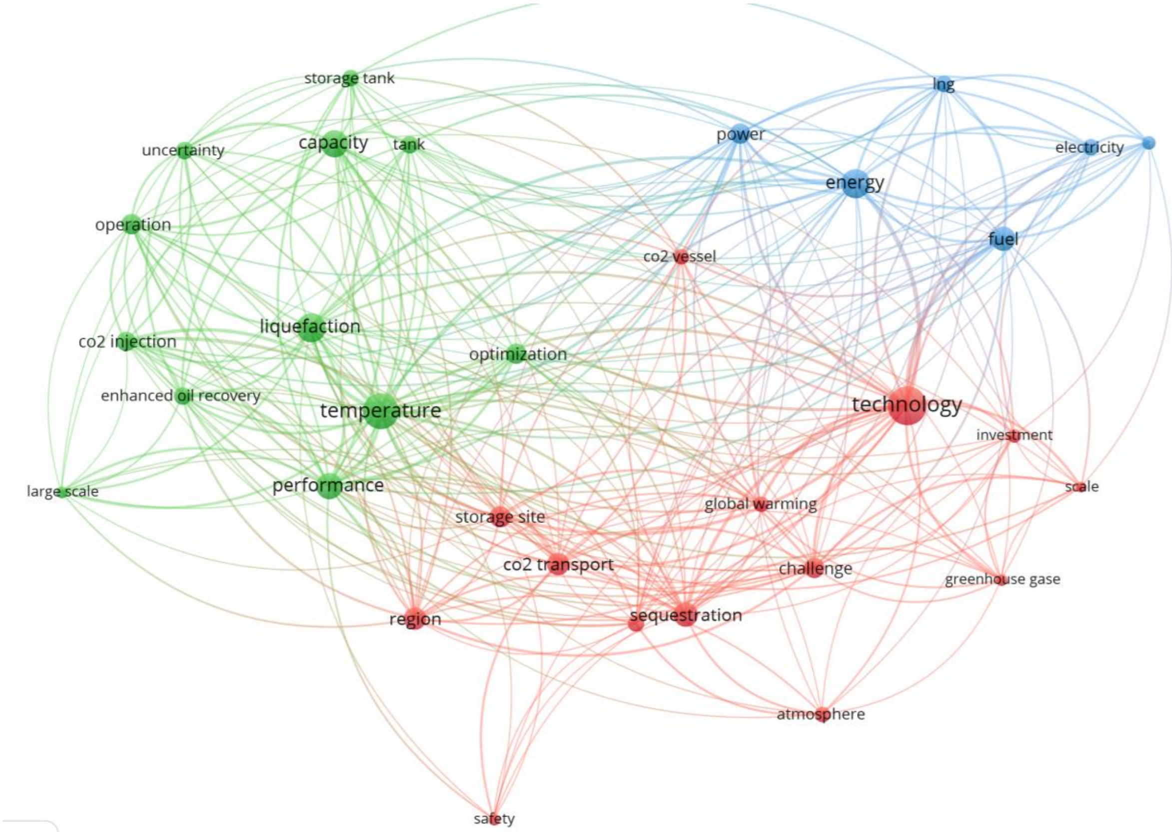
Vos Viewer calculates the relevance score by using the equation 1, where S_{ab} = similarity or the relevance between word a and word b, C_{ab} = the number of co-occurrences of the word a and word b, W_a = the number of occurrences of word a and W_b = the number of occurrences of word b (Chen, De Soto, & Adey, 2018). The relevance could also be visualized by the distance between two words in figure 20 in VOS Viewer. The shorter distance between two terms, the higher degree of similarity, i.e., higher relevance (Chen, De Soto, & Adey, 2018).

Equation 1

$$S_{ab} = \frac{C_{ab}}{W_a W_b}$$

Hydrogen and electricity have a high relevance score and are closely related to each other in figure 20. This indicates that they are both relevant and essential terms within the field of CCS. Equinor (2020) states that in order to cut emissions, it is vital to create a hydrogen economy, and for the hydrogen economy to succeed, Carbon Capture and Storage (CCS) is essential. Without going too technical in-depth, it is mainly two ways to produce low carbon hydrogen: One option is to produce hydrogen by using renewable electricity and electrolysis to split the H from H2O (water). The other option is to produce it from natural gas and capture the CO2 by-product (Equinor, 2020). The rationale of this explanation, also relates other terms such as (large) scale, LNG, investment, fuel, energy, etc., to carbon capture and storage.

Figure 20 – Text mining network term



When observing figure 20 it is important to realize that the terms are related to the research context and the associated research area. For example, "temperature," which is the second most occurred term, is associated with the temperature of CO2 and not the temperature of the weather or other things. CO2 is commonly known as a gas but also comes in liquid and solid form depending on the temperature and pressure. The distance between the two circles offers an indication of the relatedness of them. "Temperature" and "Liquification" are closely related because the temperature is an important factor for when the CO2 transforms into a liquid form. "Optimization" and "Performance" are also found in the same area of the map. The temperature affects the density and is essential to optimize when, for example, transporting CO2. Other words like "Tank," "Storage tank," and "capacity" are closely related, meaning that the three words often appear together and are highly relevant to each other.

4.8.1 Research clusters

Table 16 – Text mining clusters

Cluster 1 (red)	Cluster 2 (green)	Cluster 3 (blue)
Atmosphere	Capacity	Hydrogen
Challenge	Co2 Injection	Electricity
CO2 Transport	Enhanced Oil Recovery	Energy
CO2 Vessel	Large Scale	Fuel
Future	Liquefaction	LNG
Global Warming	Operation	Power
Greenhouse Gase	Optimization	
Investment	Performance	
Region	Storage Tank	
Safety	Tank	
Scale	Temperature	
Sequestration	Uncertainty	
Storage Site		
Technology		

The color of the nodes in figure 20 is determined by which cluster it belongs to. By arranging the different terms into clusters, it is possible to conduct a cluster analysis. The cluster analysis is a form of exploratory data analysis where keywords are divided into different groups that share common characteristics (Soetewey, 2020). The main objective for the cluster analysis is that the observations within a cluster must be as similar as possible, but the observations in different clusters must be as different as possible. Within and among the clusters in figure 20 the terms are very clearly divided, and the clusters do not merge.

Cluster 1: Climate change and geographical areas

Cluster 1 is the largest cluster and has 14 terms categorized in it. Some of the terms like “Atmosphere,” “Future,” “Global Warming,” and “Greenhouse Gases” is referring to the environmentally friendly aspect of the topic. This focus area is considered an important driving force for the carbon capture and storage topic. Other terms in the cluster refer to the different geographical areas in the carbon capture and storage chain. “CO2 transport” is found between “Storage site” and “Sequestration” in the visualization map. The term “Sequestration” is referring to the process of capturing and long-time storing carbon. The different processes of capturing and storing the CO2 are often performed in different regions, and this can be one of the reasons why “CO2 transport” is related. The “investment” and “scale” are related to each other. Large-scale projects are often associated with large investments and vice versa. The scale of CCS projects can also be related to geographical areas. Large CCS projects are likely to cover different regions and are dependent on having sufficient storage capacity, which is reserved for some geographical areas.

Cluster 2: Technical operations

Cluster 2 is referring to more technical terms than the other clusters. “Storage Tank,” “Tank,” “Temperature,” etc., is central to optimize the performance in daily operations. The optimization temperature and pressure affect the capacity of a CO_2 tank. However, there is some uncertainty regarding which temperature and pressure to use because the only CO_2 vessels in the world transporting CO_2 per now use medium pressure 15 bar and -30℃ (Yara, 2016). SINTEF (2019) states that lowering the pressure could be a better solution, but this would complicate the liquefication process. Terms like “CO2 Injection” and “Enhanced Oil Recovery” (EOR) are also found in cluster 2. These are also so-called technical terms referring to the storage part of the CCS chain, and is a type of CO_2 injection. The process of EOR involves injecting CO_2 into partially depleted oilfields to force out additional volumes of oil, with CO_2 being residually trapped and permanently stored (SCCS, 2015).

Cluster 3: Hydrogen economy

Cluster 3 displays many terms that are related to a hydrogen economy. A hydrogen economy is an economy where hydrogen is used as the commercial fuel that delivers a substantial part of a nation’s energy and services (Nehrir & Caisheng, 2016). Hydrogen is an essential part of bringing the amount of greenhouse gas emissions down to reach the targets of the Paris Agreement. One of the significant benefits of using hydrogen is its ability to store energy long-term. This makes it possible to cover seasonal fluctuations in wind or solar generation, but it can also fuel heavy transport such as ships, trucks, and trains, replace traditional fossil fuels in energy-intensive industries such as steelmaking, and be used as a cleaner and flexible fuel source in power generation (Equinor, 2020). A hydrogen economy is dependent on producing low-carbon hydrogen, which is either done by using renewable electricity and electrolysis to split the H from H_2O (water) or produced from natural gas and capture the CO_2 by-product.

In the light of the analysis and results will the next chapter conducta a discussion reflecting the main contributions, implications from policymakers and practitioners.

5 Discussion

5.1 Main contributions

This chapter conducts a discussion reflecting the findings in consideration of the research objective. The objective of the thesis was to identify the publication trend of the research field, whether the publication is concentrated on specific years, to study the directions and focuses of the research field, to identify researchers, journals, conference proceedings, and countries that have been focused on the research field and to discover future research areas. The analysis and result chapter has provided an overview of the research field by examining how partitioning elements (documents, journals, authors, etc.) are related. Results revealed that the scientific outputs of the research field experienced substantial growth with a growing number of publications and the annual total citations of articles.

Many organizations and researchers have contributed to the researchfield, but only a few influential and productive contributions have made a noticeable difference. This is among other things shown by how the journals that are the most cited, also are the ones that have published the most documents. This is a trend that I also found when it comes to organizations and authors, eventhough the organizations have one exeption: Seoul National University has been the most productive organization, but has only a quarter of the citations that the most influential organization has. On the other hand, the correlation between the author's influence and productivity is not that easy to recognize, because some of the authors have collaborated on documents that have become very influential. Nevertheless, many of the published papers on the CCS research field, are written by the same author. This may relate to the fact that the research field is a relatively new, and that the topic mainly is influenced by the researchers with high interest in the field.

The countries that have been significant contributors to the research field are mostly industrial countries. This relates to the fact that carbon capture and storage are very capital intensive, and few have the knowledge. Much of the research is conducted conducted by, and on request from, the industry. Conducting research on the topic can therefore be challenging for others because the industries and researchers that collaborates gets a head start and thereby an advantage. Many countries that influence the research field have technology that can be transferable to carbon capture and storage, and this technology is, for example, transferable from the oil and gas industry. This gives countries like Norway, that are leading on oil and gas a significant advantage. There can also seem to be a relationship between countries with significant research contributions and countries with extensive natural resources. Countries with such considerable natural resources will have a motivation to keep the oil and gas industry running because it employs people, and it is a major potential income source for the country. Adopting carbon capture and storage makes it possible to continue utilizing fossil fuels without releasing greenhouse gasses into the atmosphere. The synergies between the industrial countries, transferable technology, and the motivation to still use fossil sources are factors that reinforce each other so that the combined effect is more significant than the individual factors. The synergies help to understand why the countries have been important contributors to the research field, and why other countries have not yet participated (in a larger scale).

The lack of non-western and non-Asian countries can be a boundary for climate change. Climate change is a global problem, and it is necessary that carbon capture and storage is adopted on a global scale for it to be a soulution to the climat problematic. Broadening the number of researchers and countries where carbon capture and storage is investigated can be vital. It will globally be a significant weakness for the adoption of CCS without the contribution of less developed countries.

The geographical dispersion and the number of influential contributors can be related to the research field's maturity. The maturity of the research field a recurring topic in the analysis part. The research field is considered to be very new compared to other well-established areas. Most of the research that has been conducted on the field is published in recent years, and the period for my data collection was set to a short period (2006-2020) due to the rapid development in the field. Even within this period one can still find most of the research conducted over the last five years. It can be possible to assume that one of the reasons for this is the shifting focus toward climate change in the world, which can have provided more broad/widespread political support.

Among the most cited article it was only one paper that addressed the storage part of CCS. The article from Bergmo (2011) investigated simultaneous CO2 injection and water production to optimize aquifer storage capacity. Other papers also address the storage part, but these are often a part of other review articles and have not been so influential compared to Bergmo (2011). Bergmos article is cited 82 times but has 0 TLS, which is unusual because it means that they have no direct linkages to the other article, even though it has been cited many times. Few papers are directly related to the storage part and one can wonder if this may be because there is a gap in the research, or if it is because the topic is very complex and it is few contributors that have the competence to investigate the topic.

5.2 Implications for cleaner productions and policymakers

The political implications regarding carbon capture and storage are essential for successfully deploying full-scale carbon capture and storage: CCS has gained recognition as a feasible measure for climate change. Still, this growing appreciation of the value of CCS has not been accompanied by commensurate growth in political and policy support for the technology. The policymakers have a significant influence on the development of CCS and can also be a reason why certain countries have leading positions within the field.

One of the major factors driving CCS forward is the recognition of achieving net-zero greenhouse gas emissions is increasingly urgent (Global CCS Institute, 2020). Carbon Capture and storage are also dependent on economic viability and public support for a successful implementation. The financial aspect is much driven by the price of CO2, which refers to the price a company must pay for releasing a ton of CO2. This price is regulated through the EU Emissions trading system, which sets an overall limit on all CO2 emissions from power stations, energy-intensive industries, and civil aviation (Appunn & Sherman, 2018). The EU decides how much greenhouse gas pollution can be emitted each year, and the Companies need to hold European Emission Allowance (EUA) for every ton of CO2 they emit within one calendar year (Appunn & Sherman, 2018). If a company were to emit more or less CO2 than allowed, they could buy a bigger quota or sell their quota. The EU reduces the number of quotas available yearly, which makes them more expensive due to supply and demand. The quota price for 1 ton of CO2 has the last year fluctuated in the range of 160 NOK to 412 NOK.[1]

The cost of CCS represents the cost of avoiding a ton of CO2 being released into the atmosphere. The price for capturing CO2 will vary depending on various factors such as country, Transport distance industry, emission quantity, and CO2 concentration (SINTEF, 2019). SINTEF (2019) estimates that the total price for the planned full-scale CCS project in Norway, herby including capture, transport, and storage, will cost approximately 850 NOK per ton of CO2. As mentioned in chapter 4.7 researchers do expect the price to fall as the technology will become more efficient and cheaper – like other technologies that have been expensive in the beginning (SINTEF, 2019). When comparing the cost of buying quotas and

[1] Based on an exchange rate EUR/NOK = 10,30kr

the cost of CCS, it is very easy to decide which one is the best alternative from the economic perspective. Based on the numbers provided here, is it at least twice as expensive to use CCS and thus avoid releasing CO_2 into the atmosphere. This is a major challenge regarding the economic viability of CCS, and is one of many other factors that causes uncertainty around the topic.

There are also implications related to measuring the benefits of carbon capture and storage to ensure that it produces an objective, quantifiable environmental benefit. One ton of CO_2 permanently stored has the same benefit in terms of atmospheric CO_2 concentrations as one ton of CO_2 emissions avoided, but one ton of CO_2 temporarily stored has less value than one ton of CO_2 emissions avoided (Osman-Elasha & Pipatti, 2018). In a political environment where only some parties have commitments to the limitation of greenhouse gas emissions, and where emissions from different sources are not treated the same, the reduced amount of CO_2 will differ from the amount of CO_2 that are stored (Osman-Elasha & Pipatti, 2018). The differences may occur because CO_2 can be captured in one country but released in another country or at a later time.

5.3 Implications from practitioners

There has been a significant development in the research field of carbon capture and storage, which has resulted in an increasing number of publications from researchers, organizations, and companies. However, the concept of carbon capture and storage accelerates a new industry, and the recent industrial advancements are not always consensual with the research conducted on the field. Thus making it essential to understand the implications both from the researcher's and the practitioner's point of view. The practitioners can highlight several implications that the research have not taken into consideration.

Yuji Aibara, General Manager of CCUS – Subsea Team and Offshore Project Division at Mitsui O.S.K Lines, emphasizes the implications of the high capital investment required to develop the CCS value chain such as capture plant, transportation, injection, and storage facility. The current tax scheme and carbon price will not justify the investment without political support. Governmental support will be needed until the CCS infrastructures are developed to the extent that the industry can achieve the economy of scale and drive the cost down by learning (Y., Aibara, personal communication May 2021).

Yuji Aibara also points out the implications related to the fact that the industry is in an early stage. There seems to be a lack of understanding of the entire cost for the CCS value chain. It does not make sense that while the cost at one part of the chain is reduced, the cost at the other part increases. He believe that this will be more developed as the coordination across various industries progresses (Y., Aibara, personal communication May 2021).

5.4 Limitations of the research-thesis

This thesis was limited due to the sample extracted from the Web of Science. Web of Science is a comprehensive database but it does still not provide a complete database of every single document within the field. Some documents may exist in other databases such as Scopus or Google Scholar. The industry and the research field are both developing very quickly, but there is a chance that there is a gap between the industry and the scientific research. Solutions methods that were presented a decade ago can already be outdated due to the rapid evolvement, and also because the concept is not tested in a large scale. Time is also a limitation in this study. The period selected for data collection (2006-2020) is relatively recent, and the documents published at the end of the period have not had enough time to be widely cited.

5.5 Suggestion for further research

Compared to traditional literature review methods, I have attempted a scientific and objective approach to identify the possible future direction research that should be conducted to further strengthen the idea of carbon capture and storage. As usual, further studies in this direction are needed to obtain a more general view of the state of the art in this field. Future works should be developed by retrieving data from some other databases.

Carbon capture and storage can be an essential measure to reduce CO2 emissions by preventing a large amount of CO2 from entering the atmosphere, and it can be an important contribution in the work against the ongoing global climate changes. Few major contributors now dominate the research field, and to deal with the global problem it will be important to include several countries. Therefore, future research might investigate how carbon capture and storage can be adopted in other non-western and non-Asian countries.

6 Conclusion

The objective of this master thesis was to identify the publication trend of the research field. Furthermore, my goal was to identify researchers, journals, articles, organizations, and countries that have been central in the research field, and to study different directions, focuses and future research areas.

The research field is relatively new, despite the fact that the technology used for CCS has been present for a long time. Among the published papers the majority of documents are published in recent time, and the reserch field is dominated by a few major contributors. The main focus areas are centered around capture, transportation, and storage, which are considered as the research's conceptual building blocks. There is also a relation connected to cost, technology, hydrogen, and LNG, making them influential focus areas. Future research directions might investigate how one can reduce the high capital investment required to develop the CCS value chain and reduce the operating cost, thus making it economically viable. Future research directions might also examine how carbon capture and storage can be adopted to other parts of the world.

To conclude, the research field of carbon capture and storage is growing and maturing. Given the small number of influential contributors and the fact that some of them has relatively few linkages, provides a significant room for development. The number of published papers should also be expected to increase given the solid foundation of existing research, a foundation that did not exist a decade ago.

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