A thesis submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Master of Science

Feasibility Assessment of CO_2 Pipeline Infrastructure Required for Carbon Capture and Storage in Climate Scenarios to Meet Climate Targets.

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June, 2023

Austria

Erasmus Mundus Masters Course in Environmental Sciences, Policy and Management

MESPOM

This thesis is submitted in fulfilment of the Master of Science degree awarded as a result of successful completion of the Erasmus Mundus Masters course in Environmental Sciences, Policy and Management (MESPOM) jointly operated by the University of the Aegean (Greece), Central European University (Hungary), Lund University (Sweden) and the University of Manchester (United Kingdom).

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Jamdade, <A.A>. 2023. < *Feasibility Assessment of CO_2 Pipeline Infrastructure Required for Carbon Capture and Storage in Climate Scenarios to Meet Climate Targets*> Master of Science thesis, Central European University, Vienna.

Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:

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for the degree of Master of Science and entitled: Feasibility Assessment of CO_2 Pipeline Infrastructure Required for Carbon Capture and Storage in Climate Scenarios to Meet Climate Targets

Month and Year of submission: June, 2023.

This thesis focuses on the infrastructural requirements of Carbon Capture and Storage (CCS), a critical climate mitigation technology. Although CCS has been in operation for decades, the scale of envisioned CO_2 capture in IPCC climate scenarios is substantial. To accommodate this scale of CO_2 capture, transport, and storage, it is critical to evaluate the feasibility of this expanding infrastructure of CCS. This thesis a) identifies the infrastructural needs of CCS, b) estimates required CO_2 pipelines lengths for climate targets using the NETL-NZA model, and c) assesses the feasibility of required CO_2 pipelines using 'Outside View', The 'Outside View' incorporates historical length of natural gas and oil pipelines as reference cases, and GDP as normalization parameter to take into account changing economy. Projected CO_2 pipelines compatible with Paris Agreement seem to be feasible when compared with the historical development of natural gas pipeline length, however, the projected length of CO_2 pipelines would nearly have to be 3 times more than the historical oil pipeline length. This study indicates that in the smaller economy of the past, natural gas and oil pipelines were essential for meeting the energy needs of the society whereas envisioned CO_2 pipelines aid in reducing CO_2 concentration in the atmosphere.

Keywords: climate mitigation, CCS infrastructure, CO_2 pipelines, feasibility

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Acknowledgements

I would like to express my deepest gratitude to my supervisor Prof. Aleh Cherp for his guidance and motivation throughout my thesis. His expertise and feedback have been fundamental in shaping this thesis. I would also like to thank Tsimafei Kazlou for his input and time commitment to this thesis. Many thanks to Prof. Andrew Lowe for his motivational and inspirational words. I am grateful to all staff and faculty from Central European University, the University of Aegean, and the University of Manchester for their courses throughout the MESPOM Journey. I am grateful to my grandparents, parents, uncle, and sister for their constant love for me. Special thanks to my classmates, for constant motivation during the thesis writing period.

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List of Abbreviations

ASU: Air Separation Unit

CCS: Carbon Capture and Storage

CCUS: Carbon Capture Utilisation and Storage

CDR: Carbon Dioxide Removal

DAC: Direct Air Capture

DOE: Department of Energy

EOR: Enhanced Oil Recovery

GDP: Gross Domestic Product

GHG: Greenhouse Gas Emissions

IEA: International Energy Agency

IRENA: International Renewable Energy Agency

NETL: National Energy Technology Laboratory

NETL_NZA: National Energy Transition Laboratory_Net Zero America

PPP: Power Purchase Parity

PV: PhotoVoltaic

SCADA: Supervisory Control and Data Acquisition

SSP: Shared Socio-Economic Pathways

1 Introduction

1.1 Background

Climate mitigation is a policy priority of the 21st century. Current and anthropogenic Greenhouse Gas (GHG) emissions from various sectors like Energy, Industrial, Transportation, and Power are a major concern for addressing climate change (IEA 2022b; 2022d). Consequences of these emissions include economic losses due to increased intensity and frequency of extreme weather events (like hurricanes, and droughts), loss of life, environmental degradation, ecological obliteration, mass migrations, sea level rise, etc (IPCC 2022b; 2022a). Although the past few years have seen increased efforts to address the concern, the emissions are still not reducing fast enough to meet climate goals (IEA 2022b). Thus, it is pivotal to not only minimize ongoing emissions but also eliminate the historical cumulative emissions.

Decarbonisation of the energy sector is instrumental in meeting climate goals (IEA 2022d). Certain sectors like freights, and industries like steel, cement, and chemical are technically and financially hard to decarbonise, also called hard-to-abate sectors (Paltsev et al. 2021). For such sectors, Carbon Capture and Storage (CCS) is of interest as it can minimize emissions but can also eliminate anthropogenic emissions (Anderson and Peters 2016; Paltsev et al. 2021). CCS refers to a range of technologies that captures carbon from point sources like fossil fuel industries, or the atmosphere directly, and are transported and stored in assigned storage sites or re-used for purposes like synthetic fuels (Global CCS Institute 2020). The CCS value chain consists of the infrastructure required to purify gasses and obtain CO_2, capture this CO_2 using different methods, compress or liquefy this CO_2 and transport it to storage sites, and store them in saline aquifers underground cavities, etc (IEA 2023). CCS has been used for decades for Enhanced Oil Recovery (EOR) but at a minute scale as opposed to the massive scale envisioned in climate scenarios aligned with the Paris Agreement (Bui 2018). As of September 2022, Global capture capacity is 46 million tonnes per annum (Mtpa)[1] which is much less compared to Intergovernmental Panel on Climate Change Assessment Report 6 (IPCC AR6) Climate Scenarios (Global CCS Institute 2022; IEA 2023). The urgency of deploying CCS at scale coupled with its slow rate of deployment raises feasibility concerns for the expansion of the CCS infrastructure.

Infrastructure lays a foundation for scaling up CCS. Infrastructure for CCS majorly involves technologies for capturing CO_2 (Air Separation Units, Solvents), transporting CO_2 (Pipelines and Ships), and storing CO_2 (Injection wells) (DOE 2022; IEA 2020; 2023). Depending on the capture process, mode of transportation, or storage methods, distinct auxiliary infrastructure like liquefying stations and monitoring equipments are required (IEA 2023). Given the importance of limiting GHG emissions and the anticipated deployment of CCS in meeting the Paris Agreement goal, it is critical to identify the infrastructural requirements of CCS and assess the feasibility of the infrastructure.

To assess feasibility, this thesis utilizes 'The Outside View' methodology by incorporating reference cases to assess feasibility. Climate Scenarios generated through models explore the future (within the set parameters), however, the future is not embedded in empirical data of the past or present (Rogelj, Joeri 2022). For example, IPCC scenarios provide a combination of technologies that aid in climate mitigation and are assumed to grow at a certain rate in the future. However it is challenging to incorporate certain factors like 'public acceptance', and 'political support' in the scenarios, thus there is a gap between 'anticipated model outcomes' and 'real world outcomes' (Jewell and Cherp 2023). One way to fill this gap is to look into the past and identify similar historical analogies, examine relevant characteristics of this historical analogy (also called a reference case), and compare it with the projected outcomes of the case

[1] Most of the existing CO_2 capture is concentrated in United States.

for which feasibility is being assessed (also called as target case) (discussed in detail in Section 2.5) (Jewell and Cherp 2023). For this paper, the target case is the length of CO_2 pipelines (km) in climate scenarios and the reference case is the length of Natural Gas and Oil pipelines (km).

1.2 Research Questions and Objectives

Against this background, this thesis aims to answer the following questions:

- RQ1: What are the pipeline [and other infrastructure] requirements of CCS for achieving climate targets?
- RQ2: What are the reference cases for this construction and operation?
- RQ3: Is this construction and operation feasible and, if so under what conditions?

RQ1 aims to identify the infrastructure requirements of CCS which include solvents for capturing and purifying CO_2, pipelines, and ships for transporting CO_2, and injection wells to store the captured CO_2 (IEA 2023; 2020; Global CCS Institute 2022). RQ1 examines detailed lists of components in the entire value chain of CCS. RQ1 also examines the raw materials namely cement, iron, and steel required for the CCS infrastructure. This information is gathered from different literature, technical reports, and standards used for the construction of pipelines and other infrastructure. The climate targets in RQ1 are taken from the median value of captured CO_2 for IPCC AR6 scenarios compatible with 1.5°C and 2°C. RQ1 also fills the gap in the IPCC Scenarios by calculating the length of CO_2 pipelines that would be required to capture the projected volume of CO_2. RQ1 is answered in Section 2.4 and Chapter 5.

RQ2 aims to determine reference cases for the construction of CCS pipelines. One of the ways to assess feasibility is to look at historical equivalent reference cases (Jewell and Cherp 2023). The driving forces and the causal mechanisms for the reference case might be different from the anticipated future, but they still can be used as a benchmark. For RQ2, the reference case considered is the length of natural gas and oil pipelines. Natural gas and Oil pipelines have been around for a century, and their distribution network resembles the distribution network of CCS pipelines.

RQ3 aims to assess the feasibility of CO_2 pipelines (required by CCS) using reference cases of natural gas and oil pipelines and contributes to conditions under which this operation and construction of CO_2 pipelines are feasible. To assess feasibility, this thesis first calculates the CO_2 pipelines to be required for meeting climate targets and compares them with the historical deployment of natural gas and oil pipelines. While RQ1 closes the literature gap in IPCC scenarios by calculating the length of CO_2 pipelines required for envisioned CO_2 capture, RQ3 provides extensive information on the feasibility of the operation and construction of CO_2 pipelines.

1.3 Thesis Structure

This thesis is structured as follows: Chapter 2: Literature Review, highlights the 'Need for CCS', and knowledge gap in CCS, along with in-depth technical infrastructural requirements for CCS, followed by identification of relevant reference cases, and justification of the use of natural gas and oil pipelines as reference cases for the CO_2 pipeline. Chapter 3: Methodology, lays out the theoretical framework of the thesis by explaining the 'Inside and Outside Views' on Feasibility, and the NETL_NZA model used for the calculations of CO_2 pipelines. Subsequently, data sources, calculations, and limitations are presented. Chapter 4: Results, looks at captured Volume of CO_2 in IPCC scenarios, followed by required CO_2 pipelines to capture this CO_2, and later compares the reference case and target case. Chapter 5 Discussion, provides a feasibility assessment of CO_2 pipelines, and reflects on research questions. Chapter 6: Conclusion, concludes the thesis by briefly summarizing the findings of the thesis, discussing further research directions, and providing academic and practical implications of the results.

2 Literature Review

This chapter presents state-of-the-art literature on infrastructural requirements of CCS, Knowledge gaps within CCS literature, relationship and critical discussions within different literature, and possible reference cases for assessing the feasibility of CCS. This chapter is arranged in the following manner: Section 2.1 presents the overall status of GHG emissions followed by Section 2.2 where the need for CCS is justified, Section 2.3 identifies the knowledge gap and links with the research questions of this thesis. Section 2.4 partially answers RQ1 by identifying infrastructural requirements for CCS, and Section 2.5 answers RQ2, utilizing past and existing literature.

2.1 Climate Mitigation Challenge

Climate change is multifaceted in nature i.e. climate change is inextricably linked with Social, Economic, and Environmental factors (IPCC 2022a; IRENA 2021a). The multifaceted nature of climate change results in multidimensional consequences and risks, including unavoidable climate hazards in the short term that affect both humans and ecosystems (IRENA 2021a). In the long term, the risks to the global economy and environment due to the increased frequency of extreme events are significant (IPCC 2022a). Direct consequences include the rise in global temperatures, while indirect consequences comprise an increase in poverty, migration, etc (IPCC 2022). Due to the complexity and cascading nature of these risks, climate mitigation is vital (Islam and Winkel 2017).

Climate mitigation hinges on strategies that put emphasis on minimizing, eliminating, and/or capturing (storing) CO_2 from various sources like the atmosphere, fossil fuel plants, Industrial sectors, etc (IRENA 2021b; Paltsev et al. 2021). CCS technologies are capable of minimizing, eliminating, and capturing CO_2 (IRENA 2021b). As of 2021, 40Gt CO_2 +_ 2.9Gt CO_2 was released and the rising emission trend continued in 2022 where emissions rose to 41.3Gt CO_{2e} [2] of which energy-related related emissions were 36.8Gt (including Power, Industry, Transport, and Buildings) (IEA 2022b; Friedlingstein et al. 2022)**.** Such mounting emissions jeopardize the carbon budget. The carbon budget is the metric that indicates the remaining amount of CO_2 that can be emitted to be aligned with the Paris Agreement Goal[3](Piers et al. 2022). While Friedlingstein et al. (2022), estimate 380Gt CO_2[4] as the remaining carbon budget for limiting the global average rise in temperature to 1.5°C, updated methodologies from IPCC Working Group (WG) WG1 and WG3 along with CONSTRAIN Research Project, Carbon brief suggests a revised estimate of 260Gt CO_2 (from the start of 2023) (Constrain 2023; IPCC 2022a; Piers et al. 2022). Thus to mitigate climate change, the rate of depletion of the carbon budget should be slowed especially in energy-related sectors.

Curbing and removing emissions from the energy sector involves achieving Global CO_2 Net Zero by 2050, for which both strategies are anticipated: 'Emission reductions' as well 'Emission removals'. Some strategies for Net Zero from (IEA 2022d; IRENA 2022b; IPCC 2018) are as follows:

- Decarbonisation of the power sector through low-carbon technologies
- Electrification of end-use sectors like Heating and delivering power through clean energy technologies
- Implementation of Carbon Capture Storage and/or Utilisation and alternate fuels for hard-to-abate sectors like Industries, Aviation, Freight, etc

[2] CO_{2e} 'e' stands for CO_2 Equivalent. It is a measure where GHG gases are compared with equivalent amount of CO_2

[3] Paris Agreement Goal is to limit the average rise in global temperature below 2°C and attempt to keep it below by 1.5°C by 2100

[4] 380Gt CO_2 for 50% likelihood for limiting global average rise in temperature to 1.5°C

- And improving energy efficiency

Although individual countries will have a different combination of strategies favorable to geography, economy, social acceptance, and other factors, CCS is deemed to be a salient technology in the energy portfolio in the majority of high-emission countries, especially coal and natural gas-reliant countries (Greig and Uden 2021; Hu and Wu 2023; Sharma 2018).

2.2 The Need for CCS

IPCC scenarios are predominantly based on Integrated Assessment Models (IAMs). Different models can yield different results, i.e. the range of parameters set within these models is different, thus the outputs are different. For example, Koelbl et al. (2014) compared various models and highlighted the significance of CCS, this intercomparison was used by Bui et al. (2018), and cumulative CO2 capture capacity for limiting the global average rise in temperature to 2°C was estimated.

Table 1 indicates three CO_2 concentration levels in the atmosphere compared by (Koelbl et al. 2014; Bui et al. 2018) and the cumulative CO_2 capture capacity associated with CO_2 concentration levels.

Table 1: Cumulative CO_2 Capture estimates by Koelbl et al. (2014) along with Linear Per Year CO_2 Capture

CO_2 Concentration Levels	**Hybrid Model Cumulative CO_2 Capture (Gt CO_2)**	**Linear CO_2 capture per year from 2023 till 2100 (Gt CO_2/year)**
450 ppm	730-2411	9.5- 31.3
550 ppm	635-2962	8.24-38.4
450 ppm, limited renewables	625-2447	5.8- 31.7

Source: Reproduced from (Koelbl et al. 2014; Bui et al. 2018)

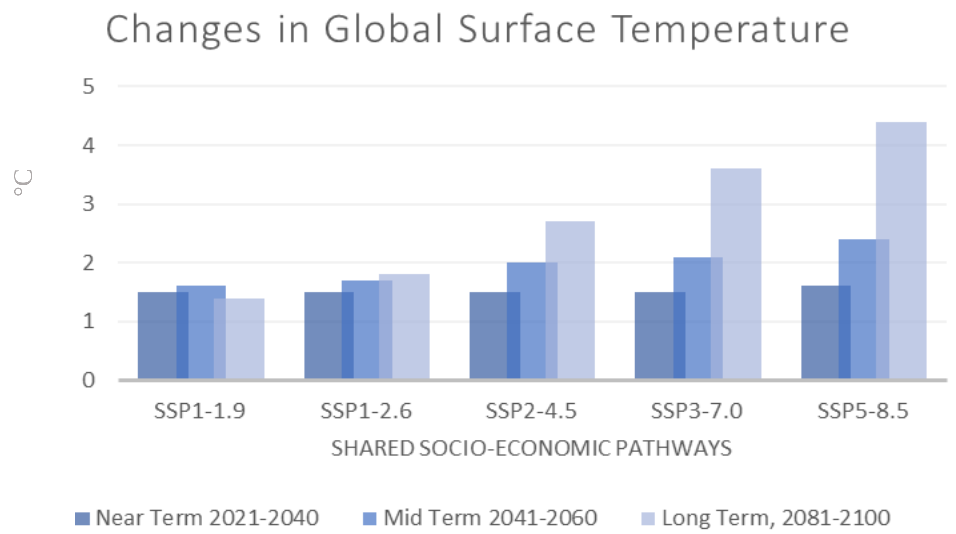
Note: Hybrid Model illustrates the estimates by (Koelbl et al. 2014; Bui et al. 2018), Linear CO_2 capture per year from 2023 till 2100 is calculated by own calculations. ppm: parts per million, Gt: Gigaton, 450ppm is consistent with limiting temperature rise to 2°C

From Table 1, calculated linear CO_2 capture from 2023 is in the range of 5.8Gt CO_2 per year to 38.4Gt CO_2 per year in 2100. These values are in stark contrast to the median value of CO_2 capture across IPCC scenarios compatible with 1.5°C and 2°C targets (see section 4.1). Thus, scenarios can evolve over time, they are sensitive to underlying assumptions and parameters, and should not be considered as forecasts but rather a benchmark for the future (Jewell and Cherp 2023; Rogelj, Joeri 2022)

An intriguing finding of IPCC (2022a) is that an overshoot of 1.5°C in all the scenarios under Shared Socioeconomic Pathways (SSPs) is inevitable as seen in Figure 1. This rise in temperature albeit temporary can only be compensated with CCS[5] technologies (Bui et al. 2018; Global CCS Institute 2022; Guo et al. 2020).

[5] Carbondioxide Removals (CDR) is described as Net Emission Technology (NET) which comes under the umbrella of CCS technologies.

Figure 1: Changes in Global Surface Temperature under Different Scenarios



Source: Reproduced from (IPCC 2022a)

Note: SSP: Shared Socioeconomic pathways, SSP1-1.9 can be represented as Most optimistic, SSP5-8.5: Least optimistic scenarios in the context of climate mitigation.

Whilst other technologies like Renewables, can reduce future emissions, CCS remains the sole technology to compensate for the overshoot of 1.5°C by removing atmospheric CO_2 (IEA 2020; IRENA 2021b). CCS is listed as one of three mandatory emission reduction technologies in the four key emission reduction technology pathways in the IPCC Special 1.5 report (Ma et al. 2022; IPCC 2018).

Furthermore, (Ma et al. 2022; IPCC 2018; Bui et al. 2018) share similar interests in making CCS an attractive option in the IAMs mitigation portfolio due to the advantages of CCS. From a technical point of view, CCS can be retrofitted into existing fossil plants, or new plants can be built with CCS fit into them (greenfit) (Akerboom et al. 2021; IEA 2020). The infrastructure of CCS can be integrated into the currently existing energy system without substantial heavy modifications, for example, CO_2 can be displaced from point sources like natural gas using CO_2 capture absorbent, shared CO_2 transportation infrastructure, and shared geological storage (Bui et al. 2018; Global CCS Institute 2021b).

Various literature identifies the need for CCS regionally. A key study of incorporating ETS (Emissions Trading System) for CCS by Hu and Wu (2023) concludes that for coal-intensive countries like China, CCS is an indispensable option to meet climate-neutral targets. Similarly, for filling up the emission gap of 25Gt CO_2 higher than the 2°C target for India, Sharma (2018) suggests CCS is critical and should not be overshadowed by Renewables. However, this study was published before the Conference of Parties (COP) 26, where India's targets were changed, hence, a more updated comprehensive study is required for India. Previous research has established that the prospects of CCS in the power sector are high, so it is intriguing to see that for a Hydro-power intensive country like Brazil, CCS still has a substantial role to play (Sharma 2018; Machado, Hawkes, and Ribeiro 2021). Machado, Hawkes, and Ribeiro (2021) estimated that it would take 12 years for CCS to be implemented commercially in Brazil. For Developed economies, Akerboom et al. (2021) claim that Netherlands and Norway are in an excellent position to pioneer CCS mainly due to ample offshore storage capacity, developed and established infrastructure, and comprehensive knowledge. But empirical data in terms of the length of CO_2 pipelines in existence today suggests that the US might be the pioneer of CCS given 95% of the transportation of CO_2 infrastructure is concentrated in the US (DOE 2022). However, the difference between US and Netherlands can be attributed to the application area, US utilizes CCS for EOR whereas the Netherlands (and Norway) is looking from a perspective of eliminating anthropogenic CO_2 (DOE 2022; Akerboom et al. 2021).

Regardless of regional differences, from an economic point of view, CCS reduces long-term abatement costs and presents a cost-effective pathway for achieving the Paris goal (Bui et al. 2018; Ma et al. 2022; Hu and Wu 2023). Guo et al. (2020) put a number on the above statement and state that CCS can contribute around 1/3rd of carbon abatements by 2050. IPCC has projected that cost of mitigation will rise by 138% in 2100 if CCS technologies are not adopted (Ma et al. 2022).

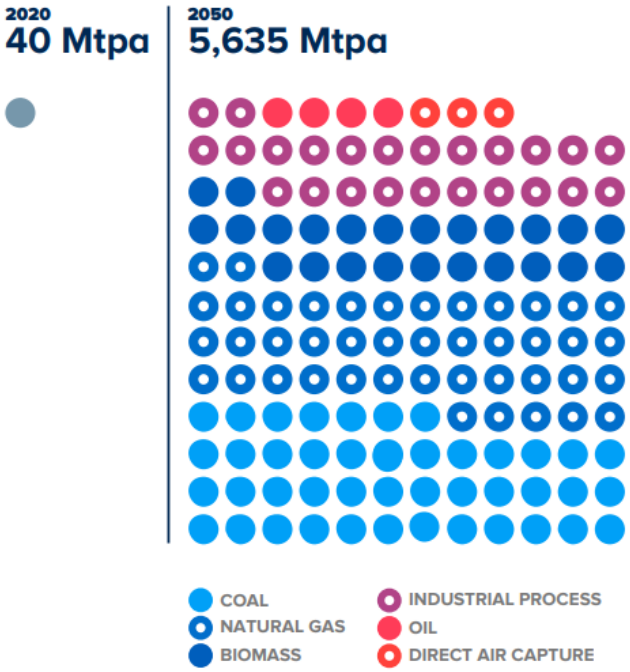
Taken together (Boddapati, Nandikatti, and Daniel 2021; Wei et al. 2021; Sharma 2018; Hu and Wu 2023) these studies support the notion that the primary implementation of CCS will be a power system. The conflicting narrative of 'CCS Vs Variable Renewable' underscores the technical requirements of the power system in terms of system flexibility, inertia, and frequency control (IEA 2020). Regardless of a low or high share of renewables, these technical requirements have traditionally been implemented by Coal and Gas-fired power plants (IEA 2020). Collectively (IEA 2020; Guo et al. 2020) outline three advantages of CCS in power systems: the risk of leaving a young fleet of fossil power plants stranded is reduced, CCS can be used for hydrogen production thereby aiding industrial de-carbonization, and CCS reduces the total cost of power system transformation[6].

2.3 The Knowledge Gap Concerning CCS

So far, two factors are regarded as major uncertainties for CCS: Speed and Scale (Van Ewijk and McDowall 2020). This statement is consistent with the findings of (Global CCS Institute 2021a) as seen in Figure 2, where the CO_2 capture capacity has to increase by 140% by 2050 compared to the 2020 capacity. For such speed and scaling of CCS, various dimensions have to come together: political will, social acceptance, technological reforms, and economic viability (Akerboom et al. 2021; Pihkola et al. 2017; Buck 2021). An important consideration is the infrastructure for CCS, as it forms the basis of CCS operation.

[6] (Guo and Huang 2020) suggests CCS can become commercially competitive if the technical requirements like flexibility and reliability of CCS in power system is fully valued.

Figure 2: CO_2 Capture Capacity in 2020 and 2050 by Fuel and Sector in the IEA Sustainable Development Scenario



Source: (Global CCS Institute 2021a)

Various studies like (Leeson et al. 2017; Jakobsen, Roussanaly, and Anantharaman 2017; Global CCS Institute 2021b) try to address the scaling-up issue of CCS. This includes designing an optimum CCS network or estimating CO_2 price through techno-economic analysis. However, the global analytical framework for infrastructure remains uncontested for CCS. Hu and Wu (2023) assess the feasibility of China in terms of the carbon tax and Emission trading system (ETS) and conclude that a combination of both along with government funds is crucial for scaling up CCS. This is consistent with Akerboom et al.'s (2021) findings of *CO_2 price acting as a barrier for CCS scaling up*[7] in the Netherlands amongst other factors. In a similar thematic study of addressing scaling-up issues, Pihkola et al. (2017) list CO_2 price as a barrier but also an enabling mechanism in the future, i.e. when CO_2 price rises in the future, CCS becomes an attractive option for investors. Collectively all these studies (Pihkola et al. 2017;

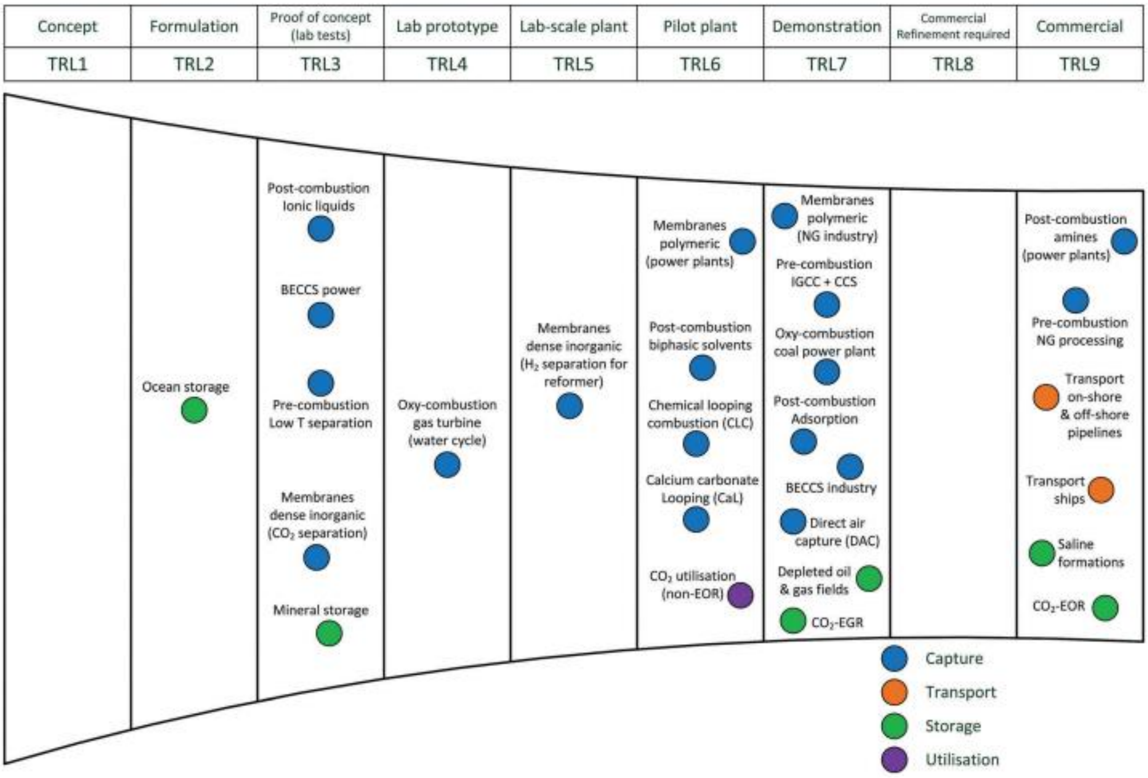
[7] Higher CO_2 price makes CCS profitable.

Jakobsen, Roussanaly, and Anantharaman 2017; Machado, Hawkes, and Ribeiro 2021; Akerboom et al. 2021) have carried out regional techno-economic analysis but none of them provide an assessment of infrastructure in terms of the amount of raw materials, length of CO_2 pipelines that will be required for CCS.

Contrary to previously published studies, Wei et al. (2021) proposed a global layout, identifying sources and sinks, potential storage sites, capture costs, and source-to-sink pipelines. The main findings of this study can be summarized as follows, a collaboration between China, EU, Russia, India, the US, Saudi Arabia, and Australia can store more than 55Gt of CO_2 by 2050. As for transportation, 80% of CO_2 transportation pipelines fall within the range of 300 km, thus, economically viable and would cost 0.12% of global cumulative GDP. As comprehensive as this study is, assessment in terms of required CCS infrastructure is still not available. However, a recent report by DOE (2022) dives deep into the CCS infrastructure required for the US to reach Net Zero. Critically evaluating the requirements of infrastructure can reduce uncertainties, provide a benchmark for other massive-scale developments, provide insights on costs, and aid in assessing the feasibility of those technologies. This thesis takes inspiration from these two studies (DOE 2022; Wei et al. 2021) and aims to fill the knowledge gap of global infrastructural requirements for CCS in different climate scenarios. Since the global infrastructural requirements are not yet explored for CCS, the global feasibility of this infrastructure is not assessed as well. As IPCC scenarios are not forecast but potential future outcomes, knowing infrastructural requirements does not tell the whole story (Rogelj, Joeri 2022). Hence, assessing the feasibility of the required infrastructure is pivotal (discussed further in section 2.5).

Figure 3 is taken from Bui et al. (2018) where the technological readiness of CCS is assessed. An interesting observation from Figure 3 is the transportation infrastructure: both shipping and pipelines are at TRL 9, and none in TRL 1, thus Pipeline and Shipping are the sole transportation technology irrespective of CO_2 capture and storage technology. Hence this thesis aims to close the knowledge of the gap in 'feasibility assessment of global pipelines for climate scenarios'.

Figure 3: Technological Readiness Level of CCS Technologies



Source: (Bui et al. 2018)

Note: TRL: Technological Readiness Level, EGR: Enhanced Gas Recovery, IGCC: Integrated Coal Gasification Combined Cycle, EOR: Enhanced Oil Recovery

In summary,

- CO_2 Transport technologies like pipelines are not assessed in IPCC scenarios, and neither is their feasibility.
- Literature on CCS infrastructure focuses on the cost of supply chains (Leeson et al. 2017), storage requirements for specific countries clustered together (Wei et al. 2021) regional case studies of CCS (Akerboom et al. 2021; Pihkola et al. 2017; Jakobsen,

Roussanaly, and Anantharaman 2017) however the literature lacks a global scale pipeline distribution. This thesis takes longer temporal distribution (Pipelines till 2100), and geographically broader distribution (over the globe).

- Although CO_2 pipelines are considered mature technology due to their use in EOR for decades supported by Ma Bui's assessment of Pipelines' TRL, the global analytical assessment falls short (Bui et al. 2018).

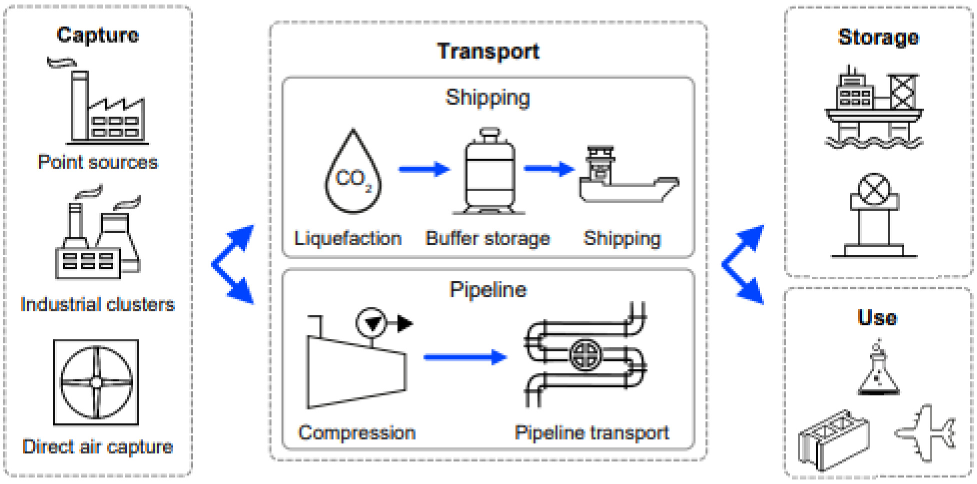
2.4 CCS Infrastructural Requirements

CCS is a portfolio of technologies and is used interchangeably with Carbon Dioxide Removals (CDR), and Carbon Capture and Utilisation (CCU), however, it is important to make the distinction as each technology plays a different role in climate mitigation (IRENA 2021b). CCS refers to processes that directly capture CO_2 emissions from point sources like fossil fuel industrial processes (IEA 2020). The Capture and Transport part remains similar for CCU, except instead of storage, the captured CO_2 is used for secondary processes like synthetic fuels (IRENA 2021b; IEA 2020). CDR (interchangeable with NET[8]) is another set of technology that involves capturing CO_2 but instead of a point source, carbon dioxide is captured directly from the atmosphere and stored underground (IRENA 2021b). CCS establishes physical as well as market infrastructure for CDRs since scientific principles and fundamental engineering remain the same (IEA 2020; IRENA 2021b). The first research question of the thesis: 'What are the infrastructure requirements for CCS'? is partially answered in this section, particularly the technical part (Transportation Infrastructure: Pipelines is discussed in section 4.2).

Figure 4 shows the supply chain of CO_2, each part discussed in detail in sections 2.4.1. till 2.4.3.

[8] NET: Negative Emissions Technology

Figure 4: CCS Supply Chain



Source: (IEA 2023)

Whilst studies from (Olajire 2010; Leung, Caramanna, and Maroto-Valer 2014) explain various capture, transport, and storage process, the gap in terms of quantitative requirements of infrastructure falls outside their scope. For starters, capturing CO_2 from point sources requires, Air separation unit (ASU) or Gasification block (see Figure 5) depending on the process that is used (Knoope, Ramírez, and Faaij 2015). CO_2 is either compressed in supercritical fluid (for pipelines) or liquefied (for shipping) depending on the mode of transportation (IEA 2023). For the storage of CO_2, injection wells are important. Along with major components, various auxiliary devices are used throughout the CCS supply chain like external valves in pipelines, monitoring systems like Supervisory Control and Data Acquisition (SCADA) for leak detection, etc. Table 2 summarizes the infrastructure required for CCS, along with a list of potential raw materials that are required.

Table 2: Summary of Infrastructure Required by CCS

Infrastructure	Components	Materials
CCS Technology	Capture, Storage, Utilisation, Transportation, Maintenance	
Capture	Air Separation units, Gasifiers, MEA, Water Shift Gas Reactors, Compressors	Oxygen, Amines, Fuel, Physical Solvents
Purification/Separation	Membranes, Scrubbers, Amino Acids	Ammonia, Bulk chemicals, Chemical Solvents
Storage/Utilisation	Injection wells, Monitoring wells	Cement
Transportation	Pipelines, Ships, Valves	Steel
Maintenance/Monitoring	SCADA, External Valves, Fracture Arrestors	Electronic Devices

Source: Reproduced from (IEA 2023; DOE 2022; Leung, Caramanna, and Maroto-Valer 2014)
Note: MEA: Mono ethanolamine, SCADA: Supervisory Control and Data Acquisition

2.4.1 Capture Infrastructure

CO_2 is released during the combustion of fossil fuels in the power sector like in thermal power plants through the combustion of coal and natural gas, in industrial processes, etc (IEA 2020). This CO_2 can be captured in three different ways: Pre Combustion, Post Combustion, and Oxyfuel combustion (Knoope, Ramírez, and Faaij 2015). The method to capture CCS depends on the type of fuel (coal, gas, etc), application area (power plants, industrial processes), the concentration of CO_2 (high, low), etc as broadly described by (Olajire 2010; Leeson et al. 2017). Pre-combustion is where fuel is treated before combustion and is governed by two chemical reactions:

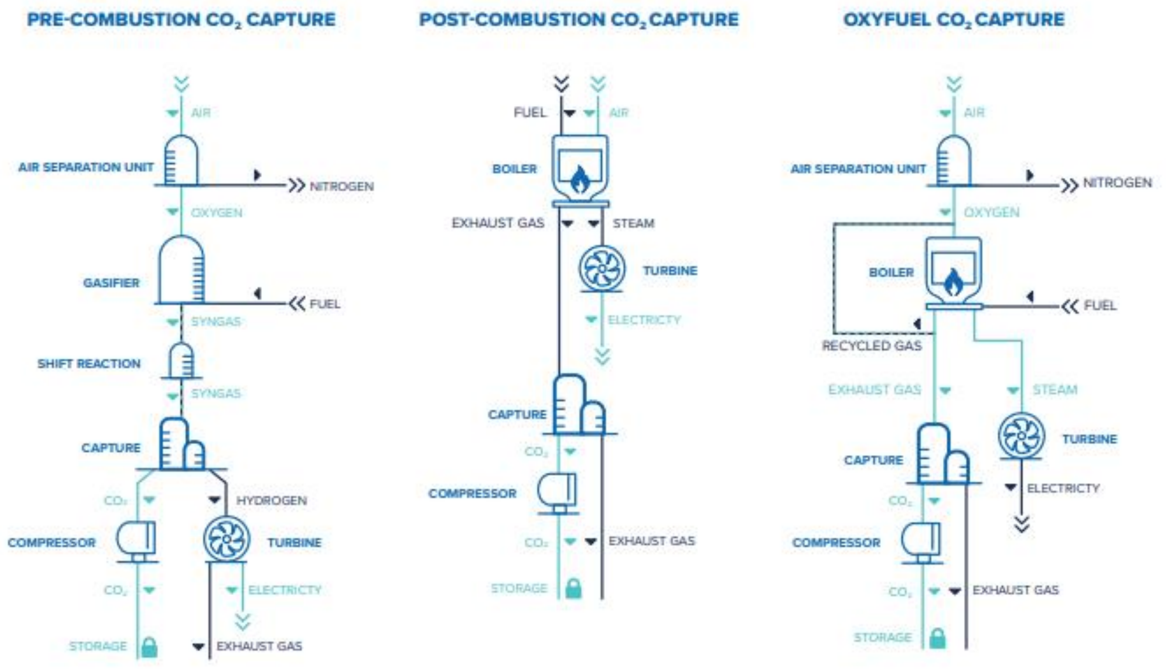
Coal (gasification) $\longrightarrow$ $CO + H_2$

here, as seen in Figure 5, coal is involved in the gasification process which produces syngas (also called synthetic gas) consisting of CO and H_2. This CO and H_2 undergo a water gas shift reaction in a gasifier which produces H_2 and CO_2 as the following reaction:

$CO+H_2O$ (water gas shift) $\longrightarrow H_2+CO_2$

This H_2 can be used for driving turbines, or for hydrogen production (Leung, Caramanna, and Maroto-Valer 2014). Precombustion is usually used in coal gasification plants, as of 2016 around 117 coal gasification plants exist in the world DOE (2016). Biomass and Natural Gas can also use Pre combustion, however, the gasification process is different (Olajire 2010).

Figure 5: CCS Capture Processes



Source: (Global CCS Institute 2021c)

CO_2 can be captured via <u>Post Combustion</u> process where steam drives the turbine and CO_2 has to be captured from exhaust gases (IEA 2023). CO_2 pipelines are sensitive to water, and impurities, hence the CO_2 captured should meet the pipeline standard to avoid leakage and corrosion (IEAGHG 2013). Impurities like SO_2 and NO_2 in the flue gas degrade the effectiveness of capture processes, moreover, the concentration of CO_2 is low (13-15 volume % for Coal, 3-4% for natural gas), in short, the post-combustion process is energy intensive (NETL 2020; Wetenhall, Race, and Downie 2014). Oxycombustion capture is derivative of post-combustion capture, except that fuel is burnt in pure oxygen (Global CCS Institute 2021c). The by-products consist of CO_2 and H_2O, and CO_2 can be captured with the condensation of water. (Kanniche et al. 2010). One major advantage of oxyfuel combustion is a significant reduction of NOx emissions and high concentration of CO_2, moreover, oxyfuel combustion can be retrofitted as well as greenfit to existing and new power plants (IEAGHG 2013; IEA 2023; Leung, Caramanna, and Maroto-Valer 2014; NETL 2020).

Table 3*:* CCS Capture Summary

Capture Methods	Pros	Cons	Infrastructure Used
Pre Combustion	Moderate CO_2 Concentration, Lower energy penalty	Applicable to gasification plants	Air Separation Unit, Gasification block, Compressor, water gas shift reactor, physical solvent
Post Combustion	Applicable to a majority of existing coal-fired plants	Low CO_2 Pressure, Low Concentration of CO_2, Energy intensive	Bulk compressor, Chemical solvents, Flue gas desulfurization
Oxyfuel Combustion	High CO_2 concentration, can be retrofitted or greenfit	Pure Oxygen is needed, and additional equipment required	Air Separation Unit, Flue gas desulfurization system, and recycle system

Source: Reproduced from (NETL 2020; Olajire 2010; IEAGHG 2013; IEA 2023)

Table 3 summarizes the infrastructure used for different capture methods. Two key points are important for further research and assessment:

- CO_2 concentration and pressure are less in post-combustion, hence bulky compressors and other components are required to process the bulk of the flue gas. Thus, more raw materials could be required as the CO_2 capture capacity changes from Mtpa to Gtpa. In short, the CO_2 capture process dictates the infrastructure required for capturing CO_2.
- Energy penalty is the additional charges that power plants have to incorporate due to energy-intensive capture processes and reduced overall efficiency of the plant (Kanniche et al. 2010), this factor supplements the economic concerns shared by (Akerboom et al. 2021; Hu and Wu 2023; Kanniche et al. 2010). In short, this might make CCS an undesirable option for stakeholders, and CCS can face barriers to future expansion.

The captured CO_2 is purified for safe and efficient transport (IEAGHG 2013). This is achieved via a range of methods like Absorption, Adsorption, Membrane separation, Cryogenic distillation, Hydrate formation, etc (Kanniche et al. 2010; Olajire 2010). It is challenging to assess the feasibility of all these separation techniques given their TRL levels are low as shown in Figure 3. In the context of the US, DOE (2022) examines the requirement of MEA (used in CO_2 purification) and TEG (used in the pre-transportation treatment of CO_2)[9]. DOE (2022) concludes that in 2050, more than 800Kt of MEA and 40Kt of TEG would be required, currently, MEA production as of 2020 was 1.2Mt (EMR 2022).

2.4.2 Transport Infrastructure

Transport infrastructure, particularly pipelines is central to the findings of this thesis. Considering economic viability, and technical specification, various literature (Knoope, Ramírez, and Faaij 2015; Global CCS Institute 2021a; Rogelj, Joeri 2022; Wei et al. 2021; DOE 2022; IPCC 2005) expect most of the transportation to come from pipelines. Onshore

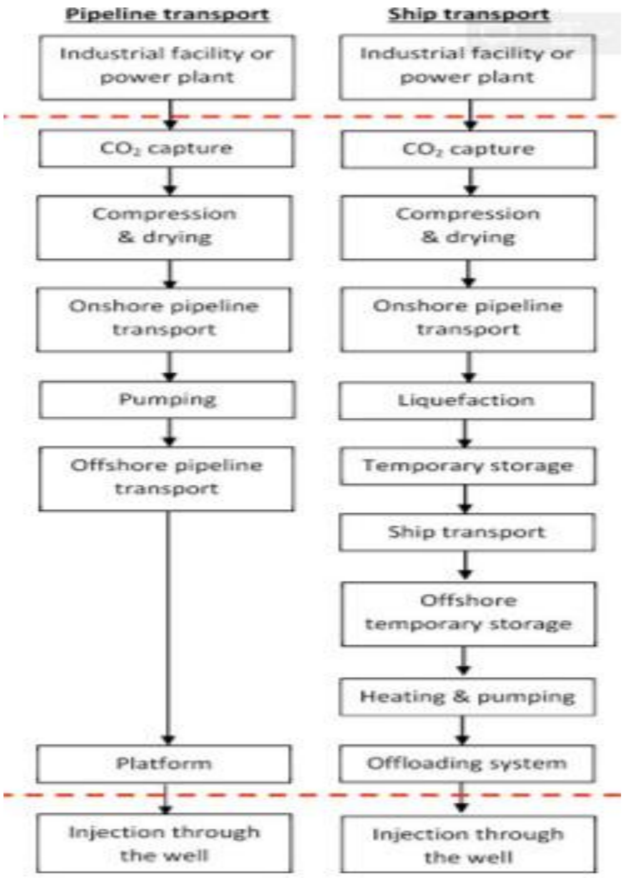
[9] MEA stands for Monoethanolamine, and TEG stands for Triethylene glycol. Both are used in CO_2 purification.

transportation is mostly from pipelines with minimum to no literature focused on railways and trucks. For offshore, the choice of transportation depends on distance, economics, and the phase of CO_2 (Leeson et al. 2017; IEAGHG 2013; Knoope, Ramírez, and Faaij 2015). Liquefied CO_2 over a distance of more than 500 km is economically viable through shipping whereas, for smaller distances, pipelines are preferred (Knoope, Ramírez, and Faaij 2015).

Shipping Infrastructure:

After the separation and purification of CO_2, depending on the distance of the storage site from the source, CO_2 can be transported via pipeline or via ships as shown in Figure 6. The thermodynamic properties of liquified CO_2 are different from the supercritical phase of CO_2 as seen in Figure 7, thus the infrastructural requirements are different as well and some additional components are required for shipping infrastructure (Knoope, Ramírez, and Faaij 2015).

Figure 6: CCS Transportation Infrastructure



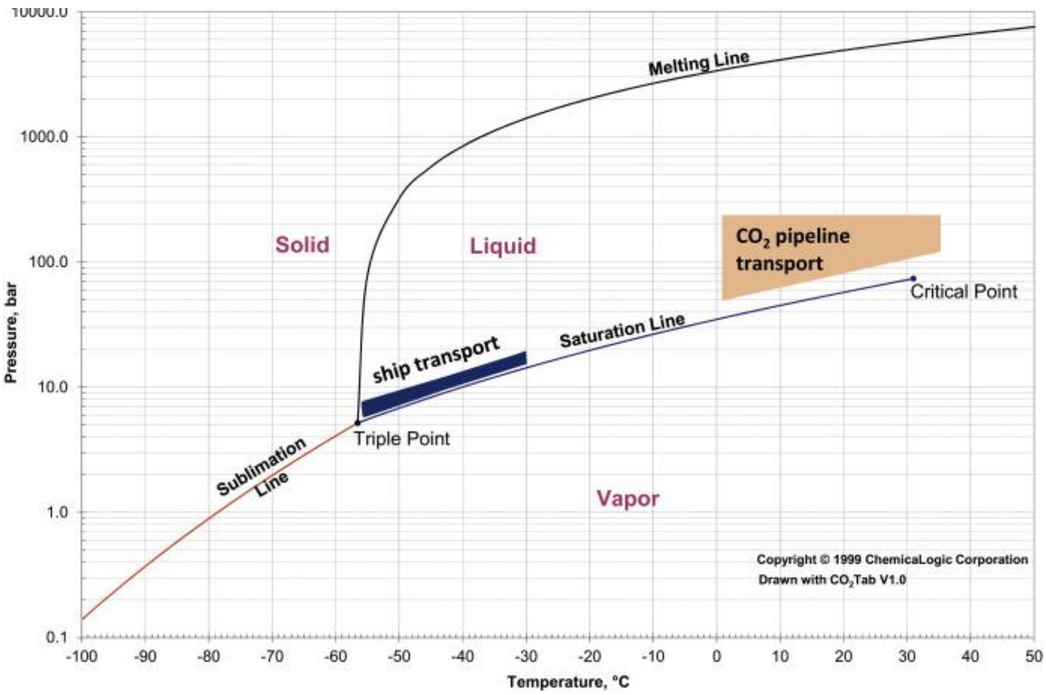
Source: (Knoope, Ramírez, and Faaij 2015)

As liquefication is crucial for CO_2 transport through shipping, the convenient way is to establish a liquefication station close to the shore (Knoope, Ramírez, and Faaij 2015; Pihkola et al. 2017). Hence, first, compressed and dried CO_2 is transferred through pipelines to the liquefaction station, and then liquefied, and stored in temporary onshore storage sites (IEA 2023; Pihkola et al. 2017). Later, ships are loaded with this liquified CO_2 and shipped to the geological storage sites, where the CO_2 is stored again temporarily. Since CO_2 must have specific pressure and should be injected in a specific manner, heating and pumping equipment is used to compress the CO_2 with specific pressure and then pumped into the reservoir (Knoope, Ramírez, and Faaij 2015). One of Finland's project demonstrations finds that the CO_2 storage site would be 1000 km from the CO_2 source and a one-way ship might be the easier way for transporting the captured CO_2 for Finland's project (Pihkola et al. 2017).

Pipeline Infrastructure

As stated earlier, virtually all the transportation of CO_2 is expected from Pipelines. Pipelines have been in existence for various decades and were central to the golden era of Oil and Natural Gas as stated by (IEA 2022d; 2023). For CO_2 pipeline transportation, an important conversion is a phase of CO_2. For CO_2 to flow through the pipeline it has to be in a supercritical fluid phase where CO_2 is compressed at high pressure as seen in Figure 7 (ICF International 2009; Knoope, Ramírez, and Faaij 2013). This conversion takes place at the interface of CO_2 capture and the CO_2 transportation process with the help of compressors (Figure 4) (IEA 2023). Similar to natural gas pipelines, there is a growing body of evidence from (Wei et al. 2021; Knoope, Ramírez, and Faaij 2013; DOE 2022) that CO_2 transportation will consist of shared infrastructure in the form of hubs and clusters, i.e. CO_2 from various sources will be collected at a 'Collecting Station', and *transported* to the 'Storage Sites'. Impurities are a major concern for CO_2 transportation through pipelines as they can change the thermophysical and phase equilibria of the CO_2 (for example water, and non-condensable gases like N_2, O_2, and Ar) (IPCC 2005; Knoope, Ramírez, and Faaij 2015). The concentration of these impurities is dependent on the method of capture and purification, hence, shared infrastructure has certain standards that further link with the standards of material to be used for pipelines (ICF International 2009). For example, Knoope, Ramírez, and Faaij (2013) present two steel grades X80 and X65 for efficient transportation of CO_2 through pipelines. The design requirement of the pipeline is the function of flowrates and hydrodynamic properties of CO_2 (like density, compressibility, and viscosity) (Knoope, Ramírez, and Faaij 2015). CO_2 flows from high pressure to low pressure, to maintain the flow 'heat pumps or centrifugal pumps' are required in the CO_2 pipeline transportation system (DOE 2022). From an infrastructural point of view, CO_2 pipelines do not require additional components like temporary storage and offloading system for offshore CO_2 transport as seen in Figure 6.

Figure 7: Carbon Dioxide: Temperature and Pressure Diagram



Source: (Knoope, Ramírez, and Faaij 2013)

Table 4 summarizes the components required for the CO_2 transport infrastructure. External valves are installed in the CO_2 pipeline to isolate functional and faulty parts of the pipelines during leaks (ICF International 2009). The pressure of the supercritical phase of CO_2 is higher than the pressure at which natural gas flows, hence thicker steel pipelines are fundamental for CO_2 transportation (ICF International 2009). To avoid fractures in the pipelines, CO_2-resistant elastomers are installed every 1000 feet (ICF International 2009). Hence, the longer the pipeline, the more valves, and elastomers are required. And the thicker the pipeline (larger diameter), the more steel is required.

Table 4: Summary of Infrastructure and Materials Required for CO_2 Transportation

Transportation	Infrastructure Used	Materials
Shipping	Onshore Pipelines, Liquefication Station, Storage: Onshore and Offshore. Ships, Heat Pumps, Offloading/Unloading Stand	Steel, Iron casings, Power Electronic Devices
Pipeline	Heat Pumps, Monitoring systems like SCADA, Maintenance pieces of equipment like CO_2-resistant elastomers, etc	Steel, Power Electronic Devices

Source: Reproduced from (DOE 2022; ICF International 2009; Knoope, Ramírez, and Faaij 2015)

From the list of components, Steel (for the pipeline) and Cast Iron (for heat pumps) can be compared by looking at the current production of Steel and Iron (see Table 5). (DOE 2022) estimates that for capturing 2Gtpa in the US, 30Mt steel, and 225.1Kt Iron would be required in 2050 as seen in Table 5. These calculations can be extrapolated to global needs and can be used as a benchmark.

Table 5: Comparison of 2022 and 2050 (required) Production of Steel, Iron, and Cement

Material	**2022**	**2050** (for 2Gtpa)
Steel	1878.5Mt	22.73-30.16Mt
Iron	1.6Bt	225.1Kt
Cement	4.1Bt	25.84Mt

Source: Reproduced from (DOE 2022; World Steel Association 2023; Statista 2023c; 2023a)

Note: 2050 (for 2Gtpa) indicates: the amount of materials required for capturing 2Gtpa of CO_2 by 2050 in the US. Bt: Billion tonnes, Mt: Million tonnes, Kt: Kilo tonnes

2.4.3 Storage Infrastructure

The final part of CCS infrastructure is the 'storage' where the transported CO_2 is injected into the ground and trapped for a longer period. There are numerous trapping mechanisms and various storage types, however, various studies (DOE 2022; Leung, Caramanna, and Maroto-Valer 2014; Leeson et al. 2017; Bachu et al. 2007) imply that geological storage would be the best-suited for trapping CO_2. There are three types of storage: Geological, Ocean Storage, and Mineral Carbonation (Tomić et al. 2018). Bui et al. (2018) claim that Ocean storage and mineral storage are still in an early development phase, whereas geological storage is commercially available (see Figure 3). Moreover, the cumulative storage capacity required for climate targets can be met with geological storage alone, hence this thesis will consider geological storage for CCS hereon (Koelbl et al. 2014; Bui et al. 2018). Table 6 shows the geological storage types and storage capacity estimated.

Table 6: Geological Storage Capacity

Storage type	Storage Capacity ($Gt\ CO_2$)
Depleted Oil and Gas Reservoir	675-900
Unmined Coal seams	3-200
Saline aquifers	1000-10000
EOR	370

Source: Reproduced from (Tomić et al. 2018)

Note: EOR- Enhanced Oil Recovery, Gt: Giga tonnes

For geological storage two main infrastructural components are essential: Injection wells[10] and Monitoring wells (DOE 2022). Depending on the type of transportation additional components can be required as well. For example, if the transportation is through ships, then additional pumps and storage are required at the storage sites to match the pressure and temperature of the CO_2 flow rates (Knoope, Ramírez, and Faaij 2013). A typical injection well consists of three iron casings: surface casing, intermediate casing, and long string casing and tubing (DOE 2022; Bachu et al. 2007).

For, injection and monitoring wells three materials are pivotal: Steel, Cement, and Iron (DOE 2022). It is important to note that steel and cement production in itself is a hard-to-abate sector, which makes CCS deployment essential for them.

[10] As per Underground Injection Control, Class VI wells are used in US

2.5 Reference cases for CCS Infrastructure

This section aims to answer RQ2: What are the reference cases for CCS?

2.5.1 Feasibility through Reference Cases

As discussed in sections 2.1 and 2.2, IPCC scenarios should not be interpreted as definitive forecasts, but rather as a starting point for further assessment of the feasibility, reliability, and probability of the ‘climate solutions’ (Jewell and Cherp 2023; Rogelj, Joeri 2022). For example, IAMs present a combination of technology to be used for achieving climate targets, however, these combinations originate from assumptions and parameters set within the model (Rogelj, Joeri 2022). They do not necessarily reflect the behavior of these solutions in the real world. This gap can be closed by investigating the feasibility of ‘climate solutions’ in the *real world* (Jewell and Cherp 2020). One of the ways to assess the feasibility of IAM scenarios in the real world is to find a comparable reference case from the past (Jewell and Cherp 2023). This thesis uses IPCC AR6 scenarios and assesses the feasibility of CO_2 infrastructure through reference cases (or historical analogies). Feasibility has various definitions, for example, (Storrs, Lyhne, and Drustrup 2023) define feasibility as ‘how well something performs within the set of relevant constraints’, and IPCC (from (Jewell and Cherp 2023)) defines feasibility as the ‘potential’ of mitigation or adaptation option to be implemented. The definition used here is from (Jewell and Cherp 2023): Probabilistic under the realistic assumption (further discussed in section 3.1.1)

In contrast with ‘What are the requirements to meet a particular target’, assessing feasibility provides a non-binary probabilistic semi-quantitative /qualitative measure of “how realistic are the requirements to be met?” (Kotagodahetti et al. 2022; Guo and Huang 2020). Especially it is important for large-scale requirements of infrastructure such as CCS. There are various ways in which feasibility can be assessed, certain studies incorporate qualitative data alone (Jenkins 2014), whilst certain studies incorporate quantitative data (Hu and Wu 2023; Bauer, Hansen, and Nilsson 2022). The majority of the literature associated with the feasibility of CCS adopts the PESTLE or TEA model. PESTLE stands for Political, Economic, Social, Technological, Legal, and Environmental assessment. Pihkola et al. (2017) used this model to identify non-technical barriers and drivers for CCS in Finland, Interestingly in that finding, CO_2 price acted as both a 'barrier' and 'driver' for CCS, however, each factor had the potential to affect another, in other words: Causal relationship could be seen, and causal reasoning is important for feasibility assessment through reference cases (Jewell and Cherp 2023).

Certain studies like Kotagodahetti et al. (2022) incorporate the Technical and Economic Analysis (TEA) Model. Parameters used by Kotagodahetti et al. (2022) for a feasibility study in 'community energy systems' are summarised in Table 7: Summary of TEA Model Parameters Table 7. The three parameters in Table 7 include, 'carbon capture rate' which is a rate that defines the amount of carbon captured using that solvent. 'Technological readiness' is a key indicator of technological maturity. As for economic performance, CCS includes Operational and Maintenance costs. Using these parameters, studies like (Knoope, Ramírez, and Faaij 2013; Leung, Caramanna, and Maroto-Valer 2014; Hu and Wu 2023; Pihkola et al. 2017) optimize the models to make CCS techno-economically feasible.

Table 7: Summary of TEA Model Parameters

Category	Sub parameter
Technical Performance	Carbon Capture Rate, Technological Readiness Level
Economic Performance	Investment Capital

Source: (Kotagodahetti et al. 2022)

And certain studies incorporate IPCC's (IPCC 2018) multidimensional framework, (Brutschin et al. 2021) evaluated IPCC's framework, and (Storrs, Lyhne, and Drustrup 2023) designed a comprehensive framework with six categories for CCUS: Economic, Social, Technological, Environmental, Institutional, and Organization. There's another way to assess feasibility which is through the 'Outside View', where historical analogies through reference cases are compared with the feasibility case i.e. case for which feasibility is to be assessed, here called a 'target case' (Jewell and Cherp 2023). Based on the comparisons, results are interpreted. Various studies (Van Ewijk and McDowall 2020; Loftus et al. 2015; Cherp et al. 2021; Semieniuk et al. 2021) used a similar approach where, the historical analogies included Flue gas desulphurization, power technologies, wind and solar power growth nationally, and energy demand respectively. Whilst comparing past analogies with future predictions is not necessarily an entire representation of the case, it is comparable enough to look at the trends, and with the relevant reference cases, the comparison could provide real-world insights. Whilst this is true, it is also important to note that in the context of energy transitions, transitions in the past were 'emergent' as opposed to the anticipated transitions of the future which are 'governed' through the Paris Agreement, Nationally Determined Contributions, etc (Kern and Rogge 2016).

2.5.2 List of Reference Cases

The reference case as mentioned by Jewell and Cherp (2023) should be able to represent causal relationships, this relationship can be enabling or blocking mechanisms which can be looked at from the enablers and barriers lens. Furthermore, the reference case should be ‘relevant to the target case in certain aspects’ (Jewell and Cherp 2023). For example, the relevance can be the ‘speed’ of transition or the ‘scale’ of transition. For identifying reference cases, this study uses ‘categories’ from the multidimensional feasibility framework from IPCC (2018), and lists all the possible reference cases for each category. Subsequently settles on ‘natural gas and oil pipelines’ as reference cases for assessing the feasibility of CO_2 pipelines. All the possible reference cases are mentioned in Table 8 below. This table is produced from a critical evaluation of various literature.

In the economic category, the *low cost* of Solar PV was one of the enabling mechanisms for its deployment between 2011-2022 (Candelise, Winskel, and Gross 2013; IRENA 2022a). CCS for EOR shares similar characteristics, as CCS has been used for decades for EOR. However CO_2 price is repeatedly highlighted by (Akerboom et al. 2021; Hu and Wu 2023; Pihkola et al. 2017) acts as both enabling mechanism (if the CO_2 price is higher than the Cost to capture carbon), and blocking mechanism (if the CO_2 price is lower than the cost to capture carbon), higher CO_2 price makes CCS profitable. Solar PV share institutional support in terms of policy, and political support that acts as enabling mechanisms for them IRENA (2020). For CCS, EU Directive (2009/31), and US 45Q Act can act as enabling mechanisms. Moreover, a growing body of evidence Sütterlin and Siegrist (2017) shows public acceptance of Solar PV and other renewables is high given the climate mitigation priority. In those aspects, Solar PV can be a reference case, however, the technical characteristics of Solar PV are different than that of CO_2 pipelines. A more efficient comparison would be to assess the electrical transmission network of Solar PV in terms of transmission lines (in km) to CO_2 pipelines (in km), however, the lack of availability of publicly available data for transmission lines, along with substantial technical differences between ‘electrical transmission lines’ and ‘pipelines’ discards Solar PV as a reference case for this thesis.

Table 8: List of Reference Cases

Category	Feasibility challenge	Reference Cases	Similarity to CCS	CCS Characteristics
Economic	Cost	Transmission lines for Solar PV (E), Natural gas, and Oil Pipelines (E)	Financial support/ Market drivers.	EOR (E), CO_2 price (E/B)
Social	Public acceptance	Transmission lines for Nuclear Energy (B). NG, and Oil Pipelines (E/B)	"Not in my backyard" sentiment for Nuclear waste storage as well as CO_2 storage.	Not in my backyard mindset (B)
Technological	Performance issues.	NA	Performance issues of CCS	Capture rate (B), energy penalty (B)
Environmental	Environmental Impacts: leakage	Oil and Natural Gas leakage	CO_2 leakages during operation.	CO_2 leaks (B)
Institutional	Policy, Legislation, Political Support	Solar PV, Wind Energy	NA	EU Directive (E)
Organisation	NA	Natural Gas and Oil pipelines, and electrical transmission lines	Hubs and Clusters	Shared Network Infrastructure (E)

Source: Reproduced from the own evaluation of the literature used in this thesis

Note: VRE: Variable Renewable Energy (Solar PV, Wind), EU European Union Directive, E: Enabling Mechanism, B: Blocking Mechanism, NA: Conclusion not available from the literature assessed.

Another technology that shares few similarities to CCS is Nuclear Energy. Nuclear energy has been in operation for decades, and public acceptance started to act as a blocking mechanism but recently the perception seems to be changing (Kim, Kim, and Kim 2014). This trajectory is similar to the (Akerboom et al. 2021; Anderson and Peters 2016; Fuss et al. 2014) conclusions, where CCS has been facing criticism from the public today but might change in the future due to climate mitigation. However similar to Solar PV, the difference in technical characteristics of ‘electrical transmission lines’ and ‘pipelines’, regard nuclear energy as out of scope for this thesis[11].

Natural gas and Oil Pipelines, on the contrary, make an ideal case for CCS in this thesis. Natural gas pipelines share similar characteristics to CO_2 pipelines except for a few technical differences (compared to natural gas, CO_2 pipelines require higher pressure of CO_2, more steel, and additional auxiliary components) (IEAGHG 2013; Hopkins 2007). While Natural gas and Oil flow from production to consumers, CO_2 flows from sources to sinks[12]. Natural gas and Oil Pipelines need pumps to maintain the pressure difference for flow, and CO_2 pipelines need heat pumps (or centrifugal pumps) to maintain the pressure difference (IEA 2023; DOE 2022). Moreover, Natural gas has been in operation for decades and scaled due to demand rise, profitability, and environmentally friendlier than alternative technology (coal) (IEA 2022d). While CCS has not been scaled but is anticipated to be scaled for similar mechanisms. A rise in CO_2 price makes CCS profitable, and assistance of CCS climate mitigation potentially might increase the need for CCS. As for Oil, it is transported through pipelines but also through trucks, railways, etc. Moreover, Oil is associated with another hard-to-abate sector ‘Transportation’. Thus, owing to relevant causal mechanisms, long operational history, technical similarities, resembling shared infrastructure, Natural Gas and Oil pipelines make an ideal reference case to assess the feasibility of CO_2 pipelines.

[11] In a centralised electrical grid, electricity produced from any energy source can flow, which makes it challenging to assess electrical transmission network specifically for Solar PV or Nuclear Energy.

[12] Source: Sources of CO_2 (like Fossil fuel plants, Atmosphere, etc), Sinks: Geological Storage of CO_2

3 Methodology

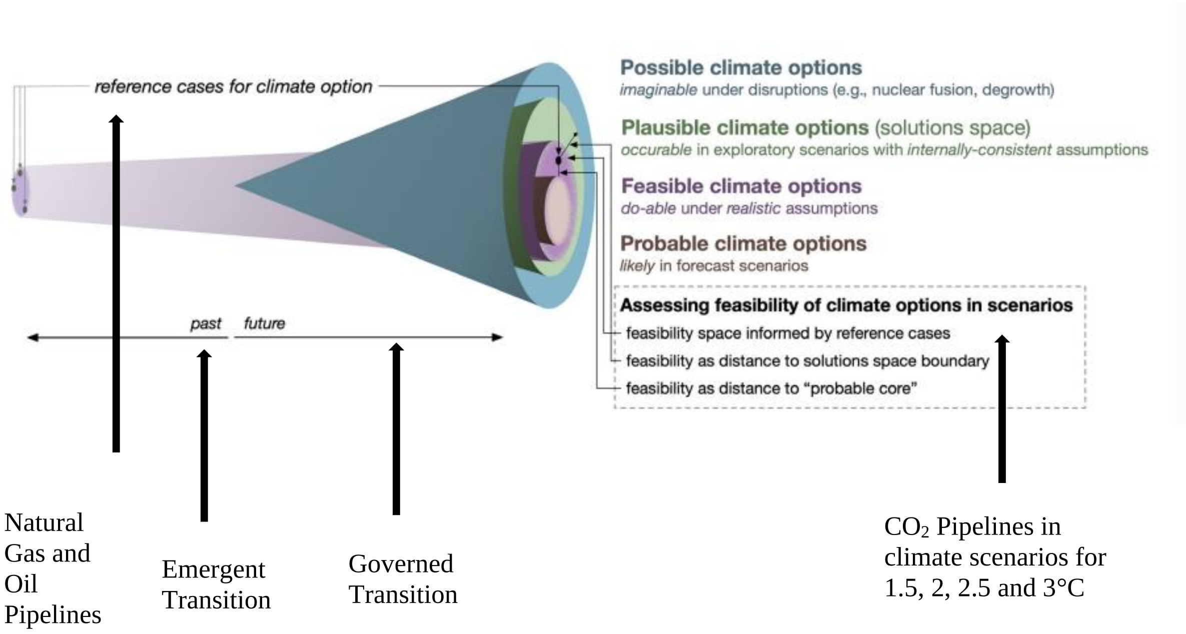
This chapter presents the methodology for assessing the feasibility of CO_2 pipelines for a median value of Volume of CO_2 captured across IPCC scenarios compatible with temperature levels: 1.5°C, 2°C, 2.5°C, and 3°C. The theoretical framework is derived from (Jewell and Cherp 2023) 'Inside and Outside Views' on feasibility coined by Khaneman. For Calculations of CO_2 pipelines for different scenarios, US DOE's NETL_NZA (DOE 2022) model along with Wei et al. (2021)'s Global Layout is used. Within this model, two assessments are carried out: Net Zero Assessment (NZ) and sensitivity analysis of Net Zero Assessment, (NZs). This study uses the historical analogy of Natural Gas and Oil pipelines (reference cases) for assessing the feasibility of CO_2 pipelines (target case). Section 3.1 'Theoretical framework' discusses the 'Inside Outside View' and 'NETL_NZA Model' used in the thesis. Section 3.2 'Data Sources' presents the data collection, data analysis, and data processing methods along with a discussion on the validity of the data. Section 3.3 Calculations and Analysis articulates the calculations employed in the thesis with a step-by-step discussion of the formulas. Section 3.4 discusses the limitations and recommendations of this methodology.

3.1 Theoretical Framework

Feasibility, as defined by Jewell and Cherp (2023), is 'possible under realistic assumptions'. In other words, it's a 'what-if' logic where the assumptions for 'if' are realistic. In the context of this thesis, 'what' refers to the total length of the CO_2 pipeline required for capturing CO_2 envisioned in IPCC scenarios, and 'if' refers to how realistic is it to build those CO_2 pipelines. The 'what' is assessed through NETL_NZA Model and the 'if' is investigated through the historical deployment of natural gas and oil pipelines. Whilst there has been criticism over the interchangeable wording of feasibility, plausibility, and probability, this definition as seen from

Figure 8 reduces the uncertainty, ambiguity, and vagueness to an extent that fits within the scope of this thesis.

Figure 8: Feasibility Definition



Source: (Jewell and Cherp 2023)

Note: From Kern and Rogge (2016) emergent transition refers to transition due to better energy services, or economic benefits whereas governed transition refers to transition with climate mitigation as a priority.

Causal Reasoning is central to scientific discussions of feasibility (Jewell and Cherp 2020; 2023). IPCC scenarios are delivered through IAMs, which incorporate certain Causal reasoning (Jewell and Cherp 2023). This causal reasoning is obtained by varying assumptions and parameters within the models used by IPCC. For the scope of this thesis, the causal reasoning of the future envisioned 'Volume of CO_2 capture', thereby 'projected length CO_2 pipelines' is met through the IPCC scenarios. For meaningful feasibility assessment, CCS Pipelines should be comparable in different contexts. The outside view (discussed in 3.1.1) employed in this thesis, bridges the gap by using the reference case of Natural gas and Oil pipelines. Natural gas pipelines have been around for decades, and have been scaled up significantly, unlike CCS pipelines which have not been scaled up but are expected to meet climate targets. Thus to make these cases more comparable, a normalization parameter of GDP (PPP[13] US Trillion $) is used in this thesis.

Considering these above principles and IPCC's multidimensional feasibility table (see section 2.5.1), Table 9 is produced. As seen from the table except for Ecological dimensions, indicators for the rest of the dimensions are available in this study and discussed in Chapters 2, 3, and 5. Thus, the inclusion of all the indicators, and their discussion in various chapters of this thesis, makes this thesis a comprehensive study of CCS infrastructure.

[13] GDP PPP stands for Gross Domestic Product, Power Purchase Parity. GDP PPP adjusts the exchange rates between the countries thus provides more meaningful comparison of Global GDP

Table 9: Dimensions and Parameters associated with CCS Feasibility discussed in this Thesis

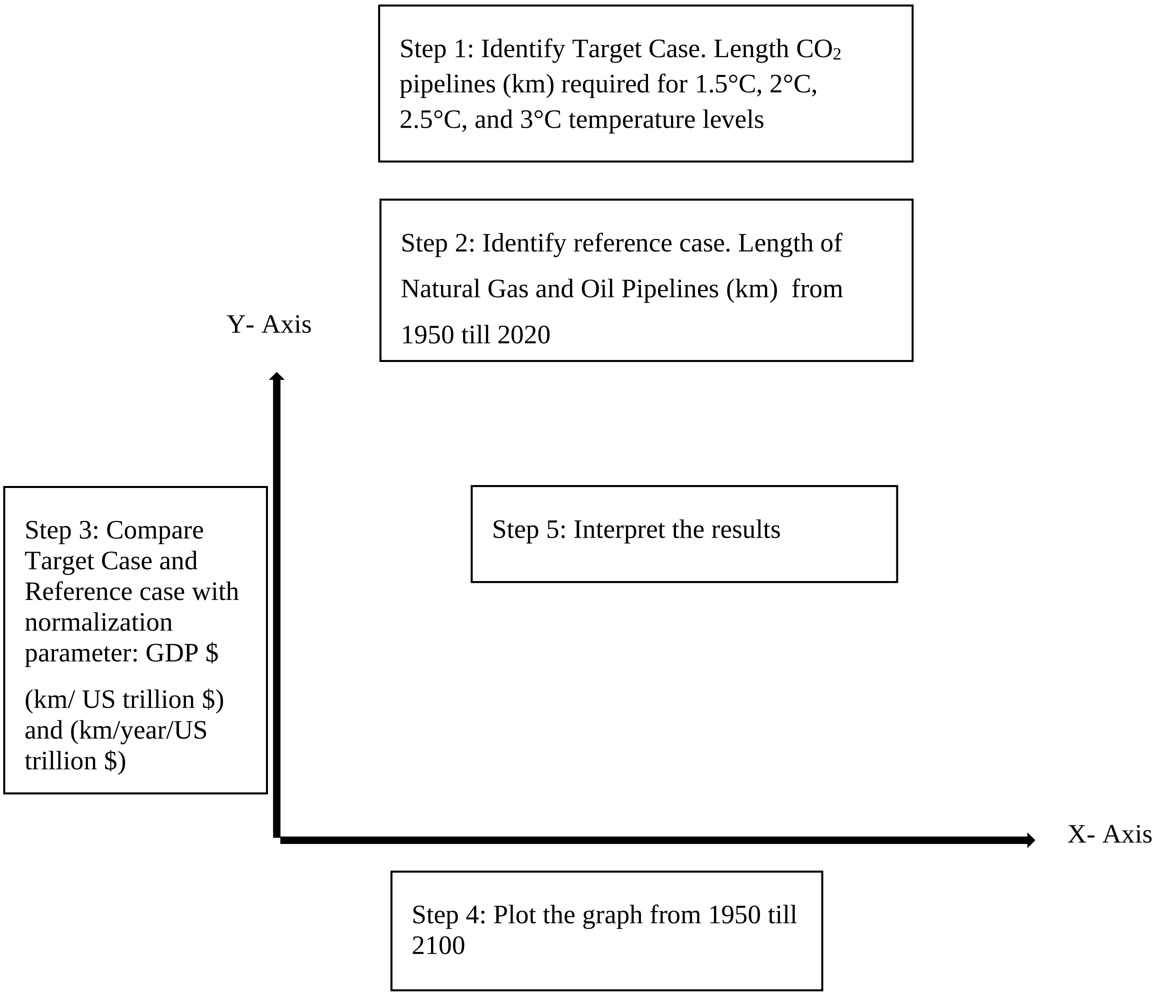
Dimensions	**Parameters**	**Explanation**
Economic	GDP (in Trillion US $)	GDP is the normalization parameter to make CO_2 pipelines comparable to Natural Gas and Oil Pipelines
Technological	TRL (level 1-9), Captured CO_2 (Gt), CO_2 pipelines (km)	TRL indicates CO_2 pipelines are mature technology discussed in Chapter 2
Socio-cultural	Public Acceptance	CCS faces criticism from the Public discussed in Chapter 2
Institutional	EU Directives (2009/31), US Tax 45Q	Institutional capacities established in the EU and US.
Geophysical	Geological Storage, Material required (in Mt)	The material and components required for CCS infrastructure are discussed in section 2.4

Source: reproduced from literature discussed in this thesis

3.1.1 Inside and Outside Views on Feasibility

The Inside and Outside views originate from Kahneman and the authors (Jewell and Cherp 2023). In the context of climate change, the 'inside' view refers to overcoming challenges to the solution of climate change by political choice, or through commitments, and the 'outside' view refers to assessing the feasibility via investigating historical analogies for the climate solution (Jewell and Cherp 2023; Cherp et al. 2018). While IAM scenarios can assess the feasibility of the inside view through techno-economic analysis, an 'outside view' provides the feasibility of the solution in the real world by looking at reference cases from the past (Jewell and Cherp 2020). The gap between the inside and outside view is bridged with 'feasibility space'. Feasibility Space is a tool that is essentially a virtual multidimensional space, which assesses the feasibility of climate solutions by implementation levels, context, or characteristics (Jewell and Cherp 2023). Figure 9 shows the steps involved in constructing feasibility space. More regional and granular data is required for the construction of regional feasibility space. This thesis utilizes 'The Outside View' and lays the groundwork for future assessment through feasibility space.

Figure 9: Steps Involved in applying 'Outside View' Methodology for Feasibility Assessment



Source: Reproduced from (Jewell and Cherp 2023)

The target case here is the length of projected CO_2 Pipelines in IPCC Scenarios till 2100. IPCC has various scenarios of which in this study, 4 temperature levels are considered 1.5°C and 2°C, these are the Paris Agreement goals (or climate targets), and 2.5°C and 3°C. The calculations and analysis in this thesis are for the median value of CO_2 to be captured across scenarios compatible with 1.5°C, 2°C, 2.5°C, and 3°C. The CO_2 capture value in scenarios are from 2030 to 2100, thus the findings can be used and reused for the three major milestones: 2030: Sustainable Development Goals SDG 2030, 2050: Global CO_2 Net Zero Target, and 2100: Paris Agreement Timeline. Results from this study can be used as a benchmark for these milestones.

The reference case as pointed out by Jewell and Cherp (2023), should be similar to the target case in relevant aspects. As discussed in Literature Review, for this thesis the reference case used is Natural gas and Oil pipelines given the similarity in contexts of technical processes: Pipeline lengths, diameter, flow rates, etc. Along with technical similarities, some of the causal mechanisms can be attested as well, for example, Natural gas pipelines significantly increased after the 1950s in the US specifically after world war II due to '*demand*', and increased natural gas pipelines in the early 2000s yielding *profits* (Hopkins 2007). In the case of CCS pipelines, the *profit* lies with *EOR and CO_2 price*, and the 'demand' is in the context of the *urgency of climate mitigation*.

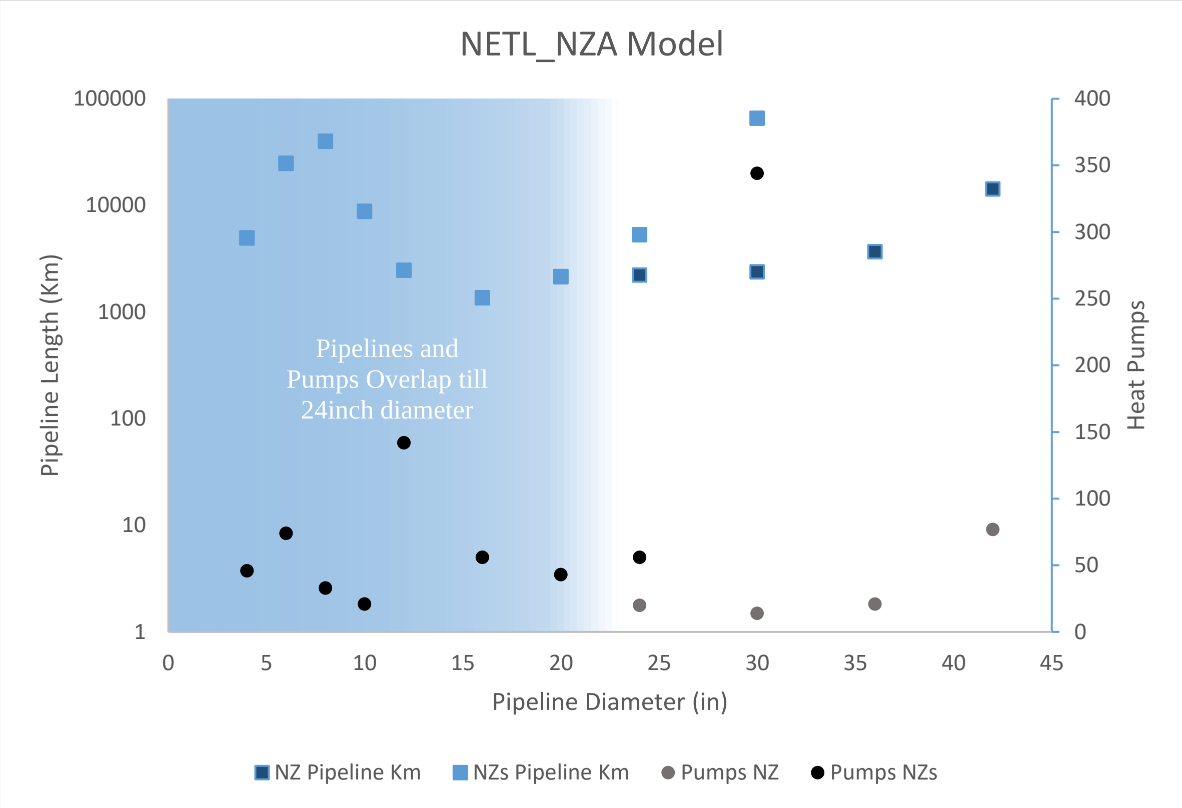
CCS projections are of the future (2030-2100), whereas Natural gas and Oil is a historical analogy (1950-2020), hence to make them more comparable, the normalization parameter used is GDP PPP (US Current International $) Thus the new metric becomes Km/$. The economy was smaller in the 1950s compared to 2020 and is expected to grow further in the future, thus the dynamics of changing economy can provide additional insights for the construction and operation of pipelines. GDP from 1950 to 2020 is used for Natural Gas, and GDP from 2030 to 2100 is taken from scenarios from IPCC AR6.

3.1.2 NETL NZA Model

US Department of Energy released a report: a response 'to Executive Order 14017 in Feb 2022', this study is based on one of the models used in that report, National Energy Transition Laboratory_ NetZeroAmerica (NETL_NZA Model)[14]. This model calculates the sum of pipeline lengths of diameter (4 to 48 inches), the number of heat pumps (for the flow of CO_2), the average annual flow CO_2 mass flow rate, etc for capturing and transporting 2Gtpa of CO_2 in the US by 2050 in 5-year intervals. Figure 10 shows the NETL_NZA Model in Km used in this thesis. Of the various outputs that this model produces, Pipelines in Km are particularly of interest for this thesis. Two assessments presented for the calculation of CO_2 Pipelines are NZ: Net Zero and NZs: Net Zero Sensitivity. The distinction between these assessments can be seen in Figure 10, till 20-inch diameter (blue shaded region), the length of pipelines and amount of heat pumps remain the same (hence they overlap for both assessments). From 24 inches onwards, the total pipeline in Km changes. NZ assumes that 36, 42, and 48-inch pipelines will be built in the future, thus the higher mass flow rates will be accommodated in these trunks (see Figure 11). On the contrary, NZs assume that the maximum diameter of pipelines will be restricted to 30-inch pipelines like today, thus 30-inch pipelines will act as trunklines, which increases the length of pipelines as seen in Figure 10. Heat pumps are essential to maintain the pressure in the pipelines for the flow of CO_2. Significantly large amounts of heat pumps are required for NZs.

14 (This model is a scaled model for 1.6Gt of CO_2 by 2050 by Princeton University)

Figure 10: NETL_NZA Model estimating total length of CO_2 pipelines to capture 2Gtpa CO_2 in 2050 in Km



Source: Reproduced from (DOE 22)

Note: Pipeline Diameters inches: 4, 6, 8, 10, 12, 16, 20, 24, 30, 36, 42, 48. NZ: Net Zero, NZs: Net Zero Sensitivity

This thesis scales up this NETL_NZA Model to estimate CO_2 pipelines (in Km) required for different CO_2 capture capacity (in Gtpa) proportionally in 10-year intervals. The varying amount of CO_2 capture is taken from the median value of IPCC Scenarios compatible with 1.5°C, 2°C, 2.5°C, and 3°C. Figure 11 shows the pipeline distribution network assumed in the model and also in this study. The pipelines are classified as Sub-Spur, Spur, Trunk, Distribution, and Sub-distribution lines.

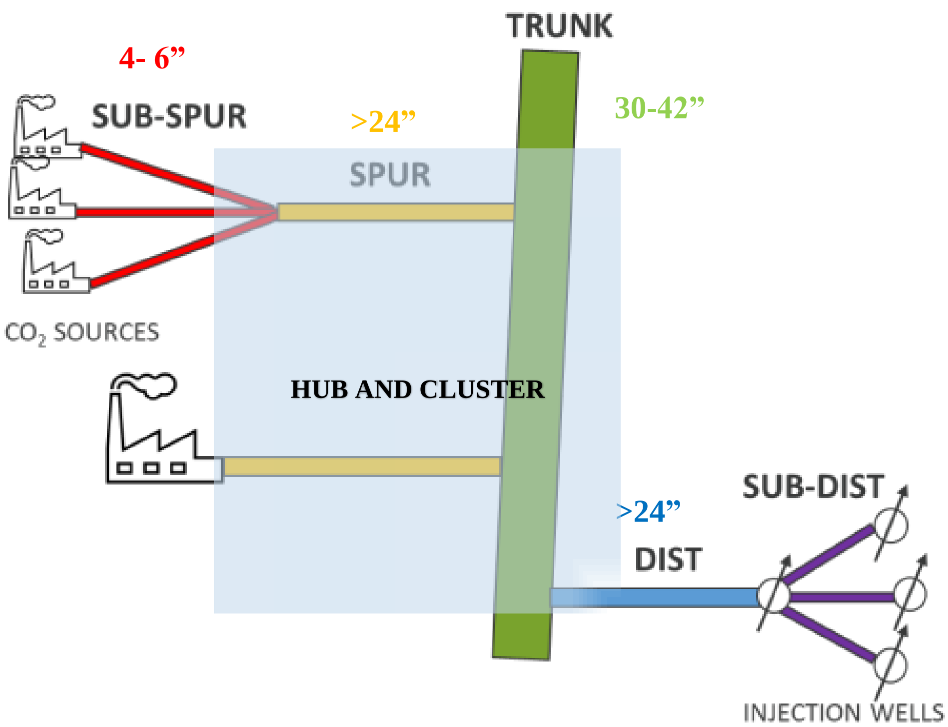
- Sub-Spur: lines range from 4 to 6 inches which connect individual CO_2 sources to usually small mass flow rates to central aggregation points. For optimum operation, usually, a network of pipelines is formed with various clusters with a central aggregation point.

- Spur Pipelines accommodate slightly higher mass flow rates and connect the clusters to the central aggregation point.

- Trunk: Trunk pipelines operate as a large highway for the CCS transportation system connecting CO_2 sources to sink. To date the biggest trunkline is a 30-inch diameter, however considering the future CO_2 flow rates, a 42-inch diameter trunkline might be required as well. Hence in this study, two assessments are carried out named NZ and NZs, NZ or Net Zero considers that a 42-inch diameter pipeline will be built in the future, and NZs or Net Zero Sensitivity considers that the 30-inch pipeline will be the highest diameter to accommodate the CO_2.

- Following trunk lines are the distribution and sub-distribution lines that transport the CO_2 from the trunk to the injection wells.

Figure 11: CO_2 Pipeline Distribution Network



Source: (DOE 2022)

Note: The shaded region indicates the shared infrastructure which can take the form of various hubs and clusters. “ indicates inches of diameter of pipelines. 4-6” diameter for Sub-Spur, more than 6” for Spur, and 30-42” for Trunks.

3.2 Data Sources

Four datasets are used in this study: Natural Gas and Oil Pipeline Dataset (reference case), CCS Dataset and IPCC Scenarios Database (Target Case), NETL_NZA Model dataset, and Normalization GDP Dataset. All the datasets were collected from various sources on the internet, a few through Ph.D. student Tsimafei Kazlou and some by asking permission from organizations (Global Energy Monitor). The datasets are acquired in CSV format, and analyzed in Excel. Graphs are created in Microsoft Excel.

The natural gas and oil dataset is collected from Global Energy Monitor after filling up the form and getting permission to use it with proper citation. This dataset contains 3000 rows and 15 columns, this dataset was cleansed and the required parameters for this thesis were used. For 'pipeline length' three measurements were available labeled as 'pipeline known', 'pipeline measured', and 'pipeline merged', of this *pipeline merge*d provides accurate insight into the length of pipelines, hence 'pipeline merged' is used in this study. 144,137 km of pipelines were missing the 'start year of the operation' in the dataset, these pipelines were adjusted to the decades between 1950-2020 through approximation based on the project description and ID provided. Data was cleansed and various analyses were performed using pivot table, mean, and correlation to understand and further explore the data.

CCS Dataset is acquired from IEA and Global CCS Institute which contains current and upcoming CCS projects. From IPCC Scenario's database (Byers, Edward et al. 2022), the median value of CO_2 capture is extracted for scenarios compatible with 1.5°C, 2°C, 2.5°C, and 3°C.

NETL_NZA Dataset is acquired from the Department of Energy US's website. It contains the model details which include diameters and sum of pipelines in km, estimated raw materials required or capturing 2Gtpa of CO_2 in 2050. Of all the details, important and relevant parameters included in this thesis are: the 'sum of pipelines in km' (calculated from miles) for diameters between (4-42 inches), and the two assessments: Net Zero Assessment (NZ) and Sensitivity Analysis of Net Zero Assessment (NZs).

Normalization Dataset contains historical GDP (1950-2020) collected from ("World Bank" 2022) and Penn World Table (Feenstra et al. 2022). Scenarios GDP (2030-2100) from IPCC AR6 is extracted from the IPCC Scenarios database (Byers, Edward et al. 2022).

3.3 Calculations and Analysis

At first, from the time series data of natural gas and oil, yearly pipeline additions (km) are converted into the cumulative sum of pipelines in decades, i.e. cumulative pipelines of natural gas and oil in km from 1950-2020.

For calculations of cumulative CO_2 pipelines, the miles in the NETL_NZA model were converted to km.

CO_2 cumulative pipelines are calculated using proportionality, i.e.

$y = kx$, ________________________(1)

The value for k is calculated from NETL_NZA Model, for NZ and NZs 'k' is calculated by taking the ratio of the 'total sum of pipelines of CO_2 in 2050 (Km)' and captured capacity i.e. 2Gtpa. The value of 'x' presents captured capacity of CO_2 (Gtpa) in different scenarios from 2030 till 2100: each value is then put in equation 1, and the total sum of the length of the CO_2 pipeline for that CO_2 capture capacity is calculated.

From the cumulative pipelines of CO_2 and Natural Gas, decadal linear additions from 1960 to 2020 for natural gas and oil, and from 2030 to 2100 for CO_2 pipelines are calculated from the formula:

$$D = \frac{S_n - S_{n-1}}{T}$$

Where,

D is the linear additions of pipelines in Km (Km/Year),

S_n, S_{n-1} is the cumulative length of pipelines (Km), and

T is the years, in this case, 10 years (year).

The normalization parameter used is GDP PPP (Current US Trillion $), each cumulative decadal pipeline sum is normalized to GDP giving a metric of Km/year/Trillion $.

$$M_1 = \frac{D_t}{GDP_t}$$

Where,

M_1 is the new metric in Km/Year/Trillion $

D is the decadal linear additions of Pipelines in Km,

GDP[15] is the GDP PPP in Trillion $,

And 't' is the decade for which normalization is carried out

Cumulative pipelines of Natural Gas, Oil, and CO_2 pipelines are also Normalized using GDP PPP giving a metric Km/Trillion $

$$M_2 = \frac{S_{n(t)}}{GDP_t}$$

[15] For 1950-1980: Due to unavailability of data from World Bank, a coefficient of 0.5 is used and GDP is calculated, later an average is taken between this value and the values from Penn World State for these decades. These averaged values are used in this thesis. For 1990-2020: World Bank Data's values are used.

Where,

M_2 is the new metric in Km /Trillion $

S_n is the Cumulative Pipeline Length (Km)

t is the decade for which normalization is carried out

GDP is the GDP PPP in US Trillion $

3.4 Limitation of the Methodology

For CO_2 pipeline calculations, this methodology extrapolates findings of the US to the globe. The issue with such extrapolation is that it is under the assumption that the US is representative of the globe. However, from the Wei et al. (2021) global assessment, it is observed that CCS plays a crucial role in countries like China, India, Russia, the US, etc. These countries share similarities in terms of the use of a higher share of global GDP, dense pipeline networks, and a high share of fossil fuel in energy systems. As the majority of CCS pipelines will be attributed to these countries, this study effectively covers a significant share of the global CCS pipeline landscape.

The dataset for Natural Gas and Oil had 101 countries which included all the major countries with high pipeline shares (US, Russia, EU, China, etc). Missing data in terms of pipelines was majorly from Africa. This study can be made more comprehensive by adding missing pipeline data from Africa to the reference case.

For CO_2 pipelines, Although the majority of CO_2 transportation is expected from pipelines, shipping cannot be excluded for longer distances. However, without any availability of shipping data, it is challenging to quantify shipping for transportation, hence excluded from quantitative assessment but discussed in Chapter 5. GDP data for decades from 1950-1990 are calculated by taking the average explained in footnote 15.

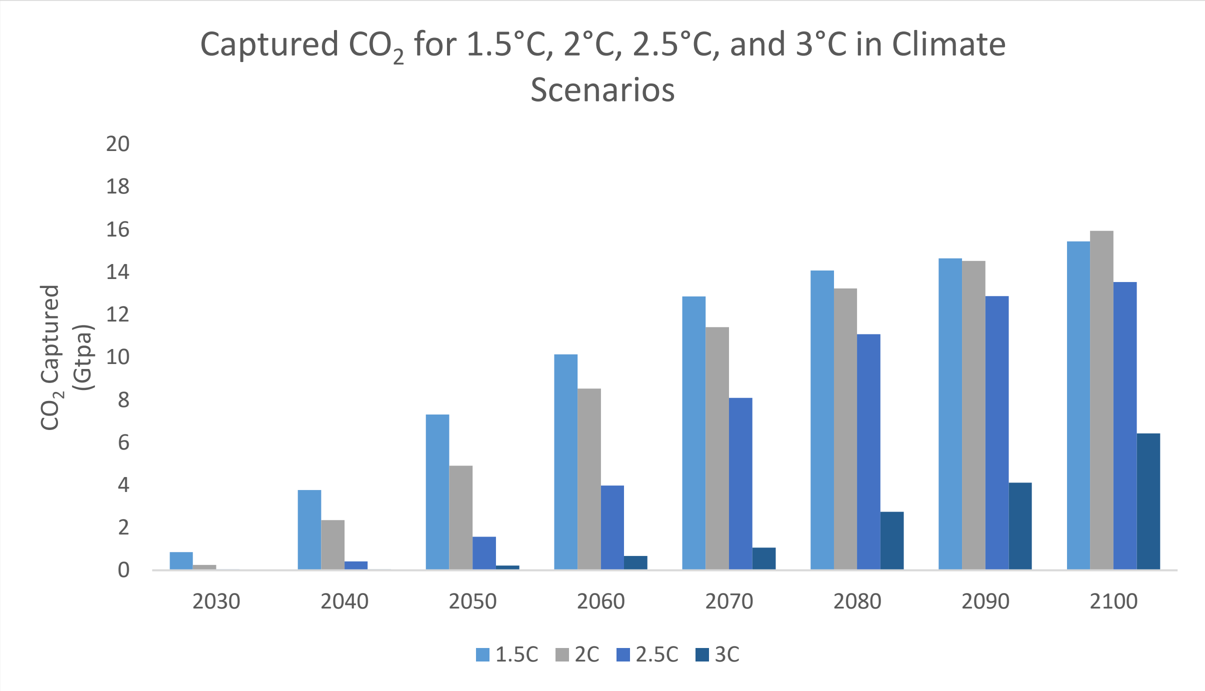
4 Results

This chapter presents the findings of this thesis. First, I summarise the volume of CO_2 to be captured in scenarios for 4 temperature levels. Subsequently, I calculate the length of pipelines for CO_2 (2030-2100), Natural Gas (1950-2020), and Oil (1940-2020). Later, decadal linear pipeline additions are calculated for Natural Gas, Oil, and CO_2 pipelines, and the last three graphs present the 'Outside View' by normalization of the reference case (Natural Gas and Oil Pipelines) and target case (CO_2 pipelines) to GDP (PPP US $).

4.1 The Volume of CO_2 Captured

Figure 12 provides an overview of the required Volume of CO_2 to be captured in median values across IPCC climate scenarios compatible with 1.5°C, 2°C, 2.5°C, and 3°C temperature rise. IPCC scenarios are complex and they have a wide range of CO_2 capture, hence, for simplification, the median value of captured CO_2 in the scenarios is considered in this thesis. An intriguing observation from Figure 12 is that CO_2 capture keeps on increasing across scenarios throughout the century, even for modest temperature levels like 1.5°C, where, Net Zero CO_2 is envisioned to be achieved by 2050. One explanation that is consistent with the literature is that CCS will be used for Negative Emissions, i.e. to remove anthropogenic CO_2 from the atmosphere.

Figure 12: Captured CO_2 for Temperature Levels 1.5°C, 2°C, 2.5°C, and 3°C in Climate Scenarios



Source: Own calculations based on IPCC AR6 Scenario Database (Byers, Edward et al. 2022)

Note*:* Coloured column stack indicates the median values of captured CO_2

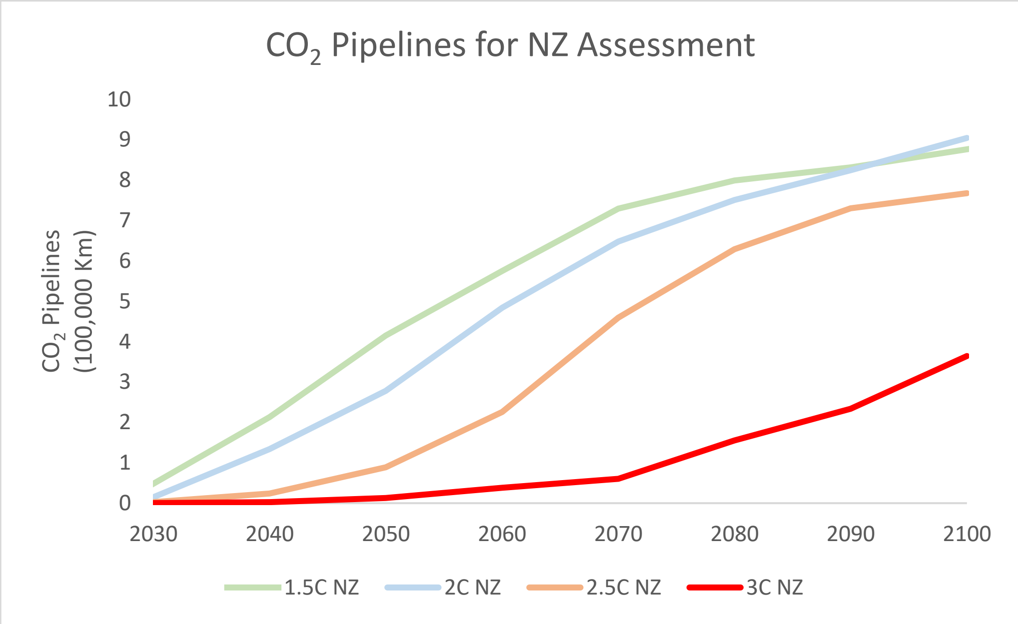
4.2 CO_2 Pipelines

Using the calculations provided in section 3.3, CO_2 pipelines required for median values of CO_2 Capture across IPCC Scenarios compatible with different temperature ranges are illustrated in Figure 13 and 14. Figures 13 and 14 depict the CO_2 pipelines required for NZ assessment[16] and NZs[17] assessment. Due to the difference in 'diameter' assumptions in the model, 37.5% more pipelines are required for NZs compared to NZ. The trajectories look similar for 1.5°C and 2°C, contrary to 2.5°C and 3°C.

[16] As discussed earlier, NZ assessment assumes that 42-inch pipelines will be built in the future. Thus, higher mass flow rates can be accommodated by 42 inch pipelines, **this reduces overall pipelines length in Km**

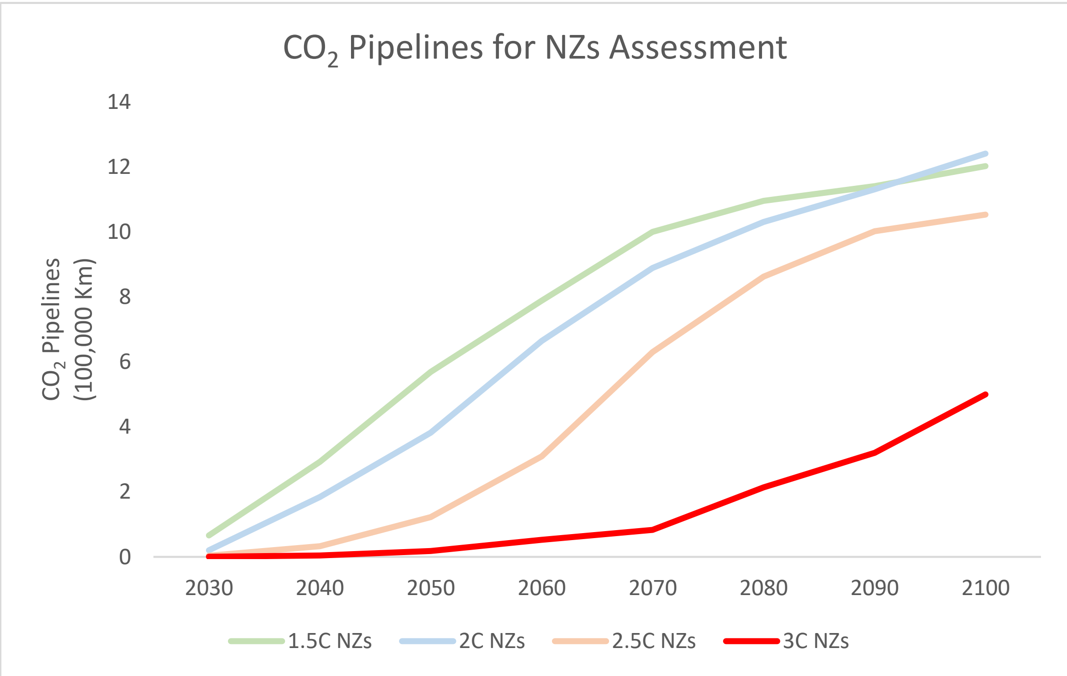
[17] NZs is a sensitivity assessment where the maximum diameter of the pipeline is a 30-inch pipeline (that is the biggest diameter in existence today for CCS pipelines), to accommodate higher mass flow rates, **more pipelines would be required** in absence of 42 inch pipelines (refer to Figure 10 and Figure 11 for the model).

Figure 13: CO_2 Pipelines Required for Capturing CO_2 for 1.5°C, 2°C, 2.5°C and 3°C Temperature Levels Assuming 42" Pipelines will be Constructed (NZ)



Source: Own calculations from (DOE 2022; Byers, Edward et al. 2022)

Figure 14: CO_2 Pipelines Required for Capturing CO_2 for 1.5°C, 2°C, 2.5°C and 3°C for Net Zero Sensitivity Assessment assuming the Maximum Diameter of Pipelines would be 30" (NZs)

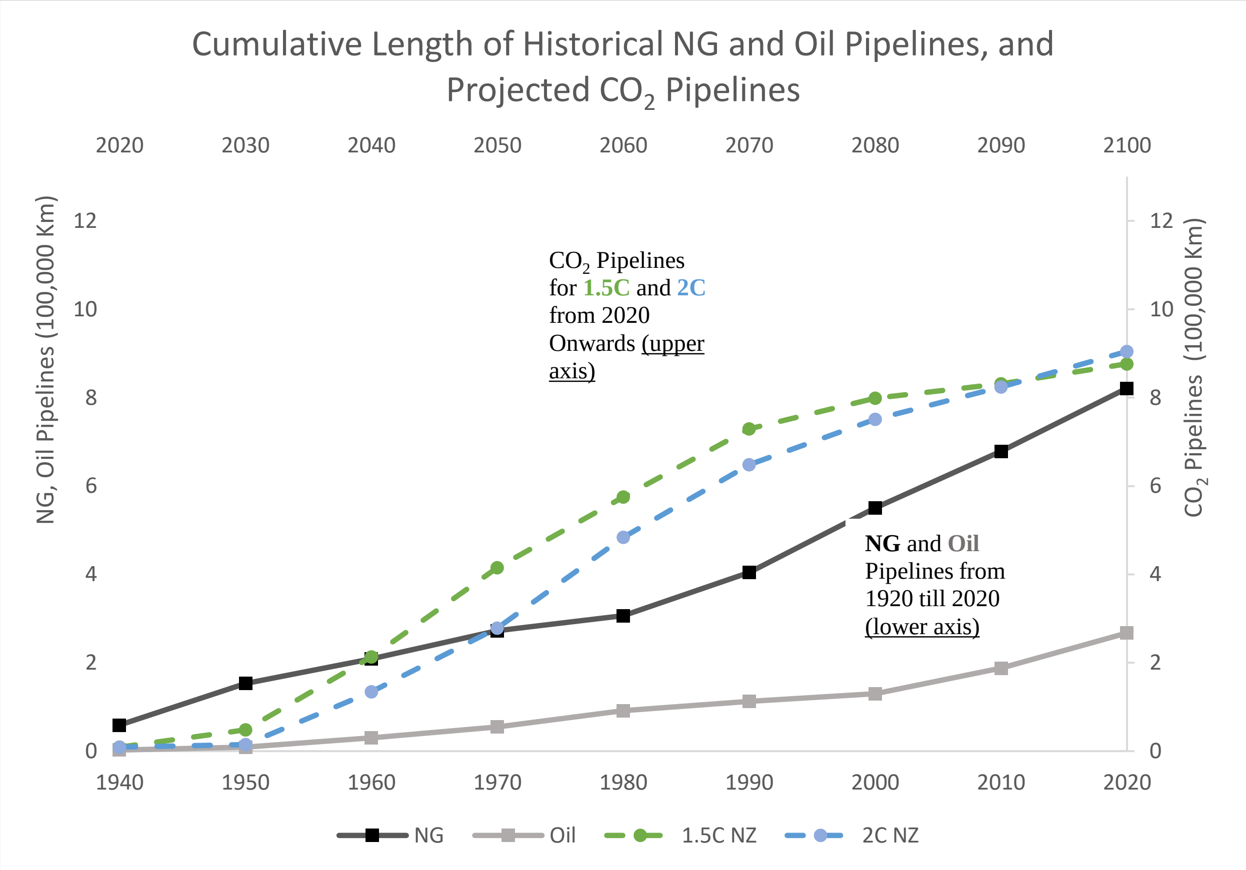


Source: Own calculations from (DOE 2022; Byers, Edward et al. 2022)

4.3 Natural Gas, Oil, and CO_2 Pipelines

Figure 15 illustrates the cumulative length of pipelines of Natural gas, Oil, and CO_2 pipelines for NZ. 4 axis are plotted, the Lower X axis and left Y axis, is for reference cases, whereas the Upper X axis and the right Y axis is for the target case. It is quite interesting to see that the 1960 and 1970 values of natural gas pipelines match with the 2040 and 2050 values of CO_2 pipelines, however, the trajectory is quite different. This highlights the difference between 'modelled outputs of CO_2 pipelines' and 'real world outcomes of historical length of natural gas and oil pipelines'.

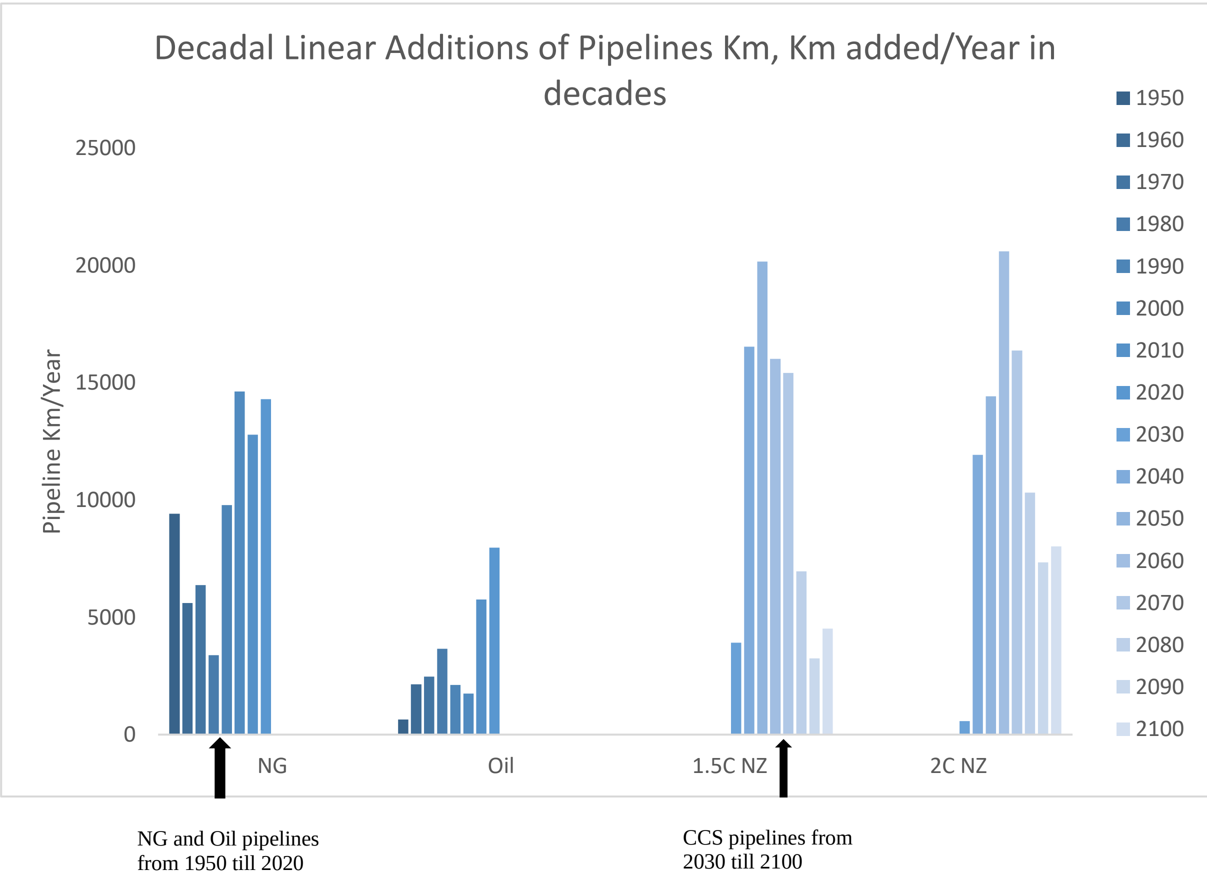
Figure 15: Cumulative Comparison of Length of Historical Natural Gas, Oil Pipelines, and Projected CO_2 Pipelines



Source: Own calculations from (Global Energy Monitor 2022; Byers, Edward et al. 2022; DOE 2022)

The starting decade for natural gas and oil pipelines is 1950 in this thesis. From cumulative pipeline additions arranged in decades, decadal linear additions i.e. pipelines added in that decade per year have been plotted for Natural gas, Oil, and CO_2 pipelines in Figure 16. Scenarios start from 2030 for CO_2, however, in 2022, there were 9000 km of operational CO_2 pipelines (Global CCS Institute 2021a). Hence, the decadal additions for 2030 are calculated using the 9000 Km value for 2020 for CO_2 pipelines. The difference in decadal linear additions is significant for CO_2 pipelines when compared to Oil Pipelines, however, it is important to note that Oil is transported through other means of transportation like trucks, and railways as well.

Figure 16: Decadal Linear Additions of Historical Natural Gas and Oil Pipelines, and Projected CO_2 Pipelines



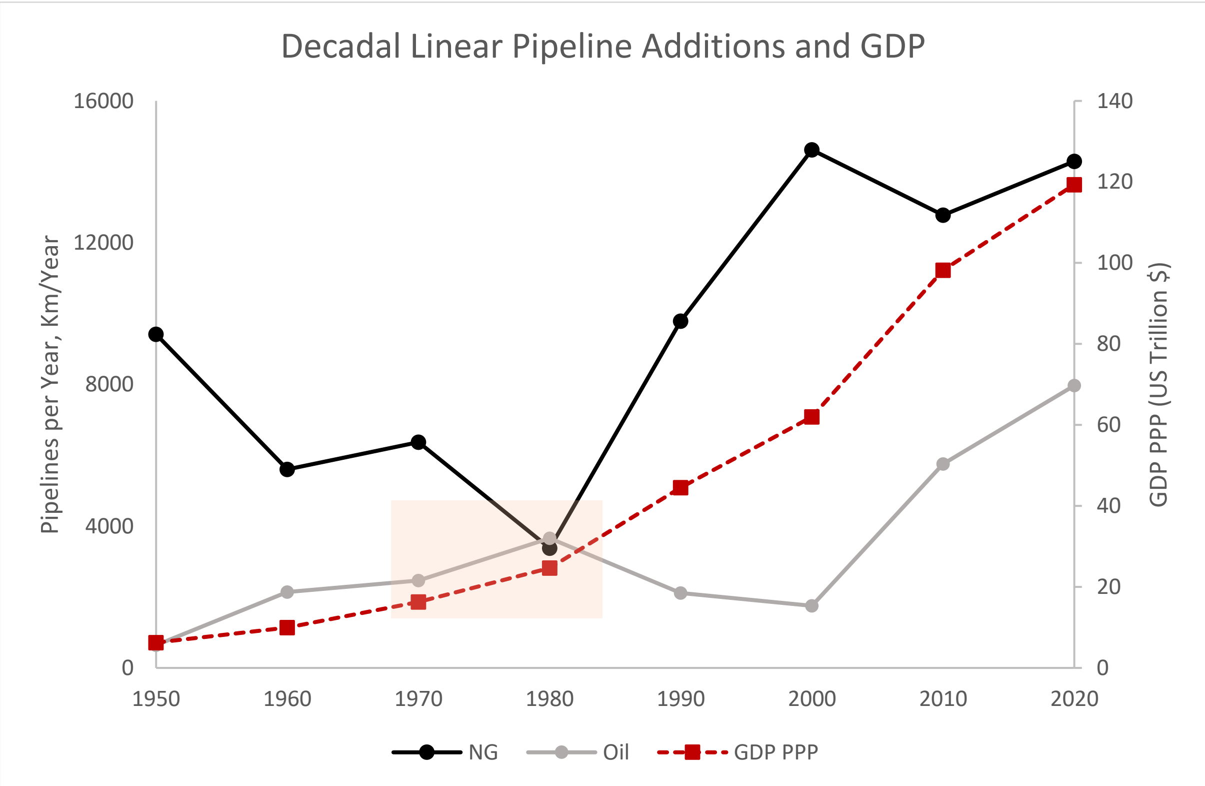
Source: Own calculations from (Global Energy Monitor 2022; Byers, Edward et al. 2022; DOE 2022)

Note: Column stack indicates, pipelines (in km) added in that decade per year, check section 3.3, (formula for D)

4.4 Normalized Pipelines to GDP

In this section, Pipelines are normalized to GDP. In the 1950s economy was smaller compared to today, while pipeline construction was higher. Figure 17 shows the steep rise in GDP and the behavior of decadal linear pipeline additions of natural gas and oil. Two key observations from Figure 17, a) In the 1970s, there was an oil crisis, from 1980, more natural gas pipelines were added compared to oil pipelines, this could be due to fuel-switching from oil to gas, and more transportation of oil through railways, and trucks, and b) GDP increases significantly in 2020 compared to 1950.

Figure 17: Decadal Linear Pipeline Additions and GDP

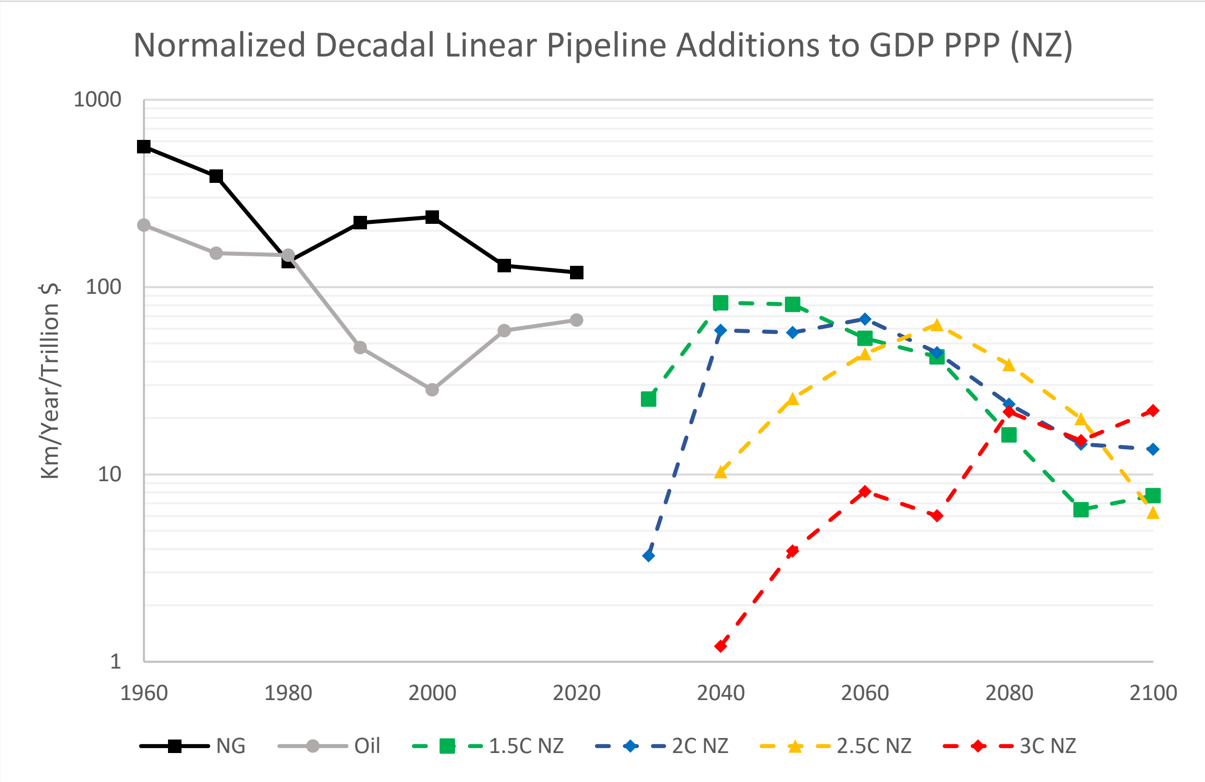


Source: own calculations from (DOE 2022; "World Bank" 2022; Feenstra et al. 2022; Global Energy Monitor 2022)

Note: The shaded region indicates the period of Oil Crises and Fuel-Switching from Oil to Natural Gas. The values for NG and Oil are decadal linear additions (Pipelines added per year in that decade)

To accommodate the changing economy of the past and future, a normalization factor of GDP PPP is considered. Figures 18 and 19 provide the normalized decadal linear pipeline additions to GDP PPP (US Trillion $). The values essentially dictate the length of pipelines added in that decade per year per Trillion $. GDP envisioned in climate scenarios for the future (2100) is significantly higher than the historical GDP (from 1950), hence to observe the trend, Figures 18 and 19 are plotted on a logarithmic scale for NZ and NZs assessment.

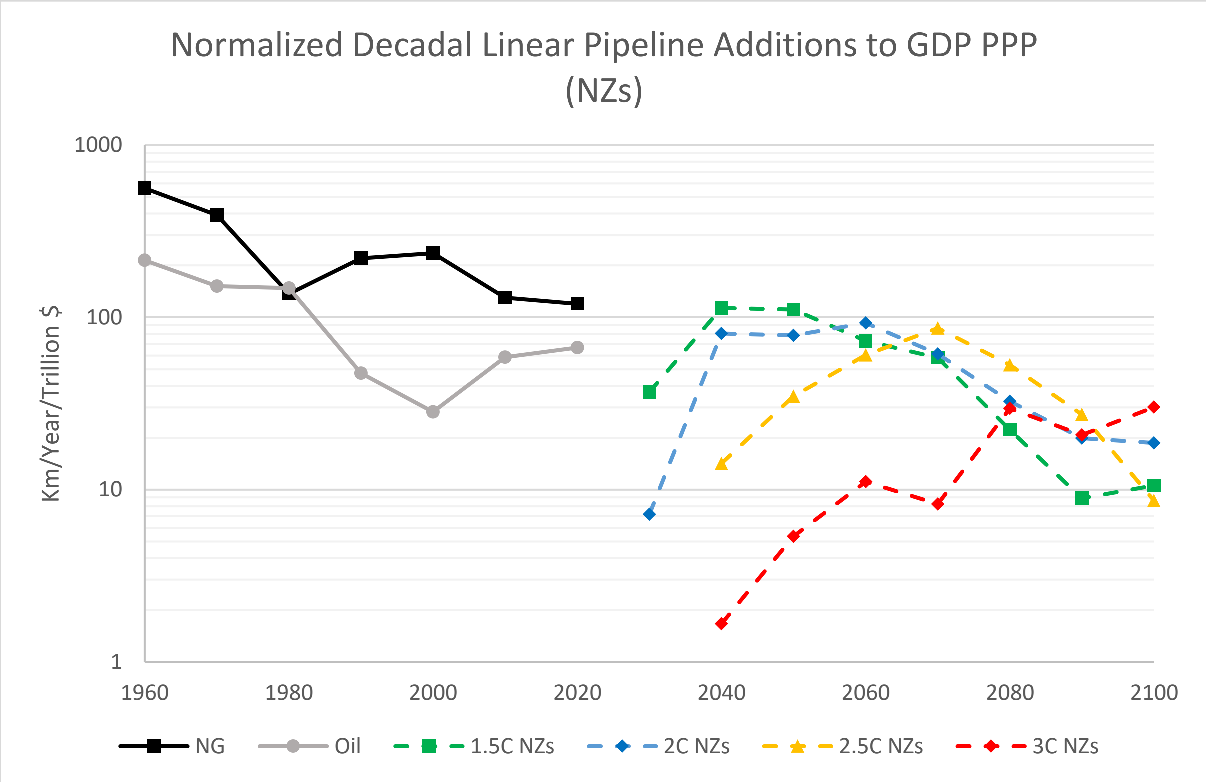
Figure 18: Normalized Historical NG, Oil Pipelines, and Projected CO_2 Pipelines to GDP for (NZ)



Source: own calculations from (DOE 2022; Byers, Edward et al. 2022; Global Energy Monitor 2022; "World Bank" 2022; Feenstra et al. 2022)

Note: For 2.5°C and 3°C, the values are negative for 2030. Negative values for 2.5°C and 3°C in the above figures are considered zero since negative values cannot be plotted on a logarithmic plot. Refer to section 3.3 for calculations (Formula for M_2)

Figure 19: Normalized Historical NG, Oil Pipelines, and Projected CO_2 Pipelines to GDP (NZs)

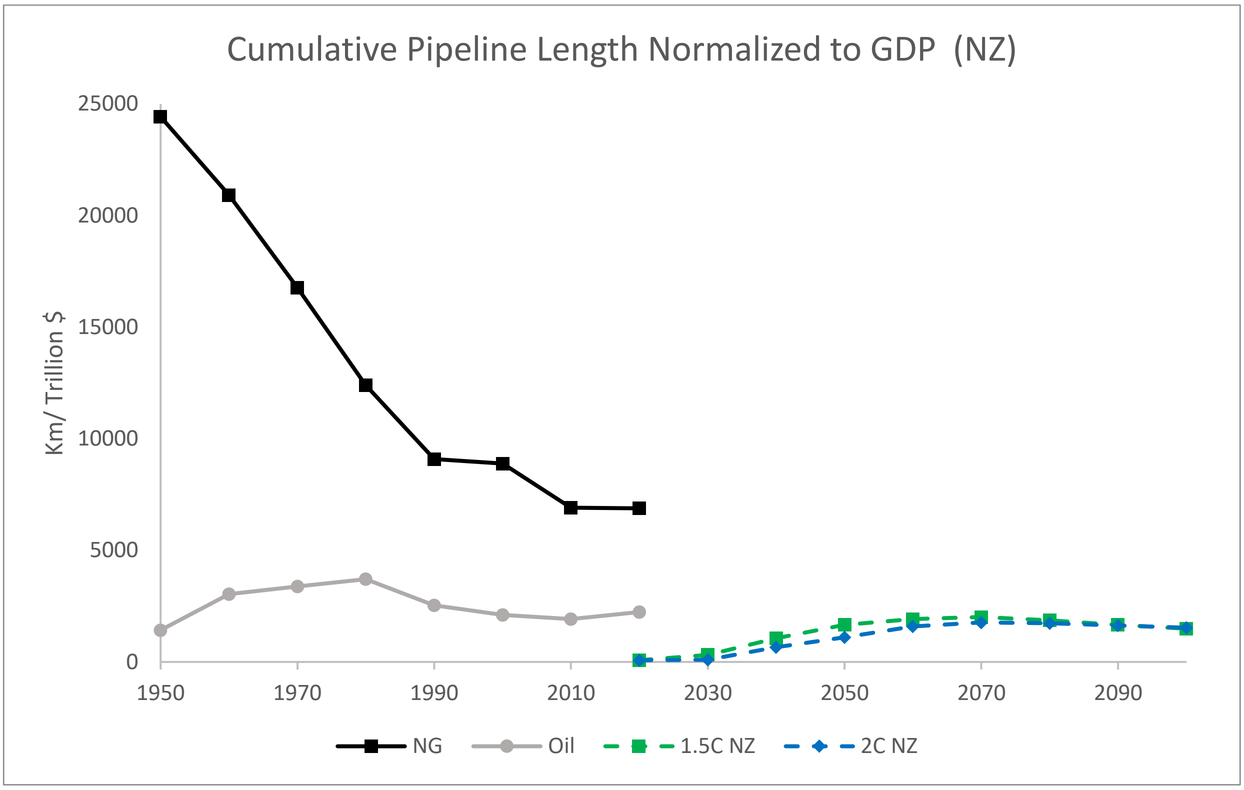


Source: own calculations from (DOE 2022; Byers, Edward et al. 2022; Global Energy Monitor 2022; "World Bank" 2022; Feenstra et al. 2022)

Note: For 2.5°C and 3°C, the values are negative for 2030. Negative values for 2.5°C and 3°C in the above figures are considered zero since negative values cannot be plotted on a logarithmic plot. Refer to section 3.3 for calculations (Formula for M_2)

Whilst Figures 18 and 19 provide normalized decadal linear additions of CO_2 pipelines, Figure 20 illustrates non-logarithmic cumulative pipelines normalized to the GDP of that year. As seen in Figure 20, assessing feasibility through the 'Outside View' is imperative. Although cumulative pipelines were increasing in the past, the normalized pipelines show a declining trend, this is due to an increase in GDP.

Figure 20: Cumulative Pipelines Length Normalized to GDP



Source: Own calculations from (DOE 2022; Byers, Edward et al. 2022; Global Energy Monitor 2022; "World Bank" 2022; Feenstra et al. 2022)

Note: Refer to section 3.3 for calculations (formula for M_1)

5 Discussion

5.1 Captured Volume of CO_2 in Scenarios

As of 2022, 46Mtpa CO_2 is captured and if the announced projects will be implemented they will result in 256Mtpa by 2030 (IEA 2022a). This is approximately how much would need to be captured in a median value across scenarios compatible with the 2°C target, but 3-4 times less than what is required in the median value across scenarios compatible with the 1.5°C target. CO_2 Capture keeps on increasing in median value across all scenarios throughout the century, even for 1.5°C where Net Zero CO_2 emissions are reached in 2050. One possible explanation for the rise in CO_2 capture is that CCS will be used for Negative emissions after 2050, where CCS will be involved to remove anthropogenic CO_2 emissions from the atmosphere. Another possible explanation is that existing and planned fossil power plants and hard-to-abate sectors will retrofit CCS to reach Global NetZero CO_2 by 2050 and thereafter keep on utilizing the power plants to avoid stranded assets[18] (Semieniuk et al. 2022).

5.2 CO_2 Pipelines

As of 2022, 9,000 km of CO_2 pipelines exist (IEA 2022c) This operational length CO_2 pipelines ought to be approximately increased twice how much CO_2 pipelines would be needed to be in operation in a median value across scenarios compatible with 2℃, and 5-6 times more in median value across scenarios compatible with 1.5℃ by 2030[19]. Increasing the diameter of CO_2 pipelines to reduces the overall total length of CO_2 pipelines (see Figure 10). Lesser length of

18 Stranded Assets in the context of fossil fuel mean shutting off resources and infrastructure before their economic lifetime (LSE 2022; Semieniuk et al. 2022)

[19] As per this research, for 260 Mt CO_2 (Median value for scenarios compatible with 2°C), around 15,000-20,000 Km of pipelines would be required. Whereas, in 2023 for 46Mt CO_2, 9000Km of pipelines are used. There could be a possibility that larger diameters of CO_2 pipelines are constructed by 2030, thus the length of CO_2 pipelines are lowered in 2030.

pipelines means lesser additional components. For cost optimization, it is logical to increase the diameter of CO_2 pipelines and reduce the overall infrastructural components (see Table 2, Table 3, Table 4). This is consistent with some of the cost optimization models used by Hu and Wu (2023) where the length of CO_2 pipelines is less.

5.3 Comparison of Reference and Target Case

This thesis claims that the historical length of Natural Gas and Oil pipelines makes an excellent reference case for assessing the feasibility of the envisioned length of CO_2 pipelines (target case). They share technical similarities, infrastructural similarities, and have relevant causal mechanisms. Between 1950 and 2021, energy consumption from oil and natural gas increased approximately 20 and 45 times respectively (Our World in Data 2022). To accommodate this increase in consumption, the total pipeline length of oil and natural gas increased by approximately 9 times and 15 times respectively. There are two explanations for this rise, a) the 1940s was marked by world war, hence there was a rise in demand for Oil and Natural Gas 'during and after' World War 2, 'the need to transport energy from one place to another' made the construction and operation of pipelines a priority (Johnstone and McLeish 2022). b) as new reserves were explored for natural gas and oil, the demand and profitability kept on increasing for them, thus pipelines continued to be constructed and operated historically (Johnstone and McLeish 2020; 2022).

The peak additions[20] of Natural Gas pipelines were in the decade 2000, and for Oil, it was in 2020 (Figure 16). The peak addition of Natural Gas pipelines is slightly lesser than the envisioned CO_2 pipelines for climate targets (1.5°C and 2°C[21]), whereas the peak addition of Oil pipelines is 2.5 times lesser than that of CO_2 pipelines for climate targets. This result also

[20] Decadal linear additions per year, see Figure 16

[21] For median value of scenarios compatible with 1.5 and 2°C

illustrates the importance of the outside view, whilst the cumulative length of CO_2 pipelines seems to follow the trend of reaching a peak and then declining, the reference cases (natural gas and oil pipelines) differ in the trend[22].

The total length of natural gas pipelines operational in 2020 is roughly the same as envisioned CO_2 pipelines in 2100, as for oil, the total oil pipeline length in 2020 is roughly 3.5 times lesser than envisioned CO_2 pipelines in 2100. It is important to note that oil still has roughly a similar share in energy production as natural gas, but oil is transported through other modes of transportation as well (like trucks, railways, airways, etc) (Our World in Data 2022; IEA 2022d). Whereas natural gas is majorly transported through pipelines, and virtually all CO_2 will be transported through CO_2 pipelines. This could mean that, envisioned CO_2 capture in climate scenarios can still be captured and transported with lesser pipelines if other modes of CO_2 transport are adopted like Ships.

Whilst the historical total length of natural gas pipeline operation in 2020 is roughly the same as future envisioned CO_2 pipelines in 2100, the context of construction and operation is different. First, Natural Gas and Oil pipelines in the 1950s were constructed even in the smaller economy due to the post world war demand, exploration of new oil and gas reserves, fuel-switching, profitability, and potential use of these energy sources as 'soft power' (Hopkins 2007; Johnstone and McLeish 2020; 2022; Kern and Rogge 2016). But more importantly natural gas and oil provide 'energy service' to the general public in terms of electricity, fuel for vehicles, etc. As for CO_2 pipelines, they don't provide any comparable direct benefit to the general public. However, CO_2 pipelines (CCS) aid in climate mitigation by removing anthropogenic CO_2 from the atmosphere. Thus, the societal benefits in terms of 'climate mitigation' is shifted from the current generation to the future generation.

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[22] For Natural Gas, the addition peaked in 2000, declined in 2010 but again rose in 2020. Similarly for Oil, the pipeline addition rose in 1980, declined for 2 decades, and then increased in 2010, 2020.

Comparison between historical and reference cases is carried out by taking into account changing economy of the past and future, this is done by normalizing reference cases and target to the changing GDP. During the Oil crises of the 1970s, ‘Oil’ was used as a ‘soft power’ tool for negotiations between the countries, also there was a minor drop in energy consumption (TWhr) from Oil (Johnstone and McLeish 2020; Our World in Data 2022). The linear addition of Oil pipelines started to decline from 1980 to 2000, and natural gas pipelines started to increase significantly. One possible explanation would be that to avoid the Oil crises in the future, countries started to put emphasis on natural gas and thus more natural gas pipelines were brought into operation compared to oil. Also, transportation became highly connected through roadways, and railways, thus oil was transported through other means of transportation as well. In either case, GDP increased steeply and continued to increase (see Figure 17). The key takeaway from this paragraph is, even if CO_2 pipelines are not constructed at the same rate as natural gas or oil, CO_2 can still be transported, if other modes of transportation like ships are economically viable.

The cumulatively significantly longer length of natural gas pipelines was in operation ‘per trillion dollars’ in the past, compared to the envisioned CO_2 pipelines ‘per trillion dollars’ in the future. Decadal linear pipeline additions ‘per trillion dollars’ for natural gas in 1960, declined 4 times by 1980. In expanding economy projected by 2100, normalized decadal linear CO_2 pipeline additions show a varied trend for 1.5°C and 2°C, and 2.5°C and 3°C. For climate targets, normalized CO_2 pipelines peak between 2040 to 2060, and then decline. These are also the ‘years’ where countries have pledged Net Zero and Net negative emissions targets globally. Thus, power plants might be retrofitted with CCS till 2060 and CCS is used for EOR and negative emissions, however after 2070, CCS is used majorly in Net Negative emissions and not in power plants, and the CO_2 capture stations for Negative Emissions are established close to the shared pipelines transportation infrastructure, to reduce the overall length of CO_2 pipelines.

5.4 Sectoral and Regional Distribution

An interesting observation from this thesis is that CO_2 capture does not decline in this century but rather continues to keep capturing CO_2 throughout 2100. One way to interpret this can be by looking at the regional differences, time scale, and profitability. In terms of regional differences, individual countries have pledged for Net Zero at different times, China in 2060, India in 2070, the US in 2050, and the EU in 2050. These are also the major CO_2 emitters and are expected to have CCS in their systems to meet the climate goals. As for timescale, once the CCS system is retrofitted or greenfitted it will continue to capture the CO_2 for the lifetime of the powerplant fleet. As for profitability, the Netherlands and the US are set to increase the CO_2 price, more CO_2 price makes CCS attractive. This also supports the medium and long-term strategies, where CCS pipelines are initially focused on Enhanced Oil recovery and then in the second half of the century provide the supporting infrastructure for negative emissions. This could potentially create two geographical divisions: where North America emphasizes on EOR and Europe emphasizes on carbon removal.

As per IEA (2022a) out of 46Mtpa CO_2 captured in 2022, more than 60% is used in Natural Gas processing, this is further set to increase in 2030. These are consistent with the literature where CCS is concentrated in fossil fuel plants (like power and heat, Natural Gas processing, and Hydrogen/Ammonia). Sectoral distribution dictates the processes that will be involved in CCS facilities thereby identifying infrastructural requirements. For example, integrated NG plants are suitable for pre-combustion capture, where ‘gasification units’ are required (Knoope, Ramírez, and Faaij 2015; IEAGHG 2013). Whereas, standalone natural gas power plants are suitable for post-combustion where bulky ‘compressors’ are required as discussed in section

2.4.1. Currently, the top 10 countries for natural gas power plants comprise a total of 1,945 Gas-fired power plants (US, Russia, China, Germany, Italy, Mexico, Iran, Thailand, Spain, India) (Statista 2023b).

5.5 Feasibility Assessment of CCS Infrastructure

In Summary, CCS Infrastructure consists of a set of technologies for capturing, purifying, transporting, storing, and/or utilising captured CO_2. Detailed components and materials required for CCS infrastructure are presented in Table 2. Natural gas and Oil Pipelines make a strong reference case for CO_2 Pipelines. CCS infrastructure seems feasible in the expanding economy as a) the historically built length of natural gas pipelines is approximately similar to projected CO_2 pipelines, b) the peak historical addition of natural gas pipelines is only 1.4 times lower than CO_2 pipelines, and c) natural gas pipelines were constructed and operated even in the smaller economy compared to that of the future. However, certain feasibility concerns arise when CO_2 pipelines are compared to Oil pipelines, as a) historically built the length of Oil pipelines is 3.5 times lesser than projected CO_2 pipelines, b) the peak historical addition of Oil pipelines is 2.5 times lesser than projected CO_2 pipelines, and compared to Natural Gas, lesser Oil pipelines were built in a growing economy. Along with these comparisons, CCS infrastructure would require the demand for raw materials like Steel, Iron, and Cement to be met[23].

Whilst it seems that CO_2 pipelines can be built and operated when compared to natural gas, an important distinction between the 'application' of these pipelines should be factored in. Natural Gas and Oil deliver 'energy service' making it beneficial for the general public, whereas CO_2 pipelines are 'mitigation technology' which does not provide any energy service to the

[23] Steel (240Mt), Iron (1.8Mt) and Cement (205Mt) global requirement from own calculations from DOE (22)

consumers. But, CO_2 pipelines play a valuable role in reducing the concentration of CO_2 in the atmosphere.

5.6 Limitations

Whilst this study looks at the Global Network of CO_2 pipelines and raw material requirements for CCS Infrastructure, in-depth regional distribution of this infrastructure is outside of the scope of this thesis. As mentioned earlier this study is an extrapolation of the US's model to the Globe, however in the future as other countries start to adopt CCS, with the availability of data, a more regional-specific model can be built for regional assessment of CCS. This study used the reference case of Natural Gas and Oil Pipelines, as discussed in the literature review, causal mechanisms for transmission lines of Solar PV and Nuclear Energy can also be undertaken with the availability of data and used as a reference case. With more availability of data, a feasibility space comprising major countries with CCS can be constructed. Importantly, although today it is assumed that virtually all captured CO_2 will be transported through pipelines, in the future 'shipping' can be an option as well.

6 Conclusion and Recommendations

This thesis set out to identify the infrastructural requirements of CCS and assess the feasibility of CO_2 pipelines in climate scenarios to meet climate targets. To achieve this, this study used the median value of CO_2 capture across the climate scenarios from the IPCC AR6 database and utilized the NETL_NZA model for calculations of the total length of envisioned CO_2 pipelines. The median value of CO_2 capture compatible for 1.5°C, 2°C, 2.5°C, and 3°C temperature ranges were considered. To assess feasibility, the methodology of 'Outside View' was applied where historical analogy (or reference case) of natural gas and oil pipelines was compared to envisioned CO_2 pipelines (target case). To bridge the gap between changing economy of the past (of reference case) and future (of target case), reference and target cases were normalized to the historical and projected GDP respectively.

This study fills the gap in IPCC scenarios by quantifying CO_2 pipeline construction and operation in terms of the total length of CO_2 pipelines required for median values of CO_2 capture compatible with 1.5°C, 2°C, 2.5°C, and 3°C across scenarios. This research appears to be the first study to estimate the total length of CO_2 pipelines required in the world, and discuss the feasibility of envisioned CO_2 pipelines using the applied methodology of 'Outside View'. Furthermore, this thesis lays the groundwork for further quantitative assessments of CO_2 pipelines in the future with more availability of data.

Major findings to emerge from this thesis in terms of feasibility of projected CO_2 pipelines are: a) Envisioned 'total' CO_2 pipeline length for 1.5 and 2°C targets is approximately similar to existing Natural Gas pipeline length, but nearly 3.5 times higher than existing Oil pipeline length, b) Peak additions per year of envisioned CO_2 pipeline is nearly 1.5 times higher than Natural Gas and roughly 2.5 times higher than Oil pipelines additions. Taking into consideration the changing economy, this research indicates that whilst natural gas and oil pipelines were operated even in smaller economies, the context of construction and operation is different from the CO_2 pipelines. The operation of natural gas and oil pipelines was driven by increased 'demand' and exploration of new reserves, and most importantly its role in providing direct service/benefits to society in the form of energy, electricity, and fuel for transportation, as opposed to envisioned CO_2 pipelines that do not provide direct energy service to the society. That being said, CCS assists in removing ongoing as well as anthropogenic CO_2 emissions. Moreover, 'pipelines' are 'means of transportation', thus the major determining factor for capturing envisioned CO_2 lies with the 'demand' for capturing CO_2. Thus, on one hand, it seems that the operation of projected CO_2 pipelines is feasible in expanding the economy when compared to natural gas pipelines, on the other hand, the lack of direct benefits in terms of 'energy service', and 'public acceptance' raises feasibility concerns. Whereas when projected CO_2 pipelines are compared to Oil pipelines, they raise feasibility concerns in terms of the higher envisioned total length of pipelines, as well lack of societal benefits similar to natural gas pipelines.

Other key Observations from this research for the identification of infrastructural requirements for CCS are: a) Across the entire supply chain of CCS, from CO_2 capture to CO_2 utilisation or storage, a range of components are required for each process, and majorly three raw materials are needed: Steel, Iron, and Cement. b) Storage and Transportation processes are commercial and well-established compared to Capture processes. c) Additional infrastructural components are required for shipping CO_2 through ships, however, for longer distances of CO_2 transportation, shipping is economically viable. d) Compared to natural gas pipelines, CO_2 pipelines operate at a higher pressure and are thicker in diameter, hence require additional steel.

The findings of the thesis have important implications for both academic and practical perspectives. From an academic perspective, this research can be further used for the construction of feasibility space with more regional granular data which could be available in the future. From a practical perspective, this research emphasizes ‘policy direction’ to accommodate shared infrastructure and provide incentives or financial support to the CCS industry to make CCS profitable and thereby aid in climate mitigation. This research signifies that international cooperation between major emitters like China, India, the US, EU in terms of establishing mechanisms to make CCS profitable through CO_2 price, shared infrastructure, and transportation network, and faster CO_2 pipeline approvals through streamlined regulatory and administrative processes can foster faster construction and operation of CO_2 pipelines.

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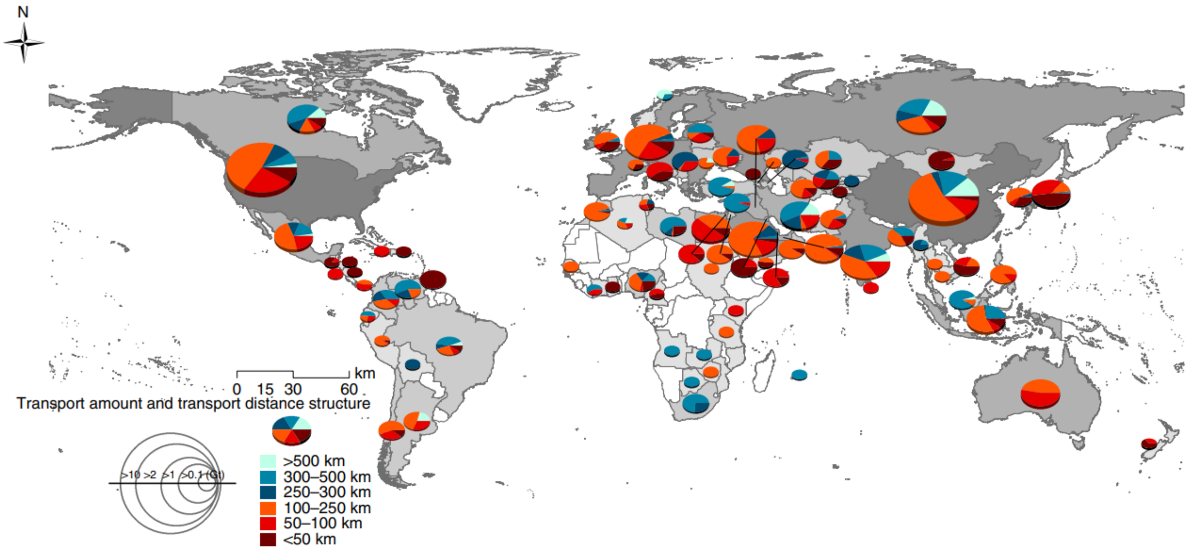
8 Appendix 1: Global Cost-Effective CO_2 Pipeline Layout



Source: (Wei et al. 2021)

The figure above presents the CO_2 transport amount and distance as per (Wei et al. 2021)'s analysis. The diameter of the pie indicates the Volume of CO_2 to be transported and the color scale indicates the length of the required CO_2 pipelines. The bulk amount of CO_2 is captured in the US, EU, China, India, and the transport distance is more (highlighted in blue) is more in China, Russia, and India. Thus, the collaboration between these major emitters for cost-efficient CO_2 source and sink matching is vital.