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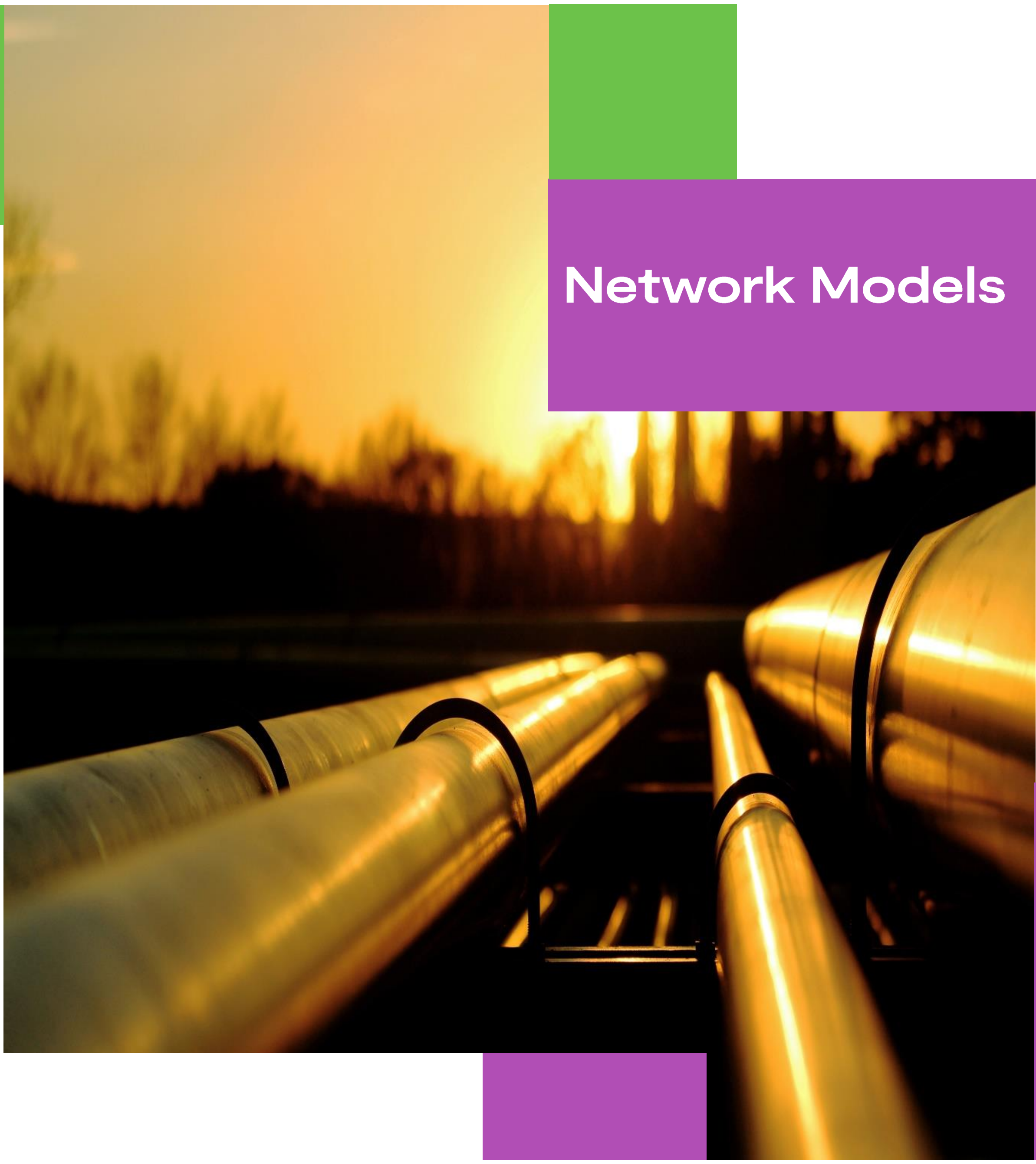

Network Models

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The results and recommendations in this report have been produced by Net Zero Transitions solely to provide insight into the future-proofing of the UK's CO_2 *transport infrastructure and the impact of key decisions on non-pipeline transport and new* CO_2 *storage development. Any information and results are subject to the accuracy of data inputs and associated assumptions. All conclusions should be confirmed before any publication or implementation. Net Zero Transitions holds no liability for any damages arising from the use of information generated by this report and makes no guarantee of the accuracy of any subsequent adjustments or amendments. Net Zero Transitions retains rights of duplication, and all reproduction is subject to prior written permission.*

Executive summary

Background

The UK's industrial emissions accounted for 71.2 $MtCO_2e$ in 2020, representing 16% of the nation's total greenhouse gas emissions.[a,b] As the UK progresses towards its net-zero targets, addressing these industrial emissions is critical. The government aims to capture and store between 20 and 30 million tonnes of CO_2 annually by 2030, increasing to over 50 million tonnes per year by 2035.[c] However, the development of carbon capture and storage (CCS) infrastructure presents significant challenges due to the high capital investment required. Costs are driven by several factors, including the cost of capturing CO_2, the choice between pipeline and non-pipeline transport (NPT), and the availability of CO_2 storage facilities.[d]

While the location of existing industrial emissions is important, it is essential to ensure that the CCS infrastructure is future-proofed to accommodate the development of future emissions, such as those arising from negative emissions technologies (NETs). The CCS network must be designed with long-term flexibility in mind, capable of supporting future emissions sources.

The UK's CCS infrastructure is anticipated to expand from current Track-1 and Track-2 projects, which include major industrial clusters such as HyNet and the East Coast Clusters.

Purpose

There are two primary approaches to developing CCS. The first is a project-by-project, organic approach, where individual projects are developed around anchor emitter, allowing for a more gradual and flexible growth of CCS infrastructure. The second approach is centrally planned and optimised, where the development is coordinated at a larger scale to ensure efficiency and coherence across the entire system. A key area of interest is understanding the cost differences between these bottom-up (organic) and top-down (centralised) approaches. This analysis can inform current decision-making to identify opportunities to reduce future costs and improve overall system efficiency.

Building on these two approaches to developing CCS, this report seeks to provide quantitative insight into the policy and investment decisions that will influence the design of the UK's future CO_2 transport and storage infrastructure. By analysing both the bottom-up and top-down methods, the study aims to inform future decision making in this space. Additionally, the report emphasises the importance of considering not only current industrial emissions but also potential future developments. This forward-looking perspective ensures that the infrastructure is adaptable and capable of meeting both present and future demands for carbon capture and storage.

It is important to note that this study is a thought experiment, intended to explore a range of options rather than offer concrete policy recommendations. The focus is on examining potential pathways and their implications, rather than prescribing specific actions for policymakers.

Methodology

To address the challenge of developing a national CCS transport infrastructure in the UK, we created a spatially and temporally resolved CCS infrastructure optimisation model. This model takes into account uncertainties in key input parameters, allowing for a more robust assessment of potential CCS infrastructure networks.

Key inputs into the model include:

- Annual emissions from UK point sources,
- Licensed storage sites,
- Storage capacity and injectivity,

- Restricted regions, including national parks, areas of outstanding natural beauty, and densely populated areas,
- Capture costs,
- Storage costs,
- Pipeline and shipping transport costs.

All data used in the model is publicly available and has been rigorously sense-checked with key stakeholders during workshops and meetings to ensure alignment with real-world data and projects.

The project uses a least-cost optimisation framework to support decision-making. However, it is important to note that this does not provide a definitive blueprint for CO_2 transport and storage infrastructure. We acknowledge that decision-making in this area will ultimately need to consider broader socio-economic factors, beyond just the least-cost approach.

Results & discussion

The results, based on adoption of a least cost optimisation approach, show that capture costs are the most significant factor in determining the structure of the CCS network. As a result, sources with lower capture costs are prioritised for connection to the network. The economic optimum reveals that large trunklines are installed in key industrial clusters, from which the CO_2 transport network expands to incorporate more remote point sources.

The optimal CCS infrastructure is strategically designed with future expansion in mind, ensuring that it can accommodate additional projects over time. Since the majority of the UK's CO_2 emissions originate from industrial power point sources, the dynamic operating nature of power plants does not significantly affect the design of the pipeline network at this level. Importantly, the overall structure of the network remains relatively stable even if capture or transport costs fluctuate, as the locations of the largest emitters and low-cost capture sources stay consistent. Finally, through the least-cost lens of this model, it was not possible to differentiate between pipeline and non-pipeline modes of transport, and quantifying and qualifying the role and value of NPT in terms of flexibility and speed of deployment.

Conclusions

Given that many of the UK's point source emitters are relatively small and located outside major industrial clusters, the development of modular capture technologies targeting these emitters will be essential for achieving the UK's climate change goals. Infrastructure development should focus on the key regions identified in the model, and transport and storage infrastructure should be designed with future projects in mind.

When considering scenarios where only transportation network costs are minimised (excluding capture costs), the results differ significantly. In these cases, sources closer to existing infrastructure are preferred, resulting in a smaller and more focused transportation network that excludes smaller, remote sources. However, for large capture targets, the solutions converge as nearly all emissions must be captured to meet net-zero goals.

In a net-zero framework, addressing the emissions of small, remote point sources will be crucial. Carbon Dioxide Removal (CDR) may offer a cost-effective solution for these emissions, or alternatively, relocating these facilities closer to CCS hubs could be considered. However, the broader societal and environmental implications of relocation will require careful consideration.

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Contents

1 Introduction

To achieve the UK's net zero target, addressing industrial emissions is crucial. The Industrial Decarbonisation Challenge (IDC), launched by UKRI in 2019, supports the development of decarbonisation technologies such as CCS, hydrogen production, and fuel switching across six key industrial clusters. The IDC has provided £210 million in public funding, with an additional £261 million from industry participants. In 2020, UK industrial emissions were 71.2 MtCO2eq, accounting for 16% of total UK greenhouse gas emissions.[1,2]

1.1 Context

In 2021, the UK initiated the cluster sequencing process for CCUS, selecting the HyNet and East Coast clusters for Track-1 deployment in the mid-2020s, while Track-2 includes the Scottish and Humber clusters, aiming for initial capture projects by 2028-29.[3,4] The IDC has funded nine major CCS infrastructure projects, with final investment decisions expected in Autumn 2024. The UK has substantial geological storage capacity, with the potential to store up to 78 billion tonnes of CO_2 in depleted oil and gas fields or saline aquifers.[5,6] According to the North Sea Transition Authority, the UK aims to capture and store 20-30 million tonnes of CO_2 annually by 2030, and over 50 million tonnes by 2035.[7]

While the initial focus is on large industrial clusters, achieving the 2035 target will require addressing dispersed industrial sites, which contribute 33.6 $MtCO_2eq$, or nearly half of the UK's industrial emissions. Balancing the costs of capture with economies of scale, and the trade-offs between capture, transport, and storage costs, is key. Given that 88% of UK point-source emissions are from sites emitting less than 100 ktpa, modular capture technologies will need to be cost-effective to make CCS viable for these smaller, dispersed sources.

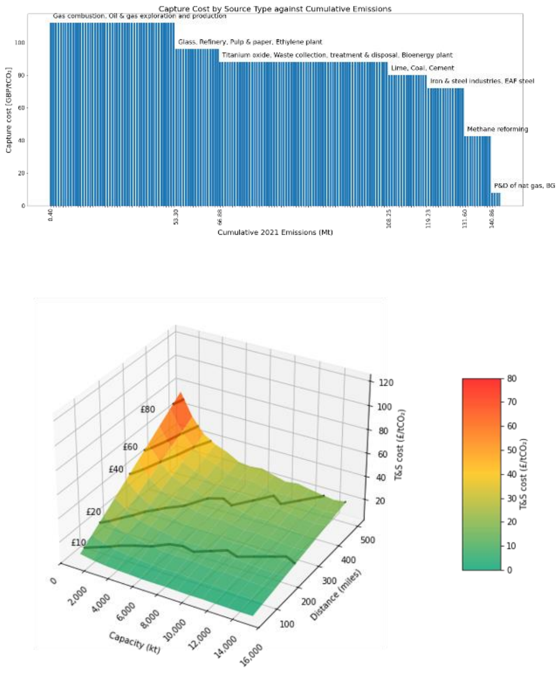

Figure 1: Trade-offs Between CO2 Capture Costs, Economies of Scale, and Transport & Storage Costs for Various Point Sources.

The top figure[8] illustrates the trade-off between the cost of capturing CO_2 from a specific point source and the associated economies of scale. The bottom figure[9] highlights the balance between capture costs and transport & storage (T&S) costs, particularly for smaller and more remote point sources.

1.2 Scope of study

The scope of this project is to provide qualitative and quantitative insights into the spatial and temporal evolution of a UK-wide CCS infrastructure that is future-proofed to meet the UK's legally binding net-zero targets. The project considers key decisions related to CO_2 transport methods (such as non-pipeline transport) and the development of new storage facilities. Using a least-cost optimisation framework, the project aims to guide decision-making for an effective national CO_2 transport and storage network. However, it does not provide a definitive blueprint and acknowledges that broader socio-economic factors must also be considered in future planning.

2 Methodology

2.1 Network optimisation model

To assess the development of a national CCS transport infrastructure, a spatially and temporally resolved optimisation model was developed. This model simulates the evolution of the CCS network over time, taking into account key uncertainties in input parameters, such as capture costs, pipeline costs, and storage availability. The model aims to provide a robust analysis that accommodates these uncertainties and reflects the realities of building a nationwide CCS infrastructure.

The optimisation model operates under two main objectives:

1. Minimising Total Costs: This objective considers the full range of costs associated with CCS, including capture, transport, and storage. The aim is to identify an economically optimal solution for achieving the UK's CO_2 capture targets by 2050.

2. Minimising Transport Costs: In this scenario, only transport costs, including pipeline and shipping costs, are minimised, representing an optimal solution for a transport operator.

The model incorporates constraints to ensure feasibility. For instance, there are limitations on the rate at which pipelines can be constructed, reflecting real-world capabilities. Physical restrictions, such as those that prevent the building of CO_2 pipelines in protected areas like national parks, are also accounted for unless deemed essential. However, it is important to note that non-economic factors, such as the socio-economic and distributional impacts of the net-zero transition, are not considered within this model. These broader considerations should be addressed by policymakers and explored in further studies to provide a more comprehensive understanding.

The model's spatial resolution divides the UK into a grid, representing potential locations for capture plants, pipelines, and storage sites. Over five-year periods from 2025 to 2050, the model optimises the CCS network's development, ensuring that CO_2 capture, transport, and storage capacity grow to meet the increasing capture targets.

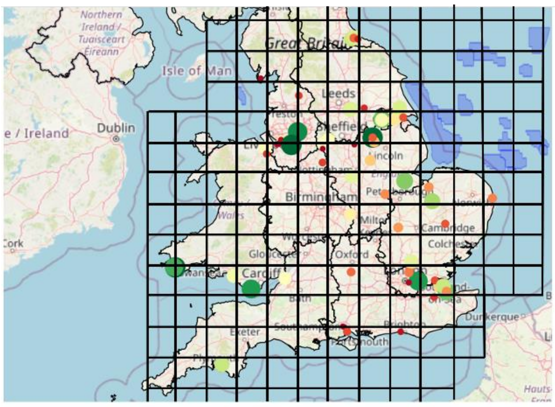

Figure 2: Spatial Modelling Example with Variable Node Resolution, Based on a 20x20 km Grid.

An example of the spatial modelling used in this work, where the area is divided into a uniform grid of nodes is shown in Figure 2. The node size, or spatial resolution, is variable, with a trade-off between resolution detail and model complexity. The results in this report are based on a resolution of 20x20 km.

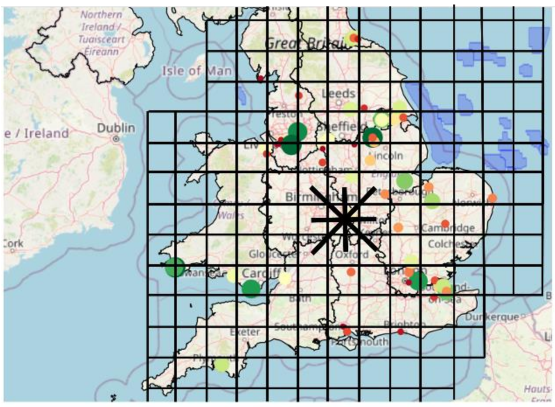

Figure 3: Potential Node Connections and Optimised Pipeline Sizes in the Spatial Model.

Figure 3 shows potential connections between nodes, represented by black lines. Each node is connected to its neighbouring nodes (horizontally, vertically, and diagonally), forming arcs. For each arc, the decision to build a pipeline and its size is optimised. The modelled pipelines range from 10" to 56" in diameter, representing real-world pipeline sizes.

2.2 Input data

To ensure the most accurate and reliable results, a rigorous data search and verification process was undertaken, utilising the latest publicly available sources and stakeholder input to provide a robust foundation for the model's input data.

1. Emission Sources: The characterisation of emission sources is based on the 2021 National Atmospheric Emission Inventory (NAEI), covering around 1,600 CO_2 emitters. The data includes site, operator, location, and annual emissions.

2. Capture Costs: Capture costs are based on the relationship between CO_2 partial pressure and cost, as described by Kearns et al. (2021). These costs have been adjusted for inflation and scale and reflect the thermodynamics of capturing more dilute sources. Sensitivity analysis addresses uncertainties.

3. Storage Sites: The model includes 28 licenced CO_2 storage sites granted by the North Sea Transition Authority, with 27 still active. A potential new storage site in the English Channel is considered in one scenario.

4. Storage Cost Estimates: Storage costs are based on the 2011 IEAGHG report and account for different cost scenarios, including the number of wells and equipment. In the UK, licenced storage sites are assumed to be offshore depleted oil and gas fields.

5. Storage Capacity and Injectivity: Capacity and injectivity data vary by site, and while not enforced in the default scenarios, they inform the discussion.

6. Restricted Regions: National parks, areas of outstanding natural beauty, and Greater London are classified as restricted regions for pipeline development, except where emission sources within the region require CCS. Some scenarios explore the impact of allowing pipelines in restricted regions.

7. Pipeline and Shipping Costs: Pipeline and shipping costs are based on a 2018 BEIS report, showing similar economies of scale for both methods (£5-30/tCO_2)[10]. Costs for onshore and offshore pipelines are assumed to be identical, with marginal differences in gas-phase vs. dense-phase CO_2 transport. The model includes costs for ports and CO_2 transport ships, with 16 UK ports considered.

2.3 Scenarios evaluated

This study adopts a scenario-based approach, with the following scenarios evaluated:

Scenario set I
The first set of scenarios aims at capturing the least cost CO_2, with a step-wise increase capture targets. This scenario exclusively aims at the economic optimum, and does not prioritise specific emission sources, e.g., Track 1 CCS projects, etc.

Scenario set II
The second set of scenarios explicitly considers current policy and planned CCS projects, i.e., the capture from the planned track 1 and track 2 CCS projects is prioritised, with capture delivered by 2030. This is then expanded to capture 40 $MtCO_2$/a from other sources.

Scenario set III
We finally explore a range of sensitivity analyses, including towards costs of capture and different modes of transport, the impact of future large emitters, impact of permitted location, and development of new stores.

3 Results

3.1 Scenario Set 1: economic optimum

This scenario focuses on determining the least-cost CCS infrastructure to achieve CO_2 capture and sequestration targets. It does not prioritise specific emission sources, such as track 1 CCS projects. Six different scenarios are explored, each with increasingly ambitious CO_2 capture targets, starting from 20 $MtCO_2$ per annum in 2030 and expanding up to 120 $MtCO_2$ by 2050.

Key observations:
Cost dominance: Capture costs dominate overall system costs, making cheaper sources such as blue hydrogen plants, refineries, cement, lime, bioenergy, and energy from waste plants the preferred choices.

Pipeline strategy: Economical models suggest building larger pipelines earlier to accommodate future expansion. The formation of industrial clusters and strategic trunk lines occurs early, driven by cost-efficiency.

Marginal costs: The cost of increasing capture volumes shows near-linear marginal costs, even when more remote or dilute CO_2 sources are included.

3.2 Scenario Set II: Current Policy and Planned Projects

This set integrates current policy objectives and prioritises CCS projects planned under the UK government's track 1 and track 2 schemes, which include clusters like East Coast (Teesside & Humber), HyNet, and the Scottish Acorn project. The aim is to capture emissions from these projects by 2030, while additional sources could raise the capture to 40 $MtCO_2$ by 2050.

Key observations:
Policy-driven network: The network is largely similar to the economic optimum, but with a priority on existing projects. Larger pipelines are planned early to accommodate future growth.

Long-term infrastructure: The results indicate the necessity of future-proofing infrastructure by investing in larger capacities upfront. Despite some geographic anomalies (e.g., Scottish emissions stored in the Irish Sea), the model reveals the importance of strategically expanding pipelines and storage facilities.

Figure 4 illustrates the spatial distribution and development of the CCS network under two different scenarios. The first map represents the "Economic Optimum" scenario, which focuses on achieving a CO_2 capture capacity of 100 $MtCO_2$ per annum by 2050 through cost-efficient infrastructure development. The second map highlights the "Track 1 & 2 Projects" scenario, which integrates current UK government policy and prioritises existing CCS projects, achieving 20 $MtCO_2$ per annum by 2050.

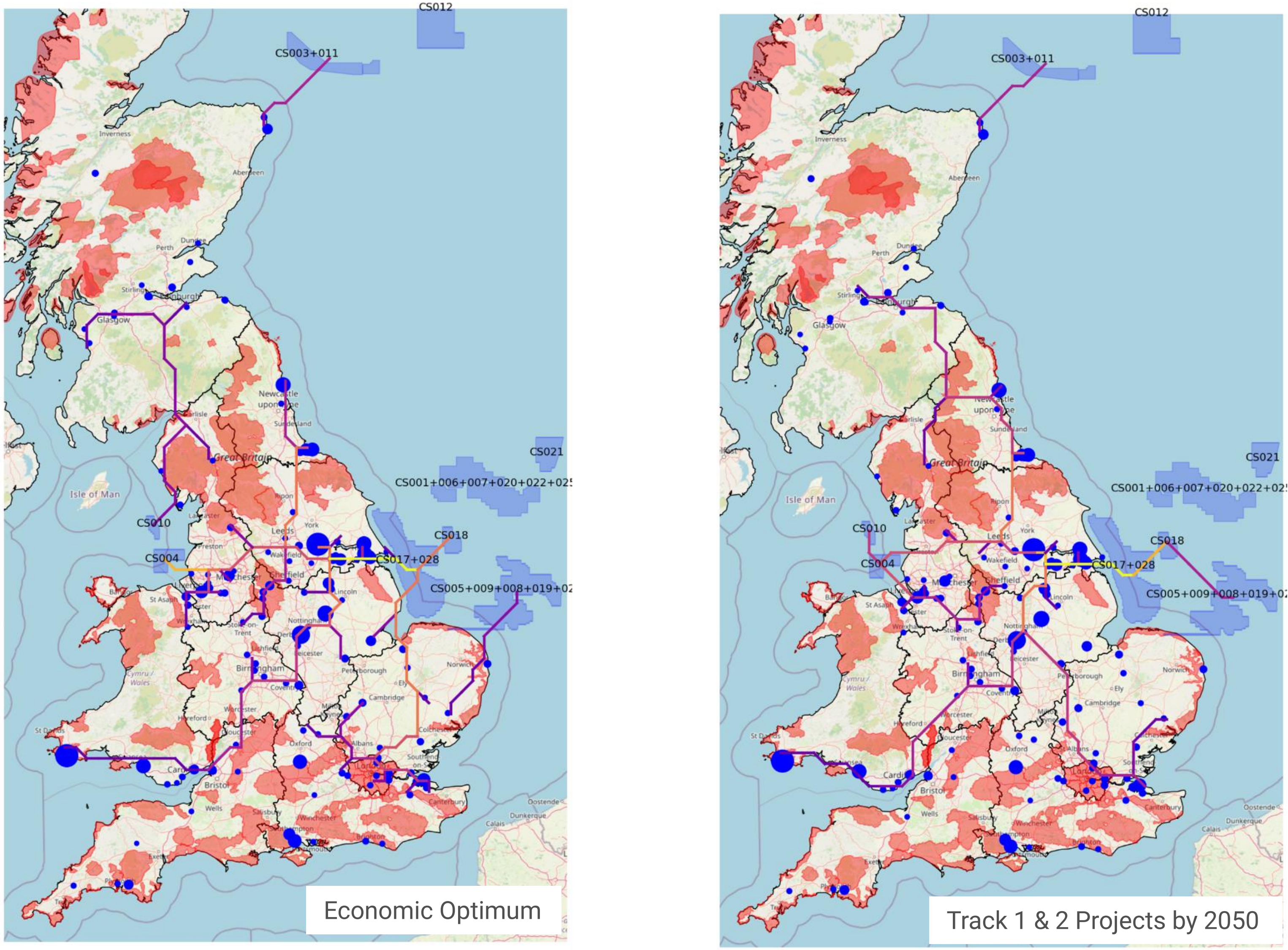

Figure 4: Comparison of CCS Infrastructure Development: Economic Optimum vs. Track 1 & 2 Projects by 2050

3.3 Scenario Set III – Sensitivity Analysis

This scenario explores the impact of uncertainties such as varying capture costs, transport costs (pipelines and shipping), restrictions on pipeline locations (e.g., national parks), and the development of new storage sites.

Key findings:
Capture cost variations: Doubling or halving capture costs does not significantly alter the prioritisation of capture sources, as shown in Figure 5. However, it impacts total system affordability.

Pipeline and shipping: While pipelines appear more economical for large volumes, shipping offers flexibility and could be deployed faster for more remote or smaller emission sources.

Geographical sensitivity: Through the lens of this study, a new storage site in the English Channel is only beneficial if its costs are comparable to existing storage locations.

The location of future large-scale emission sources, such as BECCS plants, can have minor impacts on overall system costs but significant local impacts.

Strategic Insights:
Early investment: To meet long-term climate targets, CCS infrastructure should be built with maximum capacity from the outset, avoiding future expansion costs.

Storage and capacity: The North Sea and Irish Sea storage sites are critical in all scenarios. Additional capacity may be needed by 2050, particularly in the North West region.

Hydrogen and CCS co-location: There are potential synergies between co-locating hydrogen and CCS infrastructure in industrial clusters, though they may not always align geographically.

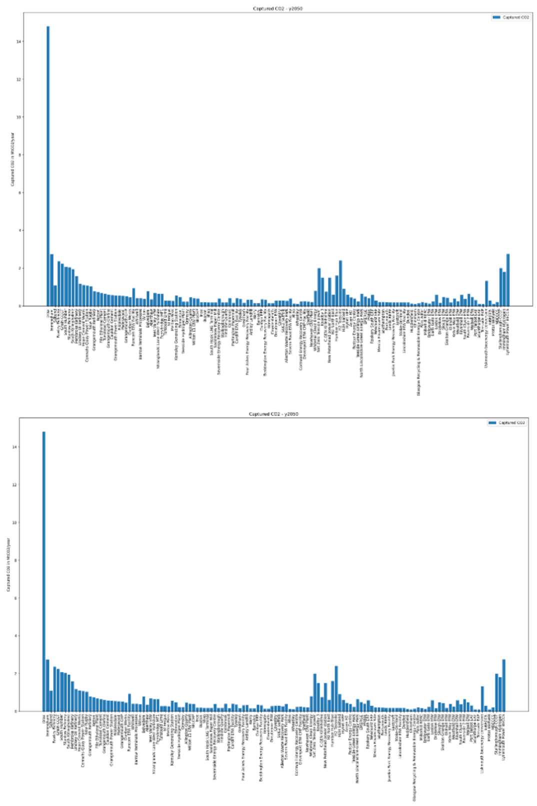

Figure 5: Sensitivity of Network Design to Varying Capture Costs: Scenarios with Doubled and Halved Capture Costs

4 Discussion

4.1 What impacts the structure of the CCS network?

Capture costs dominate the overall system costs and play a key role in determining which sources should be prioritised for CO_2 capture. Cheaper sources like blue hydrogen, cement, lime, bioenergy, and waste-to-energy facilities are preferred, even if this leads to a larger transport network. While gas-fired power plants are more expensive to capture from, they provide value as anchor points in pipeline development. The network structure is primarily shaped by the location of large, low-cost sources, with industrial clusters acting as key hubs. Long-term plans and strategic investments are essential to ensure the infrastructure can expand as capture targets increase, with minimal adjustments required due to changes in other cost factors.

4.2 Strategic development of CCS networks

Pipelines are sized from the outset to handle future CO_2 volumes, as building capacity later is more costly. The system is designed to be future-proof, and additional branches can be added to existing trunklines as the network expands. New storage sites, such as those in the English Channel, could alter the structure if they prove economically viable.

4.3 Co-locating CCS and hydrogen infrastructure

Co-locating hydrogen and CO_2 infrastructure in industrial clusters offers synergies, reducing planning and construction costs. Hydrogen pipelines, however, do not necessarily align with CO_2 pipelines, as they serve different end users. Nonetheless, the potential benefits of co-location are significant.

4.4 Non-pipeline transport

Both road and rail transport are suitable for small, short-distance CO_2 volumes, but they are unlikely to replace pipelines, which are more cost-effective for large-scale transport. Shipping offers flexibility for smaller or remote sources and may be deployed more quickly than pipelines. Both pipeline and shipping options are considered cost-effective for large-scale CO_2 transport, with costs and economies of scale being relatively similar. According to the 2018 Element Energy report for BEIS, both methods have costs ranging from £5–30/tCO2[10], ensuring consistency in assumptions for comparison.

The analysis in this report assumes different pipeline diameters, where pressure losses are calculated based on CO_2 flowrate and friction factors. This is used to estimate the capacity depending on the diameter. Identical costs are assumed for onshore and offshore pipelines, although data from the US Agency for International Development indicated that offshore pipelines were historically 1.8 to 2 times more expensive (in 1995 and 2000, respectively).[11] Despite this, the impact of this assumption is considered minor, as sensitivity analysis shows that changes in pipeline costs have a marginal effect on the overall CCS infrastructure costs.

Furthermore, the analysis assumes CO_2 is transported in its dense phase within pipelines, which is the industry standard for long-distance transport. While some stakeholders have noted that gas-phase CO_2 transport may be preferred for specific projects, the cost difference between gas-phase and dense-phase transport is minimal when compared to the total CCS infrastructure costs.

For shipping, cost estimates include both capital and operational costs for port facilities—such as liquefaction and storage—along with the cost of CO_2 transport vessels. The model considers CO_2 being shipped from 16 different ports around Great Britain, ensuring comprehensive coverage of potential shipping routes.

Road and rail transport are only viable for small, short-distance CO_2 volumes and are unlikely to replace pipelines, which are more economical for large-scale transport. Shipping could offer flexibility for smaller or remote sources and may be deployed more quickly than pipelines. However, both methods are cost-effective for large-scale CO_2 transport, and the choice depends on individual project requirements.

4.5 Storage site and availability

Storage sites in the North Sea and Irish Sea are heavily utilised, and expanding capacity, particularly at HyNet, will be necessary by 2050. Ensuring adequate storage injectivity is vital, and new sites, such as the one in the English Channel, may only reduce costs if they are comparable to existing sites. The analysis does not account for local economic impacts or logistical challenges related to cross-country infrastructure deployment.

5 Conclusions

Capture costs represent the largest portion of total CCS costs and are the primary factor in determining which emission sources to target in cost-optimal scenarios. The structure of the CCS network and the placement of key infrastructure do not vary greatly across different scenarios. Industrial clusters with CO_2 trunklines form the core of the network, expanding to include additional emission sources depending on the capture target.

Capturing CO_2 from industrial clusters is a cost-effective strategy, even without considering current policies. The network design is minimally impacted by fluctuations in capture or transport costs and restricted areas.

Both pipeline and shipping methods offer viable large-scale CO_2 transport solutions, with the choice depending on the specific needs of the project. Both approaches provide cost efficiencies at scale, and while there are nuances in the cost structures, such as pipeline diameters and offshore costs, the overall differences remain marginal within the broader CCS framework. Given that shipping and other non-pipeline transport offer benefits such as rapidity of deployment and flexibility of infrastructure that were not possible to explore in the context of this study, an extension of this work to examine the role and value of NPT in detail is recommended.

Capture remains the dominant cost in the CCS network, with transport and storage making smaller contributions over time. Importing CO_2 for storage in the UK offers limited potential to reduce costs. However, significant value lies in the strategic, future-proofed development of the UK's transport and storage (T&S) infrastructure. Investing early in a robust infrastructure will outweigh a more organic approach.

Future point sources of CO_2, even those remote from current projects, will not substantially affect the overall system's cost. Therefore, priority should be given to quickly developing essential CCS infrastructure around existing industrial clusters. Future-proofing should include consideration for future projects, ensuring sufficient storage and injection capacities. Future CO_2-emitting projects, such as BECCS, DACCS, and blue hydrogen, should be sited near key CCS infrastructure.

Support is needed for modular CO_2 capture technologies to reduce costs for smaller, remote sources. Further studies should detail capture technologies and economies of scale. The development of a more detailed CO_2 transport design tool encompassing pipeline and non-pipeline transport routes is also recommended, to better evaluate the trade-offs between pipelines and shipping, accounting for detailed local geography. Consideration should also be given to repurposing natural gas pipelines where possible.

Strategic planning is vital to ensure the infrastructure can handle future CCS projects.

This work is anticipated to inform government decision making on the development of CCS infrastructure in the UK. This will possibly have significant and long-term implications in the context of the UK's net zero transition. One important challenge in delivering this study was a paucity of accurate data describing the real-world costs of CO_2 capture and transport (on and offshore pipelines as well as non-pipeline transport). It is therefore in the near-term interest of project and technology developers to ensure that there is as much accurate data in the public domain as possible.

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7 List of figures