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Genetic Algorithm-Driven Design of CCUS and Hydrogen Pipeline Networks: Decentralised Expansion with Complex Geographical Constraints

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ABSTRACT

The development of Carbon Capture, Transport, and Storage (CCTS) and hydrogen pipeline networks is crucial for achieving deep decarbonisation in industrial sectors. However, existing network design models often assume perfect foresight, limiting their applicability to real-world infrastructure planning, which is inherently uncertain and iterative. This study introduces a novel rolling-horizon methodology for pipeline network expansion, leveraging a genetic algorithm-based approach that allows for adaptive routing and incremental infrastructure development. By comparing rolling-horizon designs to 2050-optimised networks in a case study of the Humber region in the UK, the analysis highlights the trade-offs between adaptability and cost efficiency. Results indicate that while rolling-horizon approaches better reflect real-world decision-making, they also introduce inefficiencies, increasing capital expenditures by approximately 8% for both hydrogen and CCTS infrastructure. Additionally, the study examines the economic risks associated with transitioning from blue to green hydrogen production, revealing a 20-fold increase in CCTS costs per tonne of CO_2 when hydrogen production shifts to green. The findings underscore the importance of integrating uncertainty-aware strategies in infrastructure planning to mitigate inefficiencies while maintaining adaptability to technological and policy changes.

Keywords: Carbon capture transport and storage, Hydrogen, GIS, Infrastructure, Rolling-horizon

BACKGROUND

Transitional pipeline infrastructures, such as Carbon Capture, Transport, and Storage (CCTS) and hydrogen networks, have the potential to facilitate a low-carbon transition in fossil fuel dependent industries, particularly in foundational sectors such as iron and steel, chemicals, and power generation [1]. However, the path to sectoral and site-specific decarbonisation is paved with uncertainties [2]. These challenges arise from the dynamic evolution of technologies, shifting policy priorities, and the need to align stakeholder decisions, all of which complicate the development and long-term adaptability of these infrastructures [3].

Spatially-explicit computational models enable the design and evaluation of pipeline networks by incorporating geographical, technological, and policy-related constraints. To create resilient and adaptive infrastructures, these models must address both spatial and temporal complexities. The spatial aspect involves determining optimal routes while accounting for geographical and environmental constraints, whereas the temporality considers how these networks evolve over time in response to changing demands, technologies, and policy goals.

Static models, offering a snapshot design at a single point in time, determine the optimal topology and specifications of the pipeline infrastructure for a specific configuration of sites. Topological considerations require a spatially-explicit model to ascertain the route. This has mostly been achieved using grid-based methods and pathfinding algorithms, such as the well-known A* algorithm, to develop candidate networks that a subsequent optimisation method can utilise to optimise the infrastructure [4,5]. More recently, Hammond et al. [6] presented a graph-based, multi-stage approach for pipeline

infrastructure design that generates networks across a geographically complex region for a given set of sites. Removing the need for a candidate network structure and optimising the route directly.

While static models provide valuable insights, they fail to capture the dynamic nature of infrastructure development. Temporal dynamism is crucial for understanding the impact of changing conditions over time. Existing models often assume perfect foresight in hydrogen [7,8] and CCTS [9-11] network design, where infrastructure is designed to accommodate a known future state. André et al. applied a backward approach to describe the time development of hydrogen networks, starting with the target year and retrospectively determining the configurations, therefore optimising the infrastructure for the end point. Becattini et al. [10] provided a more advanced perfect foresight approach which leverages the uptake forecast to optimise the CCTS network across all time steps. The study examines a 25-year time horizon using both static and dynamic cases to discover that the optimal dynamic strategy delays the installation of infrastructure to reduce overall costs by leveraging discounted future flows.

These approaches simplify the design process but do not mirror real-world decision-making processes and constraints, limiting its applicability to network strategists and planners. Perfect foresight assumes a level of certainty and coordination that rarely exists in practice, overlooking the iterative, adaptive nature of infrastructure development. Delaying investments risks increased long-term costs, lost opportunities for early adoption, and challenges in stakeholder alignment.

In contrast, rolling-horizon models adopt a myopic approach, where infrastructure is developed incrementally in response to immediate needs and uncertainties. Few pipeline infrastructure network models utilise non-anticipatory rolling-horizons frameworks. Johnson and Ogden [12] demonstrated this approach with their HyPAT model, which simulates hydrogen infrastructure deployment under a staged, rolling-horizon framework. However, the model's broader limitation lies in its flexibility to adapt routing and pipeline design between time steps, reducing its ability to fully explore and optimise network evolution in response to shifting spatial and operational demands.

The advantages of rolling-horizon models are grounded in their capacity to address shortcomings of perfect foresight approaches. First, as Papadimitriou and Fortz [13] argue, rolling-horizon models better reflect real-world decision-making by breaking long-term plans into iterative and manageable stages. Second, they are inherently adaptive, enabling designs to respond dynamically to changes in demand, technology, and policy over time. Third, and central to this study, is the idea that strategic insights derived from perfect foresight models overlook the complexities of real-world uncertainties. Unlike static optimisations models, rolling-horizon models integrate recourse decision-making, where future uncertainties unfold sequentially, allowing adjustments at each stage based on updated information. This aligns with principles of stochastic control and dynamic programming, which highlight the benefits of making decisions that evolve over time rather than relying on fixed, foresight-dependent solutions [14].

Building on these principles, this study introduces a novel rolling-horizon methodology for designing pipeline networks that grow incrementally while addressing complex spatial constraints. Unlike existing models that assume straight-line connections between nodes [7-10] or rely on predefined candidate networks [4,5,11,12], this approach allows the network to evolve freely. By removing the reliance on candidate networks, the methodology accommodates adaptive routing configurations that reflect real geographical constraints.

To demonstrate the applicability of this approach, the study explores the co-design of CCTS and hydrogen infrastructures, with a focus on the transition from blue to green hydrogen production. This transition poses risks such as stranded assets and operational challenges, which the proposed methodology uncovers. As far as the authors are aware, no prior studies have investigated the co-design of these infrastructures with high spatio-temporal resolution and adaptability, further underscoring the novelty of this contribution.

The methodology is described in Section 2, which is applied to the case study described in Section 3. Section 4 discusses the findings and results, and Section 5 concludes this work.

METHODOLOGY

Network Design

The proposed methodology is built upon the multi-stage approach presented in Hammond et al. [15] and Hammond et al. [6], where the routing is defined using a modified Steiner tree with Obstacles Genetic Algorithm (StObGA) [16]. The premise is that the network, described by the genome, converges on an optimal network configuration by learning to traverse across the cost surface made up of polygonal obstacles which represent geographic constraints.

This study presents an algorithmic development that enables the rolling-horizon designs of spatially-aware routes across complex terrains. At each time step, the algorithm minimises the weight network length (L_n^w), as defined in Equation 1. This is calculated over the set of arcs A, where each arc (i,j) consists of obstacle-constrained lengths ($L_{ij,o}^{obs}$) weighted by penalty w_o for obstacles $o \in O$, and obstacle-free lengths (L_{ij}^{free}).

$$min(L_n^w) = \sum_{(i,j)\in A}(\sum_{o\in O_{ij}} L_{ij,o}^{obs} \cdot w_o + L_{ij}^{free}) \quad (1)$$

The genetic algorithm's genome, given in Equation 2, describes the infrastructure's network in two parts: 1) the locations of terminal nodes, Steiner points, and bifurcation nodes; and 2) fixed-length binary list that determines which corners points of the polygonal obstacles are activated. Bifurcation nodes are introduced as nodes that are placed along existing arcs to allow for flexible expansion from a previous network structure.

$$\big((x_1, y_1), (x_2, y_2), \dots, (x_s, y_s)\big) + [1\ 0\ 1\ 0\ 0\ 0\ 1\ 1\ 0\ 0] \quad (2)$$

The pipeline design optimisation is a MINLP formulation that minimises the total pipeline costs (C) according to the objective function given in Equations 3 and 4. The capital cost (C_{ij}^C) for each arc (i, j) in the network is determined by the number of parallel pipelines (N_{ij}^p), the outer diameter (D_{ij}^{po}), and the weighted pipeline length (L_{ij}^w). The network's operating cost is assumed to be 4% of the capital cost annually. Hydraulic, structural, and commercial availability constraints are considered as described in Hammond et al. [6]. The pipeline sizes are oversized to align with the optimal final infrastructure configuration in 2050.

$$\min C = (1 + 0.04) \sum_{i|(i,j)\in A} C_{ij}^C \quad (3)$$

where

$$C_{ij}^C = N_{ij}^p (61e^{2.74D_{ij}^{po}} + 376\big(D_{ij}^{po}\big)^2 + 2290D_{ij}^{po} + 278)L_{ij}^w \quad (4)$$

Geographic Information System

The Geographic Information System (GIS) created for this study, depicted in Figure 1, is the collation of many constraints collected from publicly available datasets. These constraints are grouped into category penalties, informed by the literature [17], technical reports [18], and confidential discussions with industry experts, presented in Table 1.

Table 1: Categories of geographical features with corresponding penalty weighting.

Penalty category	Geographic features	Penalty weighting
Untraversable	National parks	∞
Very high	Rivers	50
High	Urban areas, conservation areas	5
Medium	Woodlands, historic landfills	3
Low	Roads, rails, peaty soils	1.2

CASE STUDY

The case study explores CCTS and hydrogen infrastructure design in the Humber region of the UK, a significant industrial hub with high emissions density. Two scenarios are compared across six time steps to assess their impact on the economic viability of CCTS infrastructure: 1) Blue hydrogen production plants transition to green hydrogen production in 2040; and 2) Blue hydrogen production plants continue operating without transitioning to green hydrogen.

The purpose of comparing these scenarios is to investigate the impact that this transition has on the economic viability of the CCTS infrastructure.

The study evaluates a network consisting of 9 hydrogen production plants, 45 hydrogen consumers, and

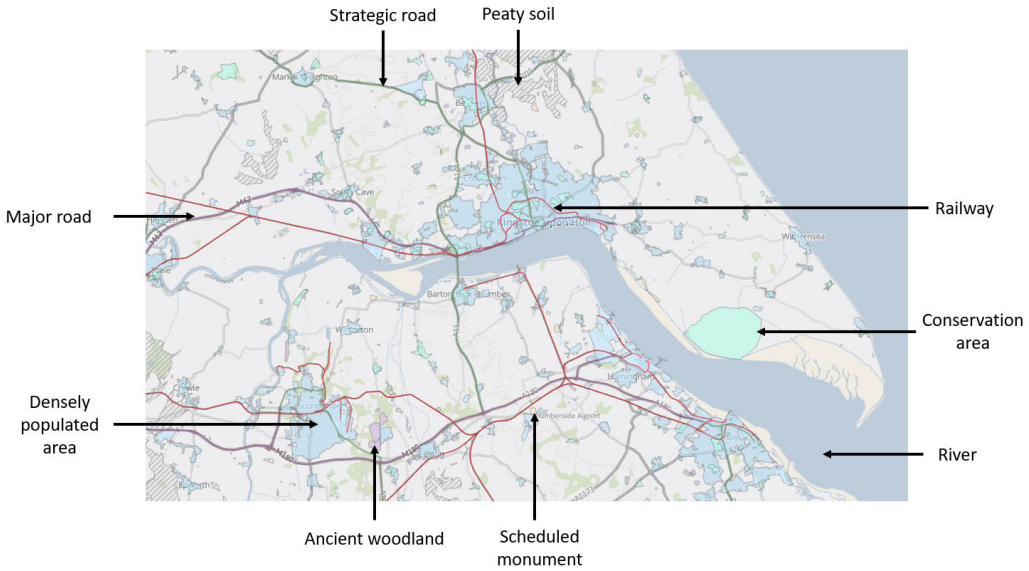

Figure 1: Geographical features considered for pipeline routing in the Humber, UK case study.

21 CO_2 capture facilities. Captured CO_2 is transported to a designated offtake point, where it is considered stored. The model assumes the presence of compressor stations at all sites with fluid outflows and at junctions where multiple pipelines converge. These stations compress hydrogen to 70 bar and CO_2 to 35 bar, ensuring efficient transport.

Pipeline design includes 817 unique combinations of inner and outer diameters, ranging from DN6 to DN2300, with a wide range of schedules. This broad range accommodates different operational and economic scenarios, ensuring flexibility in network optimisation.

RESULTS AND DISCUSSION

Design analysis

Figure 2 compares the rolling-horizon and 2050-optimised designs for hydrogen and CCTS infrastructure. The rolling-horizon approach (A1, B1) results in an incremental network expansion, with early-stage infrastructure aligning with immediate demand and gradually adapting over time. In contrast, the 2050-optimised design (A2, B2) represents an idealised final-state configuration, assuming perfect foresight of future requirements.

A visual analysis highlights the topological differences that emerge as a result of the iterative nature of rolling-horizon designs. As shown in B1 and B2, the 2050-optimised design takes a route south of the river, whereas the rolling-horizon planning approach follows a northern route. This divergence occurs due to the sequential nature of rolling-horizon planning – the network expands based on immediate cost and connectivity considerations, without foresight of potential long-term inefficiencies. As a result, rolling-horizon designs may lead to routing decisions that, while reasonable given the available information at each stage, may require adjustments as the network evolves.

Figure 3 illustrates the capital investment trends for the hydrogen and CCTS infrastructures over time, comparing rolling-horizon expenditures with the total cost of the 2050-optimised network. The difference in capital investment between these approaches is substantial. Given the high cost of pipeline infrastructure, even small inefficiencies in routing and capacity planning result in significant financial losses. For hydrogen infrastructure, rolling-horizon inefficiencies result in an additional 23.4 million USD in capital expenditures, accounting for approximately 8% of the total investment. Similarly, for CCTS infrastructure, the inefficiency gap amounts to 7.2 million USD, also around 8% of the required investment.

While the 2050-optimised design achieves greater cost efficiency, it assumes perfect foresight which is not attainable in real-world infrastructure planning. Rolling-horizon approaches, by contrast, reflect the iterative design-making process that network designers must navigate. This study highlights not only the financial

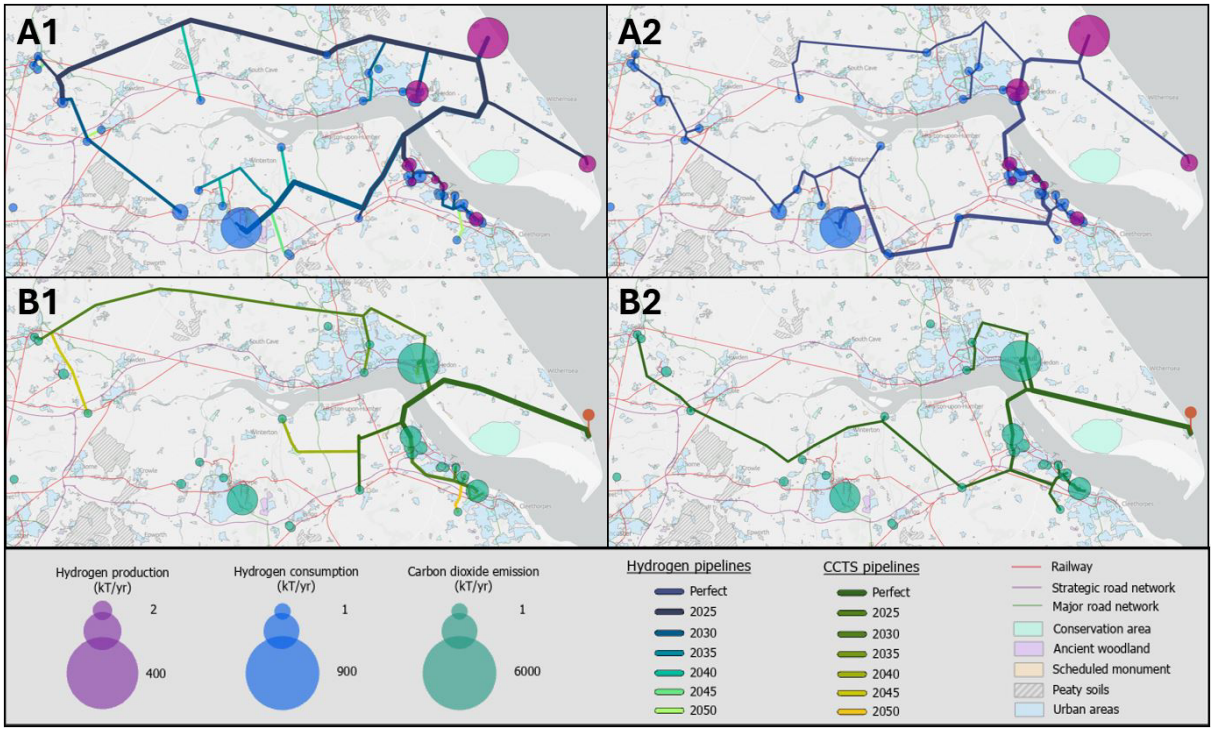

Figure 2: Rolling-horizon (A1, B1) vs. 2050-optimised (A2, B2) designs for hydrogen (A) and CCTS (B) infrastructure in the Humber region.

implications of rolling-horizon inefficiencies, but also the importance of developing strategies to mitigate them.
The design tool presented here provides a framework to test rolling-horizon strategies under various potential scenarios. By integrating uncertainty-aware decision-making, future iterations of rolling-horizon planning can minimise inefficiencies while maintaining the flexibility needed to adapt to evolving demands, technological advancements, and policy changes.

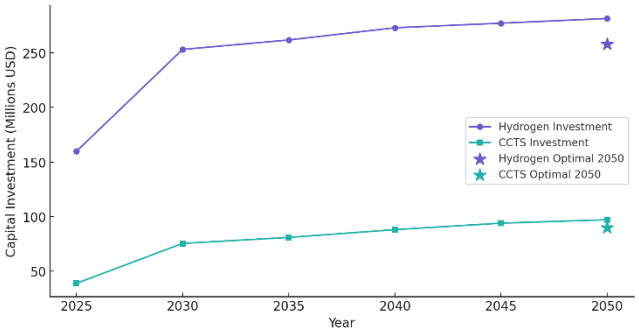

Figure 3: Capital investment in hydrogen and CCTS infrastructure over time, comparing rolling-horizon investments with the optimal 2050 configurations.

Table 2 compares the capital investment required per tonne of CO_2 saved under the two scenarios. The results indicate a 20-fold increase in CCTS infrastructure costs per tonne of CO_2 when blue hydrogen production transitions to green hydrogen. This surge occurs because hydrogen plants, which previously served as major CO_2 capture points, no longer contribute to CCTS infrastructure utilisation, reducing overall system efficiency.

It is also worth noting the operational difficulties that will coincide with such a massive reduction in fluid volume in the pipelines.

This finding underscores the interconnected nature of low-carbon infrastructure development. Decisions made in one sector, such as hydrogen production, can have significant economic and operational consequences for another, such as CCTS. As a result, strategic planning must account for cross-sector uncertainties and the evolving role of different infrastructures to avoid cost escalations and stranded assets.

Table 2: CO_2 Savings Cost ($/Tonne$CO_2$) for Hydrogen & CCTS (2025–2050). Scenario 1: Blue hydrogen; Scenario 2: Transition to green in 2040, increasing CCTS costs.

Year	Hydrogen Infrastructure ($/Tonne$CO_2$)	CCTS scenario 1 ($/Tonne$CO_2$)	CCTS scenario 2 ($/Tonne$CO_2$)
2025	423	128	128
2030	30	18	18
2035	35	21	21
2040	37	25	505
2045	42	28	544
2050	46	31	597

Critical analysis of the model

Model validation for StObGA in a previous work [6], showed >98% accuracy in predicting route length, confirming its reliability in network design.

Unlike traditional methods, StObGA does not rely on predefined candidate networks but evolves the network by bifurcating existing pipelines. This enhances flexibility and adaptability. The model is highly scalable and provides a framework for incorporating design standards, regulations, and future scenarios testing through rules build into the genetic algorithm, making it valuable for long-term planning.

A key limitation is its inability to anticipate future uncertainties in network expansion, as it optimises only for current constraints. This may limit its effectiveness in dynamic or evolving infrastructure needs.

Simulates were run on a Precision 7875 Tower (AMD Ryzen Threadripper Pro 7945WX, 12 cores, 64 GB RAM), requiring ~2 hours for infrastructure design. Parallelisation improves performance, reducing computation time compared to sequential processing significantly.

CONCLUSION

This study demonstrates the advantages and limitations of rolling-horizon methodologies for designing hydrogen and CCTS pipeline infrastructure in the context of heavy-industry decarbonisation. While rolling-horizon models offer a more flexible and realistic approach by accommodating evolving spatial and operational constraints, they introduce inefficiencies compared to long-term optimised designs. The case study analysis highlights how incremental infrastructure expansion can lead to higher capital expenditures and suboptimal routing decisions over time. Furthermore, the transition from blue to green hydrogen production presents significant challenges for CCTS infrastructure, with the cost per tonne of CO_2 increasing substantially as hydrogen plants cease to contribute to CO_2 capture. These findings emphasise the need for hybrid modelling approaches that balance flexibility with long-term cost efficiency. Future work should focus on integrating uncertainty-aware decision-making frameworks into rolling-horizon models to mitigate inefficiencies while ensuring adaptability to emerging technologies, policy shifts, and market dynamics.

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