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Least-regret hydrogen infrastructure design under demand uncertainty

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Abstract

This study presents a routing-and-sizing framework for hydrogen pipeline networks that minimises max regret across uncertain demand. An obstacle-aware genetic algorithm generates corridors over a weighted-GIS surface; a multi-period hydraulic sizing step selects commercial diameters subject to pressure, velocity, and wall-thickness constraints. Decisions are taken in a rolling-horizon so topology and capacity adapt as information arrives. Applied to the UK Humber cluster from 2030 to 2050, built length reaches 165-200 km, with a Spine-First routing strategy averaging 185km. Least-regret oversizing adds £40 m compared to a myopic approach but cuts 2040 worst-case incremental outlay from £260 m to < £80 m. By 2050, Spine-First achieves £2.07 m/km, LCOT 54 £/kt and regret 12 £/kt, rivalling a Perfect-Foresight strategy (44 £/kt; 3 £/kt). The results show how a short, centrally aligned trunk combined with anticipatory sizing reduces stranded-asset risk and budget shocks, providing a transferable least-regret template for hydrogen pipelines under deep uncertainty.

Keywords: Hydrogen Infrastructure, GIS, Least-regret, Energy Networks, Genetic Algorithm

1. Introduction

Hydrogen pipeline planning is a sequencing decision under uncertainty: where should a trunk corridor be placed, and how much capacity should be built now versus later as demand locations evolve? Early commitments are geographically specific and capital intensive; mis-sequencing risks stranded assets, while well-timed choices smooth programme budgets and preserve options. Hydrogen networks are anticipated to expand substantially in the coming decades, supporting decarbonisation in hard-to-abate sectors such as steel, power, and chemicals. At present, approximately 4,500 km of dedicated hydrogen pipelines exist worldwide [1]. However, meeting net-zero targets will require long-distance transport of hydrogen from production hubs to dispersed consumption sites at scales beyond what current infrastructure can accommodate economically or logistically [2–4]. Given hydrogen's low volumetric energy density and projected scale of consumption, dedicated pipelines are expected to be the most efficient and economically competitive option across a wide range of distances [2, 5]. Recently announced pipeline projects suggest

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that global requirements may increase nearly tenfold, exceeding 40,000 km by 2035 [6]. Despite these ambitious proposals, only around 2% of projects have progressed to a Final Investment Decision (FID), underscoring a significant gap between intent and implementation. A key reason for this gap is the complexity of planning infrastructure investments under deep uncertainty about future hydrogen markets and regional demand patterns [7].

Decisions on pipeline routing and diameter are taken early in a project's life-cycle and embed large, long-lived capital outlays in specific geographies. These commitments must be made while demand trajectories, technology costs, regulatory environments, and stakeholder acceptance remain highly uncertain [6, 8], raising the risk of costly misallocation and stranded assets. These uncertainties motivate hedging rather than optimising for a single forecast. National scale, data-driven robust optimisation shows adaptive planning outperforms static, supporting uncertainty-aware design [9]. The decision problem is to choose routing and sizing strategies that minimise regret under route misalignment and sizing shocks as uptake timing and location evolve.

Pipeline design confronts a structural trade-off between economies of scale and option value. Construction costs rise less than linearly with diameter, so the marginal cost of extra capacity is relatively low, while retrofitting or looping a pipe is technically disruptive and often more expensive than installing the larger line at the outset [10–12]. Oversizing a trunk segment can prevent future bottlenecks; however, prematurely committing to an oversized network can also backfire-Middleton and Yaw [13] quantify the 'cost of getting CCS wrong', demonstrating that early overbuilds may strand significant capacity and increase levelised costs by up to 40% under plausible demand shortfalls. A comparable dilemma occurs in route selection: a route that deviates toward uncommitted industrial sites raises near-term expenditure yet may reduce long-run system cost by shortening later branches; conversely, a minimal-cost direct route defers those outlays but may necessitate expensive detours when additional nodes materialise. Balancing these sizing and routing options against uncertain spatial-temporal growth is therefore central to prudent pipeline planning. Two hypotheses follow from this trade-off: (i) a short, centrally aligned trunk may reduce regret even if total length is not minimal; and (ii) a modest front-loaded oversizing may compress the budget-shock.

In response to such deep uncertainty, infrastructure planners are increasingly adopting least-regret (minimax-regret) approaches, which evaluate candidate strategies by their maximum opportunity cost relative to an ideal strategy tailored to each possible future. Originally introduced by Savage [14] and developed in robust optimisation contexts [15], the minimax-regret criterion avoids probabilistic assumptions and prioritises robustness over precision. It has been applied across energy and infrastructure systems planning [16, 17] and forms a core component of the broader Decision-Making under Deep Uncertainty (DMDU) framework [18]. Rather than relying on point forecasts, least-regret analysis seeks solutions whose performance remains satisfactory across a wide ensemble of plausible demand and policy scenarios. This criterion is attractive for irreversible infrastructure because it values designs that cap worst-case under-performance without committing to scenario probabilities, aligning with appraisal under uncertain industrial participation.

Within the context of pipeline infrastructure, Nicolle and Massol [12] develop an analytical minimax-regret model for a single linear pipeline and show that "build-to-proven-demand" strategies are systematically regret-maximising, formalising an established intuition that building ahead of demand can minimise long-run cost [11]. While this confirms the value of spare capacity in simple settings, oversizing within a network is more complex: future flows depend on when and where supply and demand emerge, making the benefits of extra capacity harder to predict and highly location-specific.

Bogs et al. [19] extend the regret approach to a multi-period CO_2 network, optimising pipeline designs to minimise regret across different industrial uptake scenarios. Their work shows that strategic oversizing of key routes can significantly reduce the cost of adapting to future demand changes. However, the model is limited by a simplified design representation and a fixed candidate network generated from pairwise shortest paths over a coarse spatial grid. This routing approach captures connectivity but does not guarantee a globally efficient network configuration, since it does not minimise total system cost across all nodes simultaneously. Additionally, the model abstracts pipeline design by omitting fluid dynamics and wall-thickness considerations, limiting its ability to assess the spatial and economic implications of sizing decisions.

Similar limitations are found in related CO_2 and hydrogen network models. Existing hydrogen or CO_2-pipeline design studies fall into three routing categories: (i) candidate-route models that restrict pipelines to roads or rights-of-way [10, 20]; (ii) grid or raster path-finding that links source-sink pairs via A* or Dijkstra on cost surfaces [19, 21, 22]; and (iii) graph-based Steiner or minimum-spanning approaches that minimise network length holistically while accounting for obstacles [23]. Sizing methods likewise range from fixed-velocity linear approximations [24, 25] to mixed-integer hydraulic formulations that couple pressure drop and wall-thickness constraints [23, 26, 27]. Most combine one routing family with one sizing surrogate and solve either for perfect foresight or myopic rolling horizons. Only Bogs et al. [19] consider regret metrics with limited design detail.

Table 1 summarises representative pipeline-network studies against planning-relevant features—obstacle-aware geography, multi-period treatment, minimax-regret objectives, enforced hydraulics with discrete commercial diameters, endogenous topology—and indicates whether each paper analyses least-regret in routing and in sizing.

Prior work covers important parts of the problem but not in combination. Endogenous, GIS cost–aware routing has been demonstrated (e.g., obstacle-aware Steiner/graph formulations) [23, 31, 37], and hydraulically credible sizing with catalogue diameters is also available [29, 30]. Regret-based evaluation under uncertainty has been explored—analytically for a single line [12] and for multi-period networks with simplified routing/design physics [19].

Table 1: Comparative features of pipeline network planning studies. Ticks indicate features treated in each study; see cited papers for scope and assumptions.

Study (year)	Commodity	Obstacle aware	Multi period	Hydraulics enforced	Discrete diameters	Endogenous topology	Topological regret analysis	Sizing regret analysis
This study (2025)	H_2	✓	✓	✓	✓	✓	✓	✓
Hammond et al. (2025) [23]	H_2	✓	-	✓	✓	✓	-	-
Bogs et al. (2025) [19]	CO_2	✓	✓	-	-	✓	-	✓
Nicolle & Massol (2023) [12]	H_2/CO_2	-	-	-	-	-	-	-
Mikulicz-Radecki et al. (2022) [28]	H_2	-	-	-	✓	-	-	-
Weber and Papageorgiou (2018) [29]	H_2	-	-	✓	✓	✓	-	-
Pedersen et al. (2024) [30]	CO_2	-	-	✓	✓	-	-	-
Ma et al. (2023) [31]	CO_2	✓	✓	-	✓	✓	-	-
Budiarto et al. (2025) [32]	CO_2	-	✓	-	-	✓	-	-
Efthymiadou et al. (2025) [33]	H_2	-	✓	-	-	✓	-	-
Hasturk et al. (2024) [34]	H_2 + gas	-	✓	-	✓	✓	-	-
Becattini et al. (2022) [35]	CO_2	-	✓	-	-	✓	-	-
Azhar et al. (2024) [36]	CO_2	-	-	✓	-	-	-	-
Velasco-Lozano et al. (2024) [37]	CO_2	✓	-	-	✓	✓	-	-
Solomon et al. (2024) [38]	CO_2	-	-	✓	✓	-	-	-

To our knowledge, no cited study integrates all three elements—endogenous GIS-based topology, hydraulic/structural sizing with discrete diameters, and regret-based comparison across multiple spatial uptake paths—whereas this paper does, and demonstrates the approach on the Humber cluster.

Specifically, this study aims to address the identified gaps and advance existing work through the following contributions:

- A decision framework that compares routing-sizing strategies under spatial uptake uncertainty using worst-case and average regret and a simple budget-shock risk metric.
- An formulation of obstacle-aware Steiner routing with multi-period hydraulic sizing (endogenous topology; pressure-drop and wall-thickness constraints; discrete commercial diameters), enabling cost/regret evaluation.
- An analysis of the placement of early trunk lines and design of these to reduce tail-risk, using seven deterministic 2030-2050 uptake pathways for the Humber cluster as a policy-relevant test bed.
- Insights that link strategy choice to uptake patterns, capital constraints, and risk tolerance, expressed via regret and budget-shock metrics.

The remainder of this paper is organised as follows: Section 2 introduces the model and analysis methodology. Section 3 introduces the UK-based regional case study. Then Section 4 details the results and corresponding discussion. Finally, Section 5 concludes the study by discussing the key insights and impact of this investigation.

2. Methodology

2.1. Pipeline network design

The rolling-horizon pipeline network design workflow is illustrated in Figure 1. It comprises two nested loops. The outer loop steps through real decision years; once a decision is taken it is committed. At each time step, the inner loop forms a small ensemble of forward uptake paths by sampling per-site, per-period participation probabilities $\pi_{i,t+1:t^\star}$ and, for each sampled path, routes and sizes the forward network conditional on already-built assets. From these forward designs the model derives a capacity envelope for assets to be built now (element-wise maxima of required capacity across the ensemble), and uses that envelope to choose current diameters.

At each time period the model assigns each site i a participation probability $\pi_{i,t}$ from a weighted score: $\pi_{i,t} = 0.3\, s_i + 0.7\, u_i$, where s_i is a normalised size score (constructed from reported production/consumption capacity on a log scale) and $u_i \sim \mathcal{U}(0,1)$ is a random term. The 0.3:0.7 split was calibrated to ensure larger sites appear in more than half the ensemble while preserving wide uncertainty. Forward uptake paths are then generated by applying discrete thresholds $\tau \in \{0.3, 0.4, 0.5, 0.6, 0.7\}$ to $\pi_{i,t}$ in each future period.

Network routing is instantiated with an obstacle-aware Steiner generator (StObGA; 39), previously applied to pipeline routing [23]. The objective in Equation 1 minimises the total weighted length of network edges over a GIS cost surface; obstacle weights w_o follow **??**.

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

n a candidate network; A set of network edges (arcs) (i,j); O_{ij} set of obstacle polygons intersected by edge (i,j) (**??**); L_n^w total weighted network length; $L_{ij,o}^{\text{obs}}$ length of (i,j) inside obstacle o; w_o penalty weight for obstacle class o; L_{ij}^{free} length of (i,j) outside all obstacles.

The algorithm iteratively evolves a population of networks across multiple generations. In each generation, high-performing network configurations are selected, mutated, and recombined via crossover to create new candidates. The process continues until the algorithm converges on a near-optimal solution. Compared to deterministic pathfinding approaches, the GA's stochastic nature allows for more diverse exploration of the solution space, which is particularly useful when navigating complex and discontinuous cost surfaces.

Each network configuration generated by the algorithm is encoded as a genome, shown in Equation 2. The first part of the genome encodes the positions of Steiner points and intermediate edge points, The second part consists of a fixed-length binary vector that determines which corner points of polygonal obstacles are incorporated into the network. This genome structure allows the algorithm to efficiently explore both network geometry and obstacle

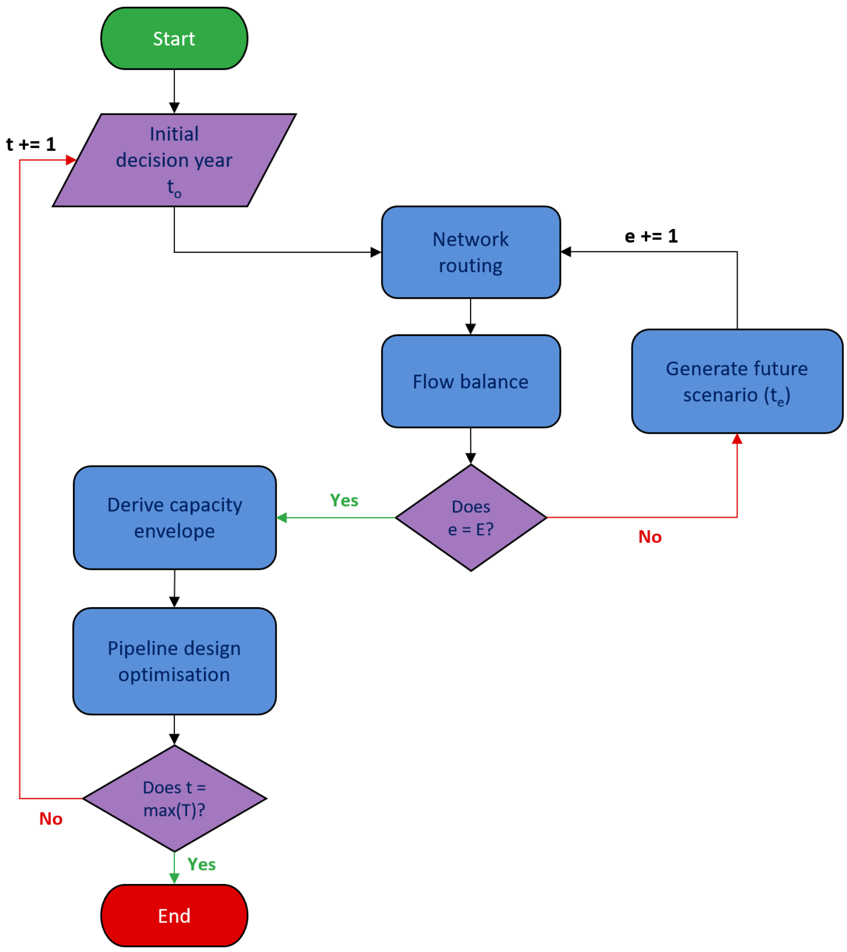

Figure 1: Schematic of the two-loop least-regret workflow. The outer loop steps through actual build years; the inner loop probabilistically samples future participation and sizes pipes to bound costs before returning to the present decision point. See **??** for pseudocode and further details.

avoidance strategies within a unified optimisation framework.

$$\{(x_1, y_1), \ldots, (x_s, y_s)\} \parallel \begin{bmatrix} 1 & 0 & 1 & 0 & \cdots & 0 \end{bmatrix} \tag{2}$$

(x_k, y_k) coordinates of Steiner/intermediate points ($k = 1, \ldots, s$); s number of continuous geometry points; right-hand binary vector toggles inclusion of candidate obstacle-corner points (1 = include, 0 = exclude); "‖" denotes concatenation of continuous and binary parts.

To support incremental growth across periods, new segments may bifurcate from the interior of existing edges as well as from existing nodes. We insert intermediate junction candidates along built edges (represented in the continuous part of the genome) and assign those edges a reduced traversal cost to bias reuse and staged expansion.

After defining the network's configuration, a flow balance is applied to determine the hydrogen flow rates through the network and to remove redundant or unused edges, ensuring that supply and demand are balanced across the network while preserving feasibility.

Subsequently, a pipeline sizing optimisation (PSO) minimises capital cost subject to hydraulic, structural, and commercial (catalogue) constraints. Unlike snapshot designs, diameters are chosen to satisfy constraints for a set of period-specific flows on each arc, enabling evaluation of staged strategies under uptake uncertainty. The key hydraulic and structural relationships (Darcy–Weisbach, Swamee–Jain closure, hoop-stress thickness, velocity bound), catalogue selection, and the multi-flow feasibility formulation are detailed in **??** (Sections C.2–C.9). We use mass flow Q (volumetric $q = Q/\rho$).

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

where

$$\forall (i,j) \in A. \quad C_{ij}^{C} = N_{ij}^{p} (61 e^{2.74 D_{ij}^{po}} + 376 (D_{ij}^{po})^2 + 2290 D_{ij}^{po} + 278) L_{ij}^{w} \tag{4}$$

C total capital cost; C_{ij}^{C} construction cost on edge (i,j); A set of built/design edges; N_{ij}^{p} number of parallel pipes on (i,j); D_{ij}^{po} outside diameter (m); L_{ij}^{w} weighted length from Eq. 1; coefficients follow the adopted diameter–cost relationship; the factor $(1 + 0.04)$ reflects the operating-cost uplift. Hydraulic/structural feasibility and catalogue constraints are enforced per **??**.

2.2. Regret analysis

Regret analysis is used to evaluate the robustness of infrastructure design strategies under uncertainty by comparing each strategy's performance to the best available alternative in each scenario. The performance metric applied is the Levelised Cost of Transport (LCOT), which represents the discounted unit cost of transporting one kilotonne of hydrogen. For a given design strategy i in scenario s, LCOT is calculated as shown in Equation 5:

$$\text{LCOT}_{i,s} = \frac{\sum_{t \in T} \frac{C_{i,t,s}}{(1+r)^t}}{\sum_{t \in T} \frac{Q_{i,t,s}}{(1+r)^t}} \tag{5}$$

Here, $C_{i,t,s}$ is total cost in period t, $Q_{i,t,s}$ is transported quantity in period t, r is the real discount rate, and T is the set of decision periods (2030, 2040, 2050).

A real discount rate of 7% is applied, consistent with the mid-range hurdle rates (7-8%) reported by Europe Economics for merchant gas-fired and CCUS assets in BEIS's 2018 cost-of-capital update [40], and identical to the central 7% rate used by the IEA for OECD energy-infrastructure LCOE analysis [41]. This figure represents a typical post-tax weighted-average cost of capital for privately financed energy infrastructure and lies within the 6-8% range commonly assumed for mid-stream pipeline investments.

Regret $R_{i,s}$, defined in Equation 6, for each strategy i in scenario s is defined as the difference between its LCOT and the minimum LCOT achieved by any strategy in that scenario:

$$R_{i,s} = \text{LCOT}_{i,s} - \min_{j} \left(\text{LCOT}_{j,s}\right) \tag{6}$$

Two aggregate regret metrics are used to summarise the performance across all S scenarios. Maximum regret identifies the worst-case underperformance of a design, given in Equation 7:

$$R_i^{\text{max}} = \max_{s \in S} \left(R_{i,s}\right) \tag{7}$$

Average regret captures the expected deviation from the optimum, given in Equation 8:

$$R_i^{\text{avg}} = \frac{1}{S} \sum_{s \in S} R_{i,s} \tag{8}$$

i design strategy; j strategy index used in the inner minimum; s deterministic evaluation scenario; S set of scenarios (size S); $R_{i,s}$ regret; R_i^{max} maximum regret; R_i^{avg} average regret.

A design strategy is considered robust if it exhibits low maximum regret, ensuring acceptable performance even under adverse scenarios. Low average regret indicates consistently good performance across a wide range of plausible futures.

3. Case study

This case study focuses on the Humber cluster in the United Kingdom, the country's most emissions-intensive industrial region and a key area of interest for hydrogen and carbon capture infrastructure development. The region includes a dense concentration of emitters and potential hydrogen users, as well as proximity to offshore CO_2 storage in the North Sea and several planned low-carbon projects, making it a high-potential zone for early pipeline deployment. These characteristics provide a realistic and policy-relevant test case for evaluating least-regret infrastructure strategies under uncertainty. A full list of case study sites, including their locations, supply/demand values, and sector, is provided in **??**. The routing engine has been validated previously against the published initial Humber hydrogen infrastructure build at corridor scale [23]; here we retain that engine and focus on multi-period strategy evaluation.

3.1. Geographic Information System

Determining the geographical constraints for pipeline routing requires extensive data collection and geographic information system (GIS) analysis. In this study, a range of environmental and anthropogenic constraints were considered, including densely populated areas, peaty soils, conservation areas, national parks, rivers, scheduled monuments, and ancient woodlands. In addition to these are linear (polyline) constraints that impose routing penalties for crossings over major roads and railways. These features were selected to reflect real-world engineering and permitting considerations.

All constraints were digitised, mapped, and classified as shown in Figure 2, and their associated penalty weightings are listed in **??**. A combination of GIS tools in the ArcGIS Pro software suite was used to process, simplify, and aggregate these features into routing-ready polygon and polyline layers suitable for integration with the StObGA model.

3.2. Scenario framework and planning strategies

To assess the implications of strategic decision-making in pipeline network design, seven deterministic uptake scenarios were constructed. The scenarios span three time periods–2030, 2040, and 2050–and capture variation in both the scale and spatial distribution of hydrogen demand and supply within the Humber region. These scenarios are:

- Maximum (S1), Medium (S2), and Low (S3) uptake — reflecting different overall levels of hydrogen adoption.
- Moderate uptake with plateau (S4) or decline (S5) — representing non-linear growth trajectories.
- North of river (S6) and South of river (S7) — capturing spatial asymmetry in regional participation.

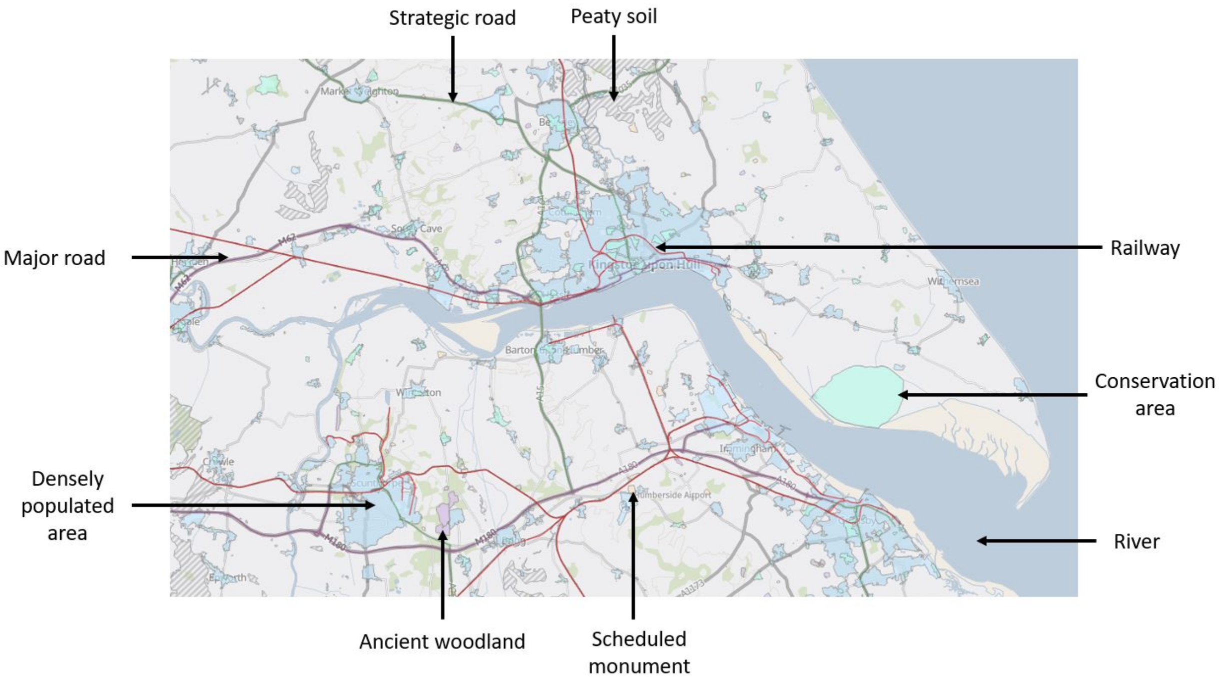

Figure 2: Geographical constraints considered by the genetic algorithm. Densely populated areas, protected habitats, transport routes and other features are transformed into penalty-weighted polygons.

Each deterministic scenario is used only for ex post evaluation: it fixes which sites are active in 2030, 2040, and 2050. The planning model does not observe this; at each decision period it takes the sites confirmed active and the assets already built, traces a least-cost route to connect them, and then forms a small ensemble of forward uptake paths by probabilistically sampling which sites join in future periods (from per-site participation probabilities; details in Section 2). For each sampled path it extends the network and records the flows required on any segments commissioned for the given decision period. These forward requirements are summarised as a capacity envelope for the time period's segments and used to choose their diameters; the decisions are then committed and the process rolls forward to the next time step.

To investigate the effect of planning assumptions on network cost and adaptability, four distinct routing strategies are applied:

1. **Myopic:** Infrastructure is routed and sized sequentially, one time period at a time, based only on currently active sites. This strategy represents limited foresight and emphasises near-term performance.

2. **Perfect-Foresight:** Infrastructure is routed and sized based on perfect prior knowledge of industrial participation in the final year (2050). Although not achievable in practice, this strategy provides a benchmark for comparison by illustrating infrastructure that is optimally designed for a known final outcome. Evaluating this

strategy reveals how infrastructure configurations optimised exclusively for a single future scenario perform when implemented incrementally across earlier planning periods.

3. **Spine-First:** Infrastructure follows the existing route proposed by the Northern Endurance Partnership (NEP) initiative in the Humber. This strategy grounds the analysis in practical considerations, building upon real-world plans developed specifically for carbon capture and hydrogen deployment in the Humber region. The model adheres to this predefined route while allowing flexible expansion to accommodate evolving site participation over time.

4. **Peripheral Route:** Similarly anchored in real-world proposals, this strategy aligns with the infrastructure plan set out by the Humber Low-Carbon Pipelines (HLCP) project. As with the Spine-First route, this strategy begins with a fixed initial network, subsequently permitting flexible extensions to meet additional or emerging demands identified at each planning horizon.

To further evaluate the influence of design flexibility, two alternative sizing strategies are applied across all routing strategies and uptake scenarios. The first is a least-regret sizing strategy, which proactively oversizes pipeline capacity in the near term to accommodate uncertainty in future demand, thereby reducing the risk of costly future expansions. In contrast, the second is a short-horizon sizing strategy, which sizes pipelines strictly according to currently confirmed participation, prioritising minimal initial investment. While this approach avoids upfront overbuilding, it may incur higher costs and reduced adaptability if future demand exceeds expectations. Comparing these two sizing approaches across varying routing and demand scenarios helps clarify trade-offs between early capital expenditure and long-term cost efficiency.

4. Results and discussion

4.1. Overview of key metrics and routes

Table 2 summarises key cost and efficiency metrics for the four routing strategies across all scenarios, highlighting differences in overall performance. Hydraulic and structural relationships used in all evaluations are hydrogen-specific and are detailed in **??**.

The **Perfect-Foresight** strategy achieves the lowest mean total CAPEX (£367.50m) and highest investment efficiency (0.41 Million pounds per kiloton of hydrogen (£m/kt)), reflecting its foresight of the final industrial landscape. It also attains the lowest levelised cost of transportation (LCOT) at 44.37 £/kt and the lowest regret at just 2.96 £/kt. However, substantial variability ($\pm$£114.06m in total CAPEX) underscores its sensitivity to scenario-specific details, illustrating that even optimal endpoint-driven designs can incur significant cost variation when intermediate planning periods are considered. Additionally, as seen in Figure 3, the final routes for the Perfect-Foresight strategy vary significantly between scenarios, demonstrating unpredictable paths that would be challenging to implement into a sequential strategy.

Table 2: Aggregate cost-effectiveness metrics across all scenarios. Spine-First rivals Perfect-Foresight on cost per-km and regret despite longer total length, while Peripheral Route is consistently the most expensive and least efficient.

Strategy	Mean $\pm$ SD (£ m)	Invest. Eff. (£ m/kt)	Cost/km (£ m/km)	LCOT (£/kt)	Regret (£/kt)
Myopic	428.70 ± 79.75	0.60 ± 0.58	2.62 ± 0.44	60.53 ± 67.32	19.12 ± 40.63
Perfect-Foresight	367.50 ± 114.06	0.41 ± 0.26	2.17 ± 0.44	44.37 ± 27.01	2.96 ± 5.32
Spine-First	381.61 ± 61.72	0.52 ± 0.51	2.07 ± 0.46	53.84 ± 55.99	12.42 ± 29.49
Peripheral Route	465.37 ± 83.41	0.64 ± 0.59	2.33 ± 0.44	67.50 ± 72.19	26.09 ± 45.34

Among realistic strategies, the **Spine-First** route consistently outperforms **Myopic** and **Peripheral Route**, demonstrating lower mean CAPEX (£381.61m), cost per km (£2.07m/km), LCOT (53.84 £/kt), and regret (12.42 £/kt). Interestingly, despite Spine-First and Peripheral Route developing consistently longer infrastructure networks than the Myopic and Perfect-Foresight strategies (as shown in Figure 3), Spine-First remains highly cost-efficient—challenging even the Perfect-Foresight baseline. The superior economic performance of Spine-First is not due to minimising total network length but rather to strategically positioning a short, centrally-aligned trunk line, enabling efficient expansion to additional sites. This accords with Heijnen et al. [42]: in capacitated network design, minimising trunk length (not total length) preserves flexibility for later expansions. For hydrogen, pressure drop scales with velocity and inversely with diameter (**??**); keeping the high-flow trunk short therefore reduces cumulative losses and stabilises downstream sizing as participation grows.

The Myopic strategy, in contrast, exhibits moderate total CAPEX (£428.70m) but higher cost per km (£2.62m/km), indicating inefficiencies resulting from its sequential, near-term decision-making process. Figure 3 illustrates that Myopic's routes are highly scenario-dependent and unpredictable. Although the Myopic strategy minimises the route's length in the short-term, the infrastructure becomes more inefficient over time as more sites participate. Consequently, Myopic incurs higher LCOT (60.53 £/kt) and regret (19.12 £/kt) relative to Spine-First and Perfect-Foresight.

The Peripheral Route strategy is consistently the costliest, with the highest mean CAPEX (£465.37m), investment efficiency (0.64 £ m/kt), LCOT (67.50 £/kt), and regret (26.09 £/kt). Figure 3 shows that Peripheral Route's economic underperformance primarily results from its geographically disadvantageous alignment along the southern periphery of the cluster. As new industrial sites participate further north, pipeline expansions incur substantial incremental costs due to increased pipeline lengths, highlighting the risks associated with initial route misalignment.

For planners, the route choice matters more than total length: align the common corridor through the centre of gravity of demand and avoid peripheral alignments that lock in long laterals. Use Regret and the budget-shock metric

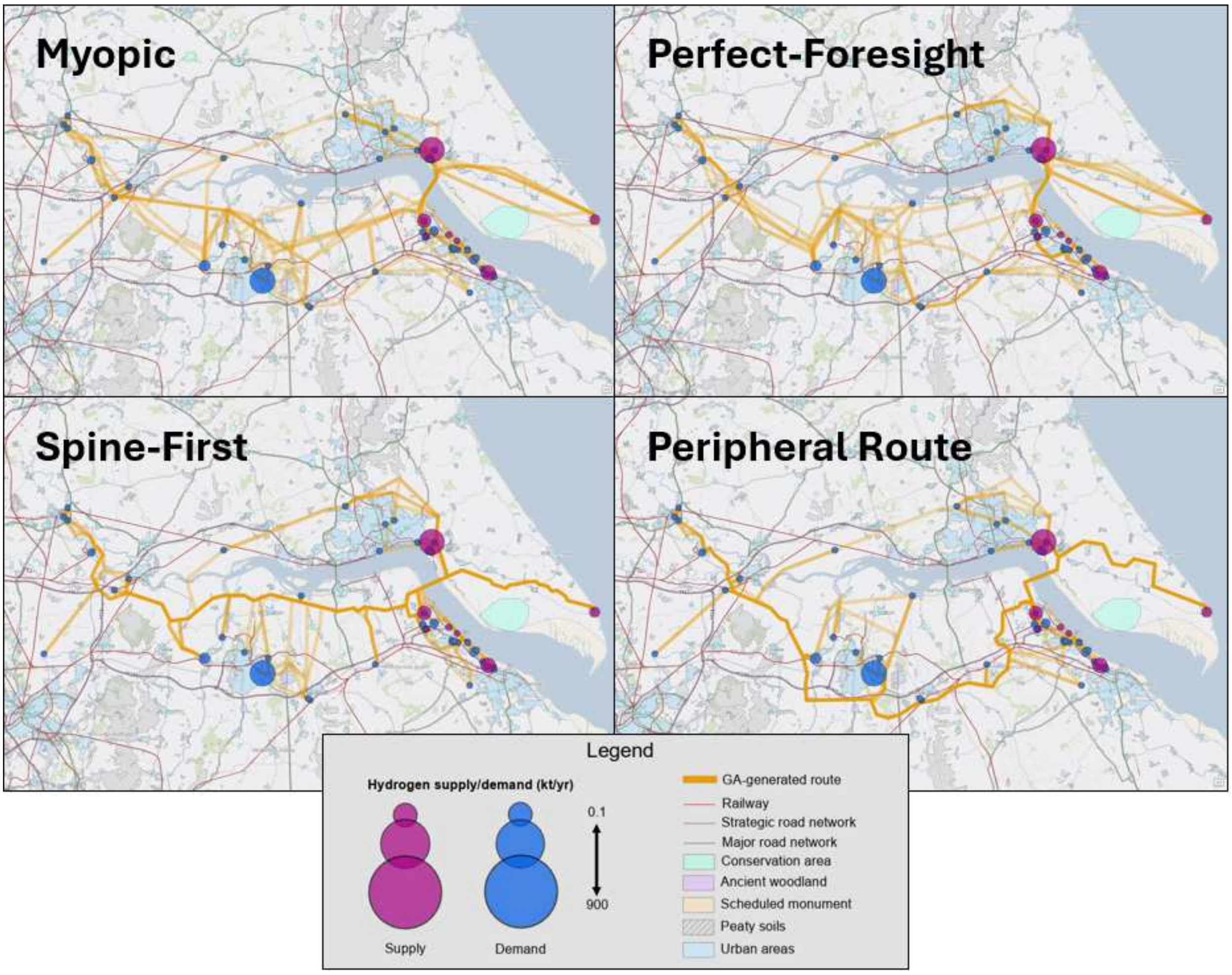

Figure 3: Aggregated final hydrogen network layouts (2050). Thick orange lines show the GA-generated route; node bubbles are net hydrogen supply/demand (kt/yr). Base layers: rail, strategic/major roads, conservation areas, ancient woodland, scheduled monuments, peaty soils, urban areas.

alongside NPV/LCOT to screen options that look acceptable on average but carry heavy tails.

4.2. Temporal evolution of the infrastructure

Figure 4 illustrates the sequential growth of the pipeline network under the Myopic strategy for Scenario 1, highlighting how early infrastructure decisions influence later developments. The maps reveal a clear phased "spine-and-branch" growth pattern: in 2030, a primary east-west trunk line bridges the Humber, connecting major supply and demand centres. By 2040, the trunk infrastructure connects shorter radial branches appearing to serve emerging secondary locations. This incremental expansion continues into 2050, with further branching toward more remote sites as the network matures and diversifies.

The orange links overlaying each panel are forecasts: they depict the routes that a forward-looking sizing algorithm would provisionally allow for when dimensioning today's pipes. Their fate provides a visual "forecast realism" check. Many orange links in one frame do become part of the built network in the next, illustrating the value of anticipatory sizing when projections align with eventual demand. Yet several never turn blue, exposing the least-regret strategy's vulnerability to stranded route speculation—capacity is reserved (and pipe diameters upsized) for flows that ultimately fail to materialise. This highlights the trade-off: forecasting can reduce the need for parallel piping and upgrading pipes, but it also risks oversizing and unused links if demand diverges.

Figure 5 shows the evolution of regret across the four routing strategies for the years 2030, 2040, and 2050. The overall temporal trend reveals that regret decreases significantly for all strategies as time progresses, accompanied by a notable compression of distributions. Initially wide and varied, regret ranges narrow considerably by 2050, highlighting how sequential build-out gradually equalises some of the early disadvantages that strategies might incur.

Comparing across strategies, Spine-First consistently demonstrates low median regret and minimal variability throughout all planning horizons, reflecting robustness derived from its centrally-aligned trunk line. In contrast, the Myopic strategy shows substantial sensitivity to demand patterns: although competitive in median regret terms, its regret distributions remain broad across all years, indicating vulnerability to scenarios where future site participation diverges significantly from early patterns. This fragility results in occasional high regret, arising from redundant routes and inefficient sizing in later periods. Perfect-Foresight exhibits high early-stage variability, where route misalignment heavily penalises certain scenarios, yet its perfect foresight ultimately delivers superior performance by 2050. Peripheral Route remains disadvantaged at all stages, confirming how initially peripheral routes lock in persistently higher costs even after long-term network development.

Figure 6 presents a "stacked-tile" view of normalised regret. Within each scenario, regrets are linearly rescaled so that 0 and 1 correspond to the lowest- and highest-cost strategies respectively. The colour scale therefore conveys relative rather than absolute performance for every strategy, scenario, and planning year. Purple denotes the best

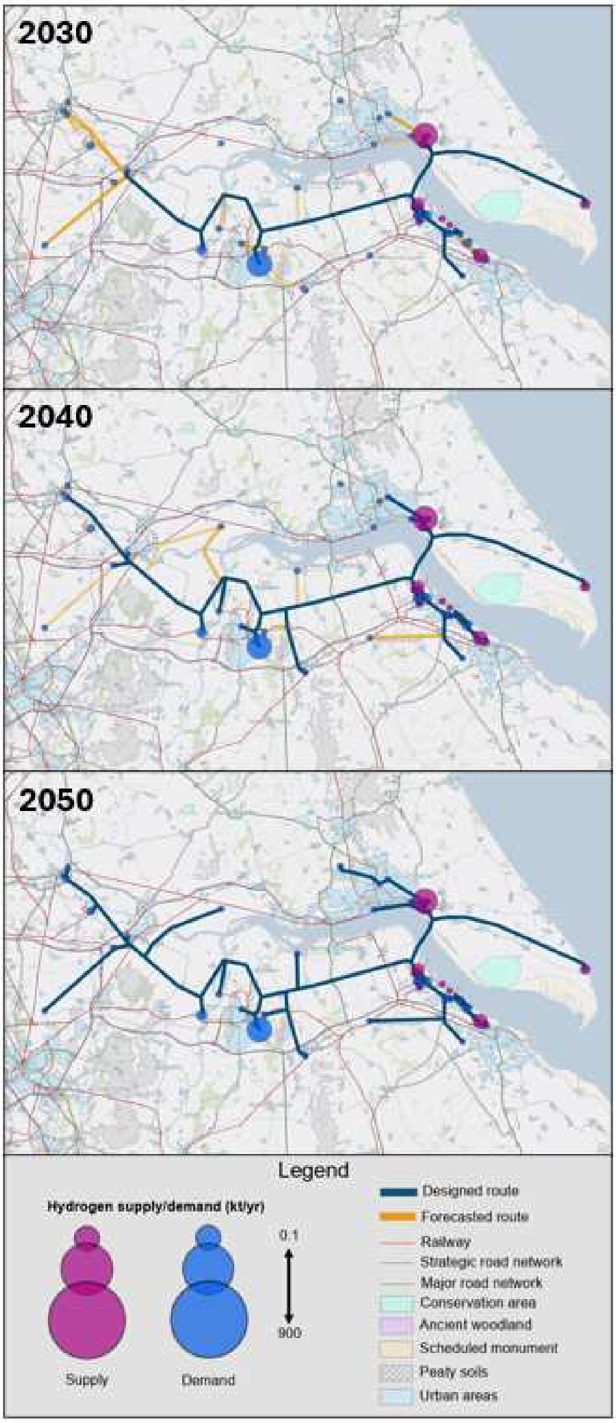

Figure 4: Sequential build-out of the designed hydrogen network. Blue = designed route; orange = forecast capacity allowances used at the prior decision point. Node bubbles are net hydrogen supply/demand (kt/yr).

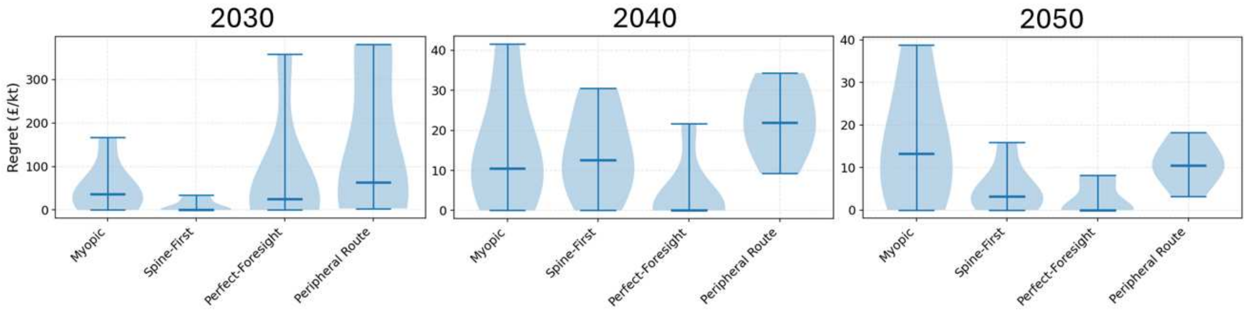

Figure 5: Distribution of levelised-cost regret by strategy over time. Vase width shows scenario spread; median markers shrink towards zero as 2050 approaches, with Spine-First consistently narrow and Peripheral Route widest.

performer in a given scenario-year combination, while yellow marks the worst.

In the first build-out period the Myopic and Spine-First strategies exhibit uniformly low or medium regret (predominantly purple-to-pink tiles). Both benefit from short, centralised routes: Myopic achieves the shortest total length in 2030 by design, and Spine-First minimises the length of its trunk line. By contrast, Peripheral Route is consistently the poorest performer (yellow tiles) because its southern alignment offers little flexibility when early adopters lie to the north or east of the Humber. There are two scenarios in which the Perfect-Foresight strategy delivers the lowest regret. In these cases, the optimal 2050 route happens to align closely with the path chosen by the Myopic strategy, so there is little spatial difference between the two. However, Perfect-Foresight holds an advantage by sizing infrastructure with perfect knowledge of final demand, avoiding the unnecessary overbuilding seen in other strategies that anticipate future flows which do not fully emerge. As a result, Perfect-Foresight achieves lower costs at the 2030 stage despite not explicitly optimising for short-term conditions. In other scenarios, where its route diverges from the more efficient early-stage alignments of Spine-First or Myopic, the additional length offsets its sizing advantage and leads to higher regret.

By 2040, colour patterns begin to diverge. Myopic regret becomes less consistent, showing a mix of purple and pink tiles alongside three scenarios with high regret, indicating uneven performance as the network expands. Spine-First remains consistent across most scenarios, confirming that a centrally routed trunk line continues to pay dividends with growing site participation. Perfect-Foresight tiles shift from pink to purple—its anticipatory sizing advantage increasingly offsets earlier routing penalties. Peripheral Route continues to perform poorly, remaining predominantly yellow.

In the final year the Perfect-Foresight strategy attains the best relative performance in the majority of scenarios, shown by widespread purple tiles in the top layer. Spine-First stays competitive—often sharing the top rank—because its short trunk still minimises distance-related costs even after successive expansions. Myopic displays medium-to-high regret, confirming that a purely sequential approach incurs lasting penalties once full build-out is reached. The

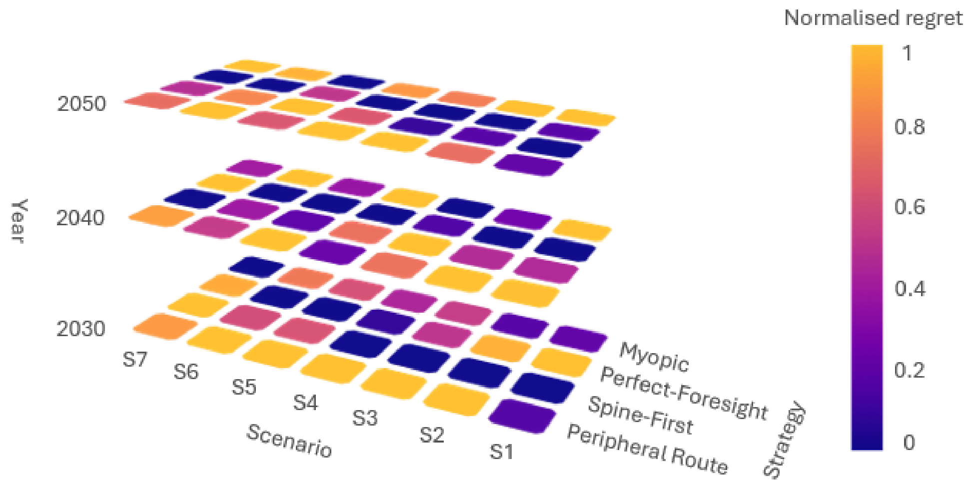

Figure 6: Heat-map of normalised regret for every strategy–scenario–year. Values are scaled within each scenario–year to [0,1]; lower (purple) is better.

only scenario where Myopic is the lowest regret is Scenario 5 where industry participation drops in 2050. Peripheral Route remains the weakest strategy across all scenarios.

Two broader lessons follow. First, a strategy that only minimises length (Myopic) may appear favourable at the outset yet accrue substantial regret over time. Second, planners can close much of the gap to the Perfect-Foresight ideal by combining a short, centrally located trunk line with judicious—though not excessively speculative—oversizing, as exemplified by Spine-First. Future work should therefore focus on integrated optimisation methods that jointly determine both trunk alignment and stage-wise capacity, rather than treating routing and sizing as separate problems.

For planning, sequence matters: commit to links that recur across scenarios and treat low-agreement branches as options with explicit triggers. Keeping the shared corridor short and centrally placed preserves flexibility while limiting the cost of later expansions.

4.3. Pipeline sizing analysis

Figure 7 compares incremental capital expenditure (CAPEX) profiles for the Spine-First routing strategy under two contrasting sizing policies: the least-regret strategy (purple), which proactively oversizes pipeline diameters to accommodate uncertain future demand, and a short-horizon strategy (orange), which only sizes pipelines for currently confirmed demand.

The least-regret policy front-loads investment, incurring a median incremental CAPEX of approximately £270m in 2030, around £40m greater than the short-horizon (no-oversizing) alternative. While this higher initial expenditure might appear disadvantageous, it provides sufficient spare capacity that virtually no pipeline resizing is required in 2040, resulting in a significant reduction of median incremental CAPEX to approximately £55m. Conversely,

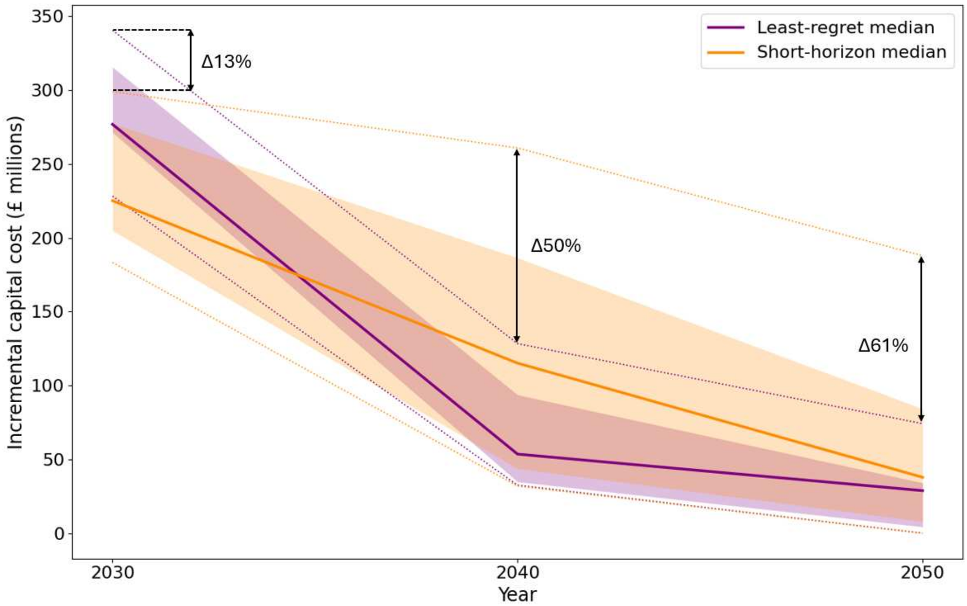

Figure 7: Front-loading vs deferral trade-off. Least-regret oversizing (purple) spends £40 m more in 2030 but median and tail-risk CAPEX by 2040; short-horizon sizing (orange) postpones cost but faces larger, lumpier outlays later.

the short-horizon strategy, while initially cheaper, faces substantial costs (£120m median in 2040) associated with resizing or duplicating pipelines once previously uncertain demands materialise.

An important implication is observed in the narrowing of the cost risk envelope under the least-regret policy. After the initial investment peak, both the interquartile range and worst-case CAPEX scenarios reduce dramatically: the upper bound shrinks from more than £330m in 2030 to approximately £130m by 2040. In contrast, the short-horizon strategy retains higher exposure to risk, with maximum CAPEX in 2040 remaining above £260m. This highlights how delaying investment decisions can expose planners to substantial financial uncertainty and budgetary risk, whereas proactive oversizing contributes significantly to financial predictability. Modest early oversizing on trunk segments reduces hydrogen frictional losses and the need for later duplication or recompression (**??**).

Further advantages of the least-regret strategy emerge when considering project financing and operational implications. The smoother incremental CAPEX profile is typically easier to finance due to its predictability, reducing the number of contractor mobilisation cycles and minimising disruptions associated with repeated construction phases. Early oversizing also improves hydraulic efficiency and leaves headroom for unforeseen offtakers or outages—benefits not captured by CAPEX alone.

Despite the apparent risk of stranded capacity should demand growth underperform, the least-regret approach demonstrates limited downside in the worst-case scenario, converging quickly towards low incremental CAPEX values by 2040 and 2050. Moreover, when assessed through discounted cash flow analysis, the higher upfront expenditure can be substantially offset by subsequent savings, reinforcing the financial appeal of proactive oversizing.

Table 3: Temporal comparison of short-horizon versus least-regret sizing. Upfront oversizing loses the 2030 "headline" contest but overtakes by 2040, reducing both average cost and regret—except for the highly path-dependent Myopic route.

Year	Strategy	Avg. CAPEX (£ m) (short-horizon)	Avg. CAPEX (£ m) (least-regret)	Avg. LCOT (£/kt) (short-horizon)	Avg. LCOT (£/kt) (least-regret)	Avg. Regret (£/kt)
2030	Myopic	240.6	308.2	398	609	-211
	Perfect-Foresight	257.1	295.5	422	517	-95
	Spine-First	238.9	288.5	425	548	-123
	Peripheral Route	276.5	355.6	486	728	-242
2040	Myopic	385.1	384.9	108	124	-16
	Perfect-Foresight	381.0	344.0	111	48	63
	Spine-First	363.0	355.9	93	82	11
	Peripheral Route	414.2	432.4	119	98	21
2050	Myopic	458.0	428.7	63	50	13
	Perfect-Foresight	426.5	367.5	62	33	29
	Spine-First	421.6	381.6	46	40	6
	Peripheral Route	490.4	465.4	73	46	27

Table 3 compares short-horizon and least-regret sizing strategies across routes and time periods. The short-horizon approach shows an initial advantage in 2030, with consistently lower CAPEX and LCOT. However, this lead is quickly lost by 2040 as demand grows and the need for mid-life resizing arises. At this stage, least-regret sizing takes over: its upfront investment enables more predictable and minimal incremental CAPEX, providing better control over infrastructure rollout. In contrast, the short-horizon strategy begins to lose control, with rising and more variable costs as previously undersized pipelines require expansion or duplication.

The Myopic route stands out as an exception. Unlike Spine-First, Peripheral Route, or Perfect-Foresight—each of which follows a relatively stable and foreseeable build-out—Myopic grows in a more opportunistic and irregular manner. This limits the effectiveness of least-regret sizing, as oversizing often occurs on routes that do not see an uptake in capacity. As a result, Myopic retains higher levels of CAPEX and regret in both sizing strategies, reflecting the compounding costs of sequential, short-term routing decisions. Meanwhile, strategies with more predictable expansion paths—especially Spine-First and Perfect-Foresight—demonstrate how combining route stability with anticipatory sizing leads to more efficient and resilient network outcomes.

For delivery, modest early diameter on trunk segments smooths spend and curbs tail risk; apply it where flows are consistently concentrated, not on opportunistic spurs.

4.4. Limitations of analysis

Several limitations frame these results. All totals are discounted at a real 7% rate; higher rates would tilt choices towards deferral and smaller initial diameters, whereas lower rates favour earlier trunk placement and modest oversizing. Operating costs are represented as a 4% uplift on CAPEX rather than explicit compressor siting and energy, which likely values designs that reduce frictional losses conservatively. Hydraulics are steady and isothermal with arc–average density; transients, linepack and detailed compressibility are not modelled. Structural checks enforce thin–wall hoop–stress rules and catalogue schedules (**??**); fracture control and hydrogen embrittlement management are not explicit. Routing costs rely on stylised obstacle weights (**??**); local permitting, geotechnics and crossing–method choices are not endogenised. Finally, participation scenarios are generated from size–weighted probabilities with thresholds; correlated adoption and policy clustering are not explicit. Taken together, these caveats indicate the findings are comparative across strategies rather than absolute cost predictions.

5. Conclusions

This study shows that two early choices—where to place the first trunk and how much to oversize—drive long-run cost and risk. In the Humber case, a short, centrally aligned trunk with modest least-regret oversizing delivered average CAPEX of £382 m and £2.07 m/km, within 4% of the theoretical benchmark, whilst avoiding the stranded capacity seen in peripheral or purely shortest-today routes. Peripheral alignment had the highest cost and regret (£465 m CAPEX), and the shortest-path approach ended with the largest tail risk.
Three policy-relevant conclusions follow:

1. Additional capacity provides insurance. Modest early oversizing raises the 2030 outlay by £40 m but cuts the 2040 worst-case incremental CAPEX from £260 m to <£80 m. Smoother spend beats disruptive mid-life rework.

2. Secure the core route early. Prioritise a short, centrally aligned trunk and let demand-led branches snap on later. Keeping the trunk short reduces cumulative friction losses and later branch lengths.

3. Appraise with tails in mind. Report maximum-regret and the budget shock (largest period-to-next CAPEX) alongside NPV/LCOT, and use them to reject options that jeopardise budgets or tariffs under adverse uptake.

These conclusions are commodity-agnostic and can be embedded at the pre-FEED stage for hydrogen, CO_2, or multi-product routes. For system modellers, the results underline the importance of co-designing routing and sizing decisions rather than treating them as separable stages. Incorporating capacity considerations into the routing objective points towards more realistic, implementable layouts; a natural extension is a capacitated, multi-source/multi-sink routing engine over real geographies that captures the interplay between pipe diameter and topology.

A key limitation is reliance on an author-defined scenario set. Future work should evaluate robustness against a broader ensemble of market and policy trajectories. Coupling the routing model with an agent-based decision model is a promising direction: allowing participation likelihoods to emerge endogenously from infrastructure availability, economics, and policy would create feedback between infrastructure and uptake, helping identify plans that not only withstand uncertainty but also shape it in a favourable direction.

CRediT author statement

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