Optimisation of Carbon Capture and Storage Infrastructure in an Integrated UK Energy System

Introduction

With the global average temperature reaching 1.55°C above pre-industrial levels in 2024, overshooting the Paris Agreement's critical limit of 1.5°C, the pursuit to halt global warming becomes urgent rendering the decarbonisation of energy systems imperative. While geological CO_2 storage is considered vital to deep decarbonisation, detailed geological characteristics are still frequently overlooked in system-level optimisation studies, instead represented with aggregated or effectively unconstrained parameters. This can limit insights into how real-world considerations like cumulative storage capacity, injection rates, and proximity to offshore infrastructure may enable - or more importantly limit - when and where CO_2 can be stored at scale using CCS (Bennæs et al., 2024; Wang et al., 2025). These questions are especially pertinent to national energy system planning, where capacity can directly limit how rapidly and broadly CCS can be deployed to meet long-term emissions goals (CCC 2025).

This study addresses this problem by developing an integrated optimisation framework for the UK energy system that explicitly represents geological CO_2 storage through reservoir-level cumulative capacity, injectivity constraints, and transport network access. CO_2 emitted from energy supply technologies is captured, transported through a pipeline network, and injected into offshore geological storage sites within the model. Rather than treating storage as a passive end point, the framework allows storage availability to shape the scale, timing, and feasibility of CO_2 capture deployment endogenously under long-term emissions constraints.

Methodology

Model overview and assumptions

This study addresses a long-term energy system planning problem: how to deploy carbon capture, transport, and geological storage infrastructure in a cost-effective way under economy-wide emissions constraints. The objective is to minimise total system cost over the planning horizon while meeting electricity and hydrogen demand and complying with a prescribed emissions trajectory.

The problem is formulated as a deterministic, multi-period mixed-integer linear programming (MILP) model from a central planner perspective and implemented in GAMS. The model represents an integrated electricity–hydrogen–CO_2 supply chain for Great Britain over 2025–2050 at a five-year time resolution. It endogenously determines investments in CCS infrastructure and the operation of energy and CO_2 flows across regions.

Electricity and hydrogen demands are specified exogenously and met domestically. Short-term operational dynamics are not represented, and electricity shedding is allowed but penalised to ensure feasibility. CO_2 emissions from energy supply technologies are constrained in line with UK Future Energy Scenarios (NESO, 2024).

CO_2 is generated from fuel consumption, captured via standalone and retrofit CCS, transported through a pipeline network, and injected into offshore geological storage reservoirs. Storage is represented using discrete reservoirs with cumulative capacity and annual injectivity limits, based on publicly available screening-level assessments (Bentham et al., 2014; Bachu, 2016). All CO_2 transport and injection flows are expressed in tCO_2/yr, consistent with the annual model resolution.

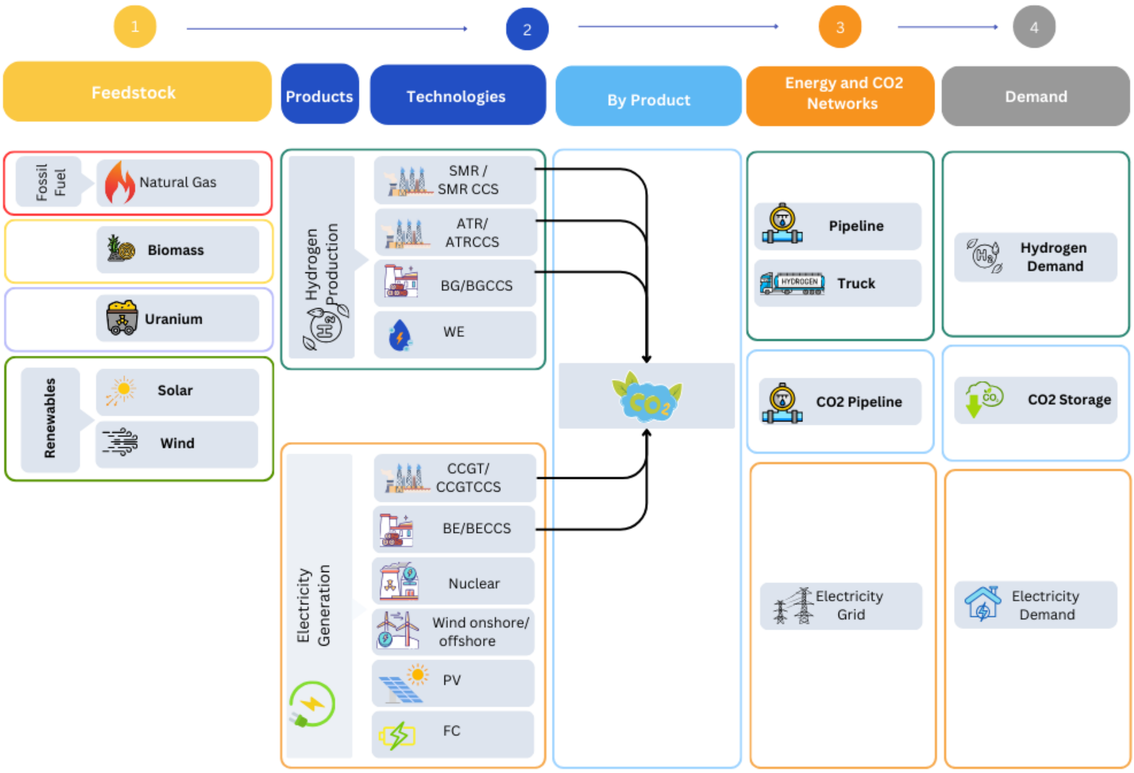

Figure 1 *Integrated optimisation model infrastructure*

Mathematical formulation

The model is formulated over five regions $g \in G$and five planning periods $t \in \mathrm{T}$ For each region and period, electricity and hydrogen balances ensure consistency between production, inter-regional transmission, and demand.

Energy balance

For each energy carrier $i \in$ Error! Bookmark not defined., region g, and period t, supply from generation and imports equals demand and exports, allowing for load shedding:

$$\sum_{j \in J;;IJ_{i,j}} Q_{i,j,g,t} + \sum_{gg \in N^1_{g,gg}} \sum_{tr \in ITR_{i,tr}} QT_{i,gg,g,t} = \sum_{gg \in N^1_{g,gg}} \sum_{tr \in ITR_{i,tr}} QT_{i,g,gg,t} + D_{i,g,t} - Shed_{P,g,t} \qquad \forall i \in \{H, P\}, g, t \quad (1)$$

CO_2 is generated endogenously from fuel consumption in energy supply technologies. Captured CO_2 originates from both newly installed CCS-equipped technologies and retrofit CCS applied to existing assets:

$$Q^C_{g,t} = \sum_{j \in Jnew} Q^{CCS}_{j,g,t} + \sum_{j \in Jold} Q^{retro}_{j,g,t} \qquad \forall g, t \qquad (2)$$

Captured CO_2 is constrained by supply-chain emissions, technology efficiencies, emission factors, capture rates, and installed capture capacity.

CO_2 mass balance

At each region and period, captured CO_2 and inter-regional inflows are balanced against transport to storage as shown by eq. (3).

$$Q^{C}_{g,t} + \sum_{gg \in N^{1}_{g,gg}} \sum_{tr \in ITR_{CO_2,tr}} QT_{CO_2,gg,g,t} = \sum_{gg \in N^{1}_{g,gg}} \sum_{tr \in ITR_{CO_2,tr}} QT_{CO_2,g,gg,t} + \sum_{s \in N^{2}_{g,s}} \sum_{tr \in ITR_{CO_2,tr}} QS_{i,tr,g,s,t} \quad \forall g,t \tag{3}$$

Geological CO_2 storage constraints
Geological storage is represented using discrete offshore reservoirs s. The cumulative stored CO_2 inventory evolves as given by eq. (4).

$$ISTOR_{s,t} = ISTOR_{s,t-1} + \sum_{s \in N^{2}_{g,s}} \sum_{tr \in ITR_{CO_2,tr}} QS_{i,tr,g,s,t} \qquad \forall g,t \tag{4}$$

Each reservoir is subject to a total storage capacity constraint as shown in eq.(5).

$$ISTOR_{s,t} \leq CAPSTOR_s \qquad \forall s,t \tag{5}$$

and an annual injectivity constraint below:

$$\sum_{g \in N^{2}_{g,s}} \sum_{tr \in ITR_{CO_2,tr}} QS_{i,tr,g,s,t} \leq CAPINJ_s \qquad \forall s,t \tag{6}$$

This formulation ensures that both long-term storage availability and short-term injection limits directly influence the feasible scale, timing, and regional allocation of CO_2 capture and storage deployment.

Figure 2 *Spatiality explicit CO_2 Balance for region g and gg and fixed year t*

Results and Discussion

Figure 3 shows how electricity, hydrogen and CO_2 infrastructure evolve over the planning horizon. Electricity and hydrogen demand are met in all periods, with no load shedding or renewable curtailment. Total electricity generation increases from around 290 TWh in 2025 to approximately 705 TWh by 2050, reflecting substantial system expansion driven largely by offshore wind and solar, while dispatchable units remain in operation to provide firm capacity.

Hydrogen demand rises towards 2050, reaching around 120 TWh in the final period. Electrolysis contributes in the early years, but as demand grows, supply shifts towards reforming technologies with carbon capture.
Gross CO_2 emissions increase with expanding energy production, while captured CO_2 grows through both standalone and retrofit CCS. In the final period, capture reaches approximately 86 $MtCO_2$, of which around 60% is transported and injected into offshore storage, indicating emerging transport and storage constraints.
Net emissions decline and become net-negative by the end of the horizon. Overall, deep decarbonisation depends not only on renewable expansion and hydrogen scale-up, but on the coordinated development of CO_2 capture, transport and offshore storage within the integrated system.

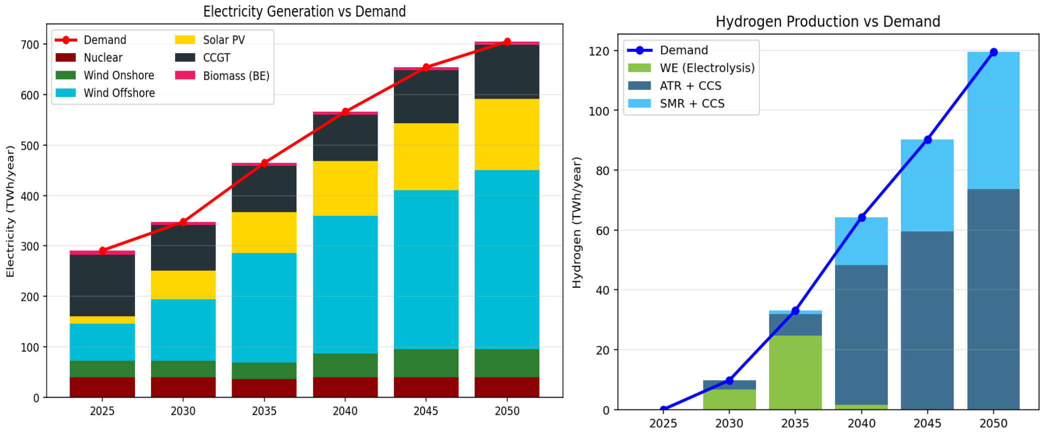

Figure 3 *Electricity generation and hydrogen production (TWh) relative to demand over the planning horizon, showing technology contributions and system feasibility.*

Conclusions

This study presents an integrated optimisation framework that explicitly represents geological CO_2 storage within a UK energy system model. The results show that CCS deployment is governed by storage capacity and injectivity, which shape the timing and scale of capture. Decarbonisation relies on the coordinated expansion of renewables, hydrogen production, and CO_2 capture, transport and offshore storage, with net-negative emissions achieved only once capture and storage are sufficiently scaled.

Future work will incorporate direct air capture (DAC) and assess CO_2 utilisation pathways such as enhanced oil recovery (EOR) to examine how alternative carbon management options interact with storage availability and system performance.

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