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# Multi-period least cost optimisation model of an integrated carbon dioxide capture transportation and storage infrastructure in the UK

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## Abstract

The commercial deployment of $CO_2$ capture and storage (CCS) technology requires whole system optimisation of the $CO_2$ supply, transport and storage chain under evolving targets or constraints. Most of the earlier attempts to model CCS networks were deterministic steady state models. The very few multi-period spatially explicit CCS models are unable to simultaneously make investment decisions for the three components of the chain for an overall cost optimal solution or they only demonstrate the evolution of the transport network. This work presents a multi-period spatially explicit least cost optimisation model of an integrated $CO_2$ capture, transportation and storage infrastructure. The model is showcased through a case study focusing on the future UK CCS infrastructure. The solution demonstrates the investment requirement and operational strategy for all components of the chain at each phase and, hence, shows how the system evolves through four time periods up to year 2050. The non-intuitive results of the multi-period model confirm that such a tool is essential for large scale CCS deployment.

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*Keywords:*

## 1. Introduction

Single chain CCS demonstration projects are essential first steps in CCS deployment. However large scale commercial deployment of CCS requires a whole system optimisation of an integrated $CO_2$ capture, transportation and storage infrastructure under targets and constraints. Also as the network of sources, sinks and transport links

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expand with an increasing mitigation burden on CCS, dynamic or multi-stage supply chain optimisation becomes essential to determine the optimal evolution of the system and ensure that current and future investment and operational decisions result in an overall minimum cost. Most of the earlier attempts to model CCS networks were deterministic steady state models. A number of publications [1-6] developed CCS supply chain optimisation models which although comprehensive they were only steady state snapshot models. The very few multi-period, spatially explicit CCS models are unable to simultaneously make investment decisions for the three components of the chain for an overall cost optimal solution or they only demonstrate the evolution of the transport network. Multi-period whole system optimisation models have been developed for hydrogen supply chains [7-9] which are similar to CCS. In the field of dynamic whole system CCS optimisation, Kemp and Kasim [10] developed a spatially explicit temporal model that only demonstrated the evolution of the transport infrastructure. Johnson *et al.* [11], Kjärstad *et al.* [12] and Boavida *et al.* [13] developed temporal CCS supply chain models which exhibited the development of CCS according to possible future energy developments. However, these were not based on optimisation and hence unable to simultaneously make decisions for whole system cost optimisation for the three components of the chain. In other words, an optimal source-sink combination was selected prior to the selection of an optimal route.

By extending the work of Prada *et al.* [2], this paper presents a multi-period spatially explicit least cost optimisation model of an integrated $CO_2$ capture, transportation and storage infrastructure, which through a flexible coding environment allows the evaluation of the techno-economic performance of the supply chain under constraints. The model is intended to be integrated with existing storage lifecycle cost analysis tools and eventually expanded towards stochastic optimisation to incorporate uncertainties and provide a solution in the form of an investment strategy.

The remainder of this paper is organised as follows; the next section presents the methodology – this includes the techno-economic modelling of the supply chain components followed by the mathematics of the optimisation model. Section 3 presents a case study which is the evolution of a CCS network through a 40 year planning horizon with respect to the $CO_2$ sources in the UK and the sinks in the surrounding seas. Results and critical analysis are also presented in section 3. Conclusions and final remarks are given in section 4.

## 2. Methodology

### *2.1. Overview of the model*

The model is formulated as a multi-period supply chain optimisation problem. The main and first problem is the cost minimisation associated with the future development and operation of a generic CCS supply chain infrastructure given the:

- Geographical locations of the sources, sinks and any transport constrains
- Emission and storage capacities and the pipelines' maximum flow rate
- The present value of the accumulated future investment and operational costs of capture, transport and storage for all capture and storage sites and all modes of transport
- Capture target at each time period
- All logical or design constraints

The design decisions are made through binary variables and the operational decisions regarding the quantity of $CO_2$ captured, stored and transported are made through integer variables. The objective function to be minimised i.e. the present value of the accumulated future annual capital and operational costs, is a linear function. The model is formulated as a Mixed Integer Linear Programming (MILP) problem in GAMS. All sources and sinks are introduced as nodes. Each node is assigned an emission or storage capacity. A mass balance is performed at each node and transport routes allow for an overall mass balance.

## 2.2. Mathematical Formulation

The objective of the MILP model is to design an evolving CCS supply chain minimising the total net present value of the capital and operational costs associated with the three components of the CCS supply chain summed over all nodes over the entire planning horizon and subject to the model constraints. The individual component calculations are made as follows:

**Nomenclature**

**Sets**

| | |
|---|---|
| i , j | Grid cells |
| p | $CO_2$ phases (gas, dense) for transport via pipeline |
| l | Linearised segments of the pipeline cost curve |
| t | Time periods |
| n(t) | The year number of the first year of each time period t |
| m(t) | The year number of the last year of each time period t |

**Parameters**

| | |
|---|---|
| x(i) | X coordinate of cell i |
| y(i) | Y coordinate of cell i |
| d(i,j) | Distance (km) between cells i and j |
| slope (p,l,t) | Slope (M$/Mt $CO_2$/Km) of pipeline cost curve relevant to phase p, segment l |
| Qmax(p,l) | Maximum flow rate relevant to phase p, segment l in Mt $CO_2$ per year |
| ftc(p,l,t) | Fixed pipeline cost (M$/Km/year) relevant to phase p, segment l |
| a(i,t) | Annual $CO_2$ emission at node i at time t |
| fcc(i,t) | Fixed capital cost of building new capture plant type k within cell i |
| vcc(i,t) | Unit cost of capture (M$/Mt$CO_2$) at node i at time t |
| b(i) | Maximum capacity at node i |
| fsc(i,t) | Fixed capital cost of building new reservoir at node i |
| vsc(i,t) | Unit cost of storage (M$/Mt$CO_2$) at node i at time t |
| Ct(t) | $CO_2$ capture target at time period |
| Leng(t) | Length of time period t |

**Variables**

| | |
|---|---|
| C(i,t) | Annual amount of $CO_2$ captured at node i at time t |
| S(i,t) | Annual amount of $CO_2$ injected into node i at time t |
| Q(i,j,p,l,t) | Annual $CO_2$ flow rate transported via pipeline l, in phase p, between cells i and j at time t |
| Z | Total CCS cost averaged over the planning horizon |
| xt(i,j,p,l,t) | 1 if a transport link of segment l, phase p is built between i and j, 0 otherwise |
| nx(i,j,p,l,t) | Total number of pipelines of segment l built between i and j up to and during time t |
| xcap(i,t) | 1 if a capture facility is built at node i, 0 otherwise |
| nxcap(i,t) | 1 if a capture facility has been built at node i at or prior to time period t, 0 otherwise |
| xstor(i,t) | 1 if a storage facility is built at node i at time t |
| nxsotr(i,t) | 1 if a storage facility has been built at node i at or prior to time period t, 0 otherwise |
| usedcap(i,t) | The total amount of $CO_2$ stored in node i prior to time t |

- Total capture cost

The total capture cost is the sum of capital and operational costs of capture at all nodes over the planning horizon. The former is the sum of the annual cash flows from the time of investment until the end of the horizon each discounted back to present value for all the nodes where the value of the binary variable $xcap(i,t)$ is non-zero. The latter is the sum of the annual variable costs during the period of operation multiplied by the amount of $CO_2$ captured, with each annual cost discounted back to present value.

$$Tot.cap.cost = \sum_{i,t} \{\sum_{n(t)}^{m(t)-1} \frac{vcc(i,t) * C(i,t)}{(1+r)^{n(t)}} + \sum_{n(t)}^{m(tfinal)-1} \frac{fcc(i,t) * xcap(i,t)}{(1+r)^{n(t)}}\} \quad (1)$$

- Total storage cost

The total storage cost is defined as the sum of the capital and operational costs of $CO_2$ injection at all storage points over the entire planning period. The capital cost of storage infrastructure at a storage site is the sum of the annual cash flows from the time of investment until the end of the horizon each discounted to present value for all nodes where the value of the binary variable $xstor(i,t)$ is non-zero. The operational cost of injection is the sum of the annual operational costs of injection each discounted to presented value for the entire period of operation. These costs are then summed over all storage nodes and all time periods.

$$tot.stor.cost = \sum_{i,t} \{\sum_{n(t)}^{m(t)-1} \frac{vsc(i,t) * S(i,t)}{(1+r)^{n(t)}} + \sum_{n(t)}^{m(t-final)-1} \frac{fsc(i,t) * xstor(i,t)}{(1+r)^{n(t)}}\} \quad (2)$$

- Total transport cost

Similarly, the total capital cost of transport is the sum of net present value of all annual fixed costs from the time of investment until the end of the horizon between all nodes where a pipeline has been built. The operational cost is the sum of the net present value of the variable costs for the period of operation multiplied by the quantity transported. The annual fixed and variable cost parameters are per kilometre and hence they are multiplied by the length of the pipeline and summed over all nodes and time periods to calculate the total costs.

$$tot.tran.cost = \sum_{i,j,p,l,t} \{\sum_{n(t)}^{m(t)-1} \frac{slope(p,l,t) * Q(i,j,p,l,t)}{(1+r)^{n(t)}} + \sum_{n(t)}^{m(tfinal)-1} \frac{ftc(p,l,t) * xt(i,j,p,l,t)}{(1+r)^{n(t)}}\} \mathrm{d(i,j)} \quad (3)$$

The model constraints are the following:

- Mass balance: At each node the $CO_2$ captured minus the $CO_2$ injected equals the net flow out of the node

$$\sum_{j,p,l} \{Q(i,j,p,l,t) - Q(j,i,p,l,t)\} - C(i,t) + S(i,t) = 0 \qquad \forall\, i,t \quad (4)$$

- Transport: The annual flow rate from i to j must be less than the maximum pipeline capacity

$$Q(i,j,p,l,t) \le QMax(p,l) * nx(i,j,p,l,t) + QMax(p,l) * nx(j,\mathrm{i},p,l,t) \qquad \forall\, i,j,p,l,t \quad (5)$$

- Capture facilities: The amount captured is limited by the emission and the capture efficiency

$$C(i,t) \le capture\ efficiency * nxcap(i,t) * a(i,t) \qquad \forall\, i,t \quad (6)$$

- Storage facilities: Equation (7) calculates the total $CO_2$ stored at i prior to time t. Equation (8) states that yearly amount injected at node i during t cannot be greater than for example a tenth of the remaining capacity of i for a 10 year time period

$$usedcap(i,t) = usedcap(i,t-1) + s(i,t-1) * leng(t) \qquad \forall\, i,t \tag{7}$$

$$S(i,t) \leq \frac{1}{leng(t)} * \{nxstor(i,t)\, b(i) - usedcap(i,t)\} \qquad \forall\, i,t \tag{8}$$

- Time evolution constraints: Whether a facility exists at node i at time t depends on if a facility has already been built at node i by time t or is built at time t

$$nxcap(i,t) = nxcap(i,t-1) + xcap(i,t) \qquad \forall\, i,t \tag{9}$$

$$nxstor(i,t) = nxstor(i,t-1) + xstor(i,t) \qquad \forall\, i,t \tag{10}$$

$$nx(i,j,p,l,t) = nx(i,j,p,l,t-1) + xt(i,j,p,l,t) \qquad \forall\, i,t \tag{11}$$

- Capture target constraint: A pre-specified capture target must be met at each time period

$$\textstyle\sum_i C(i,t) \geq Target(t) \qquad \forall\, t \tag{12}$$

- Reverse pipeline flow: The same pipelines can be used in the future for flow in the opposite direction

$$xt(i,j,p,l,t) = xt(j,i,p,l,t) \qquad \forall\, i,j,p,l,t \tag{13}$$

- Non-negativity constraints: Finally non-negativity constraints are set for all continuous variables.

## 3. Case study: Evolution of an integrated minimum cost CCS supply chain in the UK

The UK is well-placed for exploiting CCS; the $CO_2$ emitters are mostly accumulated in clusters and there is significant potential in $CO_2$ storage capacity of the surrounding offshore regions. In addition, the publication of the UK government's CCS roadmap in 2012 [14], the funding of the White Rose CCS project's FEED study [15] as well as the Peterhead full-scale gas CCS demonstration project in Aberdeenshire [16] are all placing the UK at the forefront of CCS technology commercialisation. Furthermore, the UK government's updated CCS roadmap emphasises the desire for a strong CCS industry beyond the current commercialisation projects.

For these reasons, the case study presented in this paper includes the eighteen largest $CO_2$ emission sources in the UK and ten largest sinks in the Southern North Sea and the East Irish Sea. The aim of this scenario is to illustrate the development of a CCS network from 2010 until 2050 in four, 10 year long time periods. The conditions or parameters under which the network functions i.e. costs, inflation rates, capture targets etc. are assumed to remain constant throughout each individual period. The driver behind the expansion of the network is a capture target that begins with 15% for the first time period and linearly goes up to 60% mitigation of the total emission during the last time period.

In terms of $CO_2$ sources, the EU ETS data for 2011 were used to select the eighteen largest $CO_2$ emitters, which include thirteen coal power plants, three CHP and CCGT plants and two iron and steel manufacturers. The annual $CO_2$ emissions per source range from 3 Mt to 22.4 Mt $CO_2$ per year and sum up to 112 $CO_2$ Mt per year. The aim of the scenario source and sink selection was to produce a UK wide CCS network illustrating geographical diversity of selected sites. The versatility of the model developed, nevertheless, allows to construct any scenario of sources and sinks. The corresponding fixed and variable costs of capture were obtained from Prada *et al.* [2].

The eight largest southern North Sea Rotliegendes gas fields are selected as potential candidates for storage, since they are close to many of the emission intensive sources in the UK. In addition, the availability of seismic data for the hydrocarbon fields and their expected cap-rock integrity provide favourable conditions for storage. The Triassic East Irish sea basin sinks, Morecambe North and South were also selected since they are well-placed to receive $CO_2$ from sources in North Wales and Northwest England. A total capacity of 3.43 Gt $CO_2$ is assumed for the selected sinks.

For this case study, the selected form of $CO_2$ transport is in gaseous phase via pipeline, although the flexibility of the model allows for other modes or $CO_2$ phases. Piecewise linearisation of a non-linear cost vs. flow rate curve by Prada *et al.* [2] leads to three linear pipeline segments, each associated with a maximum flow rate with fixed and operational costs per km as shown in Prada *et al.* [2]. The three sets of parameters were fed into the MILP as options for building pipelines of three different capacities 15, 45 and 100 Mt $CO_2$ per year.

A constraint applies a cost incentive if a pipeline follows the UK's existing gas infrastructure. This is represented by flagged nodes in the supply chain model, some of which are the current gas terminals or dummy locations which, if connected, represent parts of the existing gas lines. Considering the potential benefits and having tested the model for several cost reduction factors, a cost reduction factor of 50% was applied when the choice to follow the existing lines is used.

### *3.1. Results and discussion*

The blue lines in Fig.1 indicate the pipelines which follow the existing gas infrastructure. The purple pipelines indicate that $CO_2$ is now moving in the opposite direction via these lines.

In the first time period under an annual capture target of 27 Mt $CO_2$, $CO_2$ is captured from the North Yorkshire emitters including Drax and transported to Morecambe South in the East Irish Sea. During the second time period, the network expands to Nottinghamshire. Part of the $CO_2$ is now stored in West sole in the Southern North Sea via the Easington terminal. The North West is also now connected to the Morecambe Bay sinks. $CO_2$ is also captured in Scotland at the Firth of Forth and transported south to the East Irish Sea. In the third decade, with a target of 84 Mt $CO_2$ captured per year, the South East emitters join the existing network via Ratcliffe-on-Soar in Nottinghamshire. In the Southern North Sea $CO_2$ is transported via West Sole to be injected in the Leman field. At the Firth of Forth, $CO_2$ is also captured at Cockenzie. Morecambe South has no more storage capacity and the entire amount of $CO_2$ captured from the eleven emitters in the North West, Scotland, North Yorkshire and the South East during this period is injected into the Leman field. In the final time period, $CO_2$ is stored in Leman, Hewett L Bunter and West Sole in the Southern North Sea and Morecambe North in the East Irish Sea. Port Talbot steel and Aberthaw on the Coast of South Wales also join the network. $CO_2$ is captured from all eighteen sources considered in the scope of the case study.

Since the model considers the future changes, to ensure an overall optimal solution, the model's recommended strategy at a point in time might be non-intuitive. For example some of the $CO_2$ captured from the North East is transported to the Morecambe Bay rather than the obvious Southern North Sea. During the 2030-2040 period (Fig. 1 c), some of the previously built pipelines are now used to transport $CO_2$ in the opposite direction across England towards the Southern North Sea.

Throughout the planning horizon, Drax remains a major provider of $CO_2$ with almost 20 Mt captured per year. The Leman field is a major storage site in the Southern North Sea. An amount of $CO_2$ almost as high as half of the entire mitigated $CO_2$ is captured from the emitters close to the Humber and is transported to the nearby Leman field which benefits from low injection costs per unit of $CO_2$. Table 1 summarises the breakdown of the costs of the components of the CCS supply chain across the time periods.

Table 1. Total cost at time T ($) per tonne of $CO_2$ mitigated.

| | T1 (2010-2020) | T2 (2020-2030) | T3 (2030-2040) | T4 (2040-2050) |
|---|---|---|---|---|
| Capture | 35.555 | 18.76 | 11.263 | 6.152 |
| Transport | 3.473 | 1.43 | 0.671 | 0.294 |
| Storage | 9.755 | 3.45 | 2.227 | 1.035 |

## 4. Conclusions

The improved features of the CCS supply chain optimisation model developed in this work overcome many limitations of previous research in this field. The MILP tool developed in GAMS incorporates both whole system and multi-period optimisation. The simultaneous investment and operational decisions made for all three components of the chain at every time period result in an overall minimum cost supply chain. A flexible coding environment allows to investigate various scenarios in terms of scope, geography, operational constraints, and specifications of each time period, availability of sources or sinks or costs of the components of the chain.

The model's unique ability to optimise an integrated CCS supply chain under increasing mitigation targets or dynamic constraints is invaluable for the assessment of the large scale commercial deployment of $CO_2$ supply chains which are also bound to expand with the increasing implementation of CCS and the expected changes in the policies around CCS.

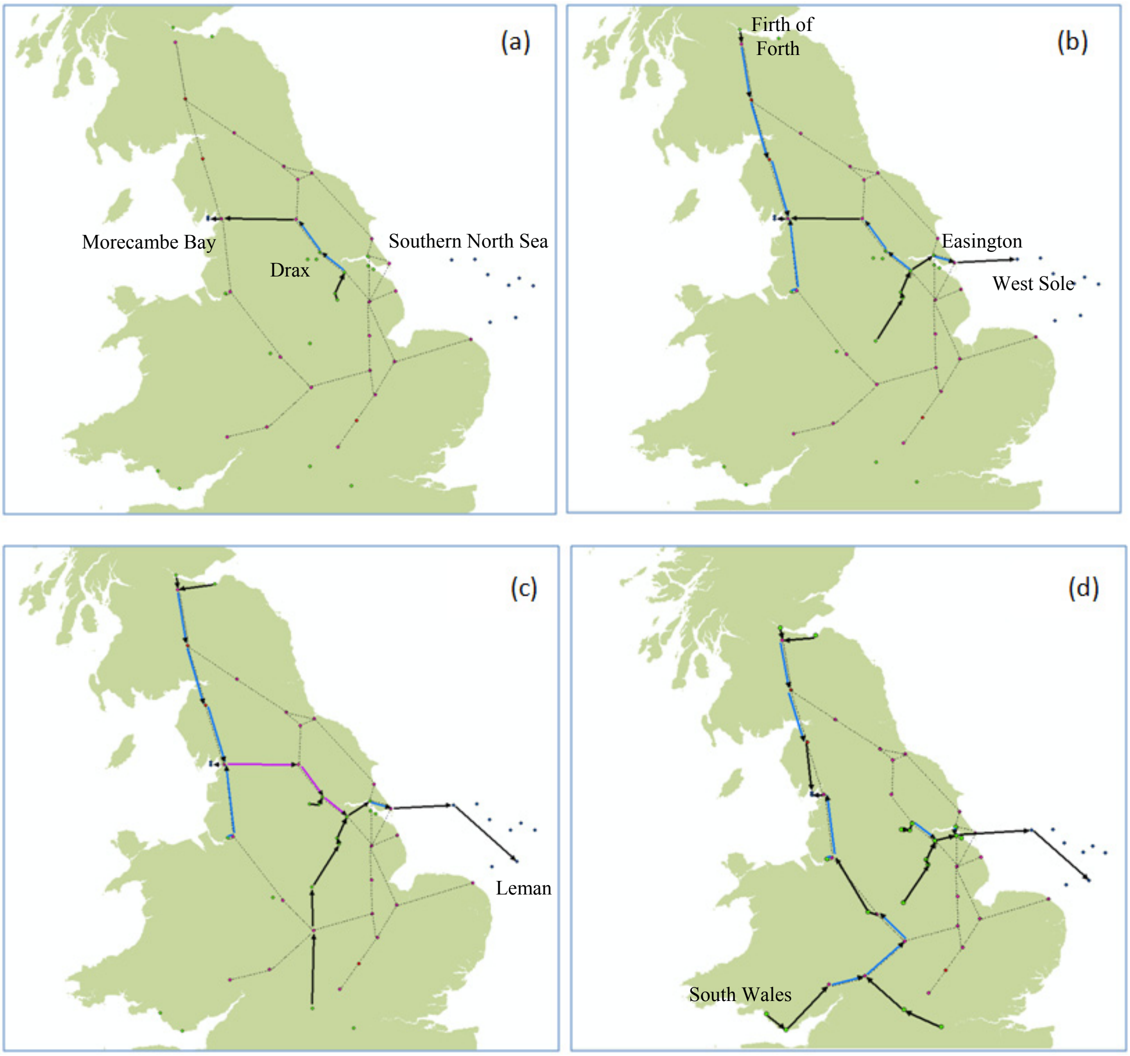

Fig. 1. (a) UK CCS network 2010-2020 – capture target 27Mt/year; (b) UK CCS network 2020-2030 – capture target 54Mt/year; (c) UK CCS network 2030-2040 – capture target 81Mt/year; (d) UK CCS network 2040-2050 – capture target 108Mt/year.

The case study presented investigated the evolution of a UK CCS system over four time periods up to year 2050 under increasing capture targets providing the means to test and validate the multi-period model. The results confirmed that at every stage the decisions are made balancing two factors. In order to minimise costs the model delays all investments until required, while current decisions are made anticipating the necessary future expansions. This non-intuitive outcome shows the advantages of such a tool as part of CCS commercialisation planning.

The optimization model could also be combined with detailed cost models for any of the chain components to form an investment planning tool which can also be used for CCS value chains cash flow analysis by operators or policy makers.

Beyond these added features and strengths over earlier methods, the MILP CCS optimisation tool developed still has some limitations. The solution provided is a deterministic view of the evolution of the CCS system. This lack of uncertainty and risk management could undermine viability of the solution, considering the uncertain nature of the parameters which directly affect the evolution of the CCS system. Such parameters are changes in market conditions or energy systems. Therefore, a main improvement that is currently being implemented involves modifying the model to a stochastic optimisation tool where the solution is provided in the form of a strategy in the face of future uncertainties.

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