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The effect of market and leasing conditions on the techno-economic performance of complex CO_2 transport and storage value chains

Anna Korre[a]*, Zhenggang Nie[a], Sevket Durucan[a], Nasim Elahi[a], Nilay Shah[b], Shabana Ahmad[c] and Ward Goldthorpe[c]

[a]*Department of Earth Science and Engineering and* [b]*Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK*
[c]*The Crown Estate, 16 New Burlington Place, London, W1S 2HX, UK*

Abstract

The complex interplay of capital and operating costs that results from different CO_2 transport and storage network configurations, and the market conditions in which they develop is investigated using the life cycle CO_2 storage cost model and the multi-period CCS network optimisation model developed by Imperial College. These tools integrate seamlessly the geological characteristics, engineering aspects and the economics of complex CCS chains. The paper demonstrates that these models capture effectively and accurately the effects of market and leasing conditions on the techno-economic performance of complex CCS value chains. The results reveal that saline aquifers and depleted oil and gas fields may differ significantly in terms of cost performance. It is also shown that it is important to evaluate the technical and economic performance of the CCS value chain as a whole, rather than in individual components in order to ensure the financial viability of CCS projects.

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Keywords: CO_2 transport and storage, costs, value chains

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1. Introduction

It is widely argued that Carbon dioxide Capture and Storage (CCS) is an essential technology for energy system and industrial decarbonisation, expected to play a critical role in global efforts to combat climate change. Governments around the world have to balance the need for domestic energy security and affordability with

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* Corresponding author. Tel.: +44-20-7594-7372; Fax: +44-20-7594-7444.
E-mail address: a.korre@imperial.ac.uk

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delivering a low carbon energy system. In this context the UK Government has set out a programme to facilitate the development of a CCS the industry with an aspiration of realising cost competitive CCS power generation [1]. In 2012 the Government set up the UK CCS Cost Reduction Task Force, whose final report in May 2013, concluded that achieving economies of scale in CO_2 transport and storage infrastructure would make the biggest contribution to the goal of cost competitive CCS-equipped power in the 2020s. Work also undertaken by the UK Energy Technologies Institute has demonstrated the benefits that can be realised by spatially and temporally optimising CO_2 transport and storage infrastructure [2,3].

A substantial body of literature has focused on capture costs, which are significant and vary in quite well defined ways depending on the technology used. On the other hand, compared to such manmade facilities, the subsurface CO_2 storage processes involve considerable uncertainty due to the natural variability of geological, reservoir properties of CO_2 storage formations, as well our relatively limited knowledge of these [5-8]. Costs associated with the development and operation of storage facilities are, therefore, highly variable and site dependent. In recent years, the ZEP Technology Platform published a ground breaking set of reports on the costs of CO_2 capture, transport and storage based on data provided exclusively by ZEP member organisations on existing pilot and planned demonstration projects [4]. The ZEP report on transport [4] demonstrated a few cases of simple CO_2 transportation and storage chains; however, the optimisation of the CCS chains was not investigated. One publication [9] presented a least-cost optimisation model of CO_2 transportation and storage for the UK, in which storage costs were not considered and the storage system was largely simplified.

This paper illustrates how the complex interplay of capital and operating costs that result from different transport and storage network configurations, and the market conditions in which they develop can be combined together to understand how uncertainties influence economic performance. Imperial College's in-house models: life cycle CO_2 storage cost model and multi-period CCS network model are used together to evaluate how different approaches to the leasing of sites can influence least cost pathways for networked infrastructure deployment and business models for operation of this infrastructure. The life cycle CO_2 storage cost model is designed to account for the key performance characteristics of storage sites (such as the areal extend of CO_2 plume, CO_2 injectivity and dynamic storage capacity with alternative injection options and strategy) and is coded within an Excel macro-enabled workbook. The multi-period CCS network model is formulated as a mixed integer linear programming (MILP) problem solved via the GAMS commercial software tool. The model objective introduced is a cost minimisation associated to the future development and operation of a CCS infrastructure and is practically treated as a multi-period supply chain optimisation issue. The approach is demonstrated through a single chain scenario analysis based on the data from the publicly available Goldeneye FEED report [10] and a Central North Sea multi-store exemplar scenario, including three aquifers and four depleted oil and gas fields, for a period of 35 years until 2050. Secondly, the multi-period CCS network model is used together with the life cycle CO_2 storage cost model to conduct the whole value chain optimisation under a number of different leasing scenarios. The results are used to analyse how the effects of technical and market constraints can influence the business models for operation of this infrastructure and the decision choices that can lead to least cost pathways for networked infrastructure deployment.

2. The CO_2 capture, transportation and storage single chain life cycle analysis

The CO_2 storage life cycle cost model framework described in Fig. 1 outlines the characteristics of the model developed, aimed at accounting for the key uncertainties in the storage site properties and operation. The cost model is modularised such that individual cost components (e.g. monitoring costs, injection facility costs, post injection care costs etc.) are broken down to detailed elements that are parameterised in order to ensure the accuracy of the cost estimates. The input data used and model parameterisations are drawn from up-to-date literature and/or communications with industry and the estimates are validated through the same process [11-14]. Fig. 2 illustrates the Goldeneye case study used as an anchor case to carry out a single chain scenario analysis, demonstrate the model functionality and assess the sensitivity of life cycle cost estimates to key storage site and operational design parameters. The information used in this case study is based on the data provided in the Scottish Power FEED report [9]. The key parameters considered are summarised in Table 1. The levelised CO_2 storage cost for the anchor case is calculated as £20.32 per tonne of CO_2 stored. The life cycle cost model estimates (Fig. 3) demonstrate that more than 80% of the costs are linked to injection platform modification and platform operation costs. Monitoring also contributes to a considerable proportion of the storage costs. All other cost items together account for less than 3.5% of the total storage costs. Fig. 4 illustrates the life cycle cash flow of the Goldeneye CO_2 storage anchor case. The results show that during the pre-injection phase, a large amount of investment is required to cover platform modification and for baseline monitoring. During CO_2 injection, the majority of the expenditure is due to platform operation and monitoring activities. The funds covering the financial responsibility also account for considerable expenditure during the CO_2 injection phase. In years 2021 and 2026, monitoring costs are significant due to the 3D seismic campaigns planned.

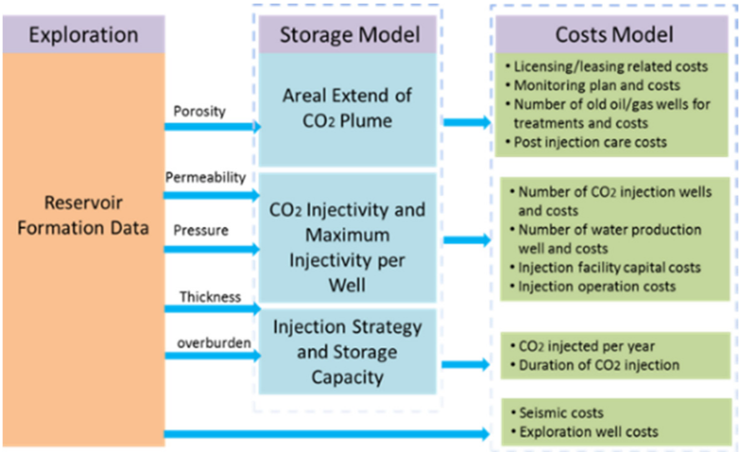


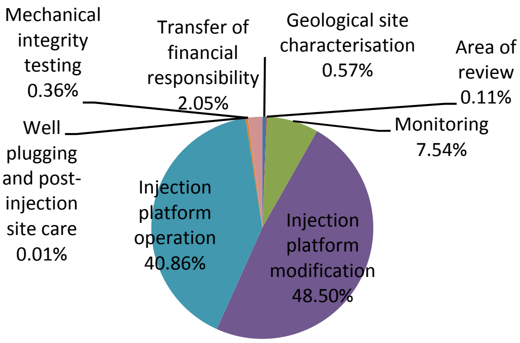
Fig. 1.Life cycle cost modelling framework implemented.

Fig. 2.The Goldeneye case single CCS chain.

Table 1. Key parameters considered for the Goldeneye CO_2 storage anchor case.

	Units	Value
Injection rate per year	Million tonnes per year	2.0*
Storage facility injection life	Years	11
Total CO_2 injected	Million tonnes	20
Area of review (monitoring area during injection)	Km$_2$	160
CO_2 storage financial responsibility	£/tonne CO_2	0.417
Number of injection wells	-	4
Modified injection platform	-	1
Water production well	-	0
Water production rate	Mt per Mt CO_2 injected	0

*: During the 10th and 11th year of injection, the injection rates are 1.5 and 0.5 respectively.



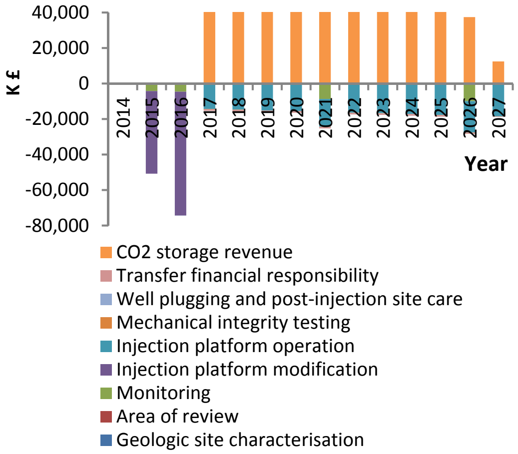


Fig. 3.Contribution of individual cost components to overall CO_2 storage costs.

Fig. 4. Life cycle cash flow of CO_2 storage at Goldeneye.

The sensitivity analysis (Fig.5) shows that the levelised costs are sensitive to the water production requirement, number of exploration wells, injection platform capital costs and platform operational costs. For new storage sites requiring exploration drilling there may be considerably higher costs than storage sites where site characterisation data are available. Storage reservoirs with water production may also have additional costs for produced water treatment facilities to satisfy environmental regulations. The different storage site scenarios considered (such as different injection rates, different injection duration and different storage capacity) are analysed in order to assess the effects of injection strategy choices and storage capacity uncertainty on the cost estimates. The multi-period CCS network model was also used to evaluate the transport costs for each scenario (Fig. 6). The levelised capital expenditures for platform modification and transport are much lower in cases with larger storage capacity or injection rate as compared to the base case (11 years, 20Mt CO_2). Fig. 6 also demonstrates that transportation costs are a significant portion of the total costs in the single chain system. This analysis confirms that with sharing or optimising infrastructure and making better use of formation capacity (or the use of adjacent storage sites) CO_2 storage costs can be reduced considerably.

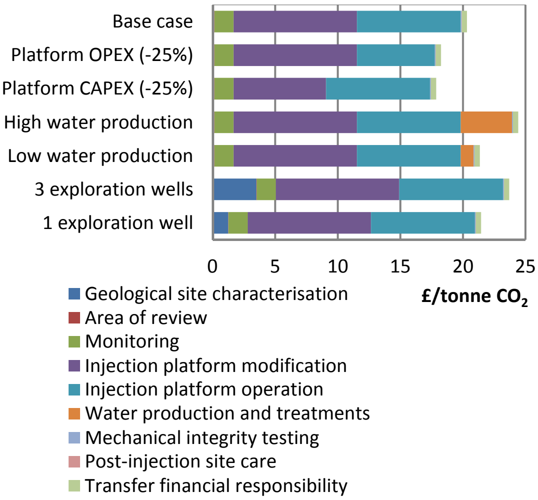


Fig. 5.The sensitivity analysis of CO_2 storage costs.

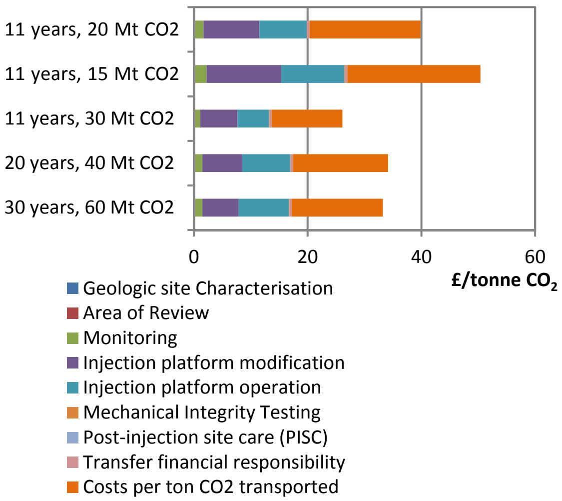


Fig. 6. The scenario analysis of CO_2 transport and storage costs.

Monte Carlo analysis has been implemented to evaluate the effect of uncertainties in the CO_2 storage processes and injection operations on costs and revenues. Uncertainty bounds were assigned to injection rate, area of monitoring, platform construction costs, and platform operation costs. Fig. 7 demonstrates that the variation of the internal rate of return (IRR) and net present value (NPV) for 5,000 Monte Carlo simulation runs carried out for a fixed CO_2 price at £30 per tonne is significant.

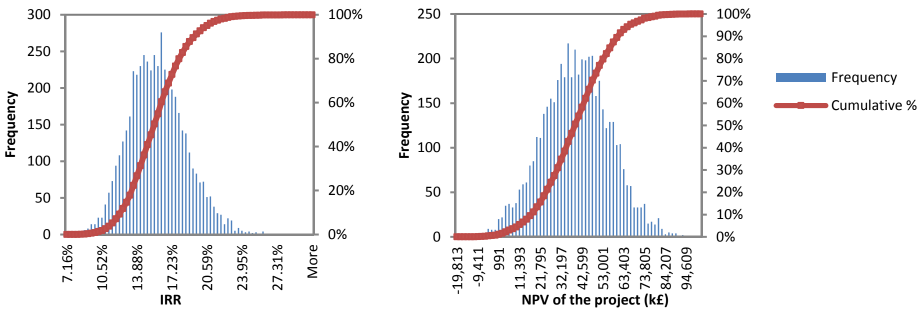
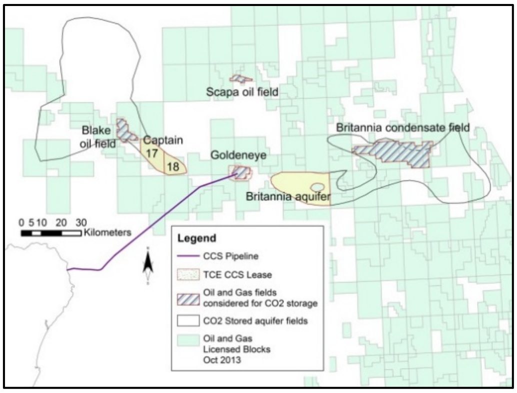


Fig. 7. Internal rate of return and net present value for 5,000 Monte Carlo runs of the CO_2 storage cost model for the Goldeneye anchor case.

3. Central North Sea multi-store CO_2 transport and geological storage network optimisation and the techno-economic performance analysis

The same tools were then used to model a Central North Sea multi-store scenario with phases of deployment, including three aquifers and four depleted oil and gas fields, for a period of 35 years until 2050. This scenario was used to analyse the life cycle costs of CO_2 transport and geological storage considering leasing options and market constraints. Seven Central North Sea (CNS) storage sites were selected for this multi-store CCS network analysis comprising three saline aquifers and four depleted oil and gas reservoirs (Fig. 8). The multi-period CCS network model was used to optimise the CNS multi-store CCS network evolution. The model was set up using the following key assumptions/constraints:

- Storage capacity: The total storage capacity of these systems is estimated at 277.73 Mt of CO_2 calculated using the CO_2 Stored database and Imperial College's own studies in the EU SiteChar (FP7-Energy-256705) and UK Research Council funded projects (EP/K035967/1 and NE/H01392X/1). The CO_2 storage capacity per site, assumed availability and assumed maximum injection rate used are also shown in Fig.8.
- Source: The CO_2 emission sources considered for the scenario are all in Scotland providing an annual CO_2 emission total of approximately 19.5 Mt.
- Mitigation target: the model aims to achieve a mitigation target of 90% of Scottish CO_2 emissions (90 % of 19.5 Mt) by purchasing carbon credits or through CCS. The model provides as outputs the CCS cost values and the optimal CCS network design.



Description	Site availability	Leasing area storage capacity (Mt CO_2)	Max injection rate (Mt CO_2/year)
Britannia aquifer block	now	22.98	2
Captain aquifer block 17	now	16.98	2
Captain aquifer block 18	now	11.24	2
Goldeneye gas condensate field	since 2011	20.00	2
Blake oil field	after 2015	28.00	2
Scapa oil field	after 2020	48.32	4
Britannia condensate field	after 2025	130.20	6

Fig. 8.CO_2 storage sites used for the CNS multi-store scenario analysis.

- Time horizon and periods: The time horizon is from 2014 to 2050. Four time periods are introduced with each time period beginning at the time when a new storage site first becomes available: 2014-2018, 2018-2023, 2023-2028, 2028-2039 and 2039-2050.
- Progression: The progression of the network throughout the planning horizon is known, due to availability of storage sites at different times and the variations in the maximum injection rates.

The model dynamically chooses the storage sites available to the network with the objective to minimise the whole network costs. The evolution of the optimised CO_2 transportation and storage network against time was generated and demonstrated in Table 2 and Fig. 9, which illustrates the cost optimised CO_2 transportation network developed through different time periods under constraints of storage site availability and injection rate limitation.

The optimisation results were used to analyse how the life cycle costs of CO_2 transport and geological storage can influence decision choices for the business models for operation of this infrastructure and the leasing options that lead to least cost pathways for networked infrastructure deployment when considering market constraints. The following scenarios were analysed:

- Open season leasing was considered through a scenario allowing the full utilisation of the optimal CNS multi-store capacity for a fixed CO_2 price (£25).

Table 2: Amount of CO_2 stored during each time period.

CO_2 stored at time t in Mt/year	T1: 2014-2017	T2: 2018-2022	T3: 2023-2027	T4: 2028-2038	T5: 2039-2050
Length of time period (years)	4	5	5	11	12
Britannia aquifer	2.00	2.00	0.99		
Captain block 17	2.00	1.80			
Captain block 18	2.00	0.65			
Goldeneye Gas Condensate Field	2.00	1.185	1.22		
Blake Oil Field		2.00	2.00	0.73	
Scapa Oil Field			4.00	2.58	
Britannia Condensate Field				6.00	5.35
Annual total (Mt)	8.00	7.36	8.12	9.30	5.35
CO_2 injected during the period (Mt)	32.00	38.15	41.06	102.32	64.2
Total CO_2 stored during 2014-2050	277.73				

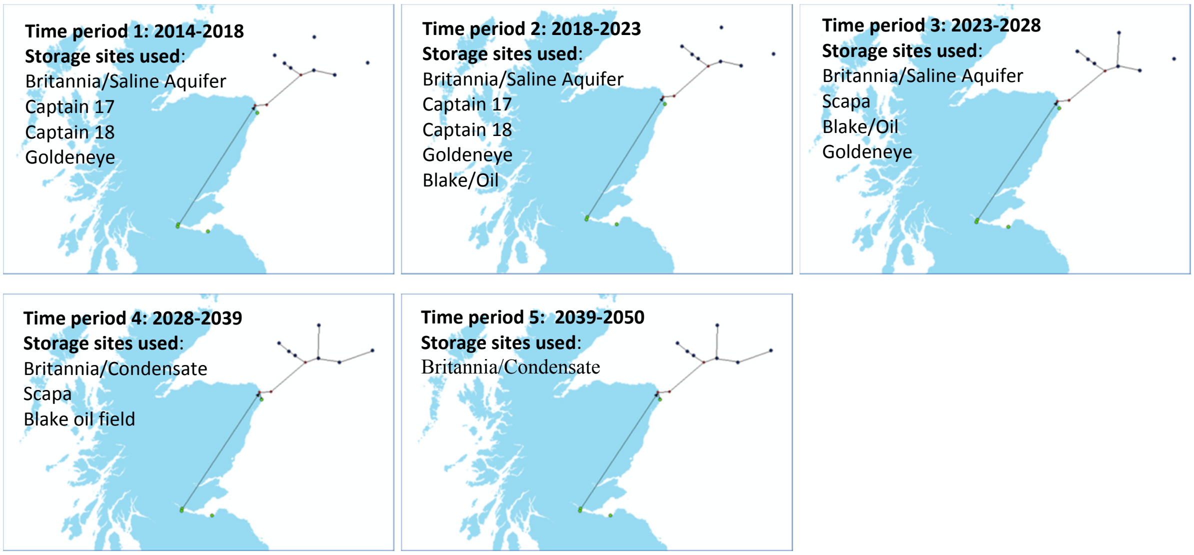


Figure 9: The evolution of the optimised CO_2 transportation and storage network.

- Auctioning with a reserve price, was considered through a scenario where a target IRR (10 %) is set for all sites and a fixed CO_2 price (£30).
- The effect of market conditions (CO_2 price) on project finances is investigated for a scenario with a fixed target IRR (15 %).

The results presented in Table 3 demonstrate that the IRR varies significantly for individual storage sites. Obviously, stores with low IRR would be less attractive as investment propositions, even if technically they are feasible and ready, until the market conditions available are more favourable. However, if all storage sites are considered as a package, the IRR of the combined multi-store is 17.08%, which is higher than the IRR (15%) normally required by industry, presenting a lower investment risk as a whole.

The second leasing option, auctioning with a reserve price, was considered through a scenario where a low target IRR (10 %) is set for all sites and the royalty fee that can be afforded per site is calculated as a guide, considering a fixed CO_2 price (£30). This scenario considers how the flexible royalty rates can facilitate decision makers to initiate the investments. Table 3 shows that, if lower royalty rates are applied for stores with lower economic performance, it may be possible to encourage decision makers to initiate the investments. If all stores were to be leased as a package, in order to meet the target IRR and CO_2 price condition, the unified royalty rate for all seven stores can also be generated by the model.

Finally, the effect of market conditions on project finances is investigated for a scenario of fixed royalty rate (15 % of the CO_2 price) and IRR (15 %). Table 3 demonstrates that the CO_2 price needs to be even twice as high for some of the storage sites in comparison to others so that may be considered favourably at the given CO_2 price and IRR. Once again the multi-store package necessitates a lower entry barrier.

In summary, Table 3 demonstrates that both saline aquifers and depleted oil and gas fields may differ significantly in terms of economic performance due to different geological conditions (depth, thickness, permeability, storage capacity, and storage complex type), the existing infrastructure and abandoned oil or gas wells. It is also shown that the multi-store scenario, as a whole, demonstrates portfolio effects, which stabilise the economic performance, lower the economic entry barriers for opening up storage sites, and may facilitate better utilisation of CO_2 storage resources.

Figure 10 demonstrates the combined cash flows of the CCS value chain during the planning horizon (2014 to 2050) for the different leasing scenarios attributed to individual storage sites. It is notable that with the fixed the cost-optimised multi-store network design, the three economic and policy scenarios considered result in variable cash-flow proving the importance of this type of analysis when considering the financial risks of investing in a given project. The information provided in Fig.10 can also be used for project finance budgeting, especially for the identification of expenditure outliers. For instance, few cost outliers after 2020 in Figure 10 (a), (b) and (c) are related to the monitoring costs of the Britannia condensate field, as it covers a large area. It should nevertheless be noted that the monitoring costs might be overestimated in the scenarios presented here since the area of review is assumed to be fixed and equal to the lease area, which is a very conservative assumption. In reality, the monitoring area extent depends on the regulations and should ideally be set on the basis of the extent of the CO_2 plume at the time of survey.

For the whole transportation network, including onshore pipelines and offshore pipelines, the target IRR of 15 % and a royalty rate at 15 % were set. Then the price for CO_2 transportation (£/tonne) was back- calculated as £ 8.51 per tonne of transported CO_2, which is lower than the transport cost of Goldeneye single chain case study. This implies that the sharing of CO_2 facilities (CO_2 transportation network or hub) has the potential to reduce CO_2 transportation costs considerably. The life-cycle cash flows of the CO_2 transportation network from 2011 to 2050 are illustrated in Fig. 11. The significant cost outliers are due to capital costs required to build the transport network.

Table 3: The results for alternative leasing options.

Storage site	Open season	Auctioning with reserve price	Dependence on market conditions
	IRR (%)	Royalty rate (% of CO_2 price)	CO_2 price (£/tonne)
Britannia aquifer	17.91	43.18	23.03
Captain aquifer block 17	30.77	57.67	17.01
Captain aquifer block 18	25.87	47.94	20.26
Goldeneye gas condensate field	6.85	22.87	31.08
Britannia condensate field	3.89	17.88	33.19
Scapa oil field	34.25	62.91	15.18
Blake oil filed	12.18	33.34	26.99
Multi-store combined as a whole	**17.08**	**39.65**	**26.33**

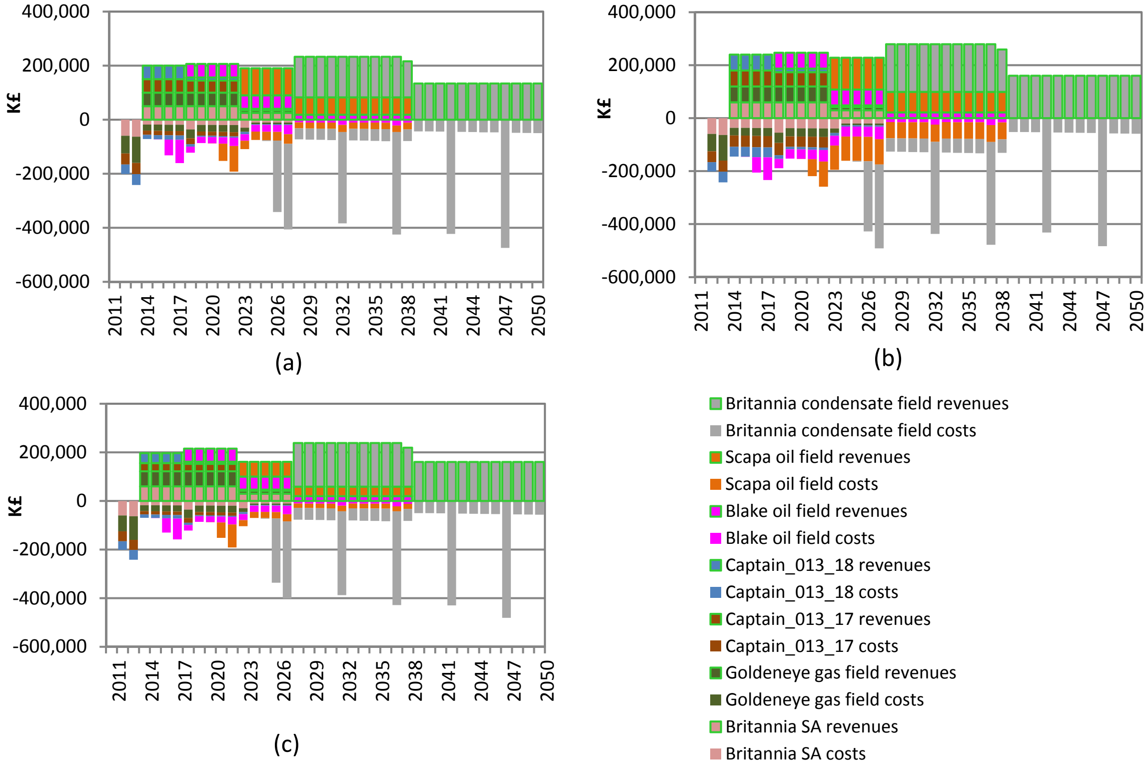


Fig 10. (a) Open season leasing cash flow per storage site during the planning horizon (2011 to 2050); (b) Auctioning with reserve price leasing cash flow per storage site during the planning horizon (2011 to 2050); (c) Dependence on market condition leasing cash flow per storage site during the planning horizon (2011 to 2050).

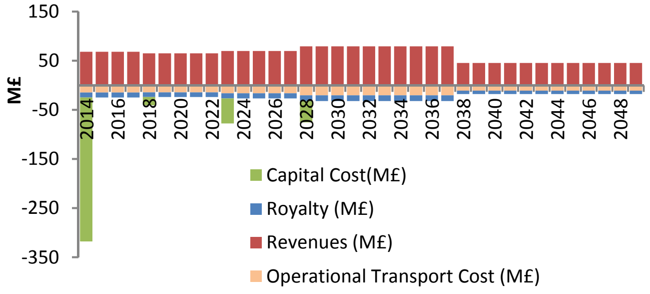


Figure 11: The cash flow for the CO_2 transportation network from 2011 to 2050.

4. Conclusions

The scenario analysis and the results illustrate that Imperial College's network optimisation and life cycle cost model for CCS value chains can sensibly capture the effects of technical and market constraints on individual storage site costs, as well as represent accurately complex multi-storage scenarios. The combined CO_2 transport and storage modelling reinforces that it is imperative to evaluate the technical and economic performance of the CCS network as a whole, rather than individual components, in order to correctly understand the financial viability of the individual components. It also demonstrates the size of the opportunity to reduce costs through transport and storage network sharing and optimisation relative to the cost of a single value chain.

Models can be sensibly built and used to analyse alternative leasing scenarios, for different user defined technical and market constraints, and provide insights that enable a better understanding of the factors that encourage market development and de-risk investments. The relative importance of technical differences between storage sites and the evolution of different market conditions can be considered stochastically, and future leasing options can be evaluated in order to maximise choice for the developer, enable policy makers to understand options that lead to lower network development cost, and quantitatively compare different infrastructure deployment outcomes.

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