Real Options: the key to unlocking CO_2 transport and storage infrastructure development

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Why Real Options?

Motivation

- The subsurface CO_2 storage processes involve considerable uncertainty.
- Costs associated with the development and operation of storage facilities are, therefore, highly variable and site dependent.
- Earlier works investigated only simple CO_2 transportation and storage chains.
- The optimisation of the transport and storage chains has not been investigated (one simplified study prior to this work).

Objectives

- Assess the complex interplay of capital and operating costs that result from different transport and storage network configurations,
- Consider geological, engineering and the market conditions in which CO_2 transport and storage option infrastructures may develop,
- Combine these to understand how uncertainties influence economic performance.
- Enable accelerated storage site qualification and "license-readiness"

CO_2 storage in the North Sea

Approach

Selection of generic CO_2 storage sites

Data gathering

3D model building

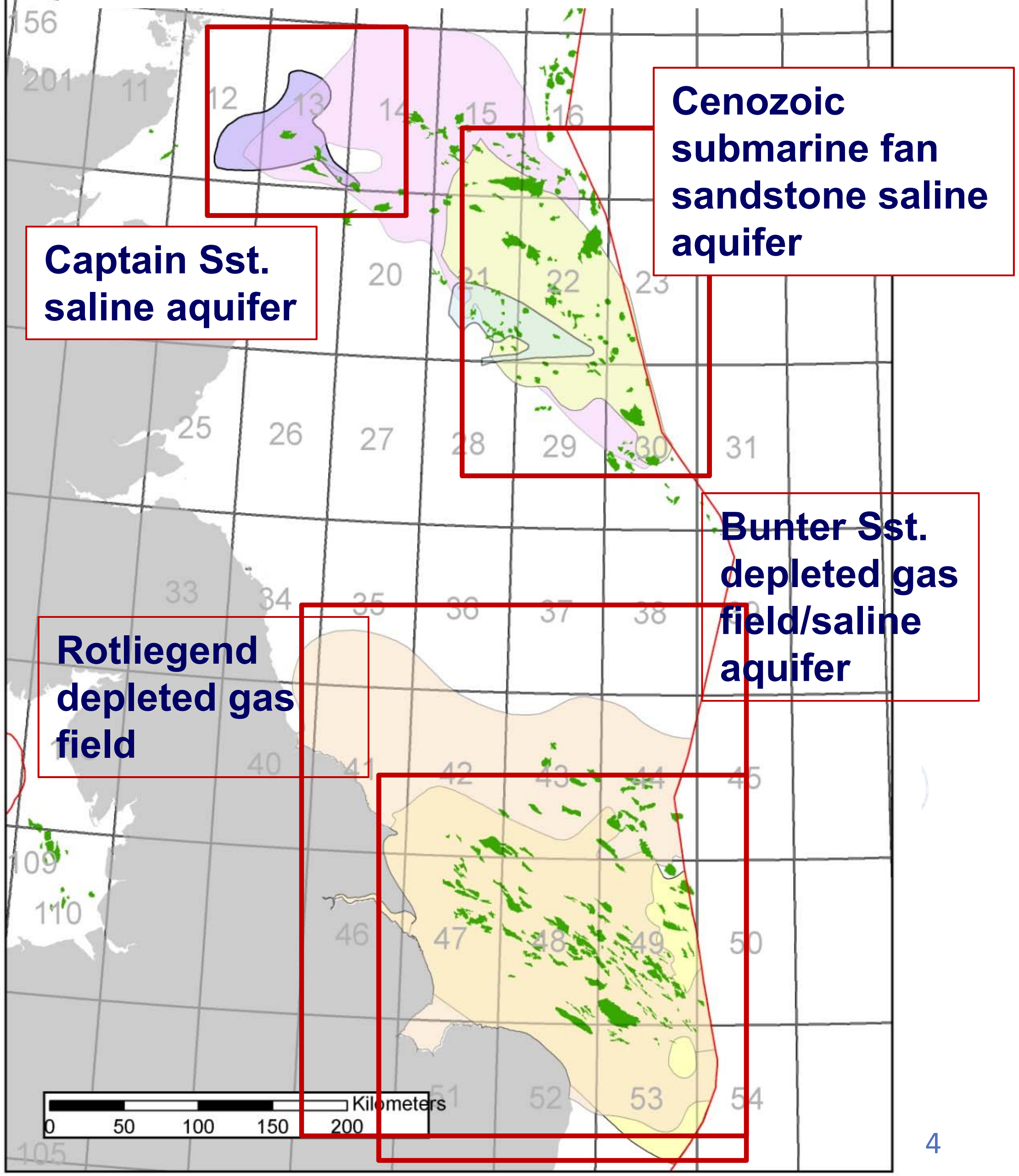
Model attribution

Dynamic modelling and validation for generic site

Reservoir modelling of generic storage site scenarios

Abstraction of high level CO_2 storage site performance relationships

Map of UKCS showing location of the CO_2 storage sites considered



Injection and storage model   Dynamic modelling

SNS Rotliegend group

Determination of key performance indicators for the Ravenspurn fields

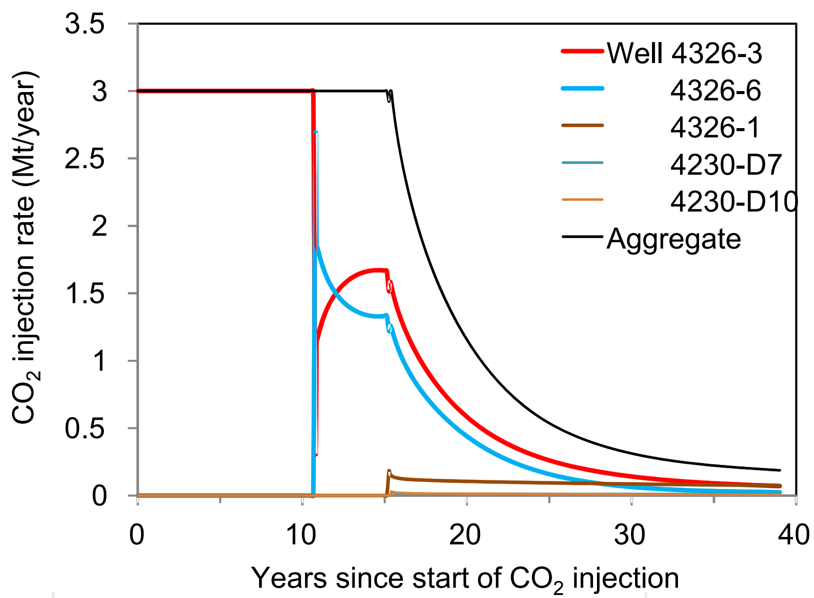
Period of Sustained Injection (PSI)

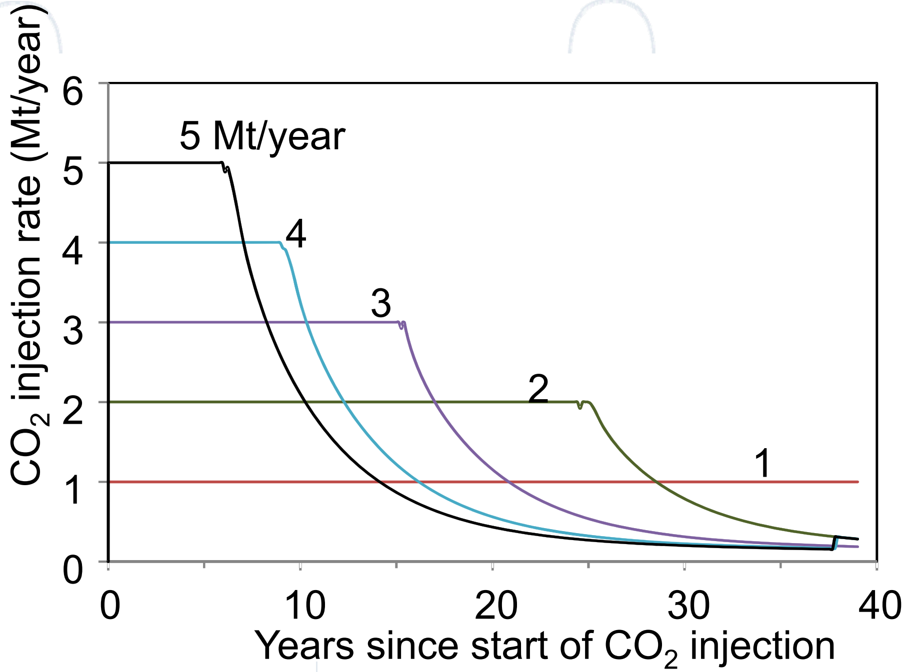
The duration wherein a pre-specified constant injection rate can be maintained

Fraction of Capacity Utilised (FCU)

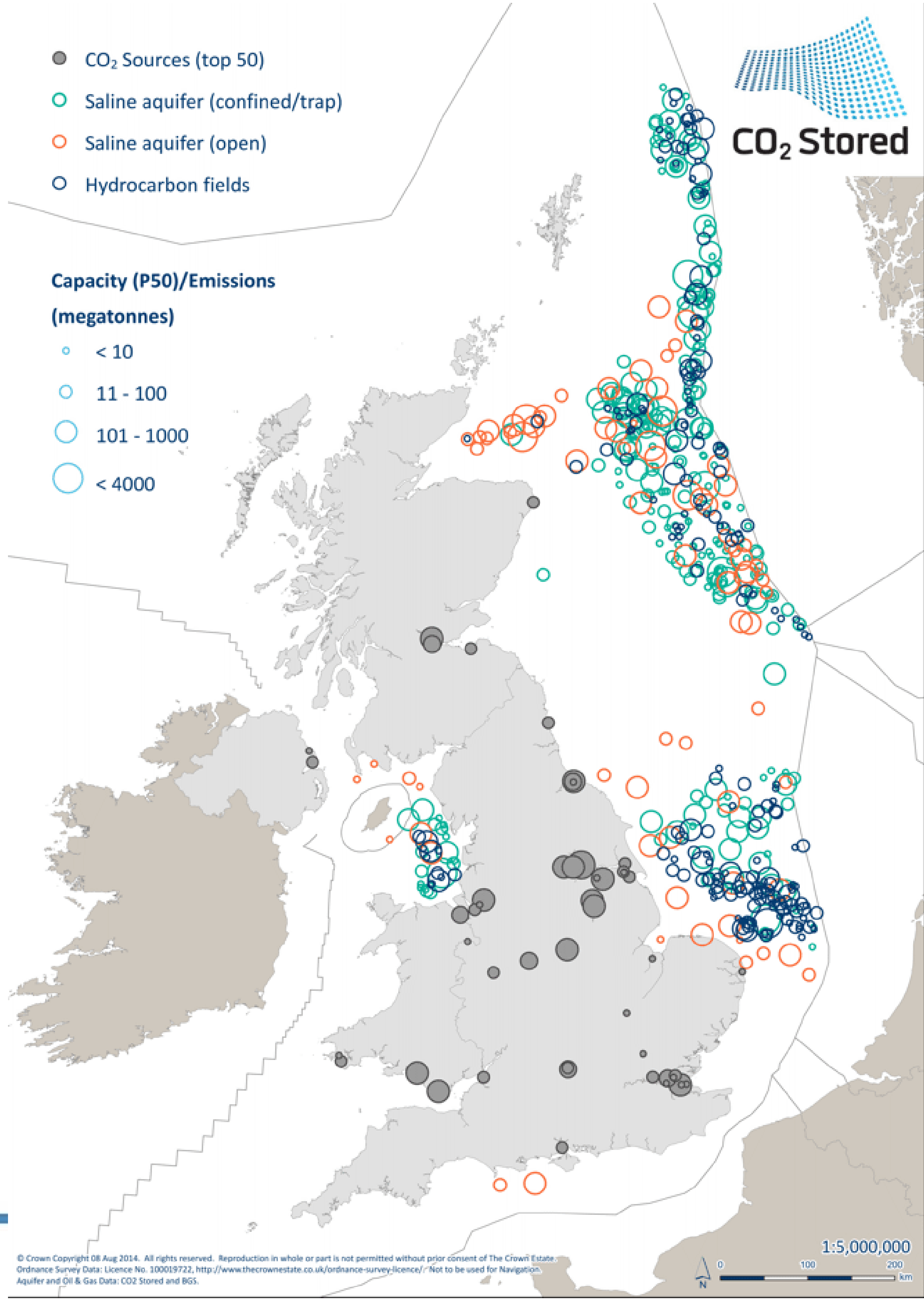
The fraction of available pore space within the reservoir occupied by CO_2

	CO_2 injection rate, Mt/year				
	1	2	3	4	5
PSI, year	50	24	14	7.5	5.1
FCU, fraction	0.38	0.36	0.32	0.23	0.19





CO_2 storage in the UKCS



Methodology

Imperial College's in-house models:

Life Cycle CO_2 storage cost model

Multi-period CCS network model

Life Cycle CO_2 storage cost model

Key drivers of the CO_2 storage cost uncertainty

Storage complex:
- Reservoir
- Structure
- Seal

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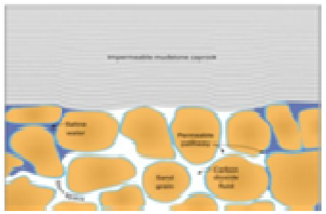
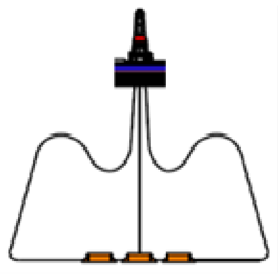
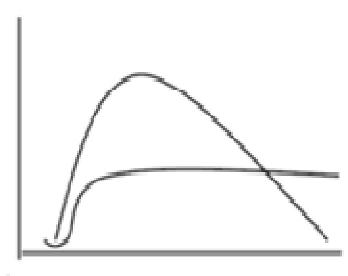


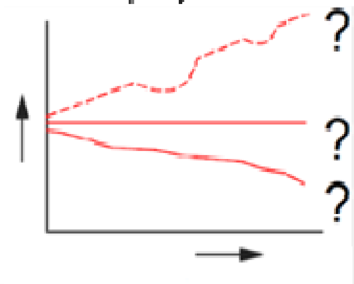
Development concept:
- CAPEX
- OPEX

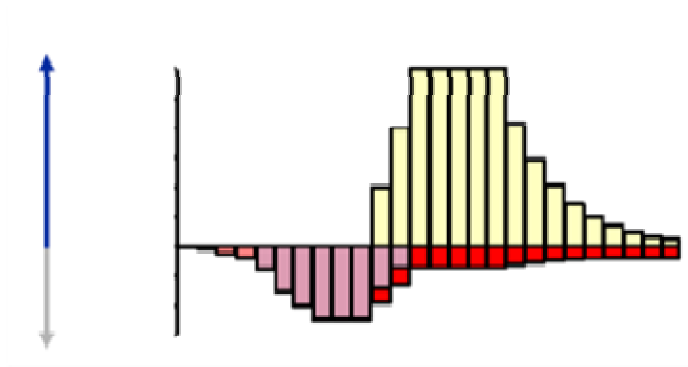


Injection strategy:
- Injection rate
- Duration

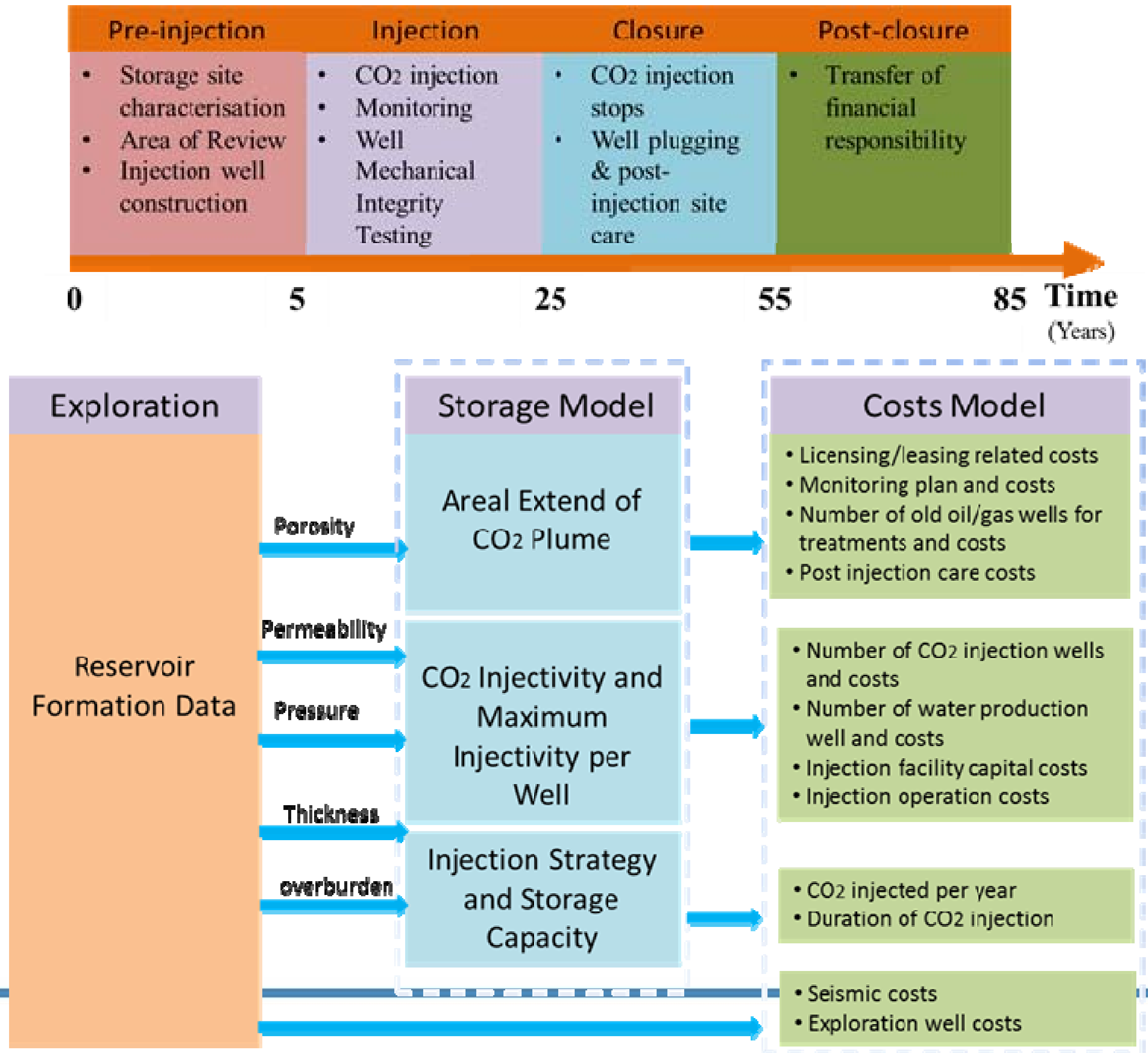


Financial factors:
- CO_2 prices
- Royalty rate

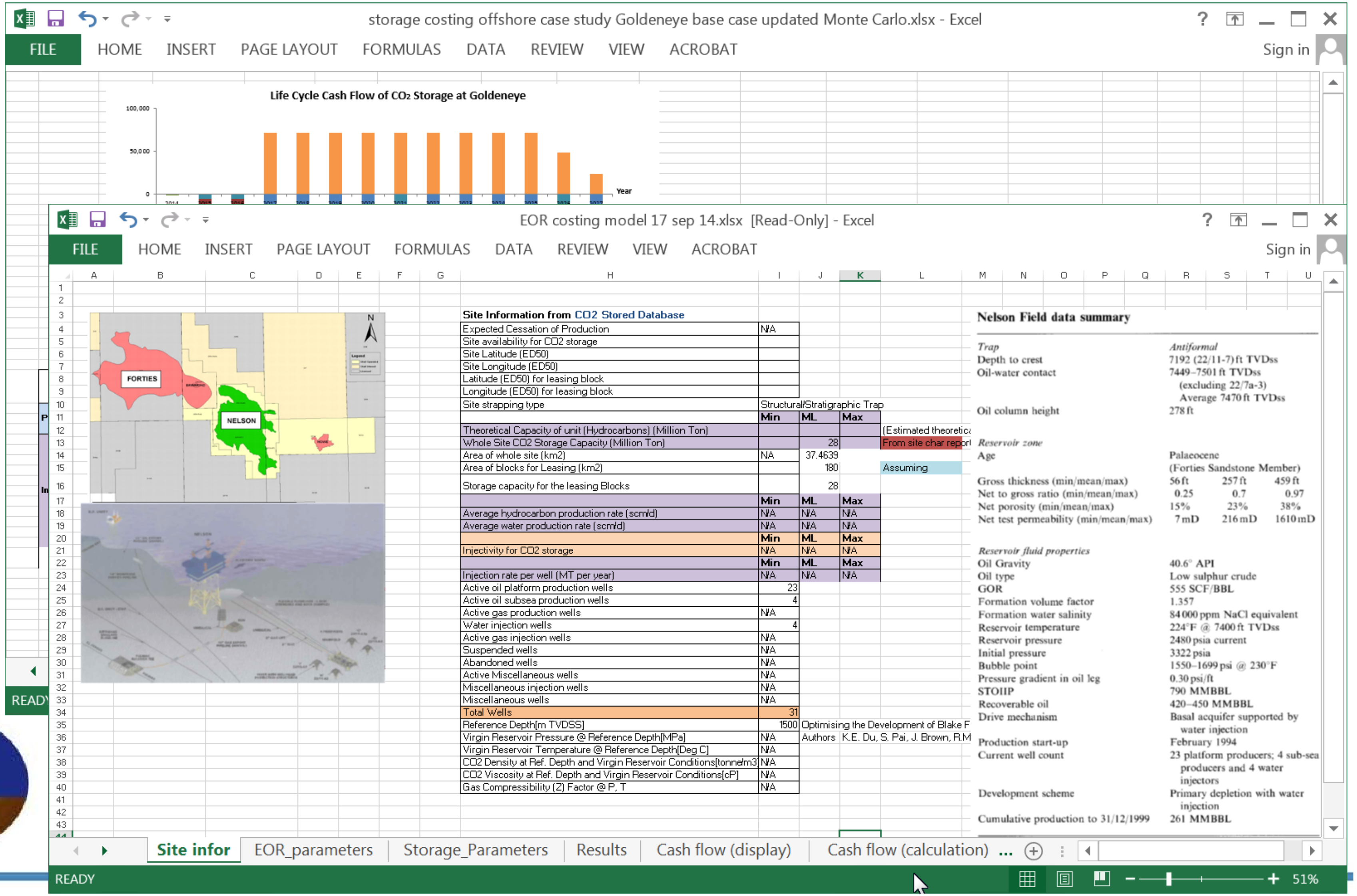




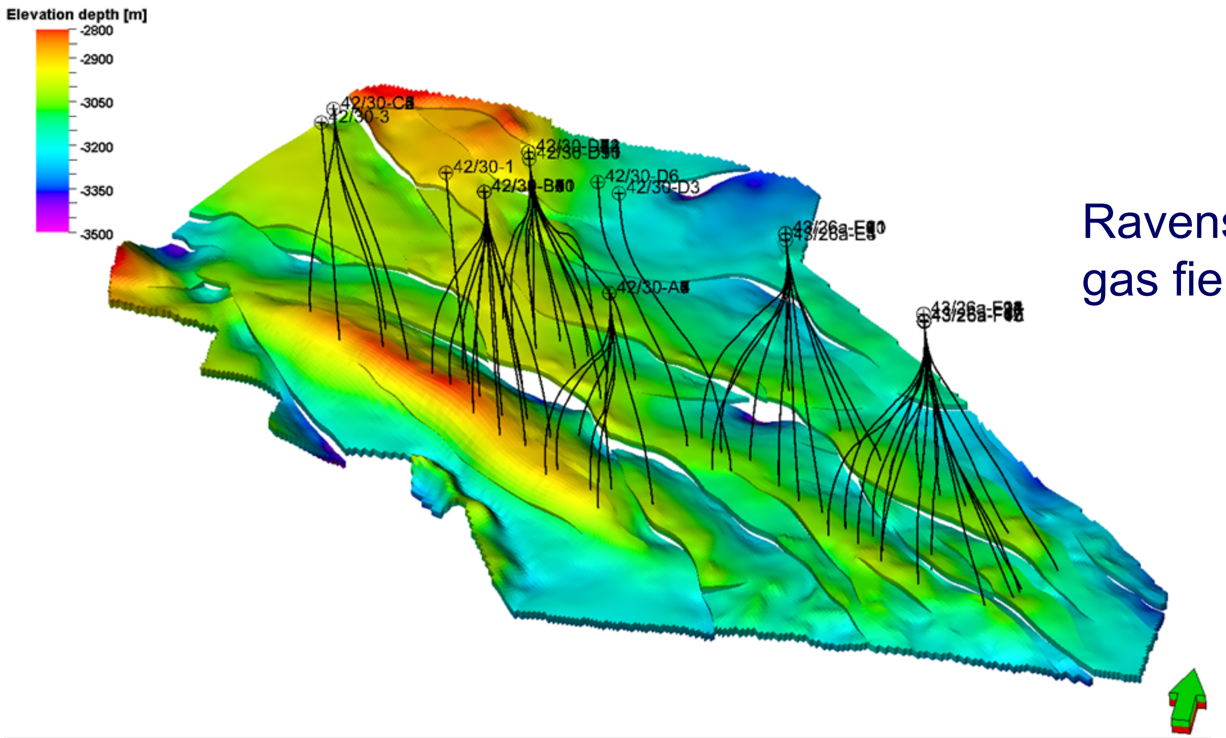
Life Cycle CO_2 storage cost model



Life Cycle CO_2 storage cost model



Life Cycle CO_2 storage cost model

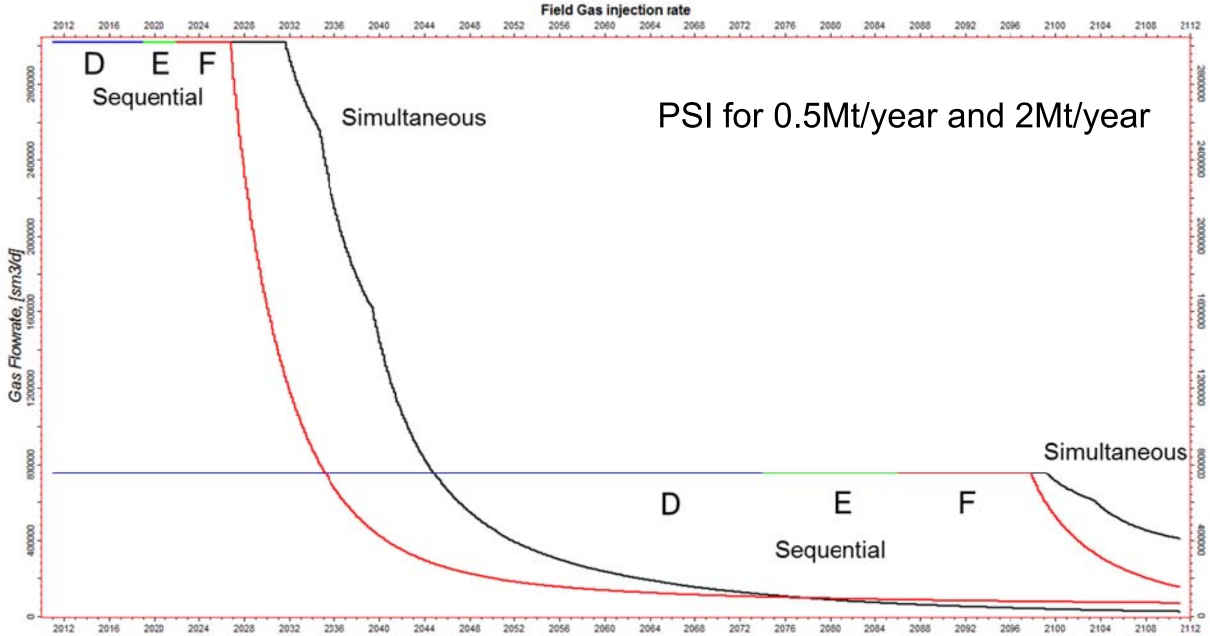


Ravenspurn gas field

	Ravenspurn South			Ravenspurn North		
	Platform A	Platform B	Platform C	Platform D	Platform E	Platform F
Number of wells	**7**	**12**	**6**	**14**	**11**	**18**

Life Cycle CO_2 storage cost model

Ravenspurn gas field (North)

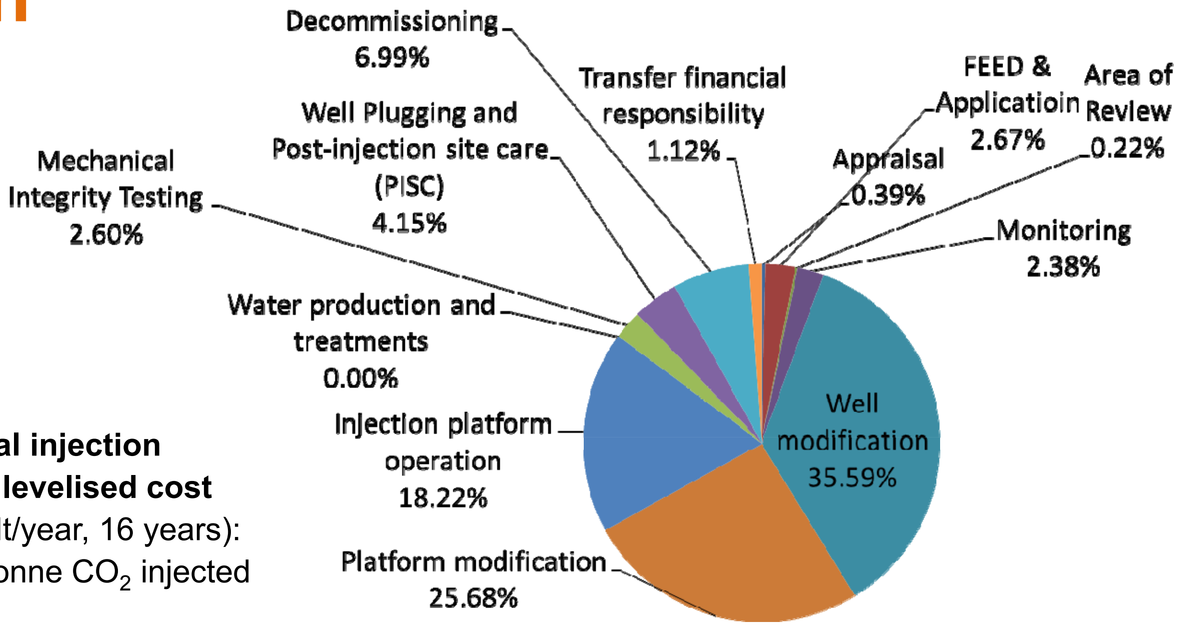


Sequential Injection

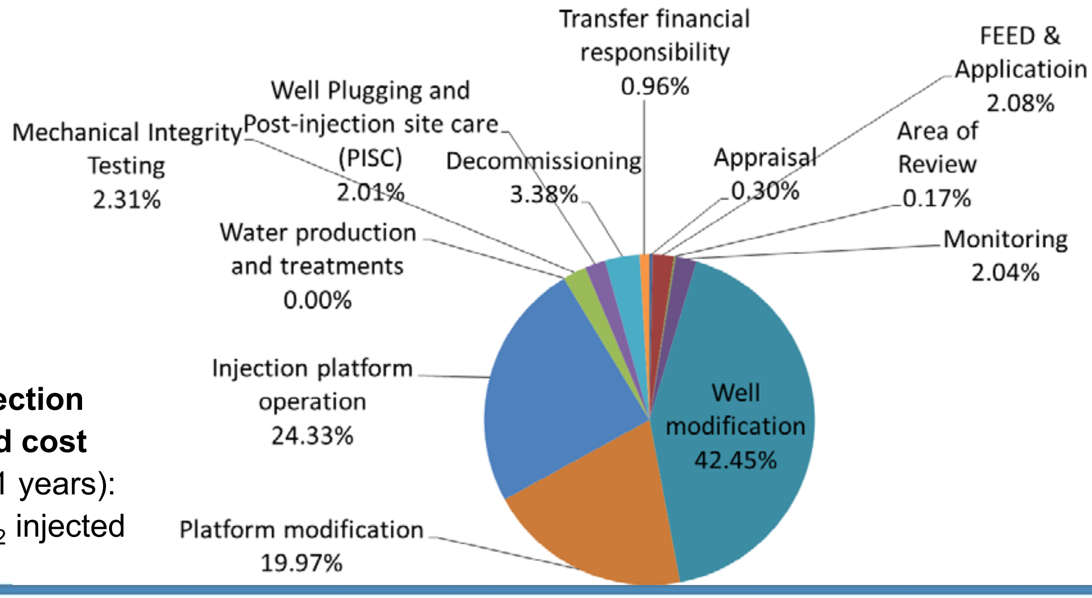
Injection rate Mt/year	Number of wells required during PSI (years)			Total CO_2 injected, Mt
	Platform D	Platform E	Platform F	
0.5	63	12	13	44
2	8	3	5	32

Ravenspurn gas field (North)

Sequential injection life cycle levelised cost
(32Mt: 2Mt/year, 16 years):
£44.73 / tonne CO_2 injected

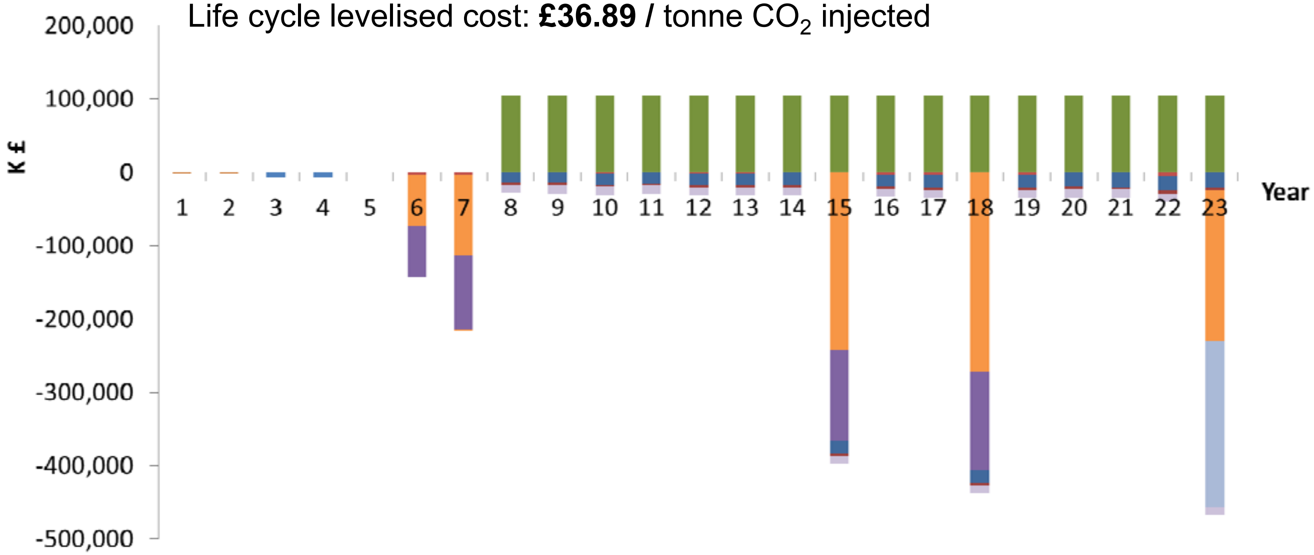


Simultaneous injection life cycle levelised cost
(42Mt: 2Mt/year, 21 years):
£51.71 / tonne CO_2 injected

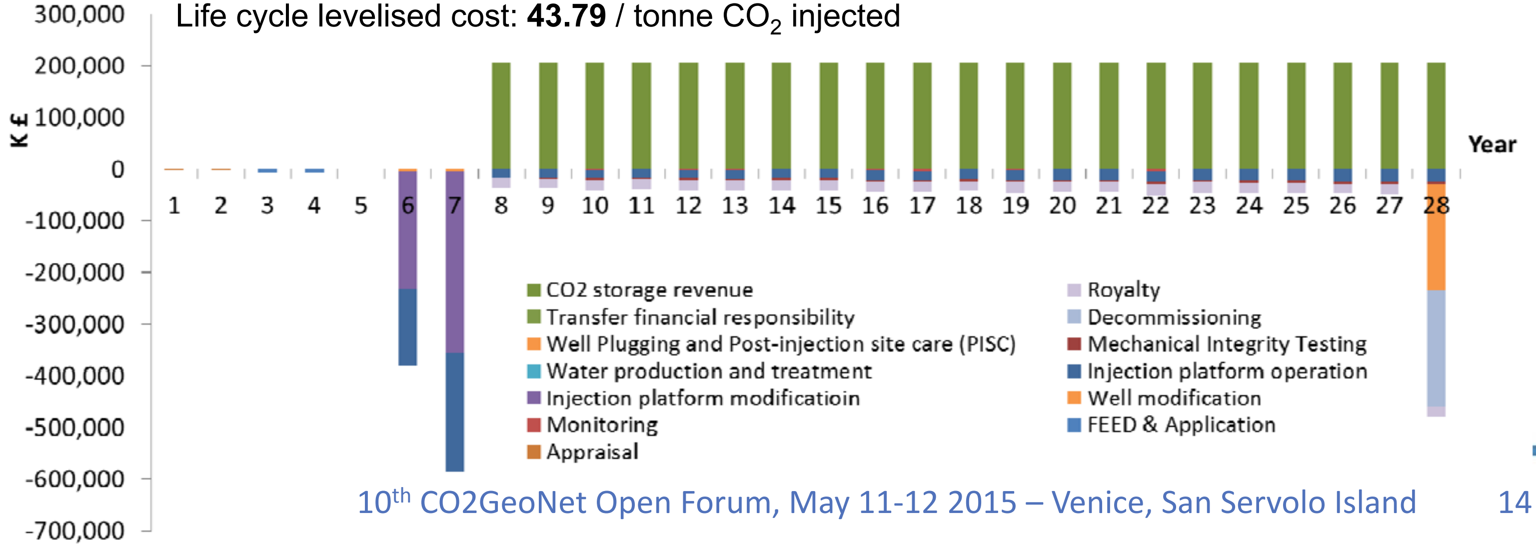


Ravenspurn gas field (North and South)

Sequential injection life cycle cash flow (54Mt CO_2, 16 years of injection)
Life cycle levelised cost: **£36.89 /** tonne CO_2 injected



Simultaneous injection life cycle cash flow (71Mt CO_2, 21 years of injection)
Life cycle levelised cost: **43.79** / tonne CO_2 injected



Ravenspurn gas field (North and South)

	Internal Rate of Return (IRR,%)		
	CO_2 price		
	£30/t	£40/t	£60/t
No subsidy			
2 Mt/year Sequential Injection	<0	8.32	29.85
2 Mt/year Simultaneous Injection	<0	6.59	14.08
0.5 Mt/year Sequential Injection	<0	<0	<0
0.5 Mt/year Simultaneous Injection	<0	<0	<0
Assuming government subsidy 25% of CAPEX			
2 Mt/year Sequential Injection	5.75	21.55	38.56
2 Mt/year Simultaneous Injection	4.63	10.63	19.04
0.5 Mt/year Sequential Injection	<0	<0	1.66
0.5 Mt/year Simultaneous Injection	<0	<0	<0
Assuming government subsidy 50% of CAPEX			
2 Mt/year Sequential Injection	19.44	32.98	49.22
2 Mt/year Simultaneous Injection	10.58	17.12	27.74
0.5 Mt/year Sequential Injection	<0	<0	6.23
0.5 Mt/year Simultaneous Injection	<0	<0	<0

Multi-period CCS network model

Optimal design of an evolving integrated CCS network
Multi-period supply chain optimisation issue

Comprehensive Whole System Cost Optimisation
Integrated Assessment of Capture, Transportation and Storage Components

Multi-Period Model
Evolution of the Network

Scenario Analysis
Effects of market conditions on chain's techno-economic performance

Stochastic optimisation
of future CCS networks under uncertainty

Future Cost Predictions & Evolution of Energy Systems

Real Topography Existing network Infrastructure Effects of the Associated Costs on Network Layout

Effects of Interest Rates on Initial Investment

Onshore/Offshore Transportation of CO_2

Multi-period CCS network model

Multi-period supply chain optimisation model solved using mixed integer linear programming in GAMS

CO_2 captured at stationary sources, transported and injected into stationary sinks over the planning horizon

Sources & Sinks introduced as Nodes	**Each Node Assigned Emission/ Storage Capacity**	**Mass Balance Performed At Each Node**	**Transport Routes Allow for Overall Mass Balance**	**Logical/ Design Constraints**

Design and operational decisions: Match quantity of CO_2 captured/stored/transported

Objectives: Reach a pre-specified CO_2 capture target at each time period (e.g. 108 Mt per year 2040-2050)
Minimise the total investment and operational cost of the supply chain over the planning horizon

Estimates: Where /when to build capture/storage facilities and the pipeline network layout, cost values for chain components

Real options analysis

Effect of market conditions on the cash flow of a CCS value chain

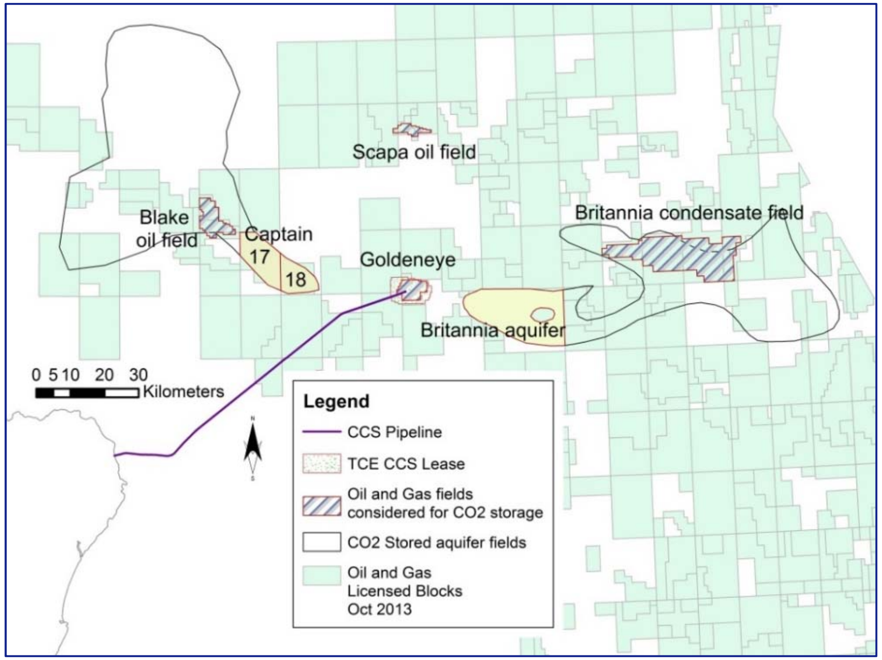
Central North Sea multi-store
CO_2 transport and geological
storage network optimisation and
techno-economic performance

Sources

Installation	Source type	Verified CO_2 emissions 2011 (kg/year)	CO_2 emission (Mt)
Peterhead Power Station	CCGT plant	2,482,116	2.48
Longannet Power Station	Coal	9,124,587	9.12
Grangemouth Refinery	Refinery	1,487,237	1.49
Cockenzie Power Station	Coal	3,945,259	3.95
Lynemouth Power Station	Coal & biomass	2,551,364	2.55

Real options analysis

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



Sinks

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

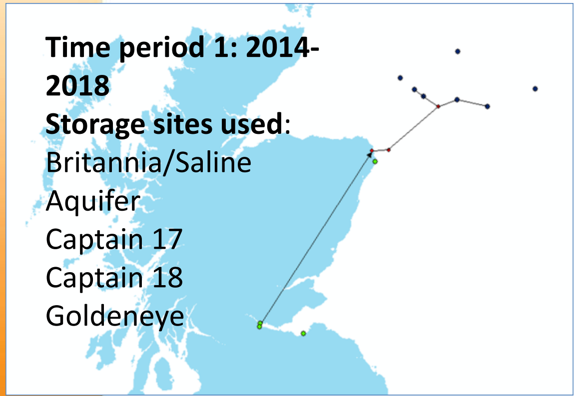
Transport and storage system evolution

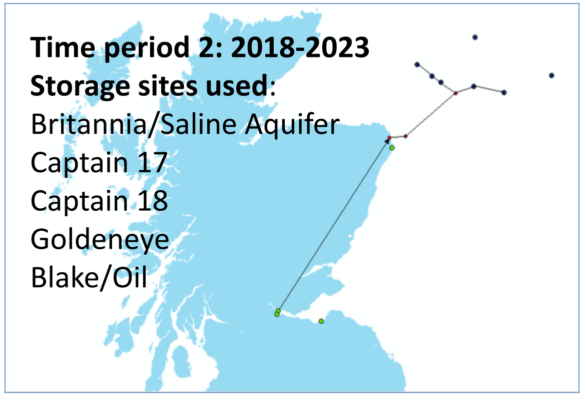
Amount of CO_2 captured during each time period

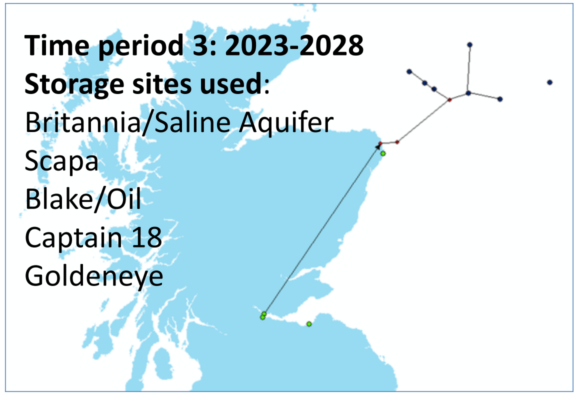
CO_2 stored at time t in Mt/year	**T1 2014-2017**	**T2 2018-2022**	**T3 2023-2027**	**T4 2028-2038**	**T5 2039-2050**
Length of time period (years)	4	5	5	11	12
Britannia aquifer	2.00	2.00	0.99		
Captain block 17	2.00	1.80			
Captain block 18	2.00	0.65			
Goldeneye Gas Condensate Field	2.00	1.185	1.22		
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**				

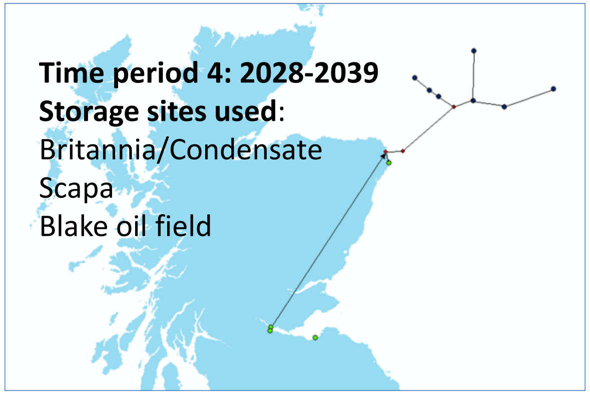
Transport and storage system evolution

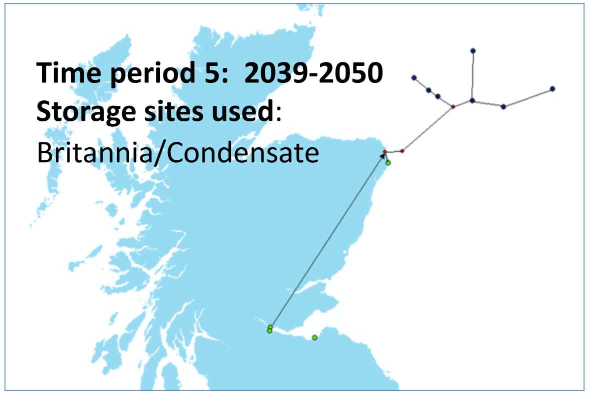
Central North Sea multi-store CO_2 transport and geological storage network optimisation and techno-economic performance





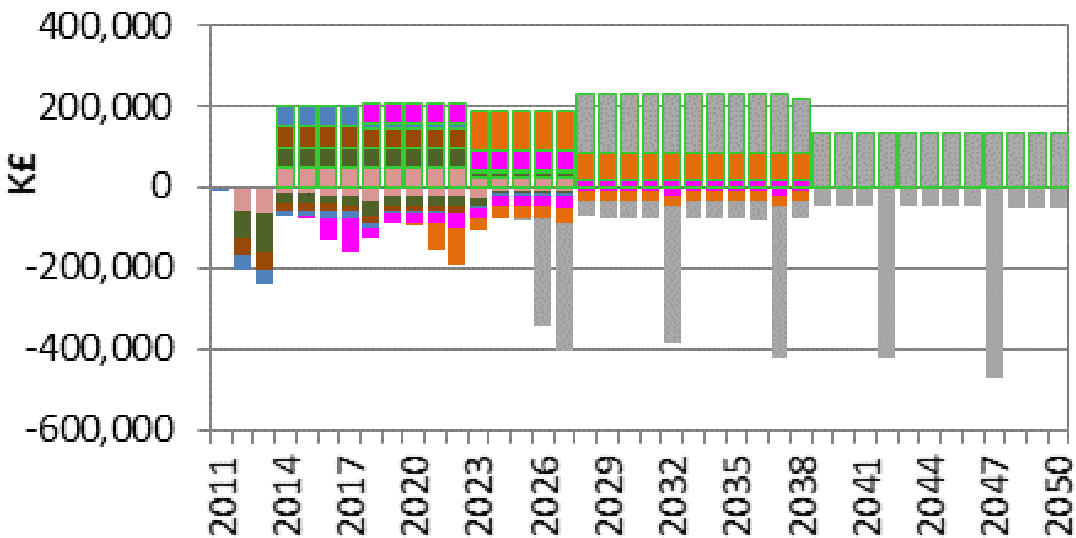






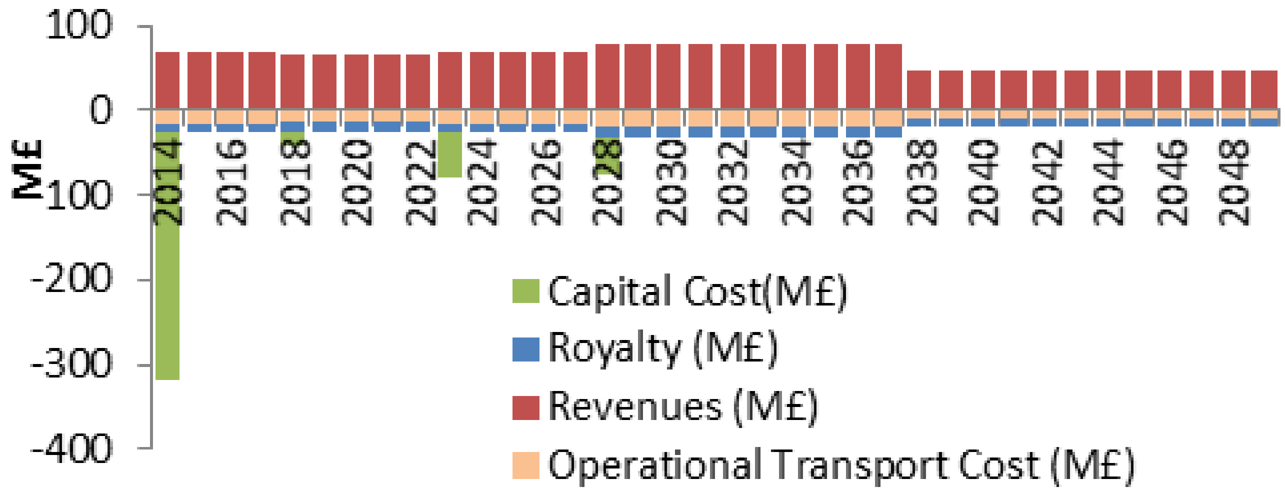
Life cycle cash flow for individual storage sites

Full utilisation of the optimal CNS multi-store capacity for a fixed CO_2 price (£25)



Cash flow per storage site during the planning horizon (2011 to 2050)

Results for CO_2 transportation network for
including onshore and offshore pipelines



If target IRR of 15 % and a royalty rate at 15 % are set, then the price for CO_2 transportation (£/tonne) is back- calculated as £ 8.51 per tonne of transported CO_2, which is lower than the transport cost of Goldeneye single chain case study.

Real Options Scenario Analysis Conclusions

- The network optimisation and life cycle cost model for CCS value chains captures the effects of technical and market constraints on individual storage site costs, as well as represent accurately complex multi-storage scenarios.
- 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.
- There is a sizeable opportunity to reduce costs through transport and storage network sharing and optimisation relative to the cost of a single value chain.

Korre, A., Nie, Z., Durucan, S., Elahi, N., Shah, N., Ahmad, S., Goldthorpe, W., "The effect of market and leasing conditions on the techno-economic performance of complex CO2 transport and storage value chains" Energy Procedia, 63, (2014), 7225-7233.

Elahi, N., Shah, N., Korre, A., Durucan, S., "Multi-period least cost optimisation model of an integrated carbon dioxide capture transportation and storage infrastructure in the UK" Energy Procedia, 63, (2014), 2655-2662.

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