


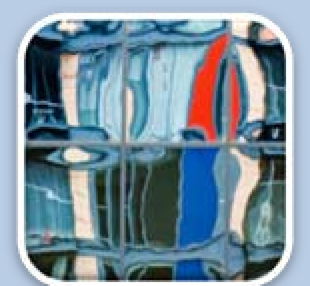




The costs of Carbon Capture and Storage (CCS) for UK industry

- A high level review

Revised Final Report V3

For BIS and DECC

26/03/13

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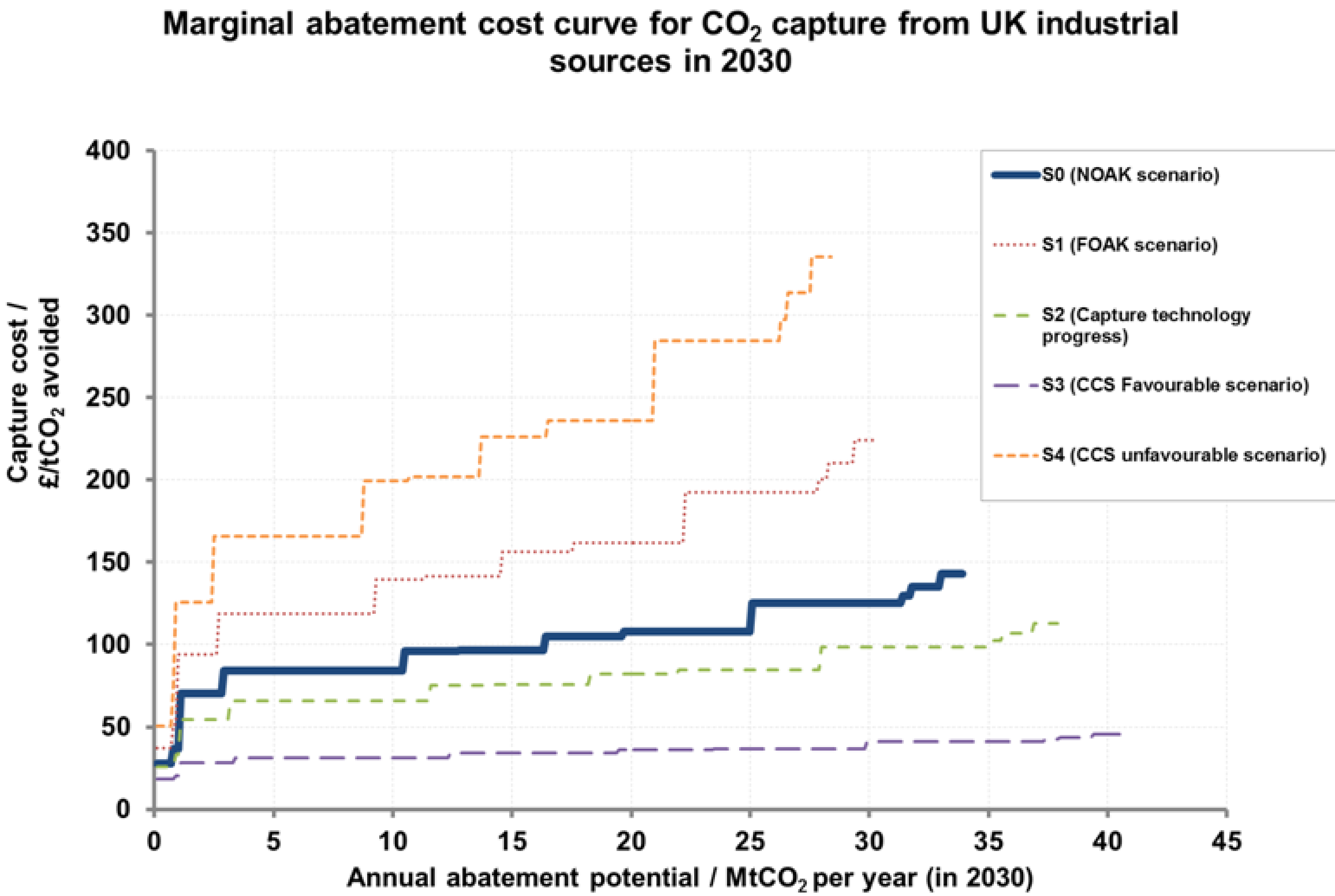
Executive Summary (1/4): CO_2 capture in several UK industrial sectors is feasible, but detailed technical analysis is required.

- Internationally Carbon Capture and Storage (CCS) is in a development and demonstration phase, with examples of partial and full chain projects in both industry and power in design, construction or operation. In December 2012, BIS commissioned Element Energy to prepare an updated 2030 CCS marginal abatement cost curve for UK industry, following initial analysis for the Committee on Climate Change in 2010. This was to be based on a short, high level analysis.
- CO_2 capture concepts have been proposed for existing industrial sectors currently represented in the UK, including hydrogen, ammonia, iron and steel, refineries, CHP, cement, and ethylene. The UK does have experience in capture, although international competition is significant. CO_2 capture could also be relevant for future industrial point source emitters.
- Capture costs depend on diverse factors CO_2 purity, scale, technology and site readiness. Even high level capture cost estimation is challenging – there are several potential technical solutions (and future technology development), diverse potential site restrictions/synergies, and uncertainties over energy requirements/supply. Encouragingly several organisations (IEA-UNIDO, Imperial College, Kuramochi, and technology suppliers etc.) are looking into this.
- Also a paucity of high quality studies of capture for industrial sites and no straightforward basis for projecting what sites will still exist and how retrofit costs will change by 2030 make it challenging to provide defensible £/t supply abatement cost curves for 2030. There may also be hidden costs (e.g. plant downtime) and benefits not explored in the present study.
- With the exception of (i) hydrogen and ammonia plants, for which capture costs are likely to be low as they reflect only CO_2 clean up and compression; and (ii) very small emitters, for which specific costs will be high, the uncertainties in capture costs are greater than the differences between sectors. Therefore it is premature to rank the majority of industrial sectors in terms of cost.

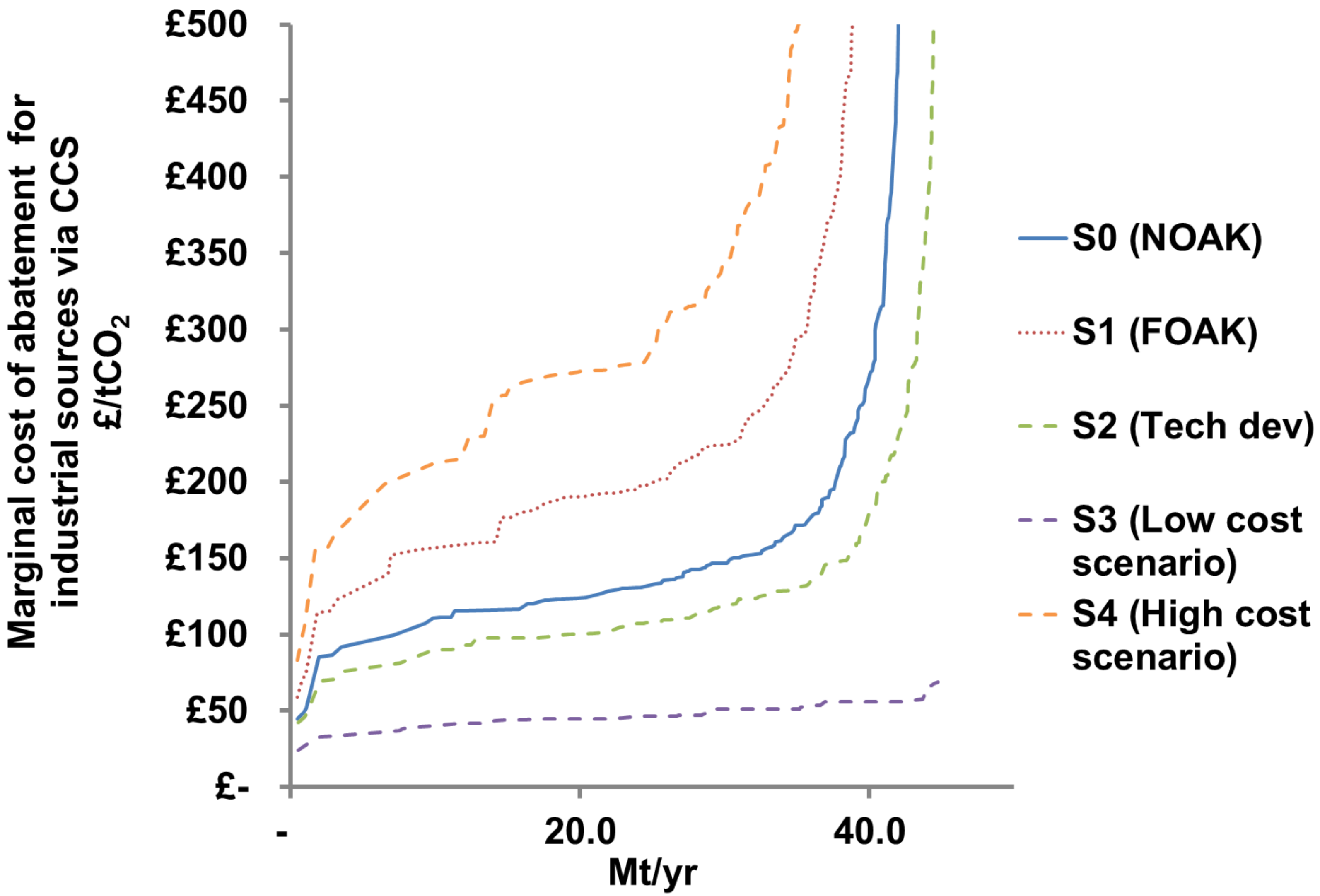
Executive Summary (2/4): CCS on existing industrial sources could reduce up to *ca*. 5% of average current UK emissions but specific abatement costs and uncertainties span nearly one order of magnitude.



Executive Summary (3/4): To deliver this, CO_2 transport and storage infrastructure, at the right capacity, specification, at the right time, affordable and simple to access must be in place.

- CCS requires a full chain of CO_2 capture, transport and storage, and therefore there is a requirement to develop safe, affordable transport and storage capacity, of the right size, in the right location and at the right time.
- This will be time consuming, with high up-front costs and diverse risks for potential infrastructure developers. Small industrial sources will not be interested in long-term storage liabilities.
- Important cost drivers are source-sink distance and economies of scale, and any industrial CCS projects will likely need to share transport and storage capacity with each other and power sources – creating challenges and opportunities, particularly around the development of clusters or hubs.
- Costs of transport and storage depend on location and geology constraints - industrial emitters close to the Humber and St. Fergus may find it straightforward to access storage. Emitters in South Wales, for example, will find it much harder unless more storage sites are discovered or extensive CO_2 transport infrastructure is in place. Even in the most favourable locations, point-to-point capture-transport-storage solutions for industrial emitters below 1 Mt/yr will likely be prohibitively expensive; indeed economies of scale are significant even up to 10 Mt/yr, implying the use of shared networks.
- However, the over-arching challenge will be creating an appropriate policy and investment model for long-term industrial CCS to drive adoption – otherwise transport and storage infrastructure runs stranded asset risks (i.e. under-utilisation).
- Government choices on how to consider industrial CCS will clearly depend on political priorities (CCS demonstration to a global audience, maximising UK CO_2 reduction, industry protection/competitiveness, cost efficiency, jobs, GVA, risk management, attracting new industry, enhanced oil recovery, managing budget and trade deficits etc.).

Executive Summary (4/4) :
Overall marginal abatement cost curve for UK industry

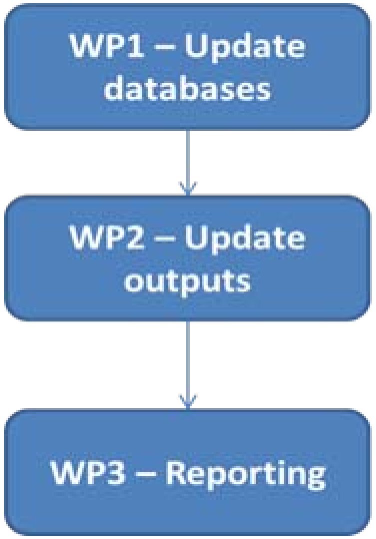


Outline

- Background
- Data and Process
- Scenario Analysis
- Transport and Storage of CO_2
- Overall CCS costs
- Bibliography

Background

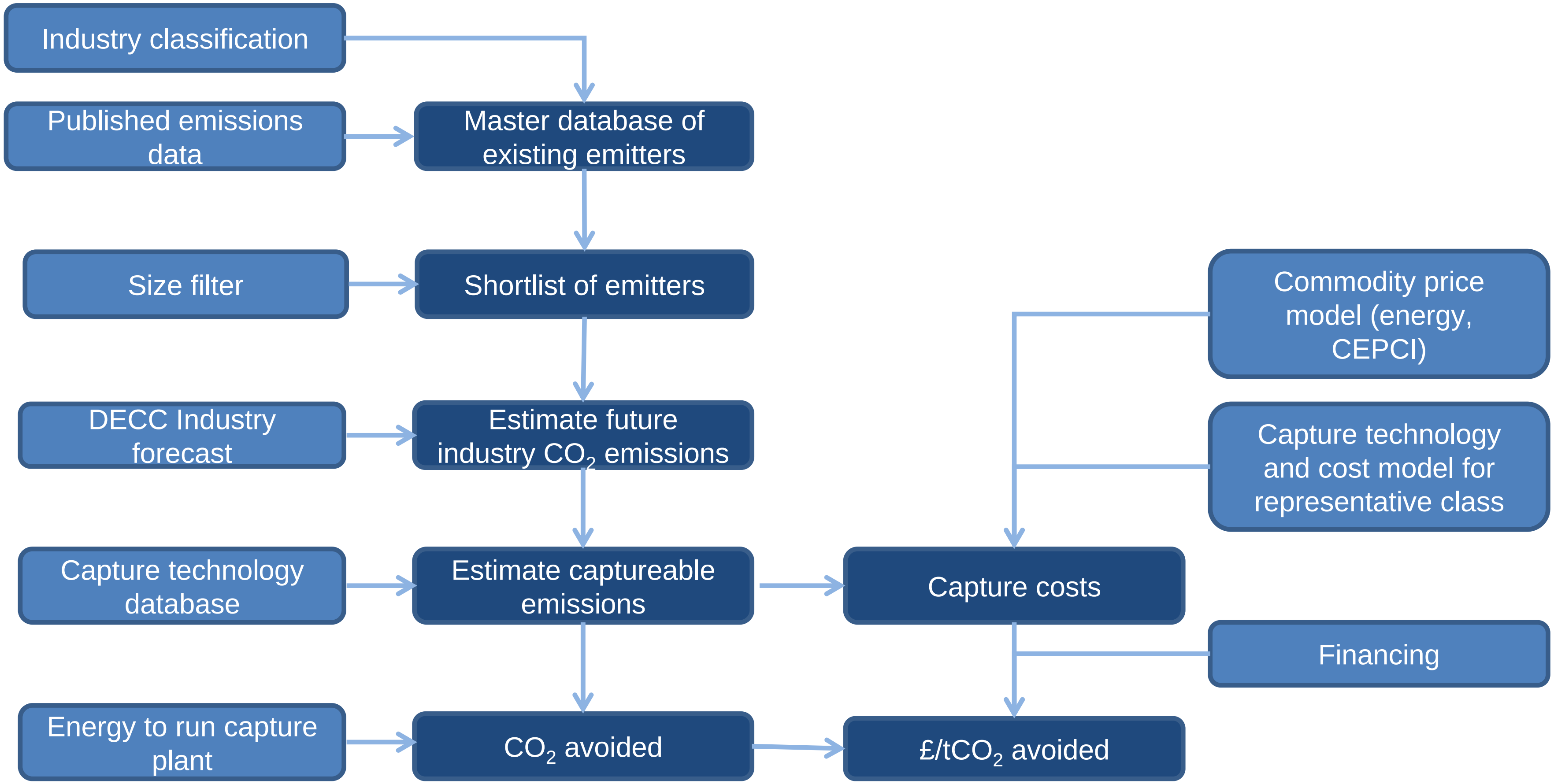
- Recent analysis by BIS has quantified the challenges and opportunities associated with rising carbon prices and regulation on the UK industrial sector.
- Carbon Capture and Storage (CCS) has been recognised as a technology that potentially allows energy intensive industry to function in the context of constrained CO_2 emissions to the atmosphere.
- In December 2012, BIS, with support from DECC, commissioned Element Energy Ltd to carry out a brief and high level desk-based review of the costs of CCS for UK industry in 2030.
- This slide-pack comprises the WP3 final deliverable from the project.



Outline

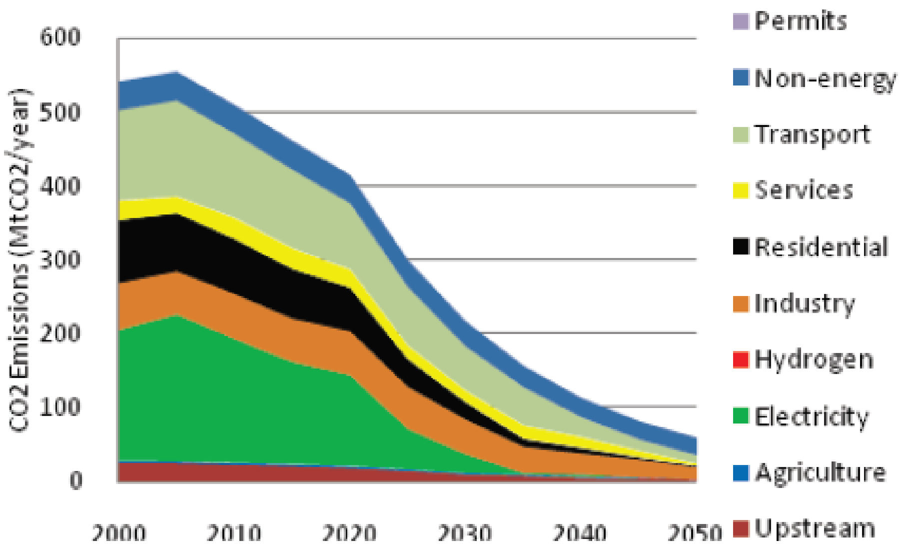
- ❑ Background
- ❑ Data and Process
  - ❑ Industrial sources
  - ❑ Capture cost review
- ❑ Scenario Analysis
- ❑ Transport and Storage of CO_2
- ❑ Overall CCS costs
- ❑ Bibliography

Techno-economic assessment process for capture from industrial sources



Industrial emissions are projected to reduce due to energy efficiency and fuel switching….

- Emissions from industry make up nearly one quarter of the UK's total emissions.
- The UK Carbon Plan states that by 2050, the Government expects industry to achieve reductions of up to 70% from 2009 levels.
- These reductions will be achieved by a combination of energy efficiency, fuel switching, and CCS.



Sectoral CO2 emissions projections from "Pathways to 2050: Key Results", AEA Technology, 2011.

The DECC Updated Emissions Projections (2012) project an 11% reduction in emissions for industry overall from 2009 to 2030. This reduction is the result of competing trends of:
•industry output increasing over time in line with economic growth (which returns to c. 2.5% by 2014, according to OBR 2012 forecasts),
•reductions in emissions driven by policies (primarily the EU ETS), and met through a combination of fuel switching and energy efficiency measures.
The reductions in emissions has a greater impact than increasing industry output, resulting in the overall reduction in emissions from this sector.

Source: The Carbon Plan, DECC (2011). Pathways to 2050, Key Results, AEA Technology (2011).
The DECC Updated Emissions Projections (2012)

Installation data has been filtered and grouped into reference plant sizes for each sector

- All installations in the EU ETS and DEFRA/SEPA Pollution Inventories with 2008-2011 emissions greater than 50,000 tCO_2/yr were included in the analysis.
- 8 sectors were identified as are suitable for CCS:
  - Iron and steel
  - Refineries
  - CHP
  - Ethylene
  - Cement
  - Lime
  - Ammonia
  - Hydrogen
- CHP, cement, and iron & steel plants show significant variability in size and were further broken down by size so that representative project costs could be estimated.
  - CHP – divided into large, medium and small
  - Iron and Steel – divided into small and large
  - Cement – divided into large and small
- In total 12 representative project types were identified.
- The next slides show the rationale for the cut-off of installations smaller than 50,000 tCO_2/yr, and then the number of sites, total sector emissions based on the average for 2008-11, and % emissions for each representative project type.

The baseline dataset using emissions from current installations was filtered by size and by eligible sectors…

UK industrial direct emissions[1]
107 $MtCO_2$

Installations in the EU ETS and Defra/SEPA Pollution Inventories
85 $MtCO_2$

Eligible installation sizes (< 50,000 tCO_2 removed)
79 $MtCO_2$

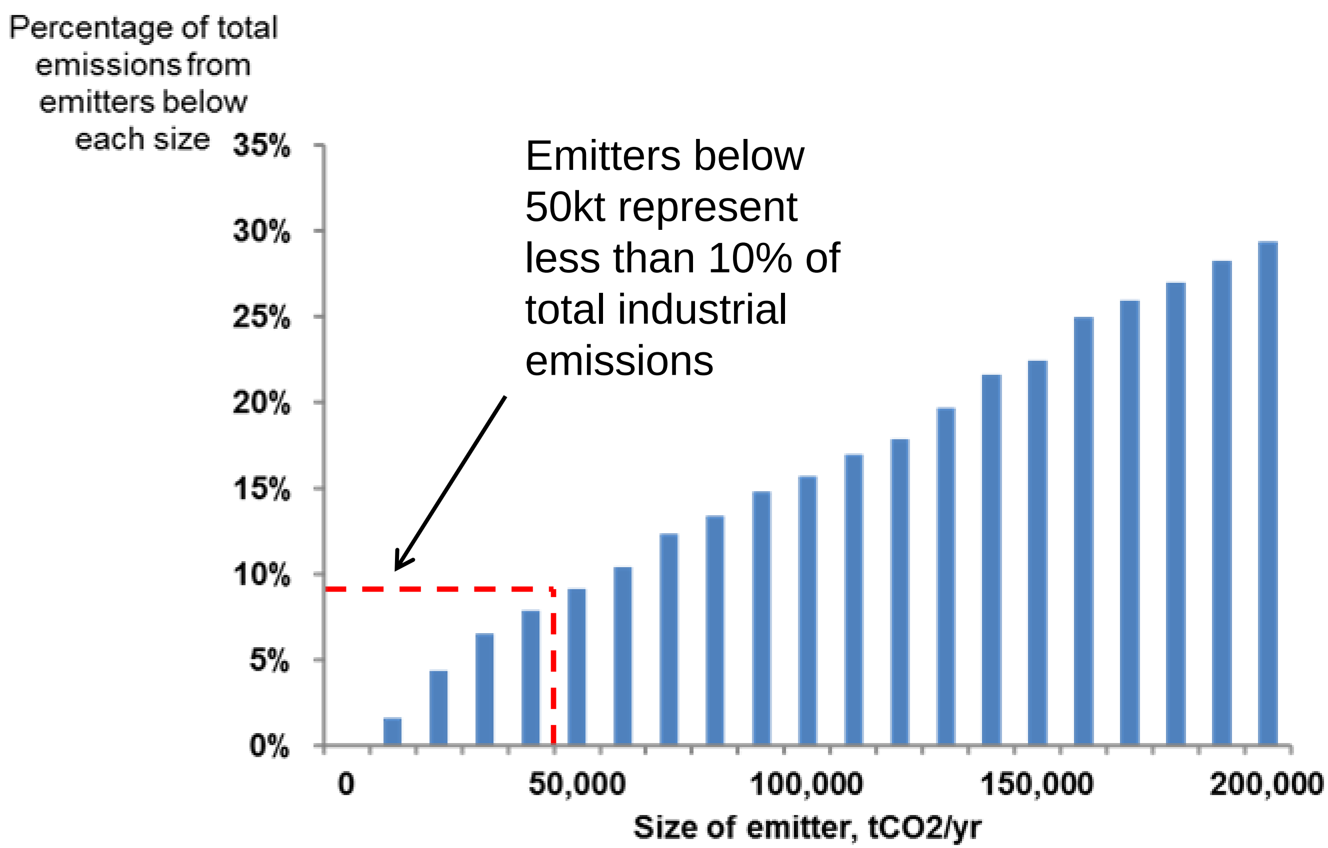
Eligible sectors (offshore and waste management removed)
60 $MtCO_2$

Capture potential (scenario dependent)

[1] Source: CCC progress report, 2012, emissions in 2011. Note: EU ETS data: average of emissions over 2008-2011 Pollution Inventory data: average of emissions 2009-2010

Although there are numerous small emitters, a size filter of 50ktCO_2/year ensures that at least 90% of industrial emissions are examined in more detail.

- A cut-off for size of emissions was established by Amec and Gastec in a report for IEA GHG (2007) which examined the challenges for UK distribution networks for CCS. Projects with emissions below 50,000t/yr were highlighted in the study as having prohibitively high CO_2 transport costs compared to the abatement potential.

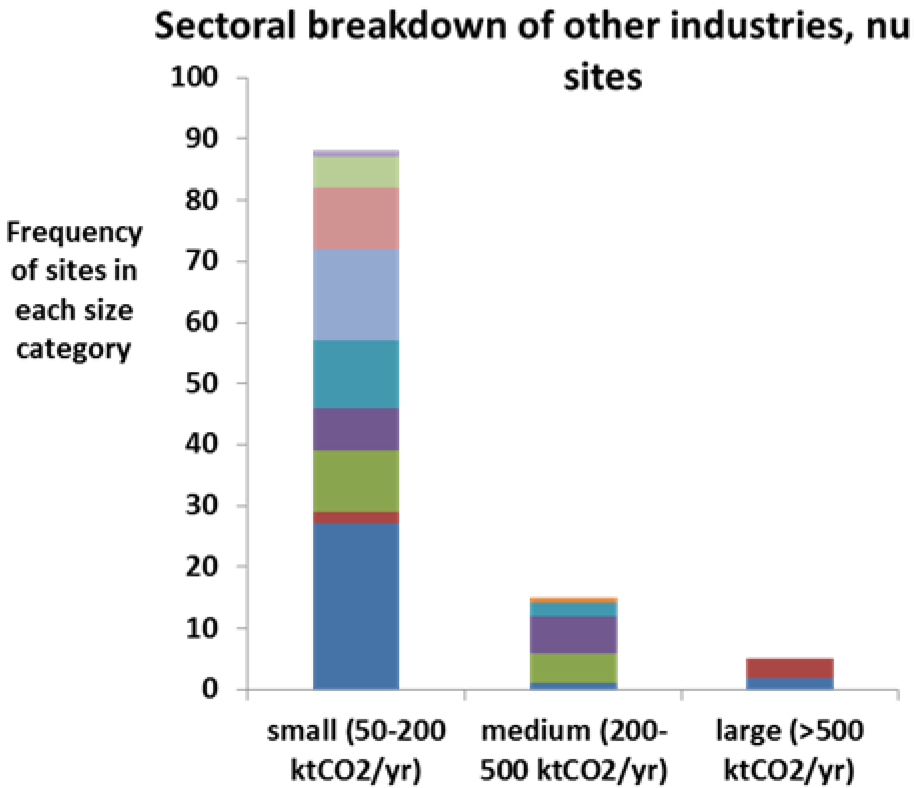


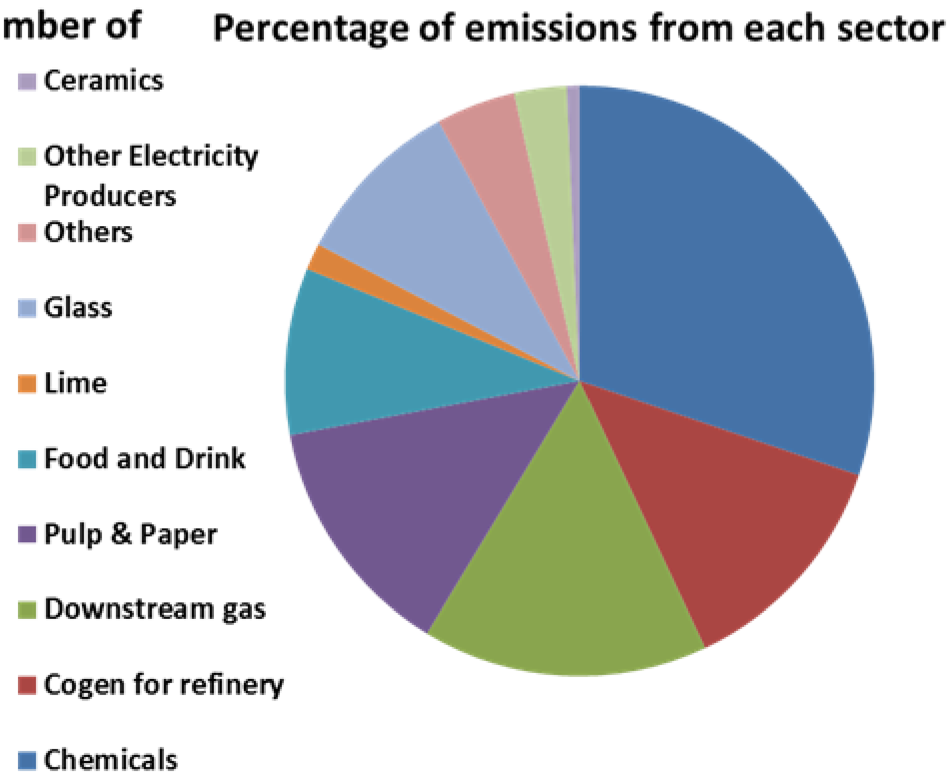
Distribution of CO_2 emissions between representative industries (emitters above 50 kt/yr)

	No of sites	Annual sector emissions $MtCO_2$/year	Emissions, % of total
Iron & Steel (large)	3	18.3	28.8%
Refineries	8	16.0	25.0%
CHP (small)	89	9.3	14.5%
Cement (large)	7	4.9	7.7%
CHP (medium)	15	4.4	7.0%
CHP (large)	5	3.5	5.6%
Ethylene	3	2.5	4.0%
Cement (small)	5	1.6	2.5%
Lime	6	1.4	2.2%
Iron & Steel (small)	5	0.8	1.2%
Ammonia	2	0.7	1.2%
Hydrogen	1	0.2	0.3%
	149	63.7	100

Source: EE analysis of EU ETS and DEFRA/SEPA Pollution Inventories, filtered to exclude emitters below 50,000t/yr

Outside of the major emitters, what are the other sectors?





- There are a range of sectors included. Most installations are CHP plants for various industries.
- For the capture costs, we have assumed that these are all CHP.

Capital cost models have been reviewed and updated

We have revised previous estimates for the capital costs and capture potential for the relevant industrial sectors.

This has involved:

1. Reviewing data sources identified in the CCC 2010 study.
2. Literature search to identify new material.
3. Verifying then adding new data sources (8) to the capital costs and capture data.
4. Identification and resolution of systematic issues in the capital cost and capture data, based on index, currency, changes, and correcting for missing data.
5. QC included standardisation of some assumptions (operating and maintenance costs for capture, the supply of heat and electricity to drive capture, and discount rate) to facilitate analysis.
6. Considering wider scenarios and sensitivities

- Source: DoE/NETL, 2010, Cost and Performance Baseline for Fossil Energy Plants (revised)
- DoE/NETL, 2007, Cost and Performance Baseline for Fossil Energy Plants. Vol. 1 Rev. 1.

Standardised datasets were produced for each sector..

LARGE CEMENT PLANT

CCS application	Value	Source/notes
Potential number of GB sites	7	All sites within the EU ETS and Pollution Inventory. Large kilns are defined as those above 450,000 tCO2/yr.
Total capture potential 2030 ($MtCO_2$)	5.1	MtCO2

Capture project description	Capture cost calculations are largely based on the Mott McDonald (IEA R&D GHG, 2008) study of a retrofit post-combution project using chemical absorption applied to a 1Mt/y cement modern plant. Both combustion and process CO_2 emissions are captured. The study assumes that additional CCS energy needs are met by new-build gas-fired CHP (CHP emissions are captured). Oxyfuel combustion with CO2 capture is not considered as it requires major rebuild of the kiln and is currently in the process modelling and laboratory phase.

Parameter	Value	Inflate to 2012	Convert to £	Source/notes
Cement plant, capital cost from literature			**127**	summed from the two components below
Total of other Capex (€m, 2008)	**164.8**	157	127	Source: Mott McDonald (IEA R&D GHG, 2008) study for a 1Mt cement/year plant. Average emissions are 0.7tCO2/t cement, therefore reference plant is close to the average of the 7 large cement plants, average emissions of 730,000tCO2/year.
Selective catalytic reduction (SCR)	*4.6*			
Flue gas desulphurisation (FGD)	*22.5*			
CO2 capture + anciliary	*31.8*			
CO2 compression	*7.8*			
Others (construction etc)	*161.0*			
Additional CAPEX		Yes or no?	Value	
Source missing important cost categories therefore need to add process contingencies? (1 yes, 0 no)	*10.00%*	0	0	Assume process contigencies are not included unless source states otherwise. Process contingencies cover any performance problems with the plant - inefficiencies, etc.
Source missing important cost categories therefore need to add project contingencies? (1 yes, 0 no)	*10.00%*	0	0	Assume project contigencies are not included unless source states otherwise. Project contingencies cover any inaccuracies in budget estimates.
Source missing important cost categories therefore need to add owners costs? (1 yes, 0 no)	*1.00%*	0	0	Assume owners costs are not included unless source states otherwise. Owners costs may include pre-production costs, land costs, inventory capital, permitting, and provision of utilities.
Need to add costs of arranging financing? (1 yes, 0 no)		0	0	Project assumption: no. Interest costs will be included in the final calculated avoided cost £/tCO2
Is the original souce US costs (1) or UK costs (0), or a combination (ratio)?	*20.00%*	0	0	Original source is EU and UK costs
Therefore Total Overnight Cost (£m)			**127**	
Additional OPEX				
O&M (£m/yr, 2012 prices)	5.1			4% default assumption (*Dolf Gielen, IEA (2003)*), excludes energy costs
CO_2 emissions				
Reference plant emissions (tCO_2/yr)	730,000			

Cement - large | Cement - small | lime | Ammonia | Hydrogen | Ethylene | CHP-small | CHP-medium | CHP-la

There are many limitations of publicly available cost data

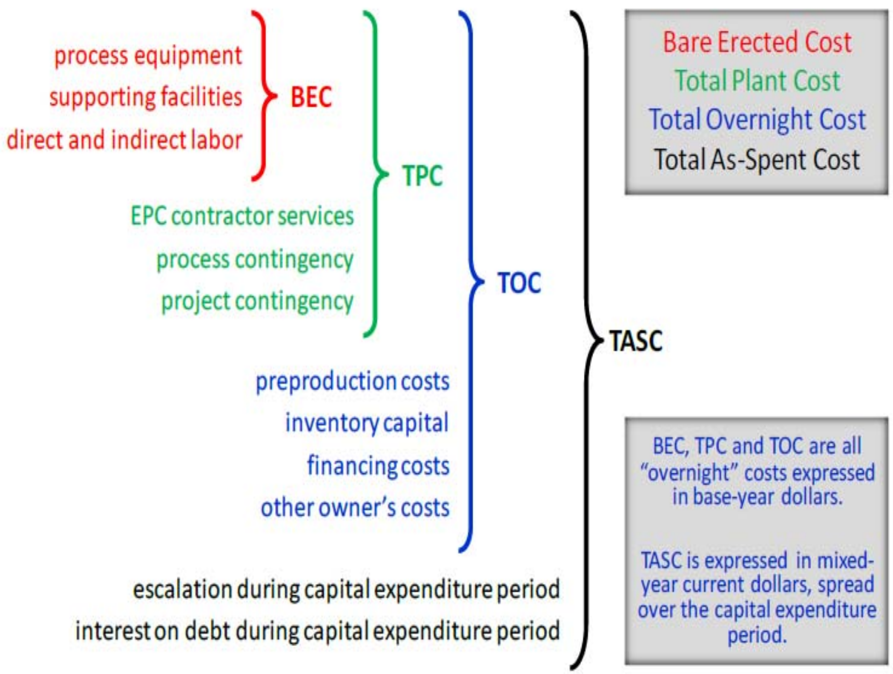
- For any given sector, there are few independent data sources, i.e. even recent compilations of industrial capture costs are based on a limited number of conceptual studies developed in the mid-2000s.
- Over the last few years global understanding of technology and project requirements has improved considerably, and the wider market for engineering costs have changed dramatically.
- In our judgement the available UK data does **not** allow reliable comparison today of the relative costs of CO_2 capture from different industries (e.g. iron and steel vs. cement vs. refineries). This stems from a number of reasons:
  - The underlying datasets were prepared by different engineers with different bases for engineering design and costing.
  - The rate at which capture technologies become available for industry and their associated footprint and energy requirements
  - Site-by-site variability in captureable CO_2 emissions and costs could be substantial.
    - “Known unknowns” are the actual technology choice and sizing of capture, nature of heat and power provision for capture, the fate of any arising CO_2 emissions, assumptions on contingencies and owner’s costs, which have been dealt with through scenario approaches.
- Also substantial uncertainties over relevant CO_2 volumes in 2030, including the potential for new sources (e.g. biofuel processing)

Plant cost standardisation

- Where necessary, plant costs were corrected for scale using:

$$\frac{Cost\ A}{Cost\ B} = \left[\frac{Scale A}{Scale\ B}\right]^\wedge\left(\frac{2}{3}\right)$$

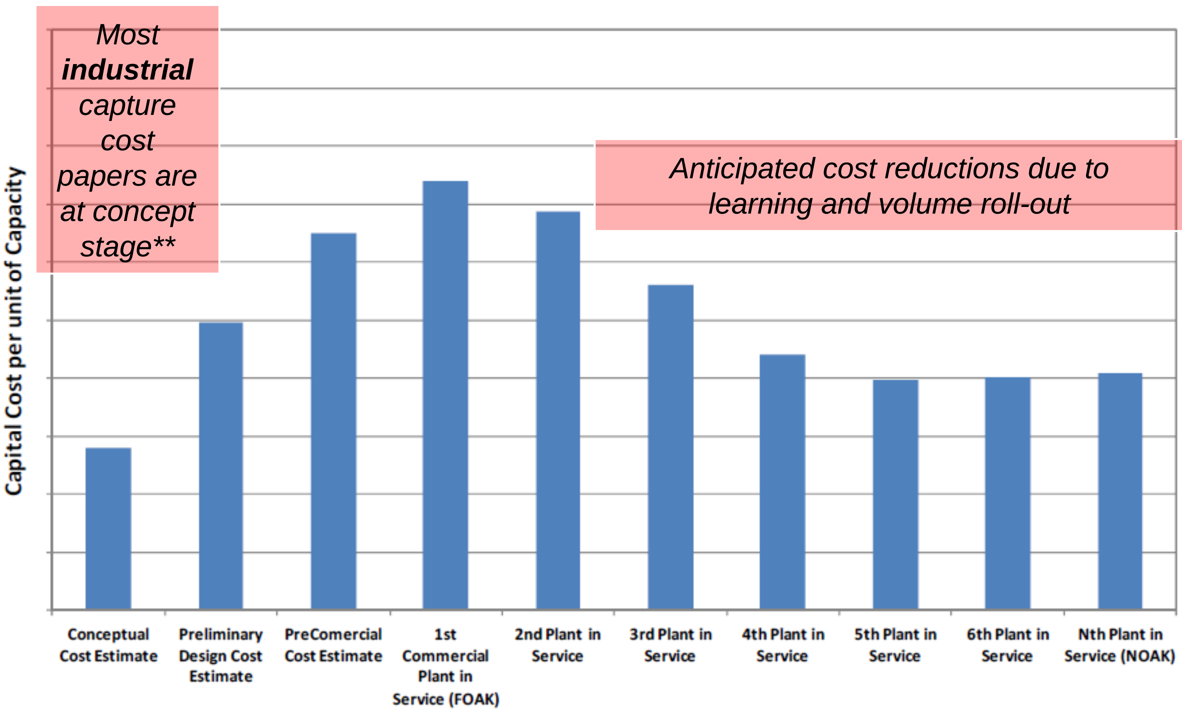
- Corrections for missing data have included corrections for process contingency, project contingency and owner's costs to provide a standardised Total Overnight Cost.



- Capital costs were standardised to Total Overnight Cost (as per NETL 2010).
- Opex was standardised to 4% of capex.
- Capital costs were then annualised using a discount rate and lifetime assumption (15-25 yrs).

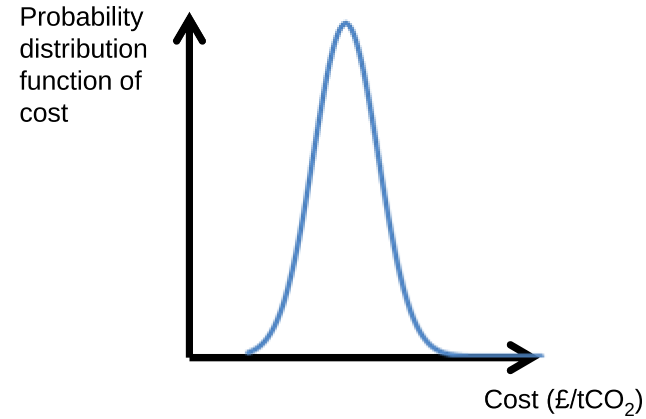
NETL 2010 Costs and Performance of Fossil Fuel Power Plants;
Kuramochi et al. Techno-economics of industrial CCS

Systematically technology costs increase between concept phase and first project, and subsequently decline.



Published capture cost estimates for ***power*** *CCS are now at detailed design*

At any given stage there are an inherent cost *uncertainty* and *variability*



** Capture from ammonia and hydrogen sources is considered mature

Source: NETL, Technology learning curve (FOAK to NOAK) Quality Guidelines for Energy Systems Studies, 2012

Treatment of additional CO_2 emissions associated with capture plant.

- To capture CO_2 emissions using today's post-combustion technologies heat is required to regenerate the solvent.
- There may be opportunities for heat (and power provision) from existing equipment onsite, use of a new gas CHP plant, waste heat, heat from gas boilers, or alternative fuels may also be relevant.
- Our previous (2010) study assumed that the additional emissions produced by the CHP plant would also be captured. However, unless the original CO_2 stream has a similar composition (and ideally temperature and pressure), mixing CO_2 streams adds complexity, and may not always be technically or economically effective.
- Except where stated, our scenarios assume that the emissions from additional CHP sites are not captured if this would likely be of different CO_2 composition.
- In the case of CO_2 capture from existing CHP systems, we have estimated a default and upper bound cost scenario for the capture of CHP emissions. The default assumes that the CHP plant has enough capacity to produce the heat required for capture over and above heat demands from elsewhere, whereas the upper bound assumes additional or replacement CHP capacity.

Where necessary, costs were standardised to reflect a UK-location, by a multiplication factor and currency adjustment.

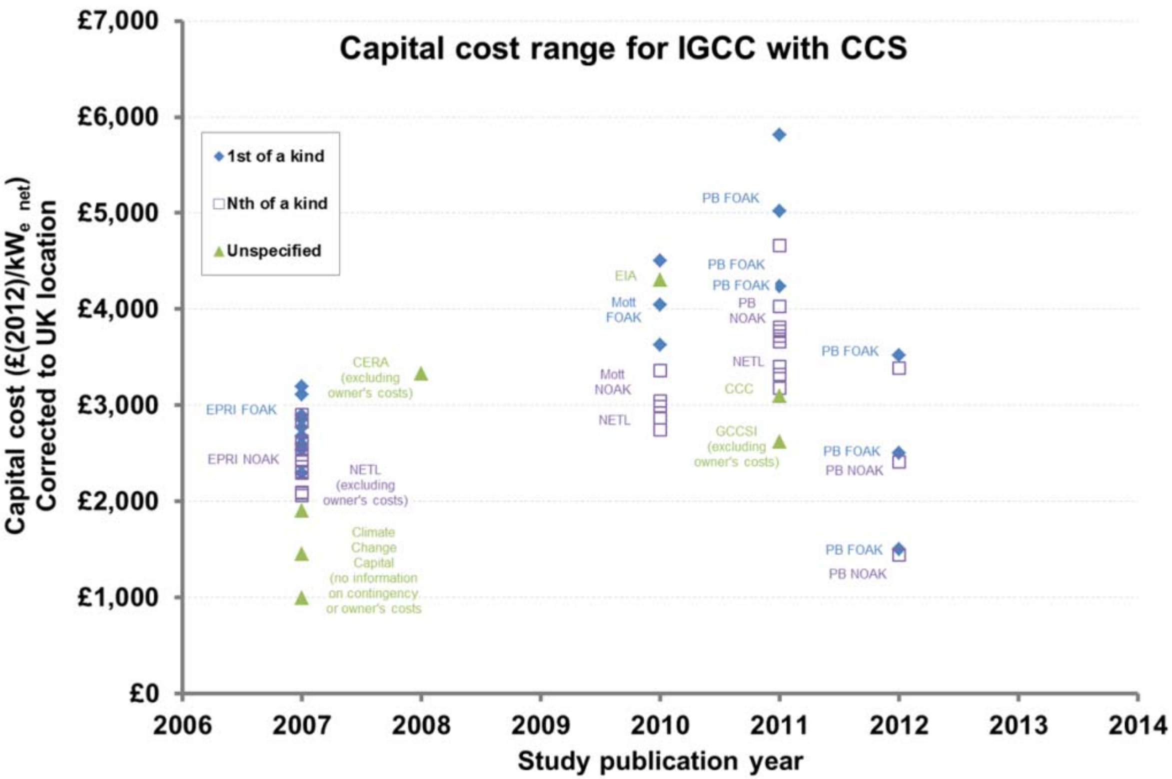
- Location is an important driver of costs, with studies showing installed costs can be between 10 and 60% more expensive in Europe than in the US (GCCSI (2011)).
- Currency fluctuations can be very dramatic, e.g. ±30% over the course of twelve months.

Region	Regional indices to transfer projects from US Gulf Coast		
	Equipment	Materials	Labour
United States	1.00	1.00	1.00
Canada	1.08	1.01	2.16
Euro Region (Germany)	1.19	1.16	1.33

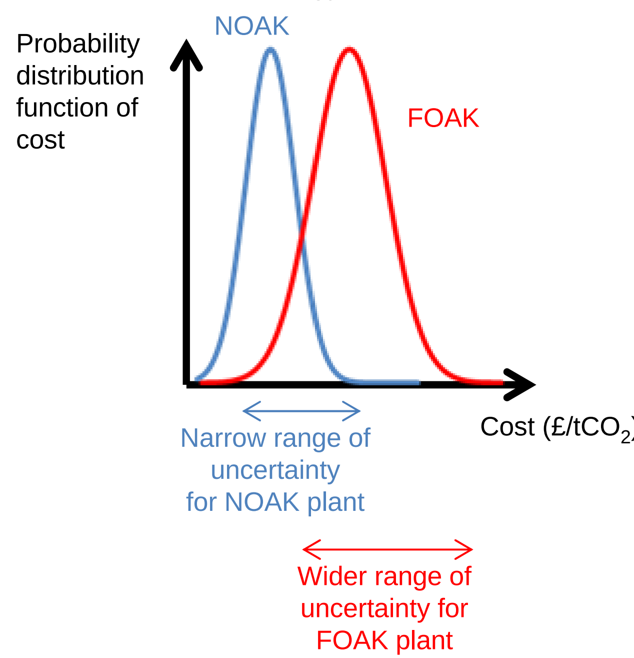
- For this study, as the capture plant costs are dominated by equipment costs (e.g. gasifiers, turbines), we have assumed a 20% uplift in costs to convert US cost estimates to UK locations, i.e. *UK £ cost per kWe = 1.20 x reported US $ cost per kWe x £/$*
- The default exchange rate is $1.62:£1

There are no definitive values for most of the levers, and so it is more useful to show a range of costs on the MACC graph

- DECC annually publishes estimates from different consultant engineers on the costs of power generation. For CCS these show a very wide range of costs.
- Consistently, we shall provide a range for industrial capture costs, rather than showing “single” values.
- We cannot be sure our reference sources correspond to “central” cost estimates…



Cost *uncertainty* also decreases as the technology matures.

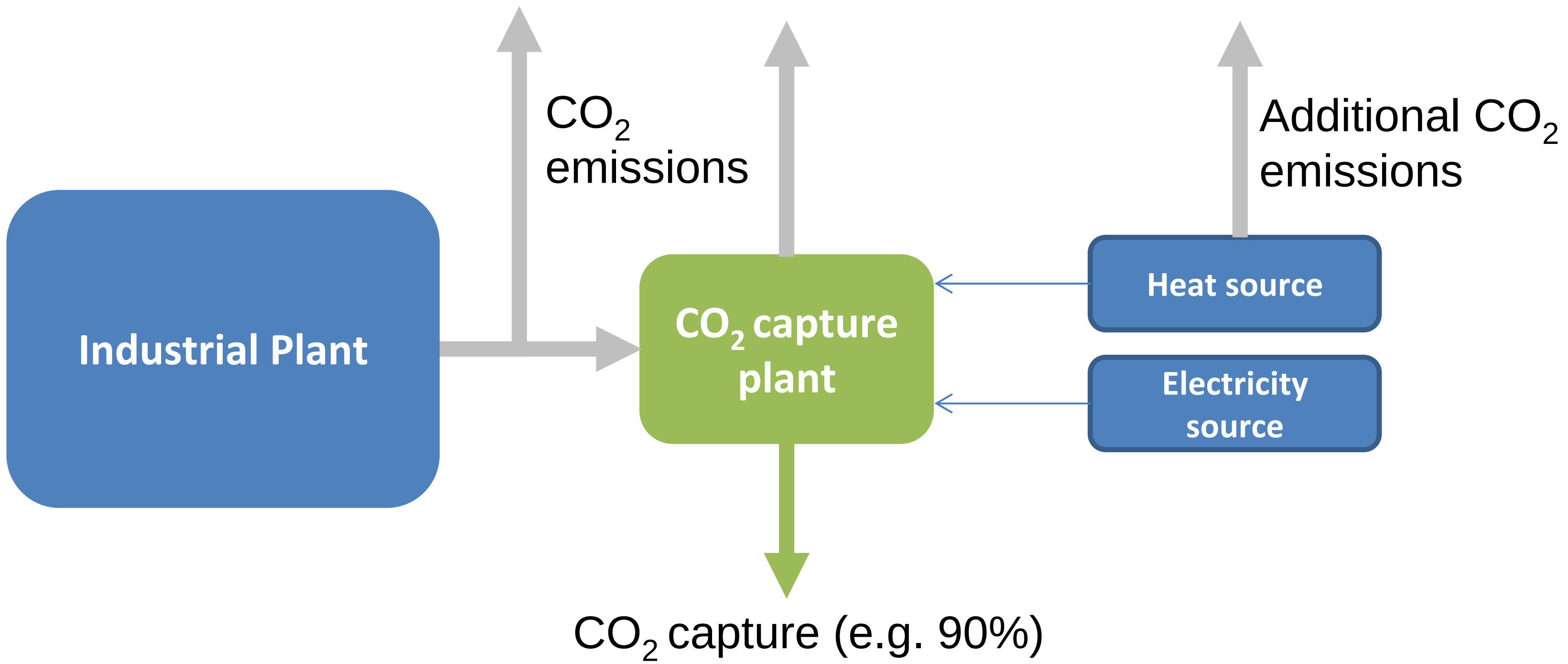


Costs are sensitive to how heat is provided

- Most studies assume that a new CHP plant will be built to provide the energy (mainly heat) required for post-combustion capture.
- Some industrial sites may be able to access excess heat from other processes to use.
- The assumption made can have a significant impact on the capture cost
- For example Johanssen et al. (2012) identify cost ranges from €40-450/$tCO_{2\ avoided}$ in a quantitative comparison of heat supply options for capture for process industries.

Source: Johanssen et al 2012. Heat supply alternatives for CO2 capture in the process industry

Heat and electricity demand of the CO_2 capture plant could be met with a variety of options



Potential heat sources:
- Excess heat from the industrial plant
- Existing CHP plant (on-site)
- New CHP plant
- Provide the heat using a boiler

Potential electricity sources:
- Existing CHP plant (on-site)
- New CHP plant
- Import the electricity from the grid

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  - Annualised Costs
  - Marginal Abatement Cost Curves
  - Sector costs in different scenarios
  - Summary tables
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Cost and technology levers can be varied to produce the MACC

- The techno-economic model includes 8 key drivers for scenario and sensitivity analysis.

Cost lever	Technology lever
Capital cost of the capture plant (£m)	% of on-site emissions capture-able
Operating cost of the capture plant (£m/yr)	Capture efficiency, also known as capture rate (%)
Energy price (p/kWh)	Heat demand for capture (GJ/tCO_2)
Discount rate (%)	
Economic lifetime (years)	

- In terms of deriving a capture cost, preliminary results show that the three most important factors are uncertainty over capital costs, fuel costs (which depend on both the fuel price and energy efficiency of capture), and the discount rate.

Scenarios have been developed to understand impacts of cost and performance uncertainties on overall costs.

Scenario	S0 "NOAK"	S1 "FOAK"	S2 "Technology development"	S3 "CCS favourable"	S4 "CCS unfavourable"
Bare engineering cost multiplier	Base	Base	Base	Reduce by 50% (e.g. site specific, industry changes, tech dev)	Increase by 50% (e.g. site specific, industry changes, tech dev)
Annual opex as a % of capex	Base (4% of capex)	Base (4% of capex)	Base (4% of capex)	3% of capex	5% of capex
External heat supplied for capture GJ/tCO_2	3.5	4.4	2.6	1.5 (tech dev)	4.4
Real discount rate & Economic lifetime	10% 20 yrs	15% 20 yrs	10% 20 yrs	5% 25 yrs	15% 15 yrs
Capture efficiency	90%	85%	95%	95%	80%
Contingencies and owner's cost	Base	Base + 33%	Base -10%	Base -15%	Base + 33%

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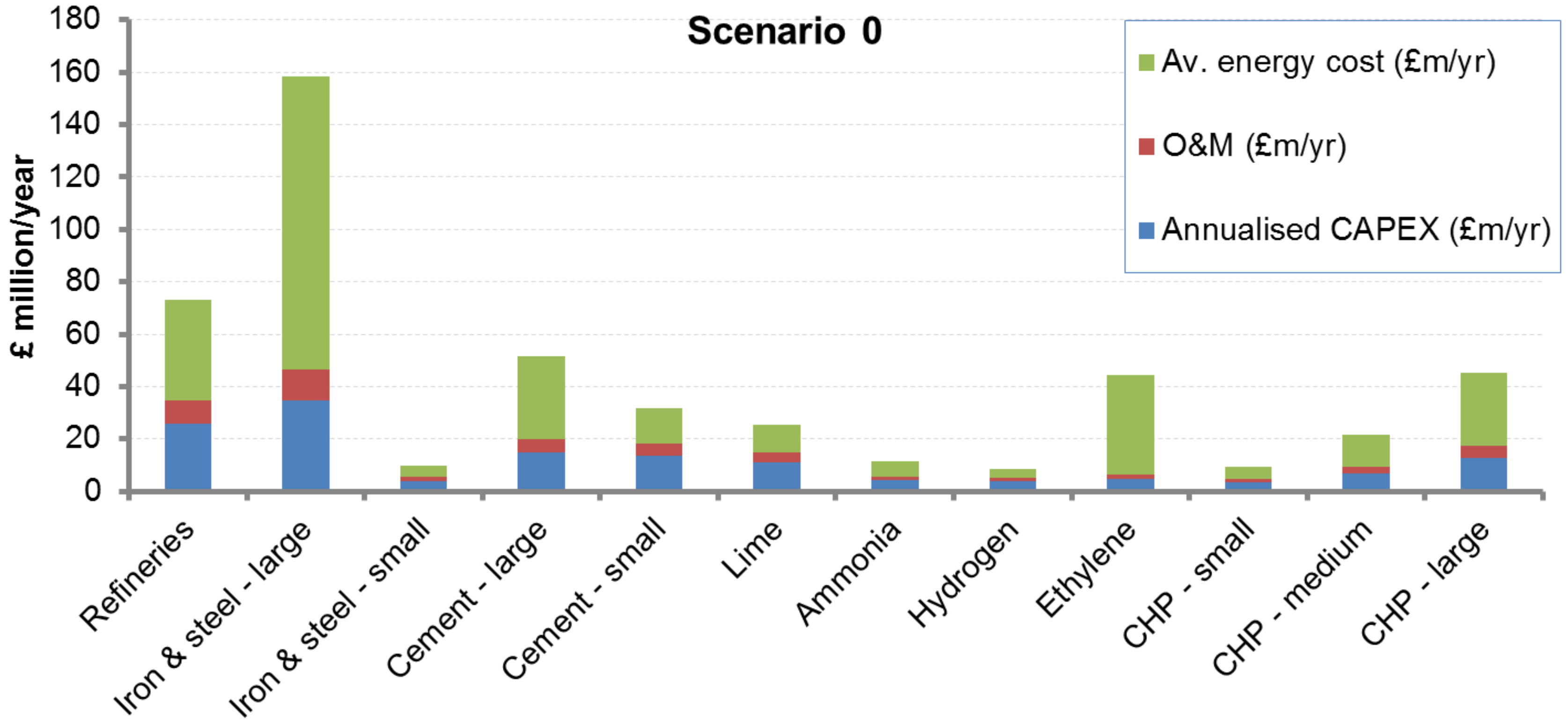
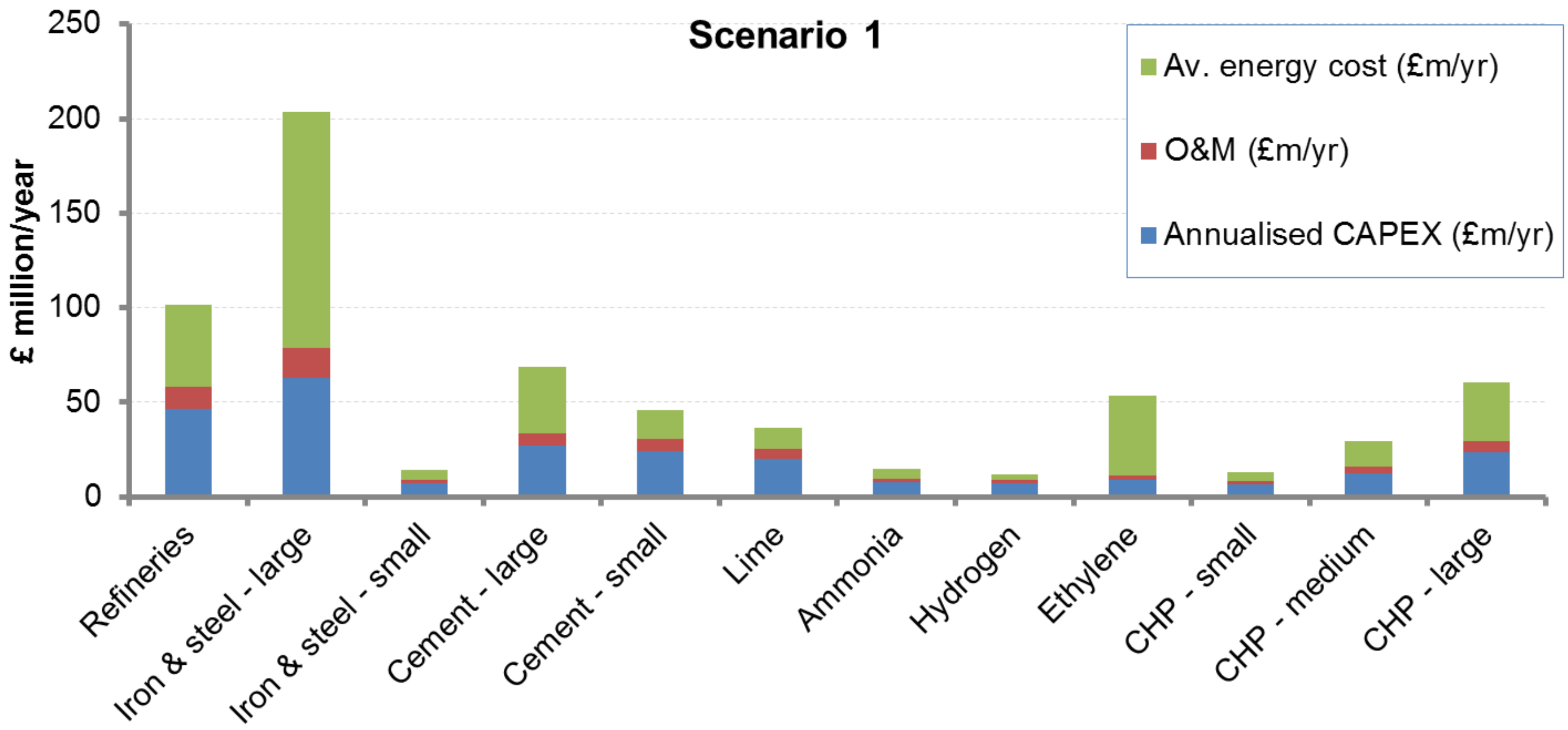
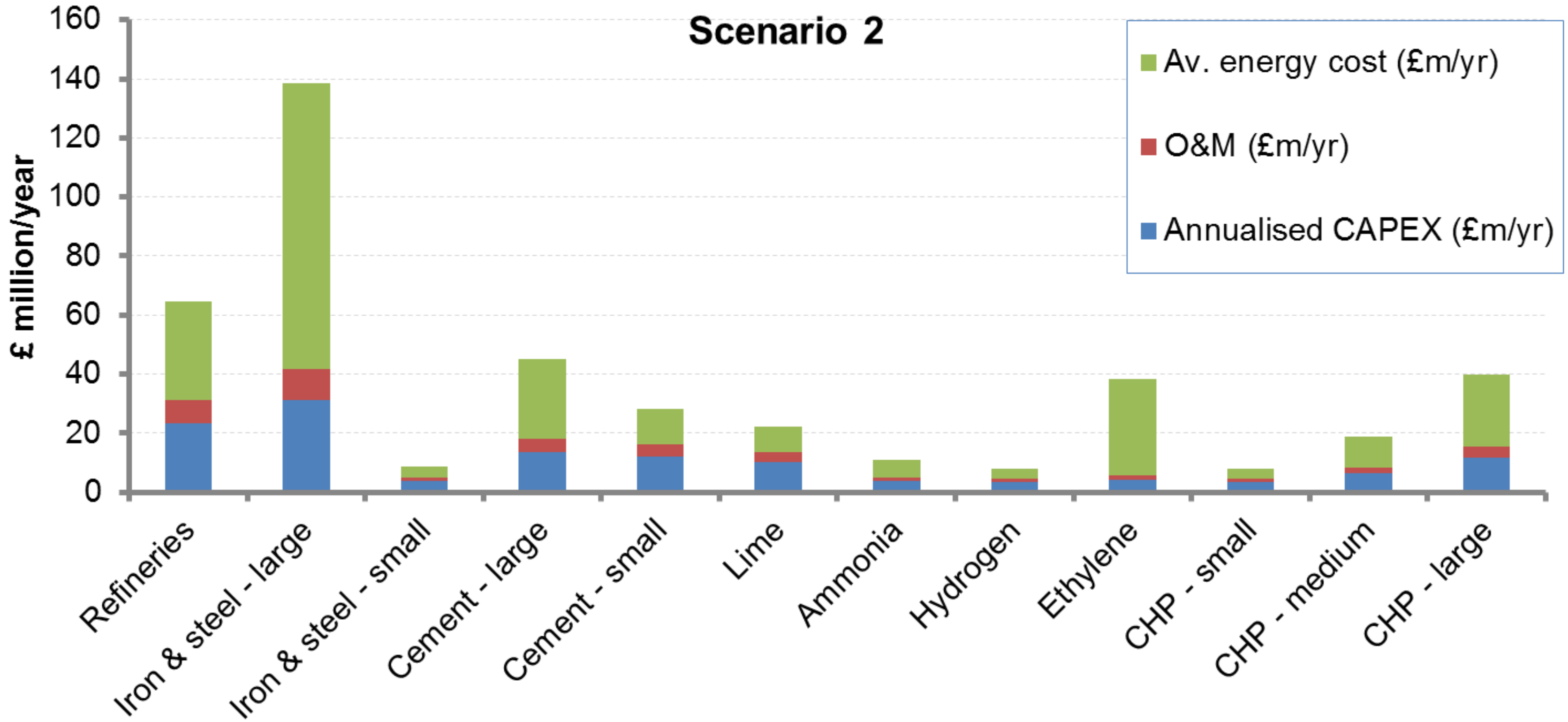
Annualised reference plant costs for the "Nth of a kind" scenario



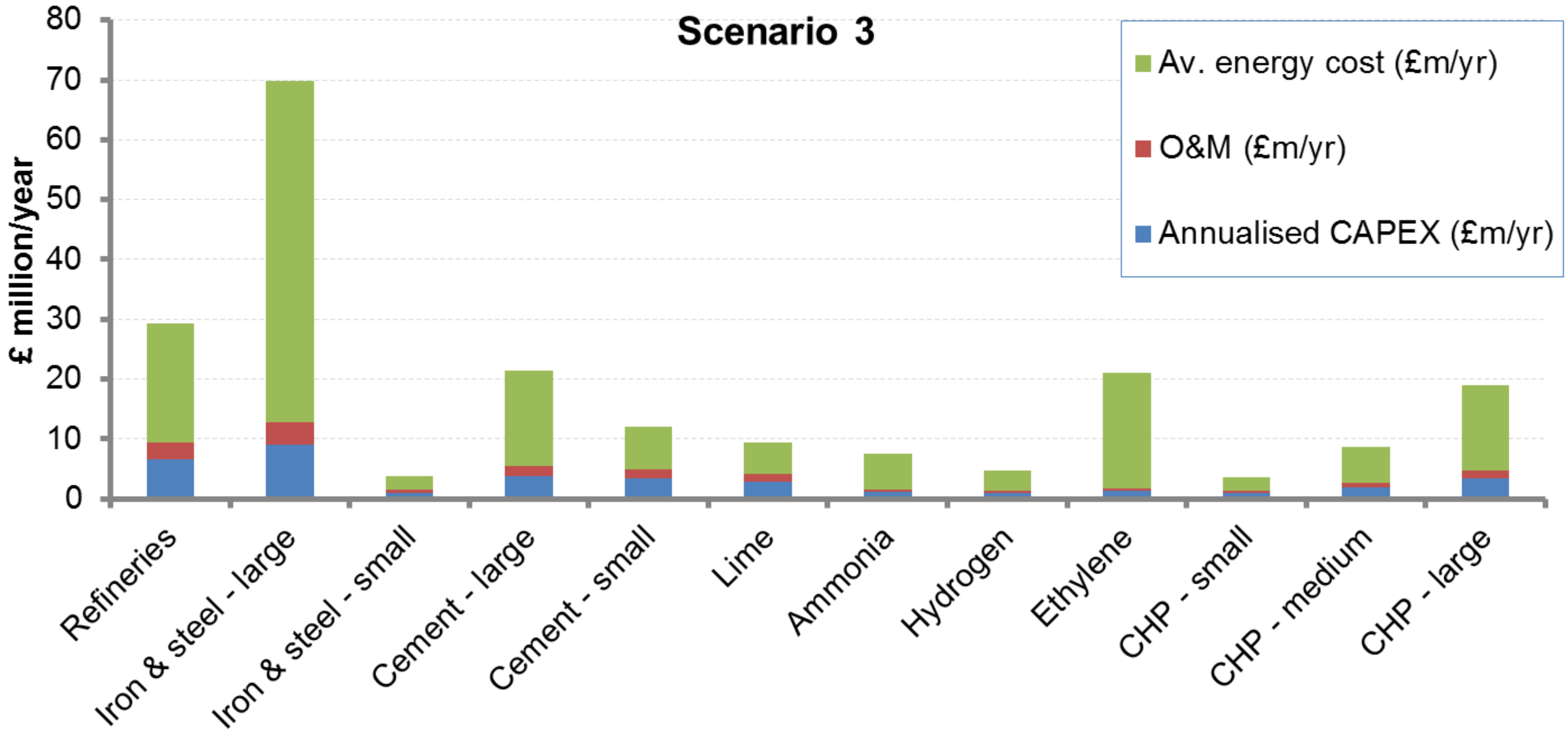
Annualised reference plant costs for the "First-of-a-kind" scenario



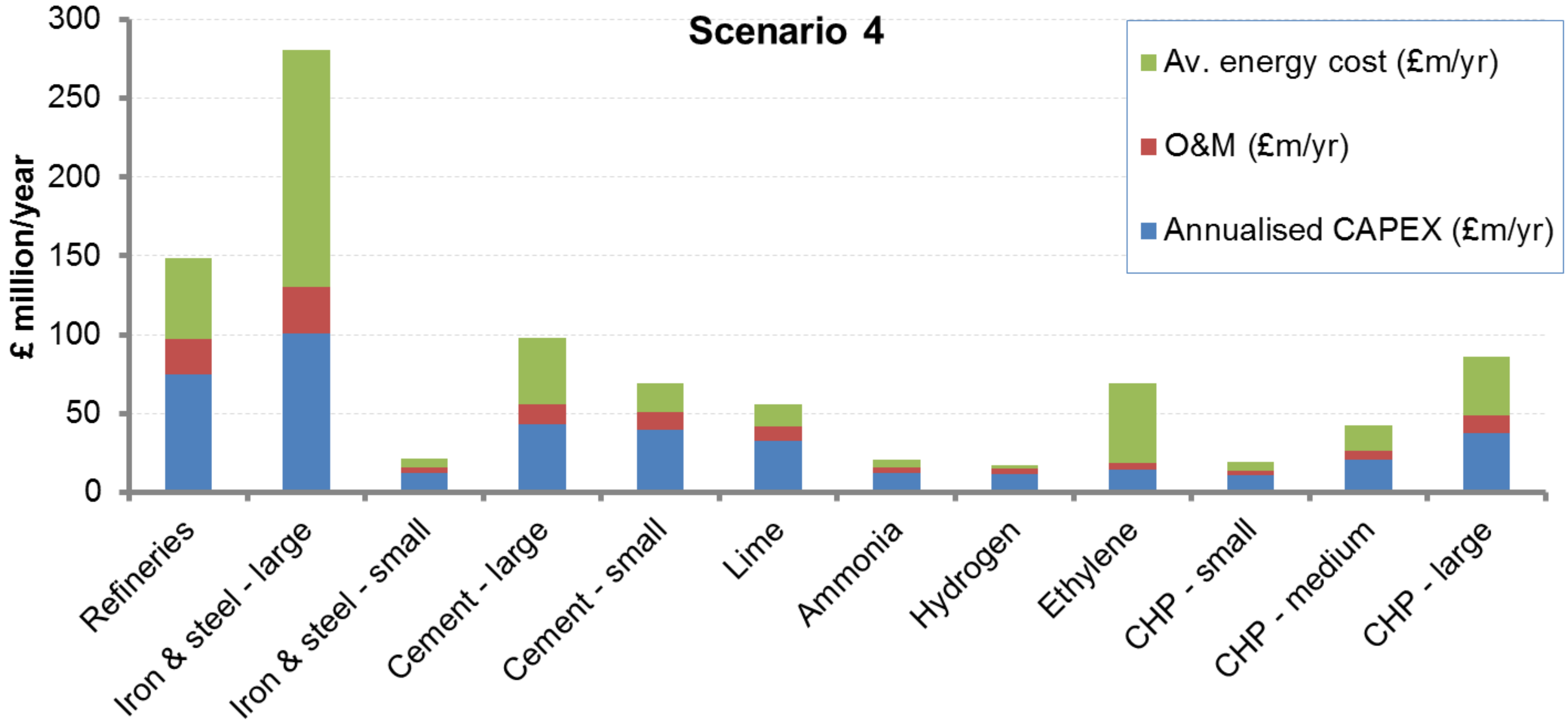
Annualised reference plant costs for the "Capture technology progress" scenario



Annualised reference plant costs for the “CCS favourable” scenario



Annualised reference plant costs for the "CCS Unfavourable" scenario



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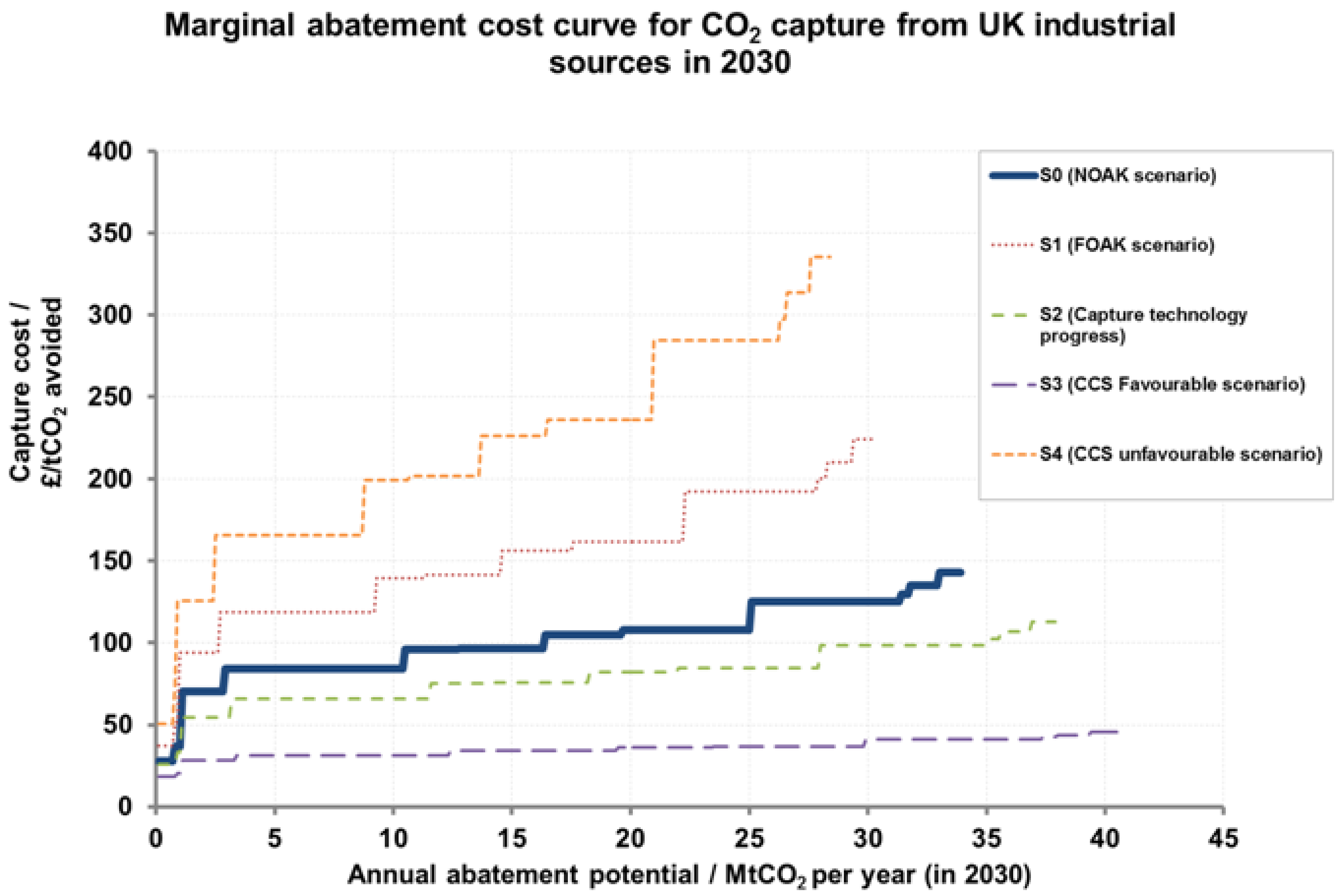
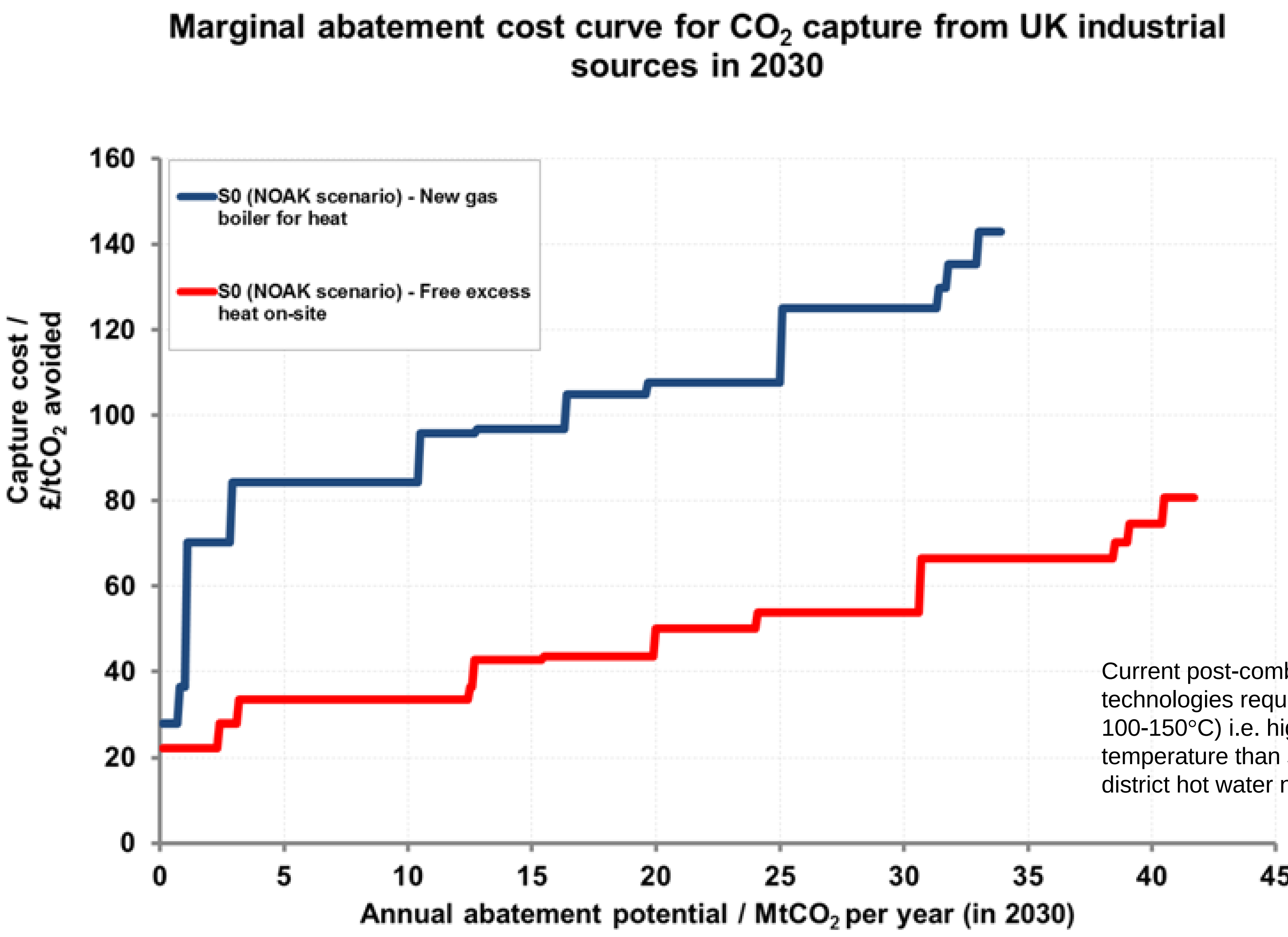
The marginal capture cost curve for UK industry in 2030 indicates 30Mt+ potential with costs in the range *ca*. £20-300+/tCO_2 (excluding transport and storage)



N.B. Sectoral ranking within the cost curve is not warranted – the current uncertainties in the capture cost and capacity are greater than the differences between sectors.

Source: Element Energy analysis

Assumptions on the heat source have a significant impact on the costs



Current post-combustion capture technologies require steam (i.e. 100-150°C) i.e. higher temperature than supplied from a district hot water network.

Caveats on the draft MACC graph

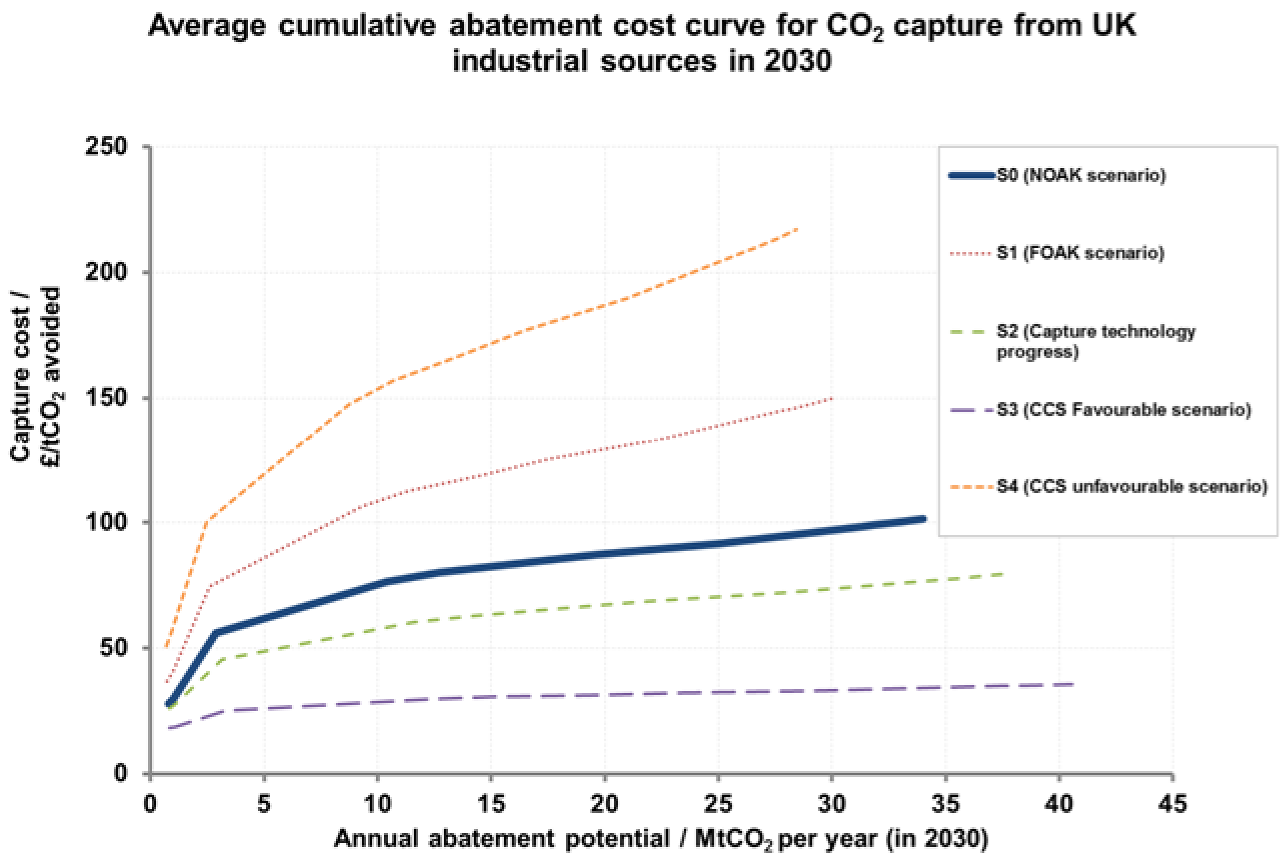
- To illustrate the impact cost and performance uncertainties, the graphs show the marginal abatement capture cost curves for five scenarios:
  - S0) “nth of a kind”, i.e. significant deployment of CCS before 2030.
  - S1) “First-of-a-kind”, i.e. little progress in CCS before 2030
  - S2) “Rapid technology progress”, where performance of CCS has improved by 2030
  - S3) “CCS favourable scenario”
  - S4) “CCS unfavourable scenario”

- The marginal abatement capture cost curve show capture only (see next chapter for transport and storage costs). Typically capture costs represent 60-80% of total system costs, but for small or inland sources could be much larger.

- This MACC assumes abatement potential is based on all relevant UK sites having installed carbon capture technology by 2030. We note that it is more likely that some of this abatement potential will be satisfied by other technologies.

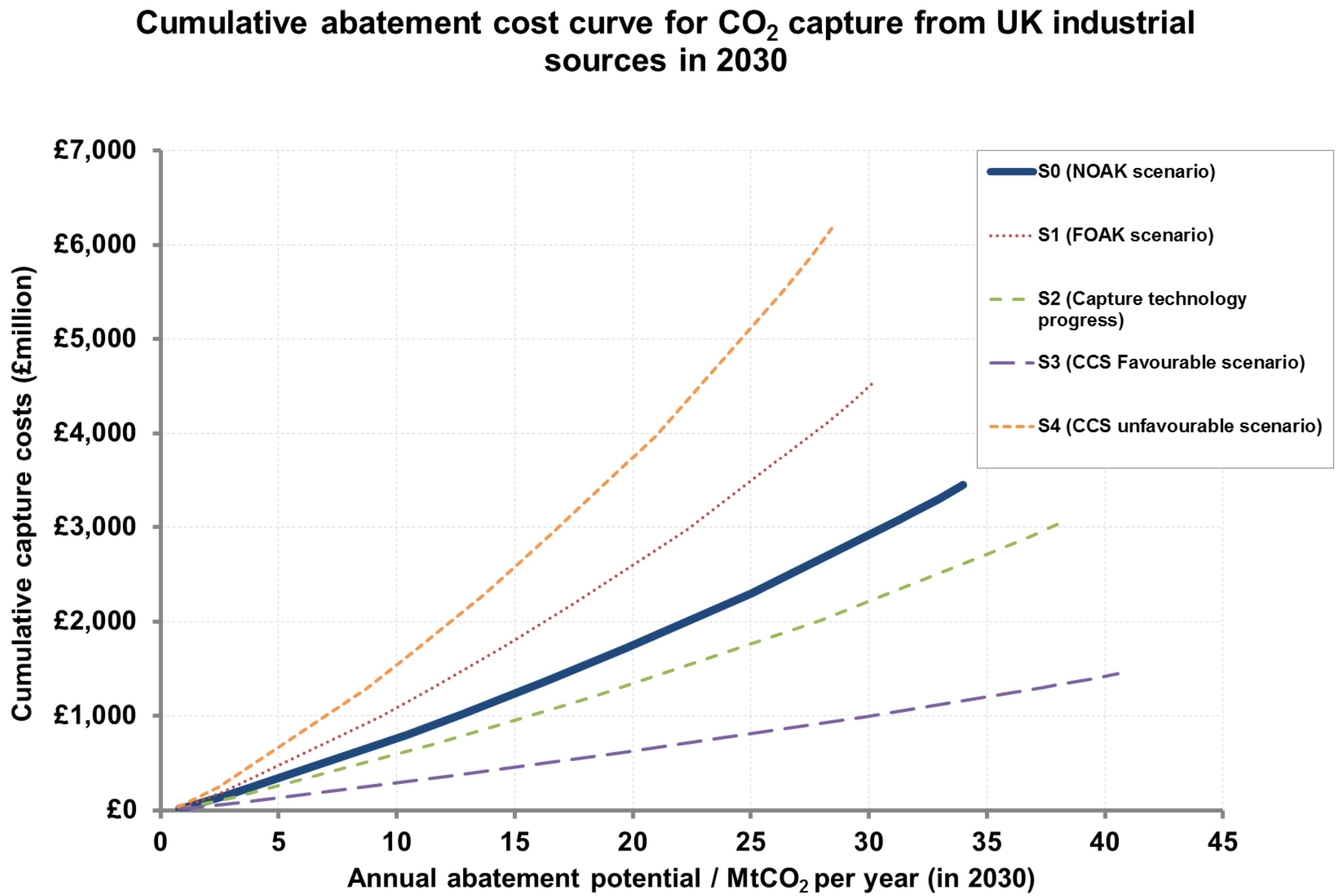
- The potential and costs for transport or storage are excluded at this stage.
- The analysis excludes site feasibility assessment, new sources in the period to 2030, capital cost reduction from new technologies, and hidden costs.

Average CCS costs - assuming all sectors implement



- The costs of capture in industry appear competitive with the CCC's estimates of the costs of decarbonising the power sector.

Cumulative industrial CCS capture costs (assuming all sectors implement) might be up to £6 billion.



- To put these costs into context, the CCC has estimated that achieving power sector decarbonisation by 2030 will have net present costs of the order of £100 billion over the 2020s.

Outline

- Background
- Data and Process
- Scenario Analysis
  - Scenario Definition
  - Annualised Costs
  - Marginal Abatement Cost Curves
  - Summary tables
- Transport and Storage of CO_2
- Overall CCS costs
- Bibliography

Summary table (1) Reference Plant Costs (S0 – NOAK scenario)

Industry	Refineries	Iron & steel - large (>3Mt/yr)	Iron & steel - small (<3Mt/yr)	Cement - large (>0.45 Mt/yr)
Number of sites in scope	8	3	6	7
Emissions from a reference plant (MtCO2/yr)	1.80	4.00	0.16	0.73
Sector specific factors	50% of onsite emissions available for capture (van Straelen et al, 2010).	65% of onsite emissions available for capture (JM Birat, Steel and CO2 – the ULCOS Program, CCS and Mineral Carbonation using Steelmaking Slag)		-
Reference project	Retrofit large scale post-combution project using amine scrubbing applied to the BP Grangemouth refinery complex (Simmonds et al, 2003)	Post-combustion capture from blast furnace emissions (IEA, 2009)	Post-combustion capture from blast furnace emissions (IEA, 2009)	Retrofit post-combution project using chemical absorption applied to a cement modern plant (Mott McDonald (IEA R&D GHG, 2008))
Adjustments to cost	Project contingencies Process contingencies Costs are adjusted to the UK Inflated and converted to £(2012) Scaling factor CHP CAPEX is removed	Derived from $/t costs Project contingencies Inflated and converted to £(2012)	Derived from $/t costs Project contingencies Inflated and converted to £(2012) Scaling factor	Project contingencies Process contingencies Costs are adjusted to the UK Inflated and converted to £(2012) Scaling factor CHP CAPEX is removed
Total overnight cost (adjusted), £m, 2012	£220	£296	£35	£127
Annualised CAPEX (£m/yr)	£26	£35	£4	£15
O&M (£m/yr)	£9	£12	£1	£5
Av. energy costs (heat and electricity - £m/yr)	£39	£112	£4	£31
CO2 captured (MtCO2/yr)	0.81	2.34	0.09	0.66
CO2 avoided (MtCO2/yr)	0.66	1.84	0.07	0.52

Summary table (2) Reference plant costs (S0 – NOAK scenario)

Industry	Cement - small (<0.45 Mt/yr)	Lime	Ammonia	Hydrogen
Number of sites in scope	5	6	2	1
Emissions from a reference plant ($MtCO_2$/yr)	0.32	0.24	0.45	0.25
Sector specific factors	-	-	No additional heat is required for CO_2 capture	No additional heat is required for CO_2 capture
Reference project	Retrofit post-combustion project using chemical absorption applied to a cement modern plant (Mott McDonald (IEA R&D GHG, 2008))	Derived from cement plants	Retrofit of post-combustion capture to high-CO_2 (98-99%) ammonia process emissions stream (IEA GHG R&D CCS in CDM study, 2008; McKinsey, 2009)	Retrofit of post-combustion capture to high-CO_2 (98-99%) process emissions stream from modern SMR hydrogen plant (IEA GHG R&D CCS in CDM study, 2008; McKinsey, 2009)
Adjustments to cost	Inflated and converted to £(2012) Scaling factor	Inflated and converted to £(2012) Scaling factor	Limited Process contingencies Inflated and converted to £(2012)	Limited Project contingencies Limited Process contingencies Limited Owner's costs Inflated and converted to £(2012)
Total overnight cost (adjusted), £m, 2012	£115	£95	£36	£33
Annualised CAPEX (£m/yr)	£13	£11	£4	£4
O&M (£m/yr)	£5	£4	£1	£1
Av. energy costs (heat and electricity - £m/yr)	£14	£10	£6	£3
CO_2 captured ($MtCO_2$/yr)	0.29	0.22	0.41	0.23
CO_2 avoided ($MtCO_2$/yr)	0.23	0.17	0.39	0.22

Summary table (3) Reference plant costs (S0 – NOAK scenario)

Industry	Ethylene	CHP - small (<0,2 Mt/yr)	CHP - medium (0.2 - 0.5 Mt/yr)	CHP - large (>0.5 Mt/yr)
Number of sites in scope	3	89	17	5
Emissions from a reference plant ($MtCO_2$/yr)	0.88	0.10	0.28	0.65
Sector specific factors	-	-	-	-
Reference project	Derived from large CHP CCS costs	Existing CHP plant is sufficient to produce the heat and electricity required for capture (NETL, 2007)	Existing CHP plant is sufficient to produce the heat and electricity required for capture (NETL, 2007)	Existing CHP plant is sufficient to produce the heat and electricity required for capture (NETL, 2007)
Adjustments to cost	Costs are adjusted to the UK Inflated and converted to £(2012) Scaling factor	Costs are adjusted to the UK Inflated and converted to £(2012) Scaling factor	Costs are adjusted to the UK Inflated and converted to £(2012) Scaling factor	Costs are adjusted to the UK Inflated and converted to £(2012) Scaling factor
Total overnight cost (adjusted), £m, 2012	£41	£31	£60	£110
Annualised CAPEX (£m/yr)	£5	£4	£7	£13
O&M (£m/yr)	£2	£1	£2	£4
Av. energy costs (heat and electricity - £m/yr)	£38	£4	£12	£28
CO_2 captured ($MtCO_2$/yr)	0.79	0.09	0.25	0.59
CO_2 avoided ($MtCO_2$/yr)	0.62	0.07	0.20	0.46

Outline

- Background
- Data and Process
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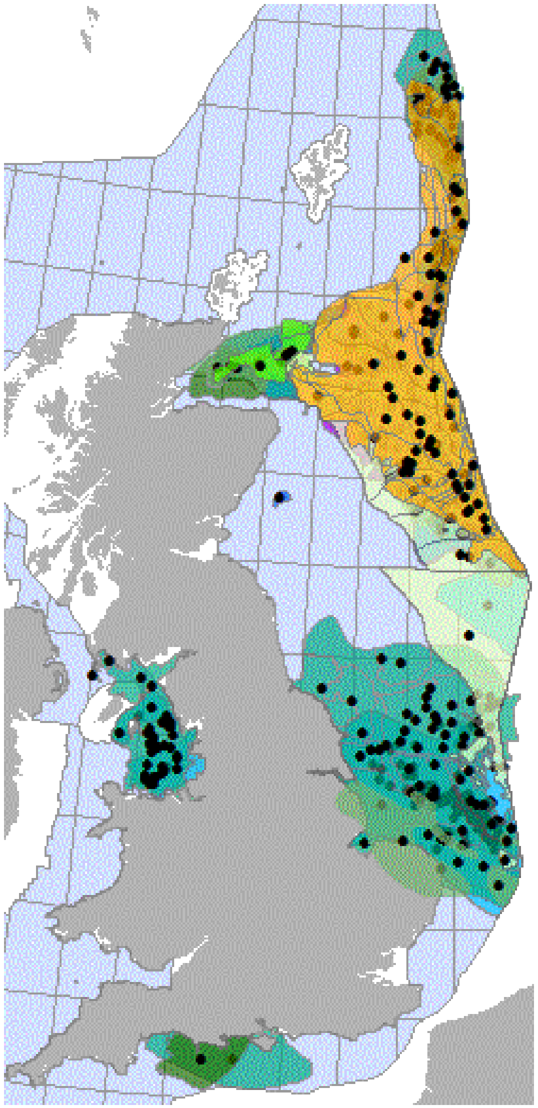
Issues around transport and storage of CO_2

- CO_2 storage is possible in deep (1-4 km) rocks that are porous (i.e. have spaces), permeable (allow fluids to flow), and have a strong caprock that acts as a seal.
- The storage capacity of the store must be sufficient to hold several years of CO_2 emissions, i.e. several millions of tonnes.
- Stores are accessed by wells – and the economics of storage will depend on the supply chain for the oil and gas industry, which have high opportunity costs.
- Individual wells can cost tens of millions of pounds, but will ideally support throughput in the region of one million of tonnes per year.
- CO_2 has complex chemical, physical and flow properties that need to be managed very carefully.
- Detailed analysis of transport and storage engineering and commercial options can take several years and cost several millions of pounds.
- The resources available to assess transport and storage costs within this study can only support very high level estimation of transport and storage options.
- Element Energy has relied on published papers and in-house cost modelling experience to develop ranges of costs for transport and storage for industrial sources for different scenarios.
- Developments and uncertainties in capture and those in transport and storage could be largely independent. To simplify presentation, we have maintained the scenario descriptions S0-S4.

ETI's UK Storage Appraisal Project identifies significant offshore capacity, but the storage distribution is complex and heterogeneous



- Nearly 600 potential storage units identified with P50 capacity over 70 Gt.
- Performance will be site specific but the types of storage are diverse and little information is available for many of them to predict performance reliably.
- Wide range of predicted well requirements and reservoir risks identified - realistic chance that many units will not actually be suitable on deep analysis.
- Storage is clustered. Most of the theoretical capacity in the Southern North Sea, Central North Sea and Northern North Sea, implying transport system will be an issue.
- Wide range of unit size and shape. Many aquifers are very much larger than traditional oil and gas fields. Some units are expected to be vertically stacked, although this has yet to be quantified and the implications assessed in depth.
- CO_2 storage costs can be estimated by understanding the requirements for appraisal, platforms, wells, pipelines etc. for which there are oil and gas analogues.
- Range of storage costs spans three orders of magnitude, depending on reservoir conditions, how the reservoir is developed, utilisation, financing, and prevailing market/regulatory conditions.
- Similar findings have been observed in other countries.

Source: UK Storage Appraisal Project (UKSAP), commissioned and funded by the Energy Technologies Institute.
Image courtesy of the Energy Technologies Institute

Three main classes of storage sites – each has a mix of opportunities and challenges

Depleted hydrocarbon field

- Well characterised sites
- Potential for infrastructure re-use (subject to timing)
- Handover between oil and gas producer, government and storage company commercially challenging
- Some technical limitations (well abandonment and injectivity)

Saline Aquifer

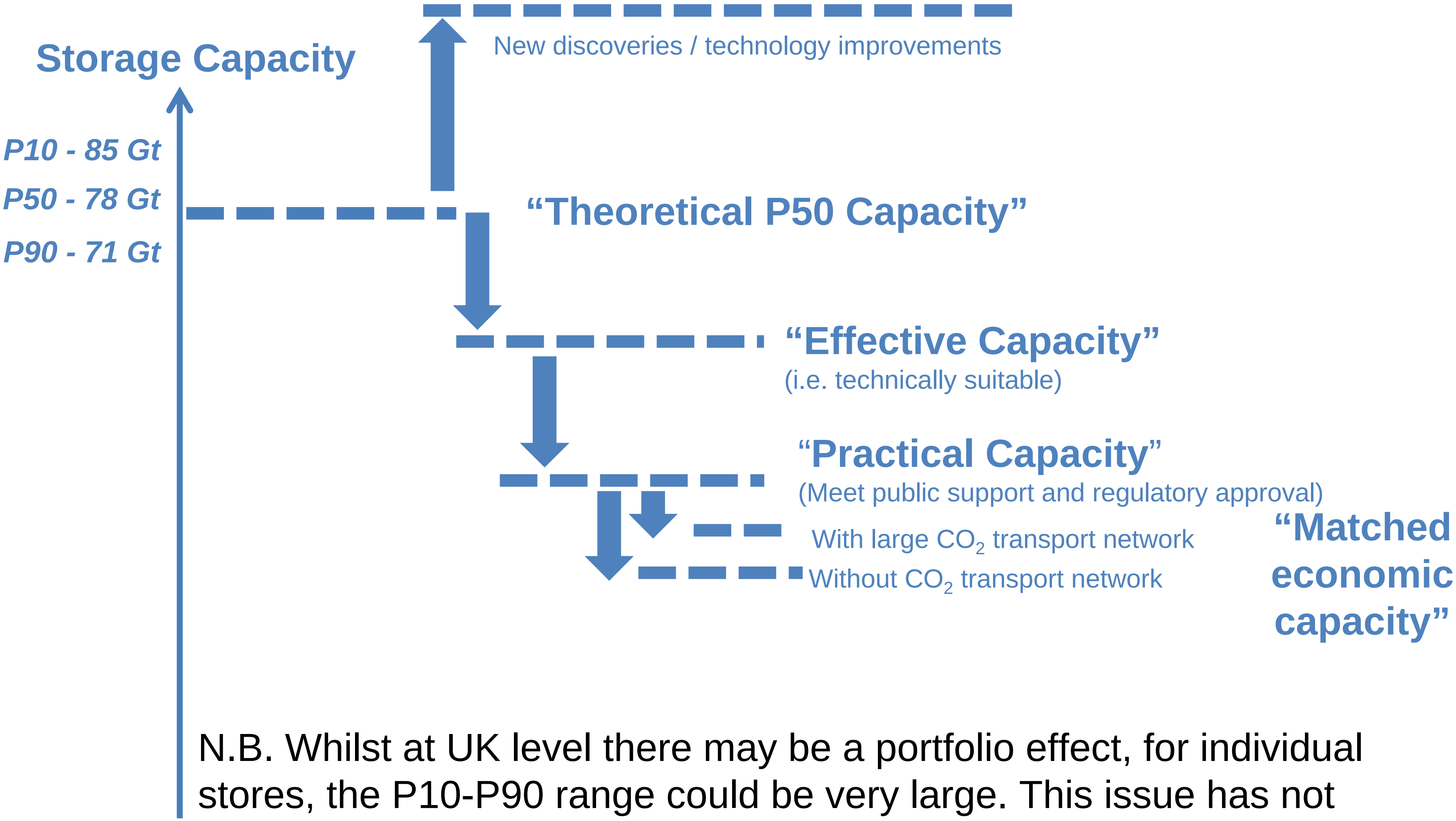
- Some units have very large theoretical storage capacities
- Most sites poorly characterised – require detailed examination which is resource intensive and time consuming.
- Some sites are spatially complex

CO_2-enhanced oil recovery

- Potential for high upsides at high oil prices for Government and oil companies
- Complex , costly projects with higher risks
- Project needs to satisfy many stakeholders
- Very narrow window of opportunity

- Source: Element Energy

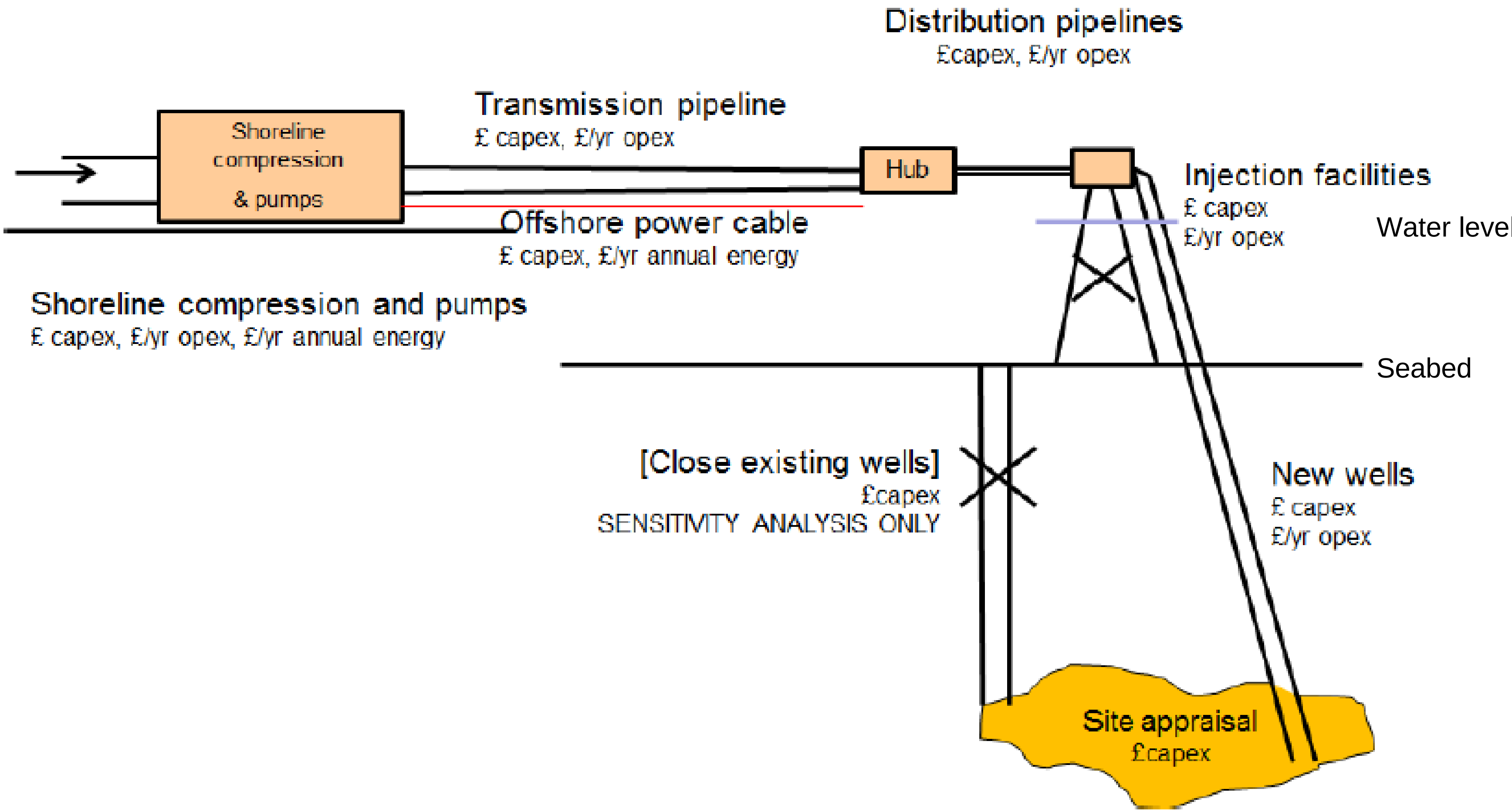
The matched economically accessible storage capacity may be significantly lower than the theoretical aggregate storage capacity identified in UKSAP upon detailed examination.



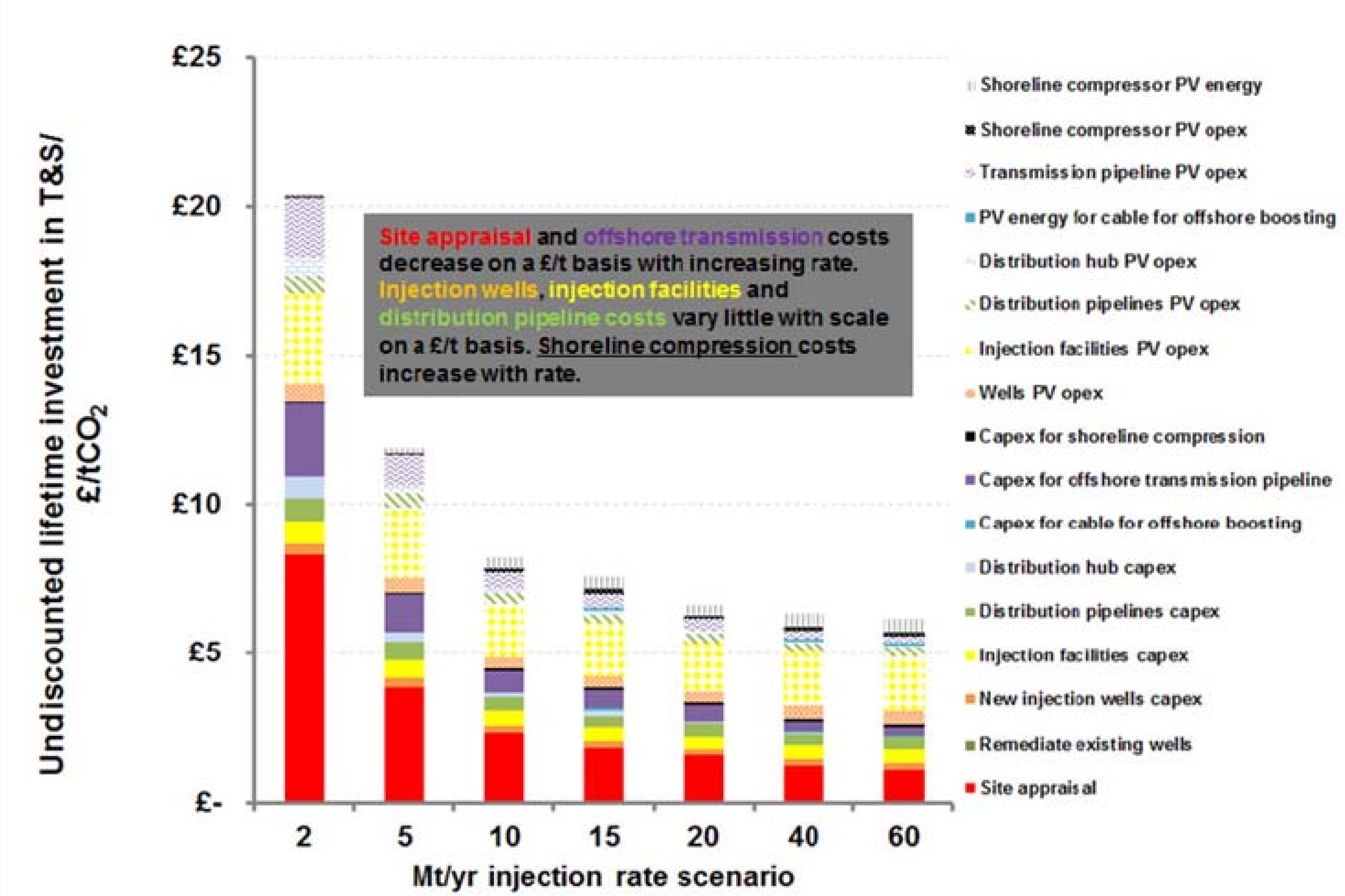
N.B. Whilst at UK level there may be a portfolio effect, for individual stores, the P10-P90 range could be very large. This issue has not been assessed in detail, and as CO_2 storage is relatively new, it is difficult to predict reliably today.

Source: Element Energy – study on CCS readiness for the European Climate Foundation

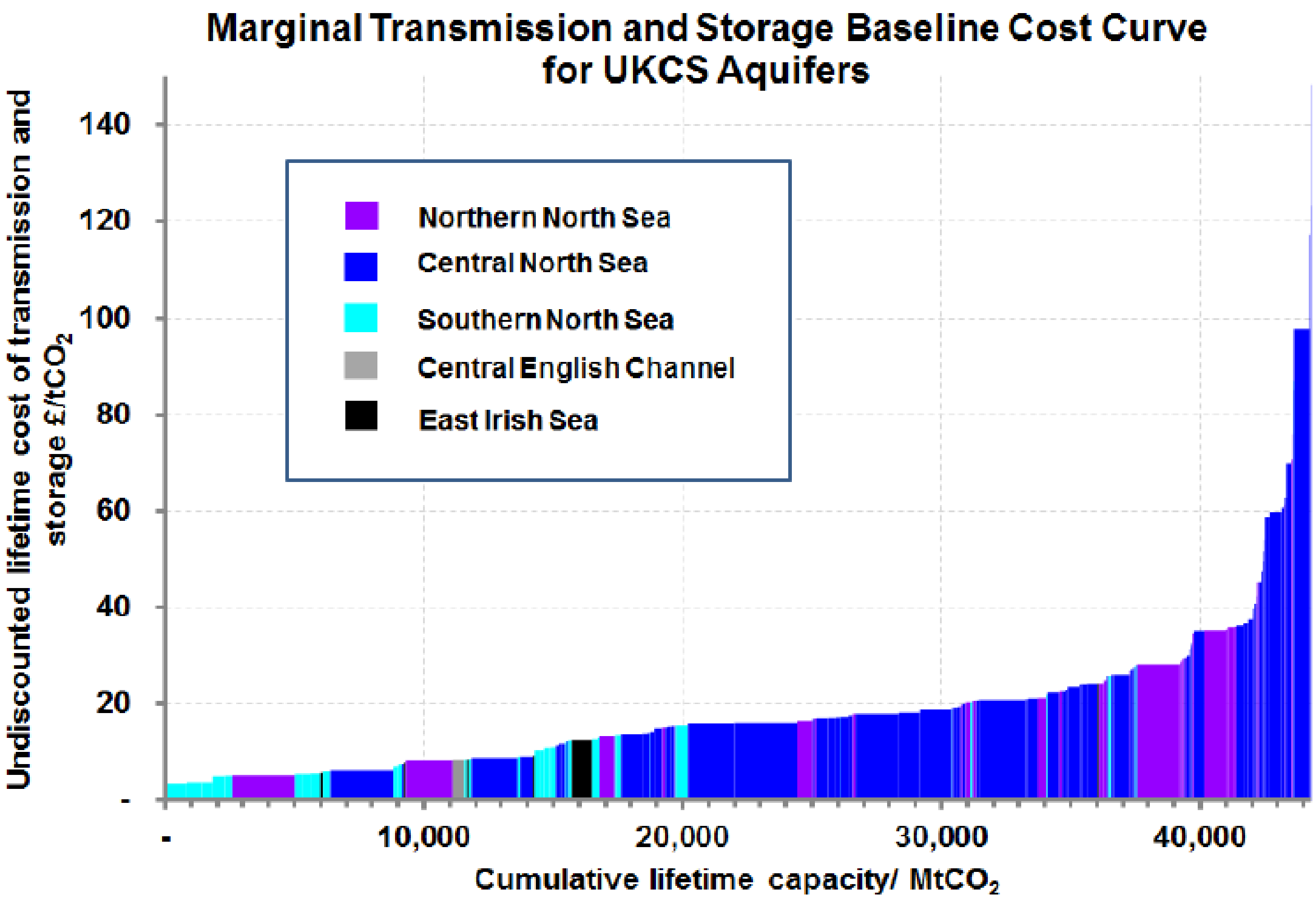
Offshore costs are driven primarily by site appraisal, well requirements, injection facilities, pipelines and boosting.



For any individual site, there are usually economies of scale in offshore CO_2 transmission and storage.



Transmission and storage per unit costs span two orders of magnitude.



Transport cost drivers

For pipelines:

•CO_2 pipelines have been in operation onshore since the 1970s and there is one offshore CO_2 pipeline in Norway.

•Overall pipeline costs are mainly determined by primarily by pipeline length, terrain, diameter (i.e. capacity), cost of steel or engineering index, and the cost of financing.

•Annual fixed operating and maintenance costs for pipelines are expected to be about 1-3% of capital cost, although there will be some fixed and variable costs for for compression and pumping.

•Re-using pipelines offers dramatic cost reduction, but constrains locations of sources, storage, capacity and future flexibility.

•Commercial success requires high utilisation in early years, which is sustained over many decades.

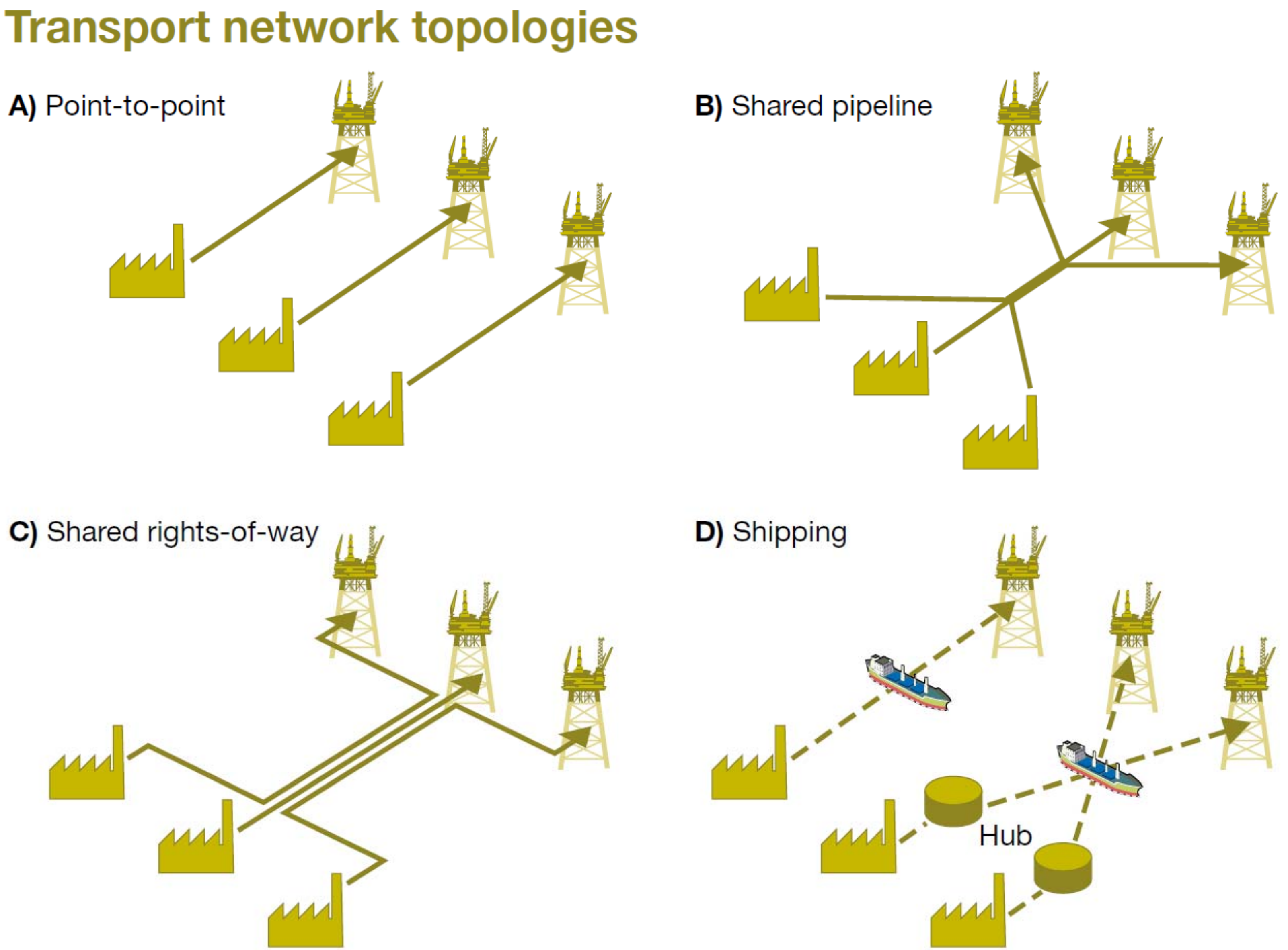
•This implies a high level of certainty around technology, markets, policies/regulations across the entire CCS chain is required to achieve lowest costs.

For shipping:

•CO_2 shipping requires appropriate and compatible designs for liquefaction, loading, unloading and further legal/regulatory clarity, particularly for cross-border shipping.

•Shipping costs are relatively insensitive to capacity and distance, making this option relatively flexible.

Multiple transport options are relevant for connecting UK sources with UKCS sinks, including new pipelines, re-used pipelines, shared pipelines and CO_2 shipping and hub concepts.



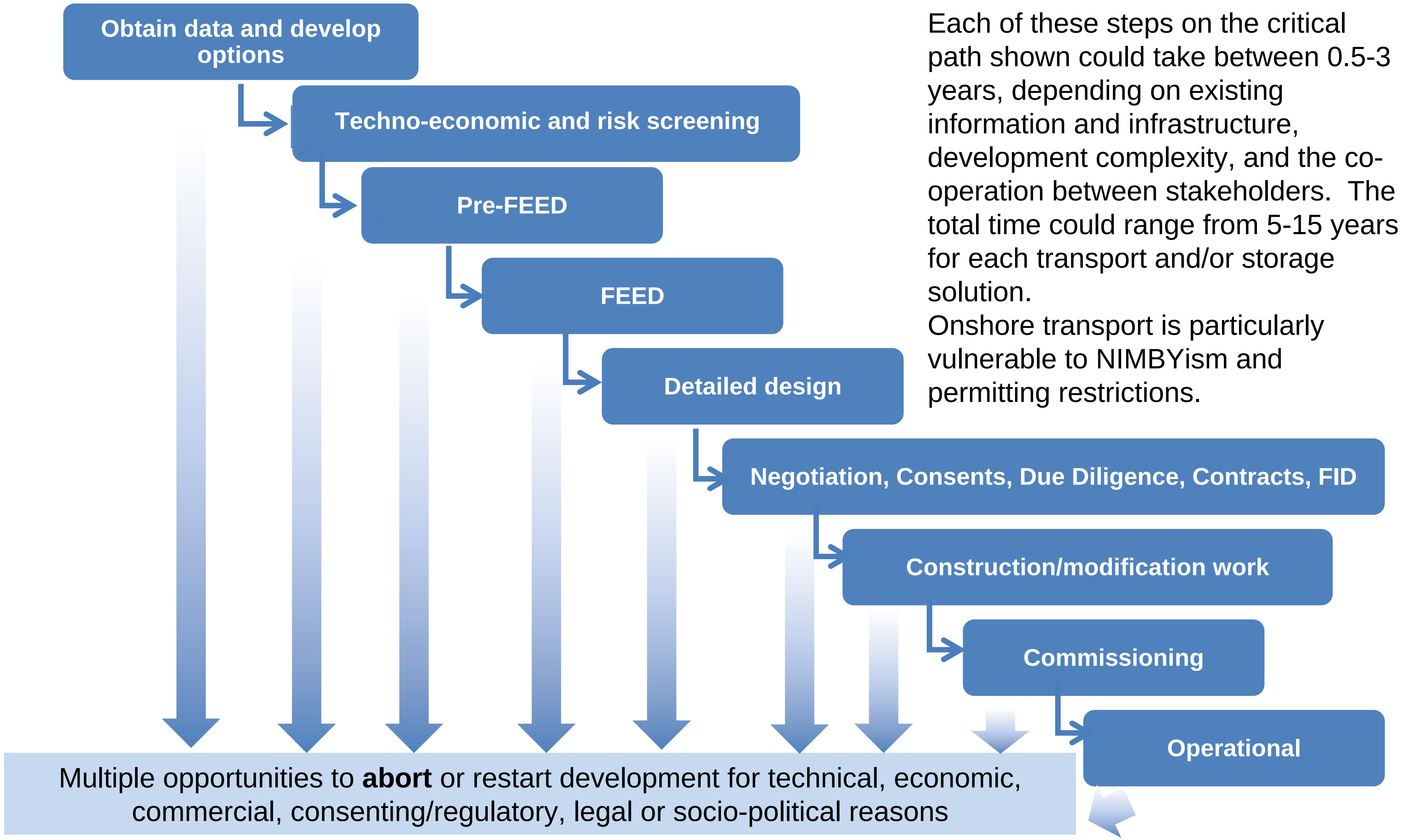
Element Energy *et al.* (2010) One North Sea

Assessment of transport options

Topology	Advantages	Disadvantages
A1 – New point to point	• May be easier to finance under current climate • Does not require estimation of future demand. • Does not require co-ordination between multiple stakeholders • Reduces risk of low pipeline utilisation.	• Average cost per tonne across all networks is higher than with shared infrastructure. • Multiple pipelines across different routes means large planning hurdles and disruption to those affected. • No flexibility to accommodate additional sources at low cost.
A2 – Re-use of existing pipeline	• Very low capex • Very low lead time • Simpler consenting process • Existing owners have a good understanding of pipeline	• Operating conditions (capacity, pressure, composition) highly constrained, relative to new build. • Infrastructure is old and performance may be reduced or risks of failure increased relative to new build. Performance guarantees for use with CO_2 unlikely to be available for 30+ year old assets. • Start and end locations fixed. • Transition from use for natural gas to CO_2 needs to be managed carefully – may be difficult to retrieve pipelines that are not abandoned appropriately.
B – Shared pipeline	• Low transport cost when operating at full capacity. • Enables connection of marginal sources. Could attract new sources e.g. industry to the region. • Lower planning hurdles and disruption since multiple sources share one trunk pipeline.	• High initial cost. May require public sector funding initially. • Risk of low utilisation if demand is lower than forecast. • Requires common entry specification for CO_2. • Complex business models.
C – Shared rights of way	• Low risk of low utilisation due to insufficient demand. • Lower planning hurdles as new pipelines are built on shared rights of way. • Capacity matched to demand.	• Transport costs are higher than for shared pipelines with same throughput. • Does not significantly reduce costs for smaller, marginal sources. • New pipelines may still face planning hurdles despite following existing pipeline routes (see Box).
D - Shipping	• Low upfront costs • Flexible in the event of sink failure CO_2 can be routed to other storage sites. • Suitable for projects where multiple, small sinks may be required, or where project lifetimes are small. • Capacity matched to demand	• Very high transport costs compared to mature pipelines. • Large number of ships required to meet high demand. • Need to agree specifications across a wide geographical range.

Source: Element Energy

If industrial sources need stores to be operational by 2030, then site appraisal and route planning will need to progressed by the early 2020s.



Each of these steps on the critical path shown could take between 0.5-3 years, depending on existing information and infrastructure, development complexity, and the co-operation between stakeholders. The total time could range from 5-15 years for each transport and/or storage solution.

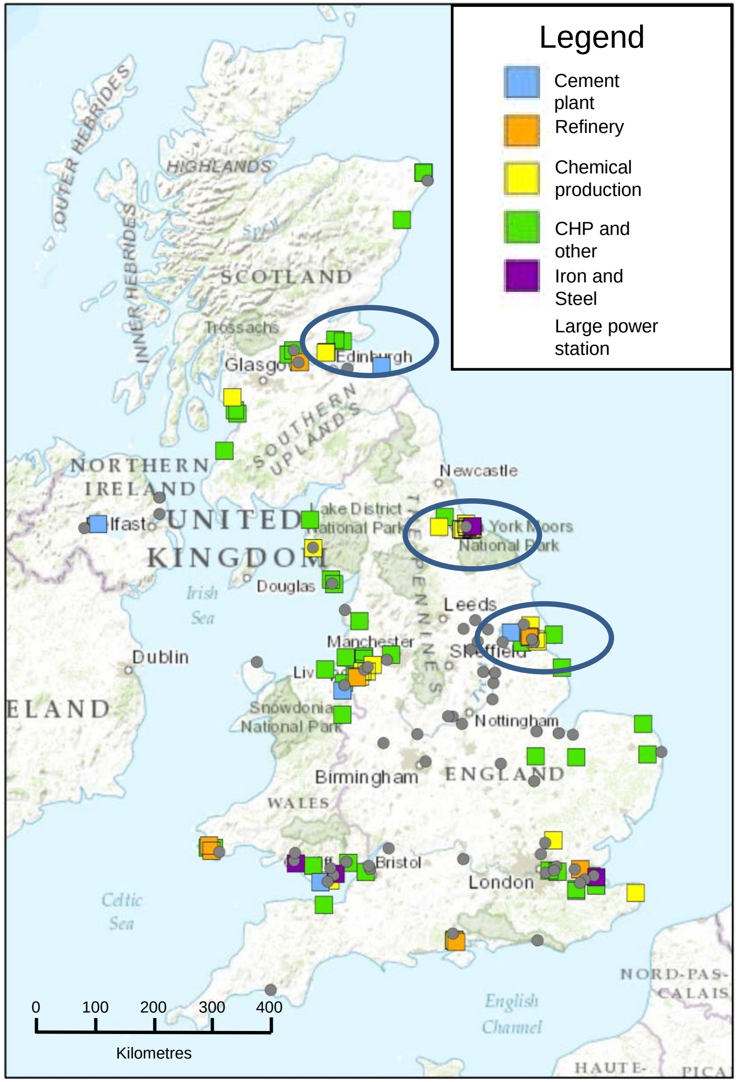
Onshore transport is particularly vulnerable to NIMBYism and permitting restrictions.

Source: Element Energy

Opportunities for networked CO_2 transport infrastructure are being developed at regional level

- The Regional Development Agencies One North East, East of England Development Agency, Yorkshire Forward and Scottish Enterprise examined plans for networks for CO_2 transport infrastructure.
- Work from these has helped CCS demonstration/commercialisation candidates, and plans by National Grid Carbon to develop a CO_2 pipeline in the Humber are now well advanced.
- Since the abolition of RDAs, some of the momentum has been maintained by CO_2Sense in Yorkshire, and the PICCSI cluster in Teesside. Scottish Enterprise remains active, recently examining options for integrated infrastructure CCS and CO_2-enhanced oil recovery.
- Outside the UK, the Rotterdam Climate Initiative is a similar model of a public/private partnership to develop a CCS network.

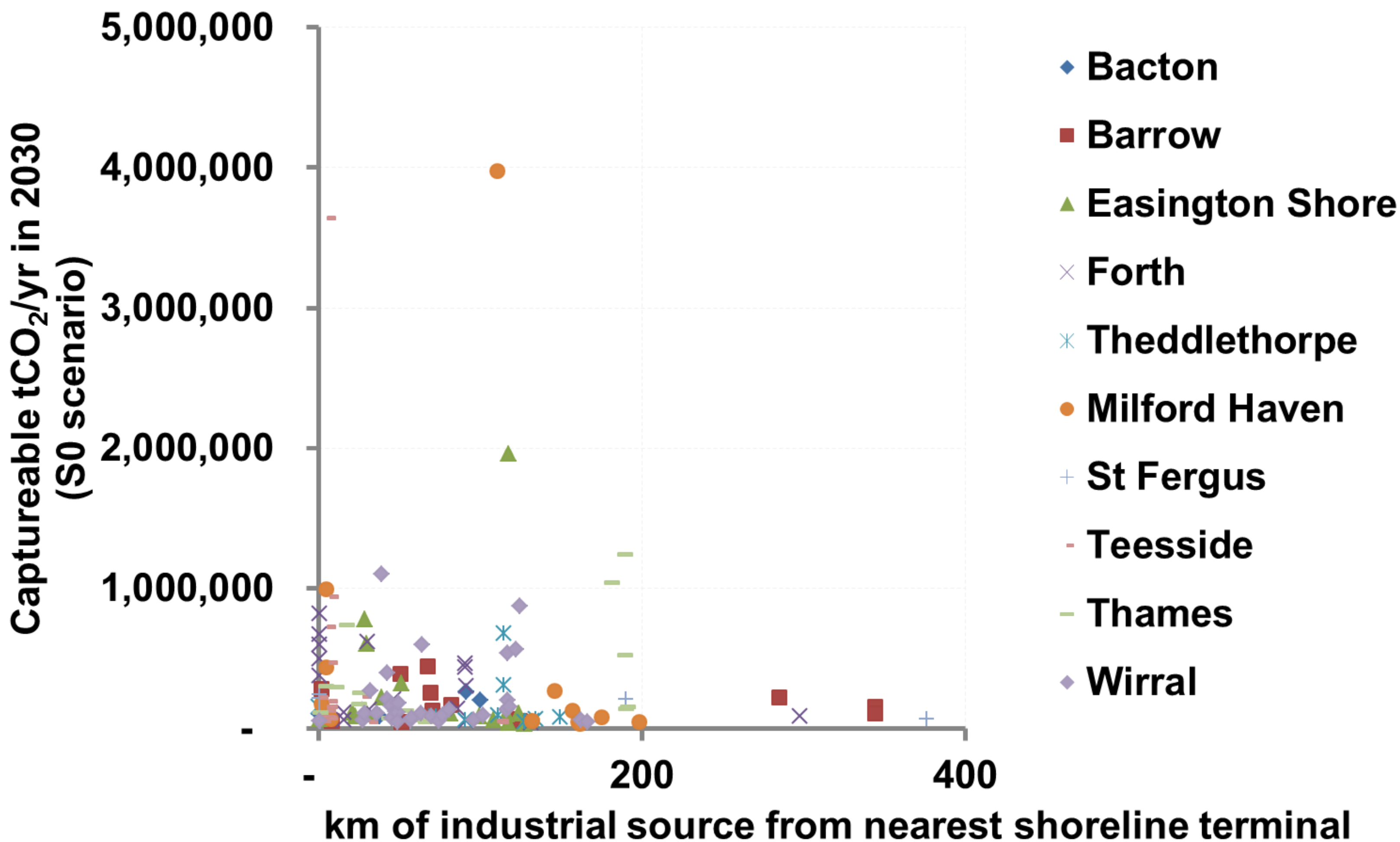
Due to high risk and difficulties of obtaining permissions for new onshore pipelines the most relevant sources are near the shoreline.



- Onshore “linear” infrastructure (e.g. pipelines, railways, transmission, motorways) requires very long lead times to manage the concerns of diverse stakeholders.
- The most promising locations for industrial capture in 2030 are therefore those where significant co-operation is already underway to establish a CCS network, i.e. in Scotland, Tees Valley and Yorkshire (circled).
- Industrial emitters in other regions may need active co-ordinators to develop their own CCS networks and address stakeholder concerns.

Map illustrates locations of existing large UK CO_2 emitters near shorelines that may be relevant for CCS deployment in the period up to 2030. Locations of selected fossil power stations are also shown as these may provide opportunities for shared CO2 transport and storage infrastructure.

What about other regions? Majority of industrial emitters, including all large emitters are within 200 km of their nearest shoreline terminal.



Each shoreline hub faces distinct spatial and scale challenges in supporting CCS growth.

Parameter	Bacton	Barrow	Easington Shore	Forth	Theddlethorpe	Milford Haven	St Fergus	Teesside	Thames	Wirral
Stakeholder Organisation	Negligible	Negligible	High	High	High	Negligible	High	High	Negligible	Negligible
Number of potential industrial capture sources	4	14	16	18	10	14	7	21	16	32
Median distance of industrial source to shoreline hub/km	65	76	67	39	115	139	1	7	56	61
Median industrial source MtCO2/yr	0.15	0.14	0.10	0.25	0.09	0.08	0.10	0.10	0.16	0.11
Mt/yr for largest industrial source	0.3	0.4	2.0	0.8	0.7	4.0	0.2	3.6	1.2	1.1
Combined emissions $MtCO_2/yr$	0.6	2.4	4.8	5.7	1.6	6.4	0.9	7.6	5.3	6.9
Proximity of shoreline hub to offshore storage	<100 km	<100 km	<100 km	200-300 km	<100 km	> 300 km	<100 km	200-300 km	200-300 km	<100 km
Proximity to potential power CO_2 capture sources	Medium	Medium	High	High	High	High	High	High	High	High

Favourable for industrial CCS development

Intermediate challenge for industrial CCS development

Very challenging for industrial CCS development

N.B. Theddlethorpe and Easington are in close proximity.

Source: Element Energy

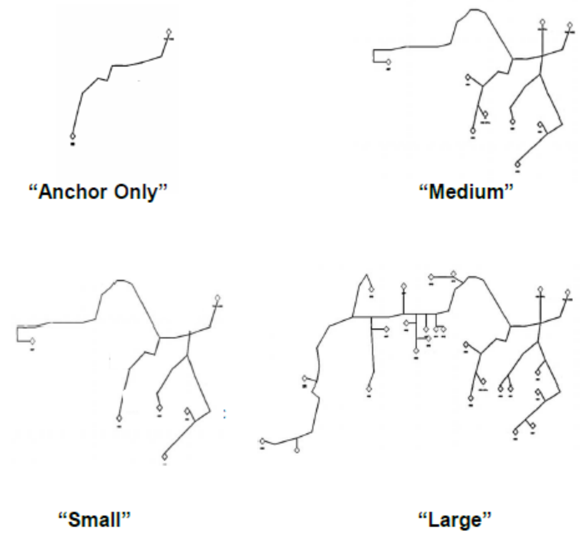
Scenarios for CO_2 transport and storage costs for industry

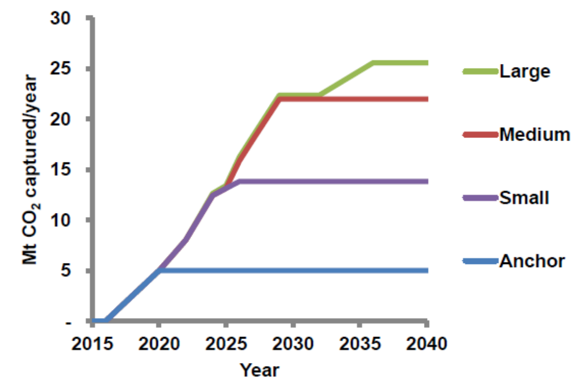
- Since the design, availability and business model for CO_2 transport and storage for UK industrial sources in the period to 2030 is very uncertain, and there is therefore a very wide range of potential costs associated.
- At one extreme, there may be no available transport and storage capacity for industrial emitters. (The effective cost of transport and storage is then the price of building a dedicated source-sink connection).
- At the opposite extreme, industrial sources may be able to share transport and storage infrastructure which has been fully paid for by others, and where the industrial emitters needs only pay the marginal variable costs of access.
- In between these regimes, a more plausible 2030 scenario is where some capacity is available for industrial emitters at “average” costs in shared CO_2 transport and storage infrastructure, but only at a limited number of hubs.

Shoreline Hub Case Study: The Tees Valley has the highest concentration of industrial emissions.

In the Tees Valley, sources are densely clustered onshore and an integrated transport networks could be developed for a wide range of CCS scenarios.

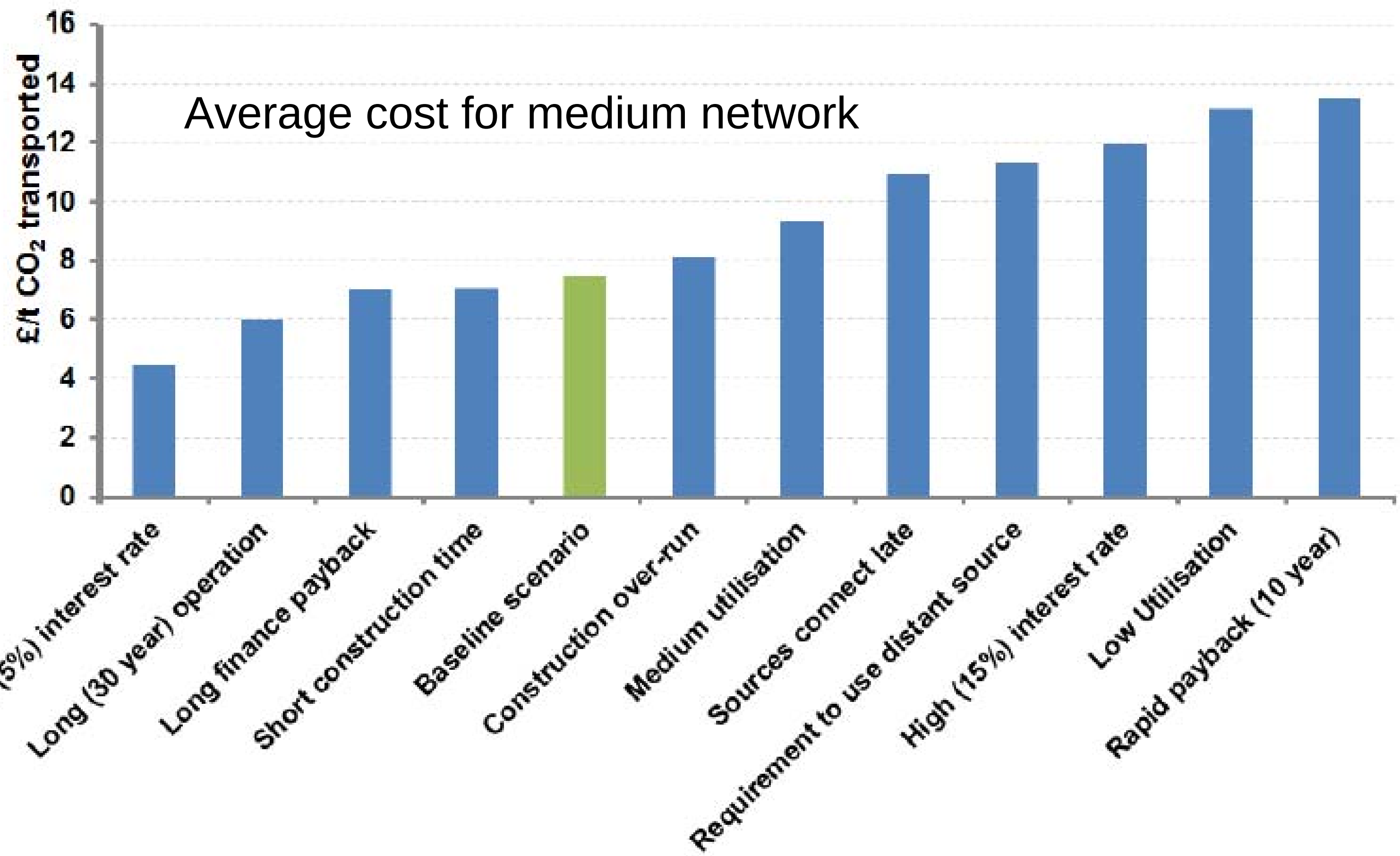
Description	Metric	Anchor Only	Small	Medium	Large
Environmental effectiveness	$MtCO_2$/yr captured	5	14	22	26
Financeability	Combined capex for capture, transport and storage	£650 m	£1.8 bn	£3.0 bn	£4.2 bn
Cost effectiveness	Average capture cost £/tCO_2 abated	£18	£25	£29	£36
	Transport £/t CO_2	£12	£7.30	£7.40	£7.40
	Storage £/t CO_2	£14	£13	£12	£12
	Total £/tCO_2 abated	£44	£45	£48	£55
Flexibility and stability	Ratio of sites capturing CO_2: sites not capturing	1:35	5:30	8:27	35:0
	Ratio of CO_2 emissions captured: emissions not captured	5:21	14:12	22:4	26:0
Lead time / complexity	Number of sources connecting	1	5	8	35





Above, illustration of onshore network topologies and utilisation. Left, key performance indicators for the different networks, showing how the challenge of investment increases with network capacity.
Reproduced from Element Energy et al. (2010) The investment case for a CCS network in the Tees Valley.

Many uncertainties could affect the costs of CO_2 transport for the emitters in the Tees Valley…



- When all combinations of uncertainties are considered, the range of potential tariffs spans £2-100+/tCO_2!

European industry estimates of transport and storage costs

- The Zero Emissions Platform Task Force is an industry-driven coalition that advises the European Commission on CCS. Its focus to date has been on the power sector, although it is now beginning to consider CCS in industry.
- In 2011 ZEP published reports on average CO_2 transport and storage costs in Europe.

Method of CO_2 transport	2.5Mt/yr x 180 km ±50%	Large integrated networks (average cost, 20Mt/yr x 180 km) ±50%
Onshore pipeline	£4.5/tCO_2	£1.3/tCO_2
Offshore pipeline	£7.8/tCO_2	£2.8/tCO_2
Shipping incl. liquefaction	£11/tCO_2	£9.2/tCO_2

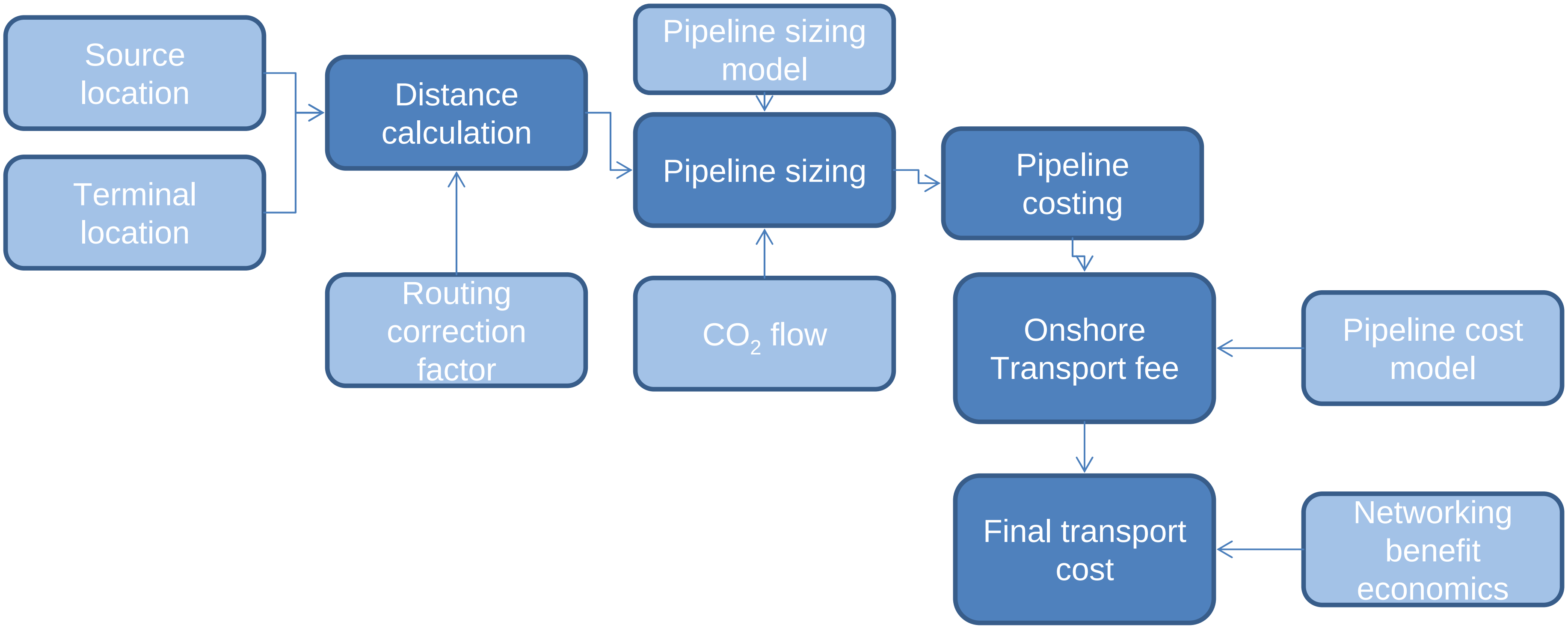
- For storage, onshore storage is expected to be considerably cheaper than offshore, but this has created political difficulties in Europe, and there has been no significant potential for CO_2 onshore storage identified onshore for the UK to date.
- Costs of offshore storage identified by ZEP span €2-20/t depending on site-specific issues. Included are high pre-FID costs for detailed site assessment.

Source: Zero Emissions Platform (2011) Transport Report & Storage Report
http://www.zeroemissionsplatform.eu/library/publication/168-zep-cost-report-storage.html

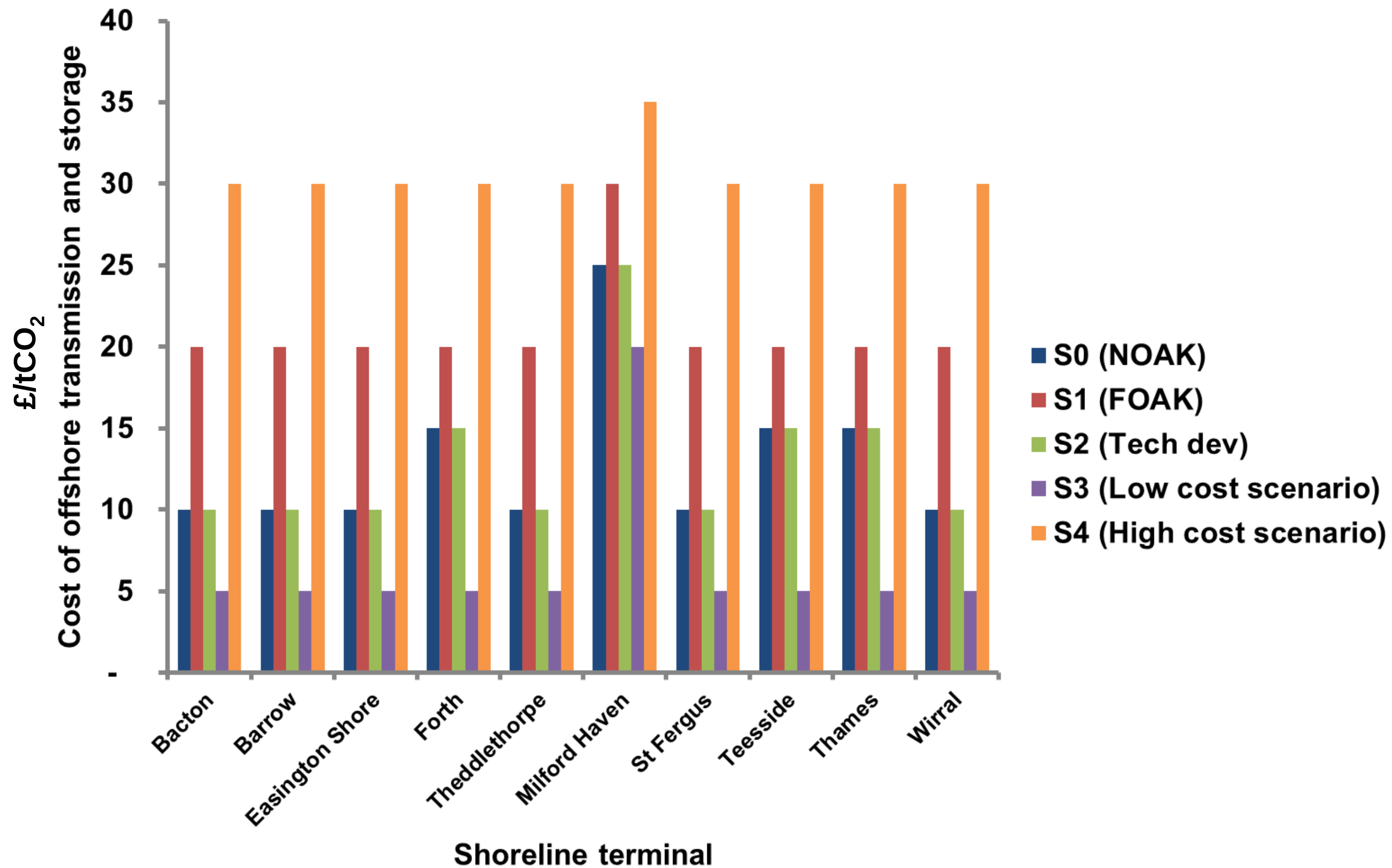
CO_2 transport and storage scenario modelling

- The transport and storage costs are calculated by combining predicted onshore transport cost, offshore transport cost and storage costs.
- The developments and uncertainties in capture and those in transport and storage will be largely independent of each other. However, to simplify presentation by using a limited number of scenarios, we have maintained the scenario descriptions S0-S4.
- We further simplify by assuming S0 (NOAK) = S2 (Technology Development)
- S0 (NOAK) and S2 (Technology Development) assume that there is significant transport and storage infrastructure onshore and offshore, operating at high utilisation, and costs are shared between industrial emitters and the power sector.
- S1 (FOAK) assumes that there is limited transport and storage infrastructure in place, implying few economies of scale and opportunities to share costs, and higher tariffs reflecting risks for infrastructure developers.
- S3 (low cost scenario) assumes that all stakeholders have co-operated strongly to build efficient transport and storage infrastructure before 2030, and tariffs are low to reflect the low risks for infrastructure developers. The scenario assumes extensive re-use of infrastructure, adoption of CO_2-Enhanced Oil Recovery and that the majority of infrastructure is paid for from the electricity market.
- S4 (high cost scenario) assumes there is limited co-operation between stakeholders leading to inefficient transport and storage infrastructure onshore and offshore, and correspondingly high system tariffs.

Onshore transport cost model identifies costs of transporting CO_2 by pipeline to the nearest potential terminal.

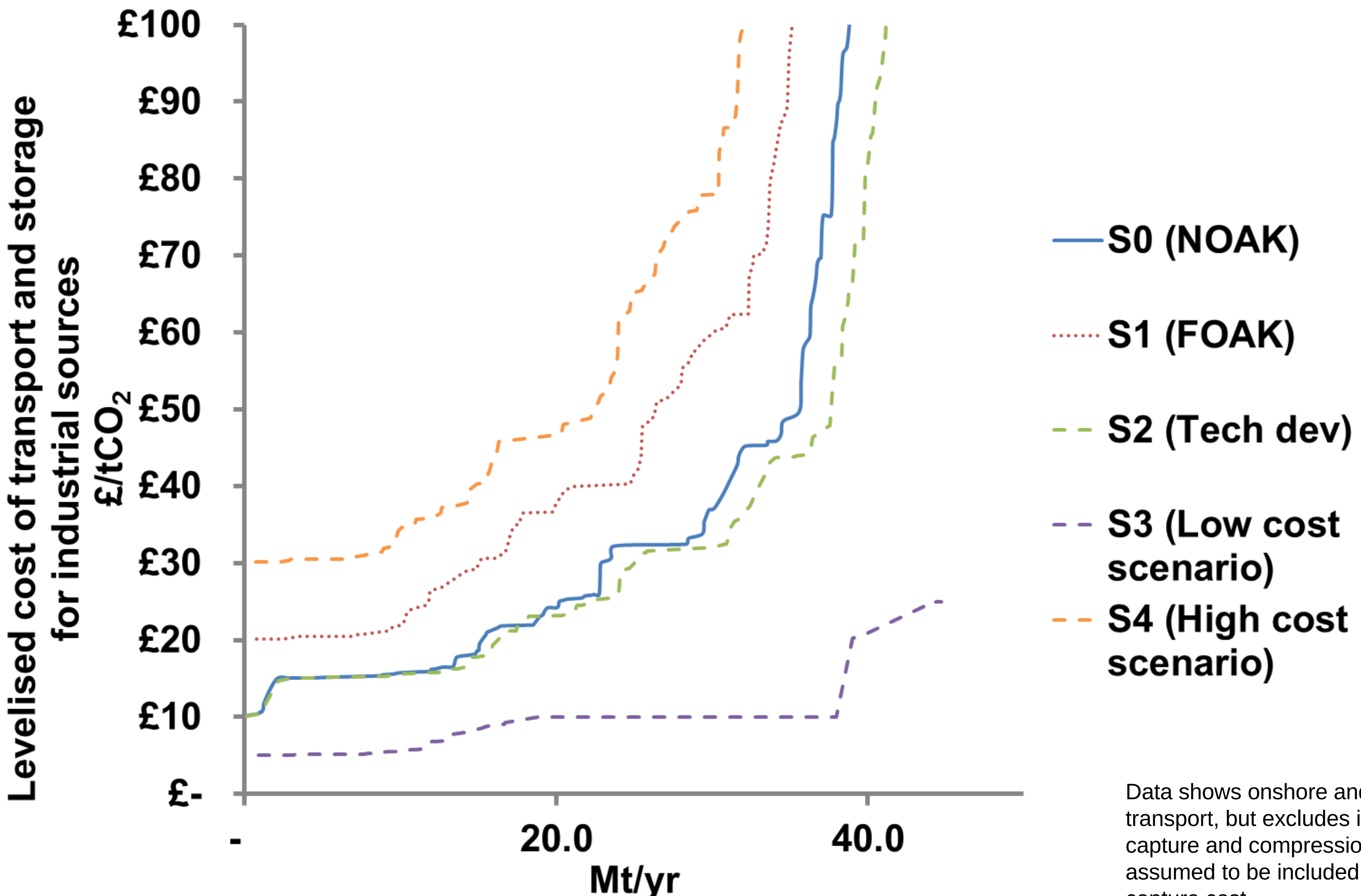


Scenarios for average offshore CO_2 transport and storage costs from potential shoreline terminals were developed.



Source: Element Energy analysis – assumes that industrial sources will share offshore networks with power sources. Estimates are derived from team modelling of a wide range of offshore configurations.

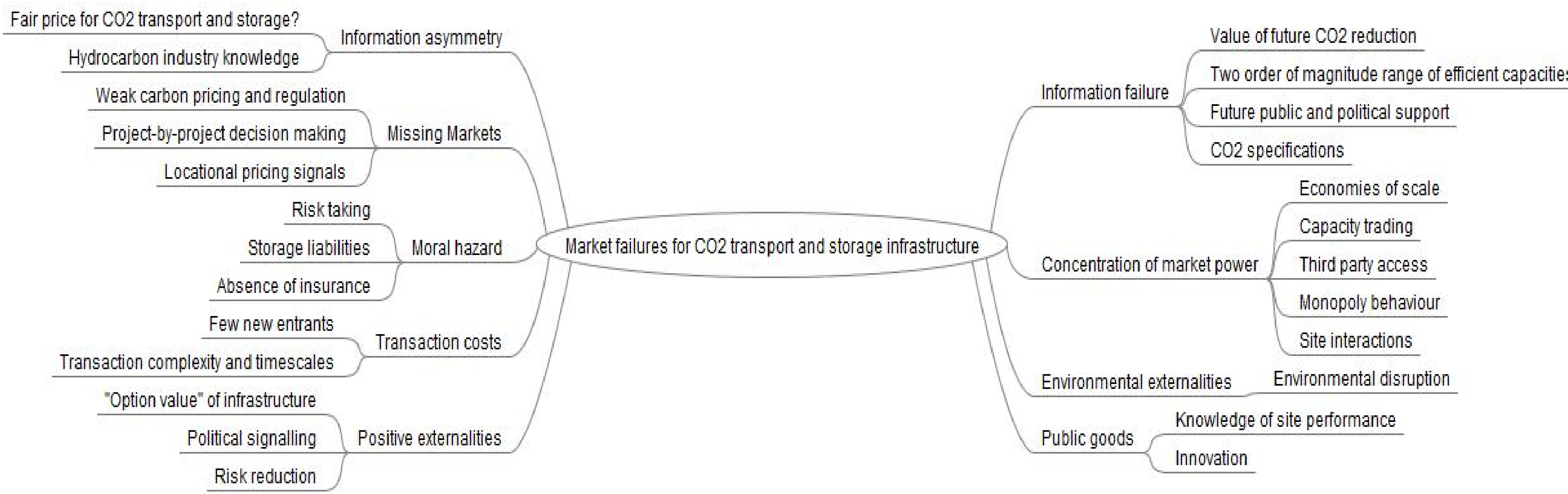
Estimated CO_2 transport and storage costs for industrial sources



Data shows onshore and offshore transport, but excludes initial capture and compression, which is assumed to be included within capture cost .

Source: Element Energy analysis

Diverse market failures are likely to restrict the development of efficient transport and storage capacity for industrial sources.



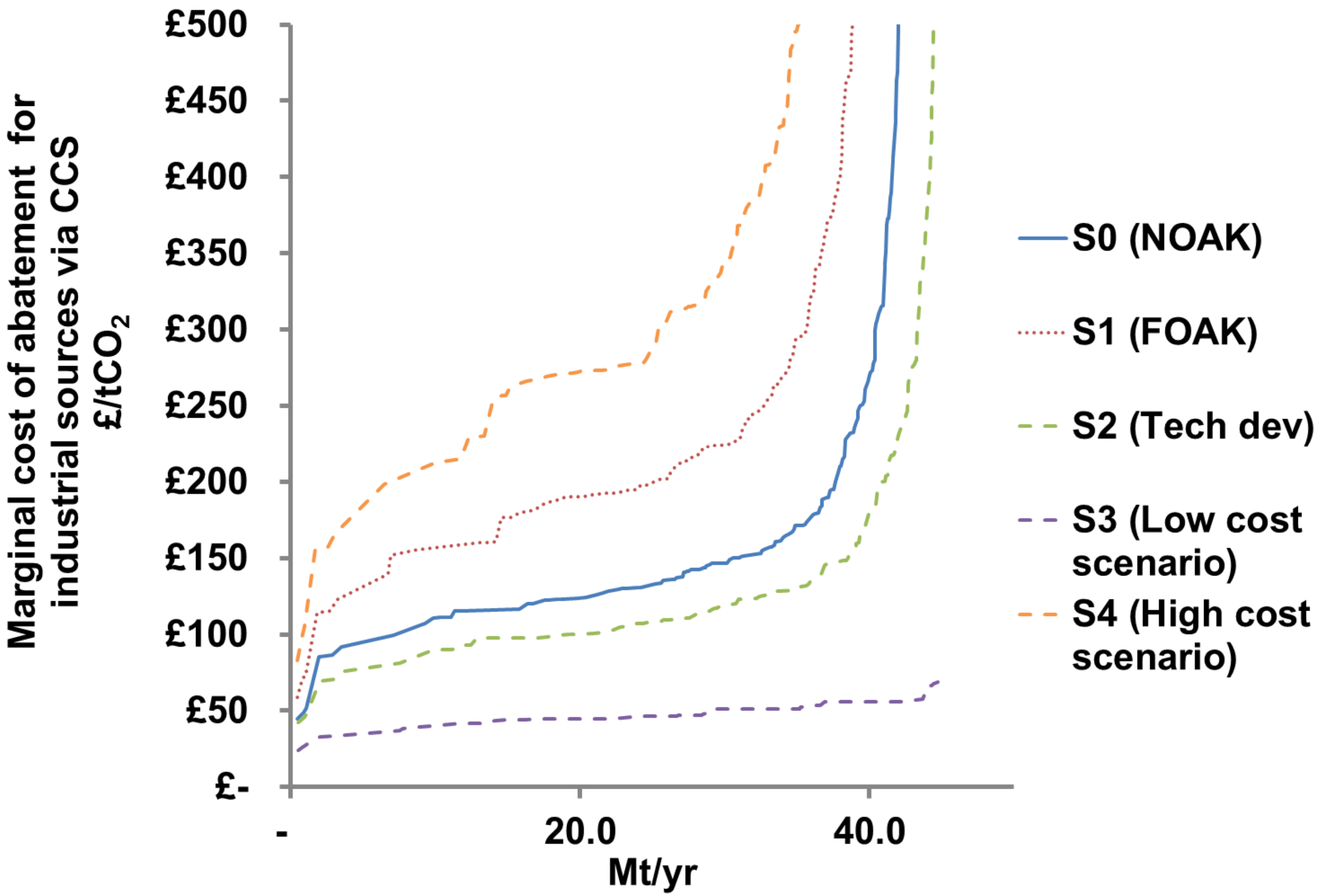
- The capture analysis suggests that a wide range of CO_2 transport and storage capacities (0-30+MtCO_2/yr) may be required in 2030.
- To our knowledge, no industrial source of CO_2 has yet invested meaningfully in transport and storage infrastructure.
- The existing framework for decision making around CCS is focussed on individual power projects and is unlikely to deliver options for economically efficient levels of transport and storage capacity to support up to 30 Mt/yr CCS in industry in 2030.
- However with appropriate policy interventions, and significant co-operation from market actors, transport and storage costs could deliver a the “low cost scenario”.

Source: Element Energy analysis

Outline

- ❑ Background
- ❑ Data and Process
- ❑ Scenario Analysis
- ❑ Transport and Storage of CO_2
- ❑ Overall CCS costs
- ❑ Bibliography

The industry 2030 CCS chain costs span a wide range from £20/t-£500+/tCO_2 avoided.



Source: Element Energy analysis

Commentary on Industry CCS MACC curve

- A major uncertainty is over whether existing industrial fossil fuel-based CO_2 emissions will still be at comparable volumes at the same locations in 2030 – sources may close, relocate, change fuel type, improve efficiency, change output, and entirely new emitters may emerge (e.g. biofuel refining).
- This is out of scope of the present study but CCS planning will be improved if 20yr+ forecasts for CO_2 emissions are collected on a site-by-site basis.
- CO_2 capture from industrial sources is not "new"; however capture feasibility, detailed designs and costs for retrofitting existing UK industrial plants are much less well understood than CO_2 capture from new power stations (for which there are still large cost uncertainties…)
- Location matters, largely because of the fixed location of storage sites (mostly under the North Sea) and the large economies of scale that imply all but the largest industrial sources will only be able to implement CCS if they can share transport and storage costs with other CCS projects.
- Policymakers and other stakeholders have the opportunity to play a substantial role in lowering the costs of CCS for some industrial sources, by ensuring public support for CO_2 reduction, promoting CCS readiness in UK industry, creating a stable economic and co-operative framework to support reduce the costs of finance, promote technology development, and optimising transport and storage infrastructure.

Outline

- ❑ Background
- ❑ Data and Process
- ❑ Scenario Analysis
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- ❑ Overall CCS costs
- ❑ Bibliography

Literature reviewed - 1

Year	Name	Comments
2009	IEA Energy technology Transitions for Industry, Strategies for the next Industrial Revolution	Approximate annualised CCS costs per tonne for some of the major sectors. Iron & steel: 25 – 60$/tCO2 Cement: only other papers are referenced, gives range of $38-170/tCO2 Ammonia: only other papers are referenced, <$50/tCO2 Ethylene: only other papers are referenced, >$50/tCO2 Pulp and Paper (Black lignite IGCC, type of CHP): capital costs increase by $320/kW of electricity is CO2 capture was installed.
2008	IEA GHG CO2 capture in the Cement Industry. Mott McDonald	Breakdown of capital costs for a cement plant with post-combustion CO2 capture. Capital cost of additional post-combustion plant of €294million, for a 1Mt/year cement plant, based on installation of a coal-fired CHP plant. Estimated the increase in costs of cement manufacture with capture, based on a 25 year lifetime, 10% discount rate, and the assumption that any excess electricity produced by the coal CHP plant can be sold to the grid. Cement with no CO2 capture, €66/t, cement with CO2 capture, €129/tonne
2008	IEA GHG Carbon dioxide capture and storage in the clean development mechanism: assessing market effects of inclusion. Environmental Resource Management	Cost estimates for CCS in several sectors. The study draws heavily on capital cost estimates from McCollum and Ogden (2006). As part of the capital cost methodology a retrofit cost multiplier of 1.5 is assumed. The study assumes that on-going operation and maintenance costs are 4% of the capital cost, and that a capture efficiency of 98% is possible throughout the chain. Ammonia production: $66million capital costs (does not include the capital cost of heat and power production.) Petroleum refinery: references Simmons et al, 2003 Hydrogen plant: $45 million capital cost (does not include the capital cost of heat and power production). Cement Plant: $320million capital costs for a 1MtCO2/yr plant

Literature reviewed - 2

Year	Name	Comments
2003	A study of a very large scale post combustion CO2 capture at a refining and petrochemical complex. Simmonds et al	Scenario based on retrofitting a post combustion, amine based capture facility, to the Grangemouth refinery and petrochemical complex (2Mt CO2/year). Study notes that a new utility complex is required to meet the high energy demands of the CO2 capture plant, as existing utility capacity is constrained. Study assumes that all complex CO2 sources can be captured, but does not include capture of emissions from the CHP plant. Total cost of the capture plant unit is $476 million, including $149 million for utility and offsite systems.
2012	Electricity Generation Cost Model – 2012 update of non renewable technologies	Costs of gas turbine CHP plant, £56.5 million, based on 46MW plant.
2009	Steel and CO2 – the ULCOS Program, CCS and mineral carbonation using steelmaking slag. Birat	For an integrated steel mill, the major CO2 stream form the blast furnace accounts for 69% of all steel mill emissions to the atmosphere.
2011	UNIDO/IEA Technology Roadmap, Carbon capture and storage in industrial applications	Capital costs are not quoted, instead costs of capture, transport and storage per tonne of CO2 are given: Refineries: $45-125/tCO2 Iron & Steel $65-80/tCO2 Cement: $60-150/tCO2 High-purity sources: $35 - 75/tCO2
2009	Cement technology Roadmap	Post-combustion technologies would not require any fundamental changes in the cement process and therefore could be suitable for new kilns and for retrofitting. Oxyfuel technology, using oxygen instead of air in cement kilns, would result in a relatively pure CO2 stream, but extensive research is still required. Energy requirements for cement production expected to increase by 20% to provide the energy for capture. Estimated capital cost of €100-300 million in 2030 for a 2MT/yr clinker plant.

Literature reviewed - 3

Year	Name	Comments
2009	European Cement Research Academy CCS project – Report about Phase II	Reports costs estimated from the IEA GHG (2008) study described earlier, which along with other reported cost estimates results in a range of estimates between €100-300 million for the capital cost of a 2Mt/yr clinker plant. Report mainly covers detailed study of flue gas characteristics, plant layouts, developments in solvents, and research into oxyfuel capture.
2013	CO2 capture in oil refineries: assessment of capture avoidance costs associated with different heat supply options in a future energy market. Johansson et al.	The capture avoidance cost is highly sensitive to the assumption of the heat is supplied and the heat demand. For an oil refinery, estimates range from €40-263/tCO2 avoided depending on whether the heat is supplied through one of four options, NGCC, NG boiler, biomass boiler, or use of excess heat, combined with a heat pump.
2012	Comparative assessment of CO2 capture technologies for carbon intensive industrial processes. Kuramochi et al.	A consistent techno-economic assessment of capture technologies in key industrial sectors, based on extensive literature review and the standardisation of key parameters: - capacity factor 91-97% - interest rate 10% - plant lifetime 20 years - fuel prices, CO2 compression pressure, and grid electricity CO2 intensity all standardised. Estimates for capture costs in the short-medium term (2007 prices): Iron & steel: 40-65€/tCO2 Cement: >65€/tCO2 Refining and petrochemical: 50-60€/tCO2 based on oxyfuel capture Normalisation of plant scales by applying a generic scaling formula
2010	Prospects for cost-effective post-combustion CO2 capture from industrial CHPs. Kuramochi et al.	Costs of capture from industrial CHP assuming that the CHP is operating at partial load, and additional energy requirements can be met by increasing the load. Estimates that costs of capture from 200MWe CHP plants may be €33-36/tCO2 avoided by 2020-2025 (2007 prices).

Literature reviewed - 4

Year	Name	Comments
2013	Techno-economic prospects for CO_2 capture from distributed energy systems. Kuramochi et al.	Standardises costs of CCS across a range of distributed energy systems. Costs for building a new NGCC CHP plant (5MWe) with post-combustion CCS integrated are €3800/kW output. 2007 prices
2012	Technology learning curves (FOAK to NOAK), NETL	Sets out a learning curve methodology which generates predictions of NOAK plant costs from FOAK values.
2010	Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report	Sets out relevant CCS technologies for key industrial sectors as well as summarising the range of costs reported in other papers, largely the IEA papers summarized earlier.
2010	CO_2 capture for refineries, a practical approach. van Straelen et al.	Considers post-combustion capture at refineries. Estimates that only 40 - 50% of refinery emissions are suitable for capture at costs of €90-120/tCO2. These costs would increase significantly if more CO2 sources were to be captured
2010	Costs and performance baseline for fossil energy plants, Vol. 1. NETL	Establishes baseline performance and cost estimates for fossil energy plants, including detailed breakdown of cost categories e.g. owners costs, project and process contingencies, and considers IGCC and NGCC both with and without carbon dioxide capture and sequestration.
2011	Cost estimation methodology for NETL assessments of power plant performance	Sets out cost categories for a range of capital cost levels, from bare erected costs to total overnight cost.
2011	Economic Assessment of carbon capture and storage technologies, 2011 update. WorleyParsons Schlumberger for the Global CCS Institute	Costs of CCS on a levelised cost of production basis for power plants and a range of industrial applications. Estimates annualised product costs of $88/tonne steel, or $57/tonne CO2 for the Euro area (assume this includes the UK). This is in 2011 prices, and includes the cost of the CHP plant.
2012	ZEP Cost reports	Reports available on capture, transport and storage costs

Literature reviewed - 5

Year	Name	Comments
2012	Element Energy et al. for Scottish Enterprise: The impacts of CO_2-EOR in Scotland	Illustrates scenarios for how CO_2-EOR deployment in the North Sea could reduce costs.
2012	Element Energy for Green Alliance and the European Climate Foundation	Illustrates the needs and challenges for CCS readiness, and the potential sharing of industrial and power
2011	Energy Technologies Institute - UK Storage Appraisal Project	Comprises detailed analysis of potential costs for offshore transmission and storage of CO_2 across a wide range of shoreline terminals, storages and scenarios.
2011	Element Energy *et al*. for One North East – The Investment Case for a CCS network in the Tees Valley	Quantifies the economics of CCS networks in the Tees Valley.
2011	AMEC for One North East – Engineering study for a CCS network in the Tees Valley	Describes technical configurations and costs for capture and transport
2010	Element Energy *et al.* for the Committee on Climate Change – the costs of CCS in UK industry and gas power sectors	First high level estimate of the costs of capture for UK industry
2010	Element Energy *et al*. for the North Sea Basin Task Force: One North Sea	Illustrates potential CCS and infrastructure deployment scenarios in the North Sea region
2009	Element Energy *et al*. for IEA GHG : Global opportunities and challenges for CO_2 Pipeline Infrastructure	Describes drivers of pipeline economics and challenges to deployment.
2007	Element Energy *et al*. for DTI: CO_2 pipeline infrastructure for the UK and Norway	Quantifies the importance of clusters for CCS in the UK
2007	AMEC for Yorkshire Forward: CO_2 pipeline infrastructure for the Humber	Technical analysis of a shared pipeline in Humber region
2009	PB Power for DECC: CO_2 pipeline study	Detailed costs for CO_2 pipelines