# UK Costs for a Range of CCS Technologies

UK CCS Research Centre Biannual Conference, Cambridge

27th March 2018

# UK Costs for a Range of CCS Technologies

## Agenda

1. Introduction
2. BEIS 2017 CCS Study Overview
3. Methodology
4. Key Assumptions
5. State of the Art Technology Results
6. Novel Technology Potential – 2 examples
7. Conclusions

# UK Costs for a Range of CCS Technologies

## Wood Overview

**55,000**
People

**60+**
Countries

**400+**
Offices

**160+**
Year history

**$10bn**
Revenue (AMFW/WG) Combined

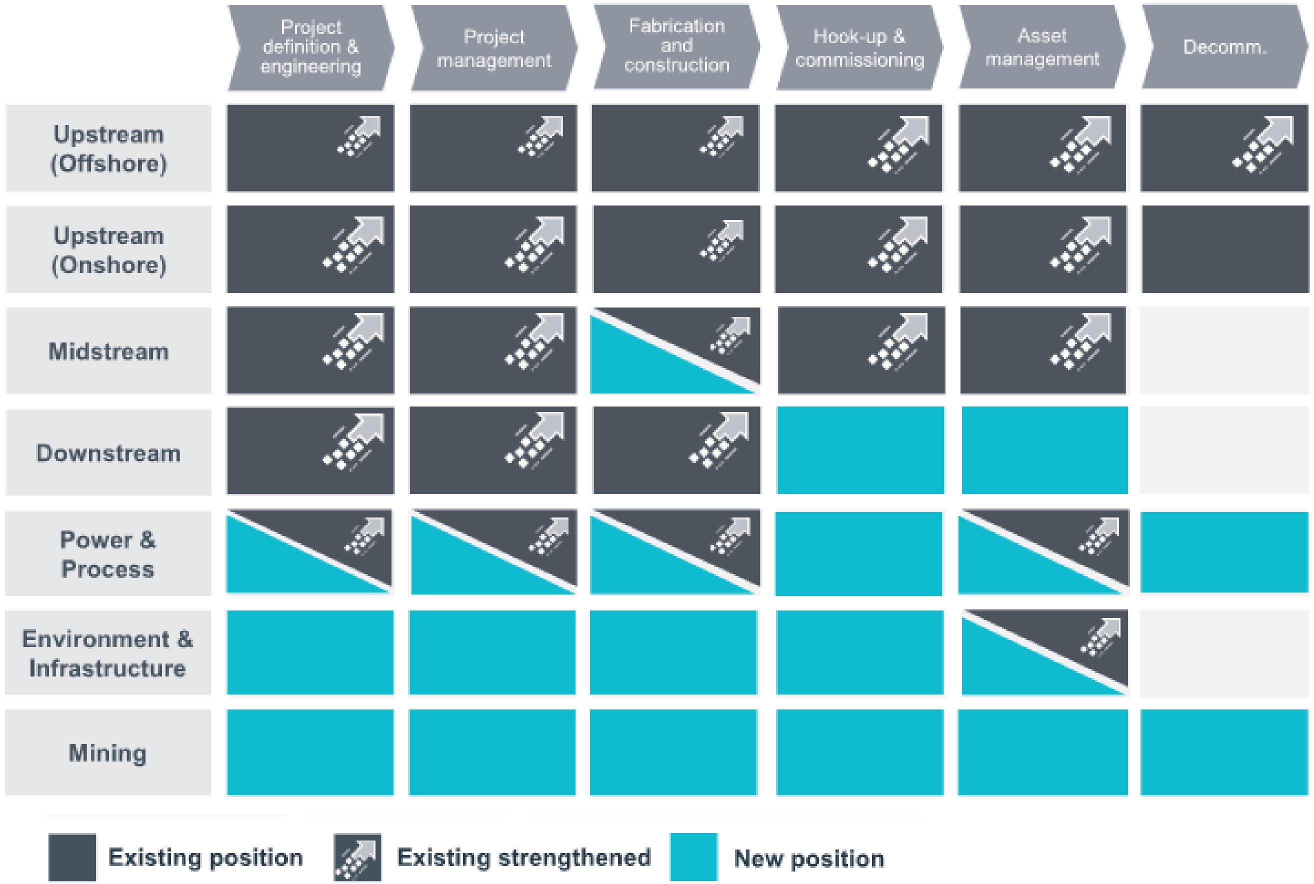
Sectors and markets we operate in:

| | | |
|---|---|---|
| Clean Energy | Chemical | Refining |
| Environment and Infrastructure | Manufacturing | Marine and Defence |
| Mining and Minerals | Nuclear, Power and Process | Oil & Gas |

# UK Costs for a Range of CCS Technologies

## Wood Overview

The recent combination has brought together world-class expertise from established brands, Wood Group (incl. legacy Mustang & Kenny), Amec and Foster Wheeler



# UK Costs for a Range of CCS Technologies

## Introduction

- Wood, (formerly Foster Wheeler), has performed over 50 CCS studies since the mid-1990s.
  - Comparing state of the art technologies (benchmarking)
  - Assessing new technologies
- Performed several CCS FEEDs
  - DF-1 Peterhead
  - Hydrogen Power Abu Dhabi
  - E.ON Kingsnorth
  - Don Valley Power Project
- Various pre-FEEDs including:
  - Statoil Snovhit Train II
  - Cameroon LNG

# UK Costs for a Range of CCS Technologies

## Introduction

- Wood (formally Foster Wheeler) work has covered CCS from power generation, LNG liquefaction, refining, hydrogen production, CTL/GTL, natural gas treating, cement and steel production.
- All work incorporates equipment, construction and commissioning cost data from real projects built around the world.
- In 2017 we have been performing studies for several clients.
- This presentation will share results from a study in progress for UK Department for Business, Energy & Industrial Strategy (BEIS) with input from IEAGHG, ETI and others.

# BEIS 2017 CCS Study Overview

# UK Costs for a Range of CCS Technologies

## BEIS 2017 CCS Study Overview

- Key aims of the study included:
  - Technology performance & cost update of state of the art CCS technologies
  - Assessment of selected novel technologies, biomass & hydrogen schemes with CCS

- State of the Art CCS Technologies included:
  - Natural gas CCGT with proprietary amine-based post combustion capture
  - Natural gas reforming combined cycle with pre-combustion capture
  - Supercritical pulverised coal with proprietary amine-based post combustion capture
  - Supercritical pulverised coal with oxy-combustion capture
  - Coal gasification combined cycle with pre-combustion capture

- 2017 study aims to incorporate latest cost & technical performance:
  - improvements in the base power plants
  - further development & operational experience from CCS schemes in operation.

# UK Costs for a Range of CCS Technologies

## BEIS 2017 CCS Study Overview

- Novel technologies, biomass & hydrogen CCS schemes:
  - Allam cycle natural gas oxy-combustion
  - Molten carbonate fuel cells for post combustion capture
  - Biomass CFB with post combustion capture*
  - Biomass CFB with oxy-combustion capture*
  - Biomass gasification combined cycle with pre-combustion capture*
  - Natural gas SMR hydrogen unit with post combustion capture*

  *Results not included in this presentation

- Final report is not yet published, thus the results presented today are not yet set in stone.

# Methodology

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## Methodology

- Source data for costs and plant performance:
  - Base power plant:
    - Simulation (Gatecycle & Hysys)
    - Published data from operating plants and vendors
  - $CO_2$ capture processes:
    - Developed from vendor data for similar projects or published data
    - Cansolv provided cost & performance data for all post combustion cases
  - $CO_2$ compression & dehydration
    - Developed from simulation & vendor data for similar projects
  - $CO_2$ transportation & storage
    - Applied as a cost penalty per tonne of $CO_2$ captured, not considered in detail.
- Material & energy balances provide basis for thermal efficiency calculation & high level equipment sizing.
- Capital & operating costs provide basis for levelised cost of electricity (LCOE).

# Key Assumptions

# UK Costs for a Range of CCS Technologies

## Key Assumptions

- Greenfield site, coastal location in the North East of England.
- 9ºC, 80% humidity, 400 ppmv $CO_2$ in air.
- UK grid natural gas, internationally traded bituminous coal.
- $CO_2$ compression to 110 bar (abs).

- Baseload power generation at:
  - 90% availability for post & oxy combustion cases
  - 85% availability for pre-combustion cases

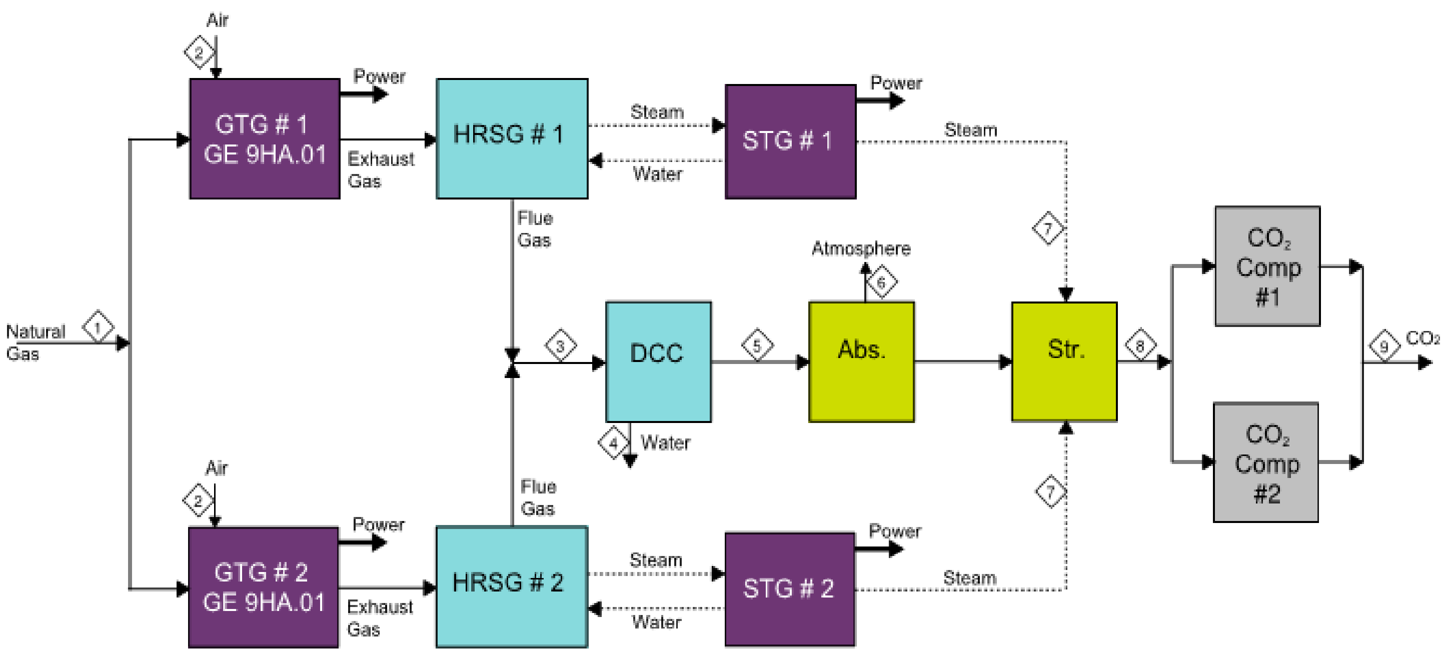
- 1Q2017 cost figures in GBP
- Nth of a kind cost build up basis
- Equity financed
- 25 year life
- 8.9% discount rate
- Prices of feedstocks & $CO_2$ emissions based upon BEIS profiles

# State of the Art Technology Results

# UK Costs for a Range of CCS Technologies

## State of the Art Technology Results

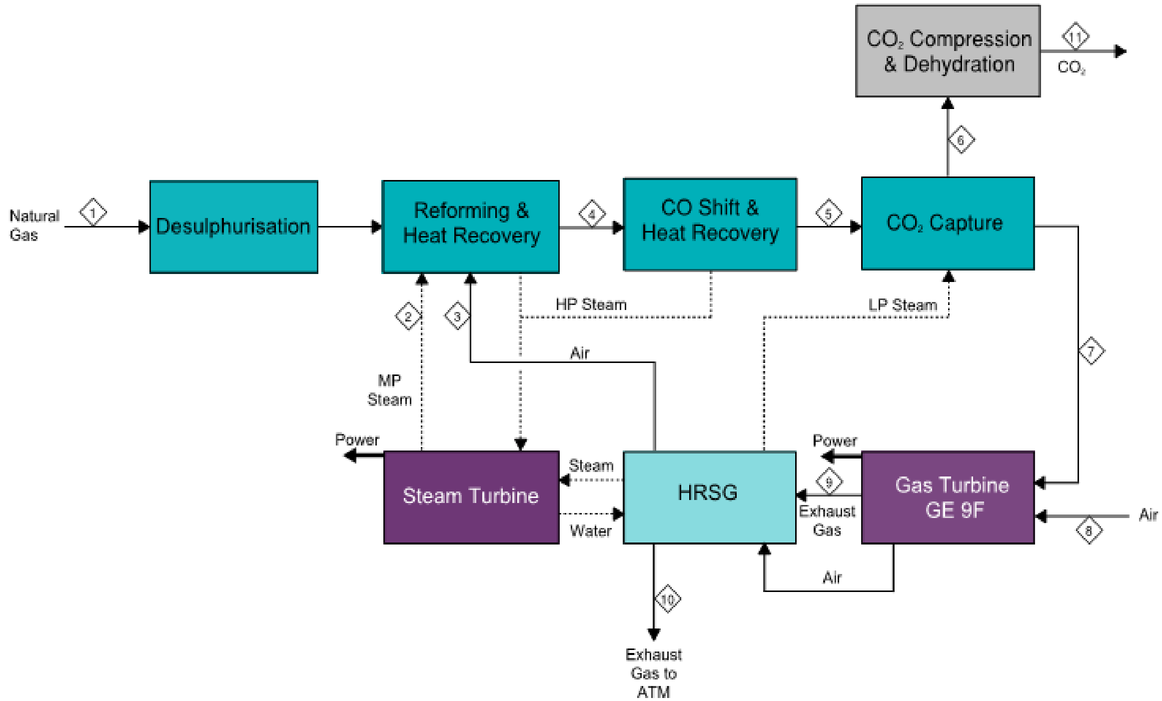
- Natural Gas CCGT with Cansolv $CO_2$ Capture
  - 2 x GE 9HA.01 gas turbines in combined cycle, scale 1,200 MWe nominal
  - Single train of $CO_2$ capture using combined concrete structure for direct contact cooler & absorber



# UK Costs for a Range of CCS Technologies

## State of the Art Technology Results

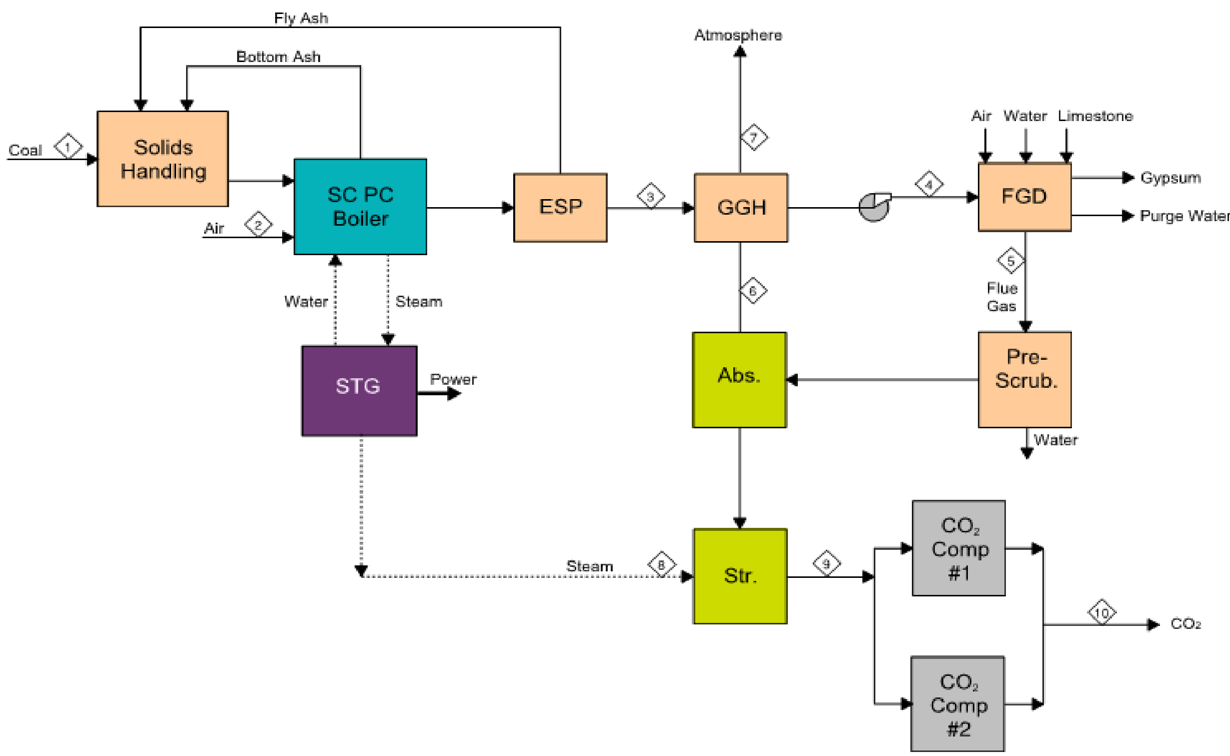
- Natural Gas reforming combined cycle with pre-combustion $CO_2$ capture
  - 40 bar auto-thermal reformer
  - 2 x GE 9F syngas variant gas turbines in combined cycle, scale 950 MWe nominal
  - Two trains of full system including Selexol process for $CO_2$ capture.



# UK Costs for a Range of CCS Technologies

## State of the Art Technology Results

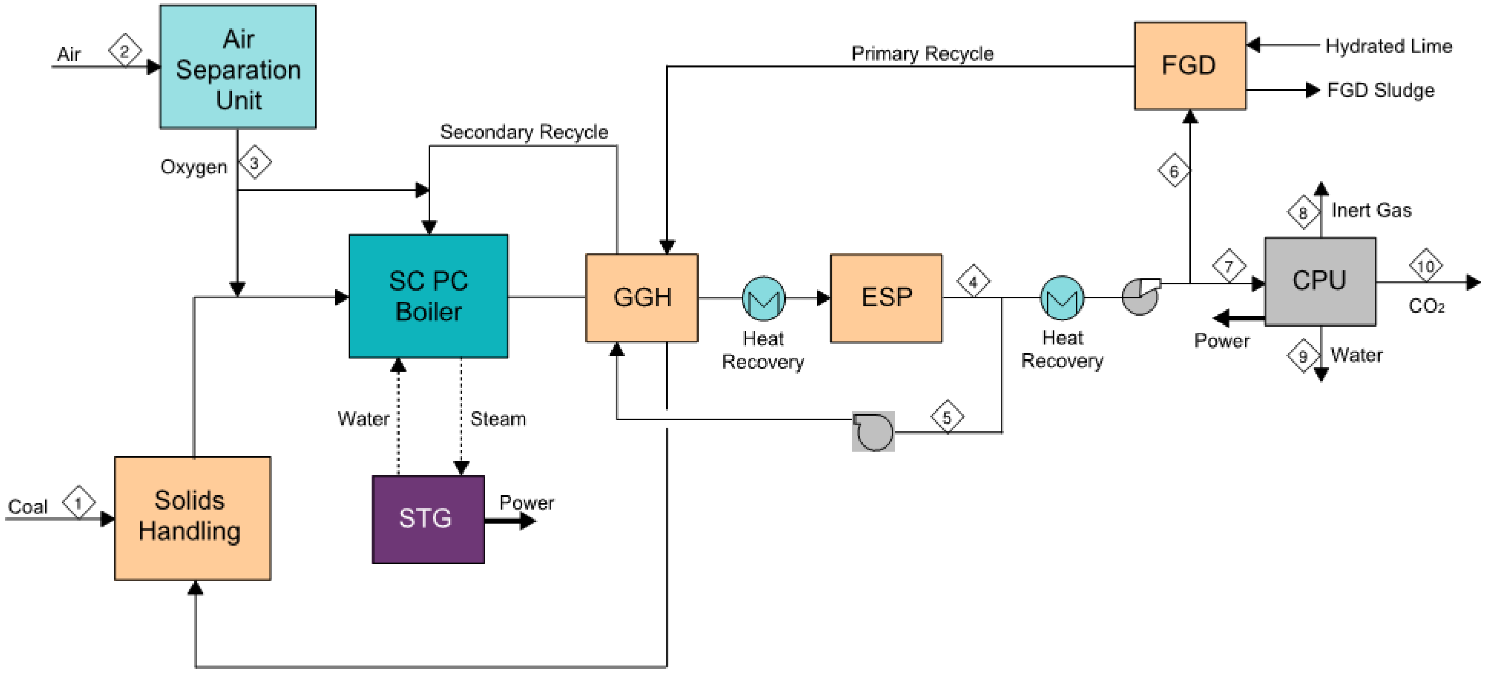
- Supercritical pulverised coal with Cansolv $CO_2$ capture
  - Steam generator at 620ºC & 270 bar with MP reheat and a steam turbine at a 1000 MWe nominal scale.
  - Single train of $CO_2$ capture using combined concrete structure for pre-scrubber & absorber.



# UK Costs for a Range of CCS Technologies

## State of the Art Technology Results

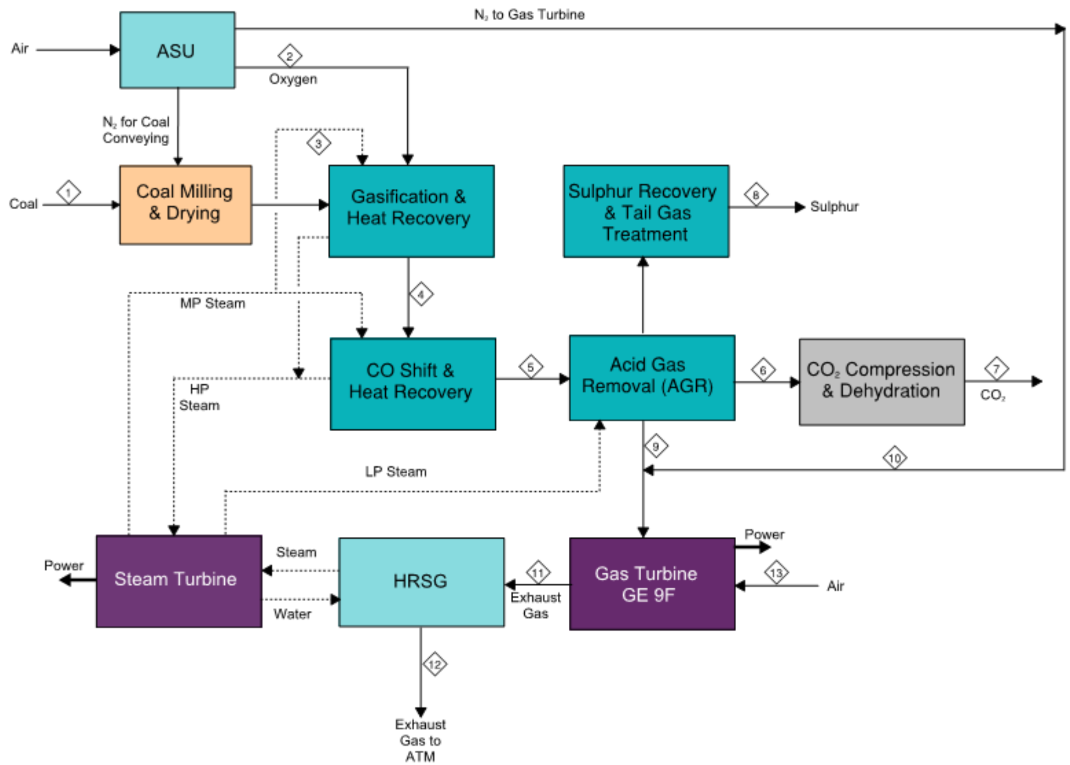
- Supercritical pulverised coal with oxy-combustion $CO_2$ capture
  - Steam generator at 620ºC & 270 bar with MP reheat and a steam turbine at a 1000 MWe nominal scale.
  - $CO_2$ purification & compression based upon Air Products process.
  - Cryogenic ASU.



# UK Costs for a Range of CCS Technologies

## State of the Art Technology Results

- Integrated gasification combined cycle with pre-combustion $CO_2$ capture
  - 40 barg Shell gasification process
  - 2 x GE 9F syngas variant gas turbines in combined cycle, scale 1050 MWe nominal
  - Two trains of full system including Selexol process for $CO_2$ capture.



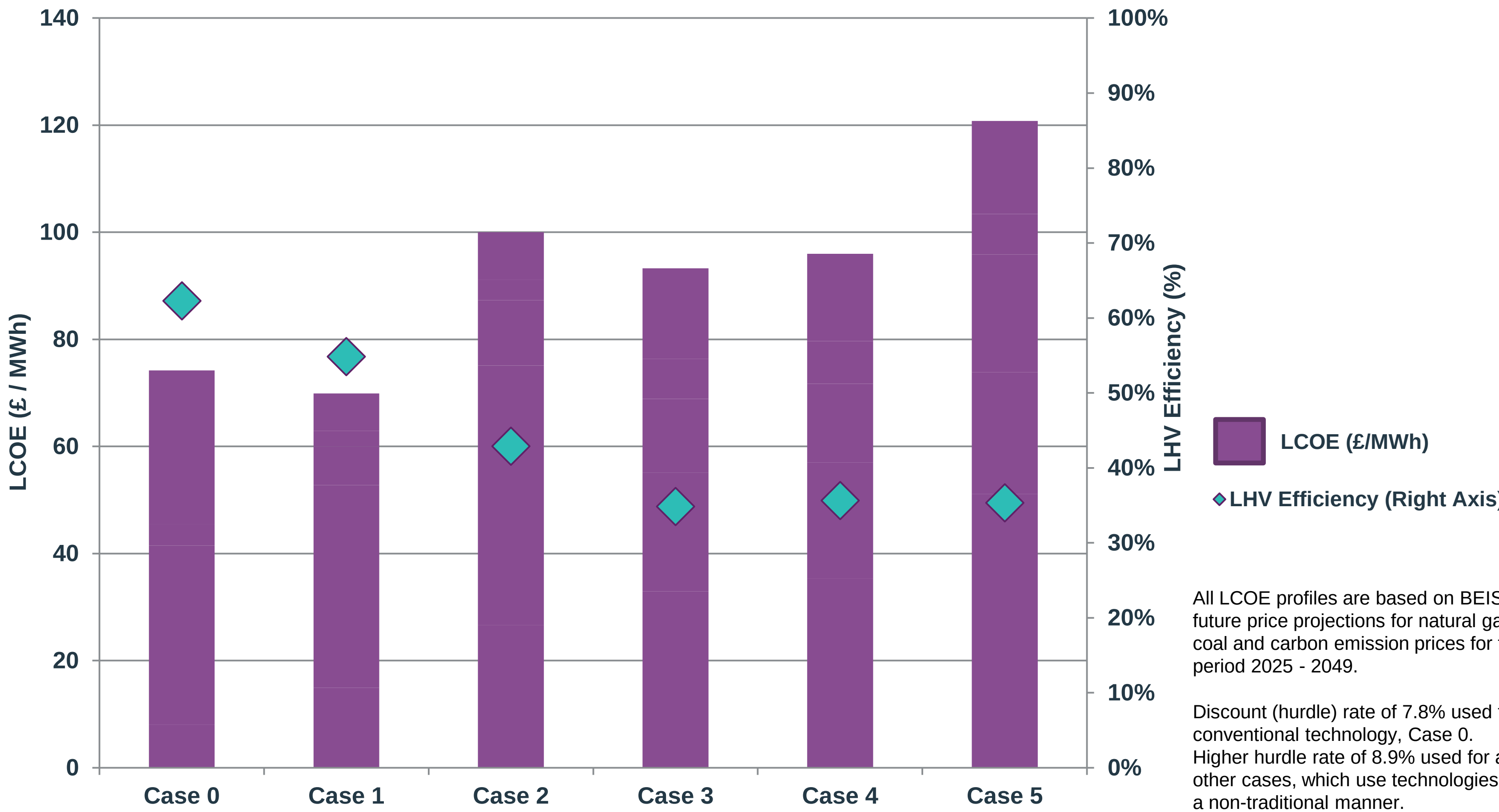
# UK Costs for a Range of CCS Technologies

## State of the Art Technology Results

| | | Unabated CCGT | Post-Combustion on Gas | Pre-Combustion on Gas | Post-Combustion on Coal | Oxy-Combustion on Coal | Pre-Combustion on Coal |
|---|---|---|---|---|---|---|---|
| | Units | 0 | 1 | 2 | 3 | 4 | 5 |
| Total gross installed capacity | MWe | 1229.4 | 1144.3 | 919.1 | 953.5 | 1112.8 | 1062.8 |
| Total auxiliary loads | MWe | 20.9 | 79.7 | 101.3 | 139.4 | 280.2 | 263.0 |
| Net Power Export | MWe | 1208.5 | 1064.6 | 817.9 | 814.2 | 832.6 | 799.8 |
| Net Efficiency - Year 1 (LHV) | % | 62.3% | 54.9% | 42.9% | 34.9% | 35.7% | 35.3% |
| Net Efficiency - Year 1 (HHV) | % | 56.2% | 49.5% | 39.0% | 33.3% | 34.1% | 33.8% |
| Total $CO_2$ captured | kg/h | 0 | 361539 | 353319 | 692310 | 685896 | 673147 |
| Carbon capture rate | % | 0.0% | 90.8% | 90.4% | 90.0% | 89.2% | 90.3% |
| Carbon Footprint | kg $CO_2$/MWh | 329.4 | 34.3 | 45.8 | 94.6 | 100.2 | 90.4 |
| Direct Materials Cost | £M | 335.3 | 493.5 | 649.6 | 853.1 | 903.7 | 1152.2 |
| EPC Contract Cost | £M | 583.6 | 845.3 | 1107.1 | 1547.4 | 1701.6 | 2151.1 |
| **Total Project Cost** | **£M** | **672.2** | **968.2** | **1,256.3** | **1,732.2** | **1,901.9** | **2,396.3** |
| Total Operating Cost (excl. Fuel & Carbon) | £M pa | 36.4 | 109.8 | 118.5 | 188.6 | 195.1 | 215.6 |
| Income from Elec Export | £M pa | 730.6 | 586.9 | 609.3 | 598.8 | 630.2 | 719.6 |
| **Levelised Cost of Electricity** | **£/MWh** | **74.2** | **69.9** | **100.0** | **93.3** | **96.0** | **120.8** |
| Cost of CO2 Avoided | £/t$CO_2$ | 0 | -14.5 | 91.1 | 81.3 | 95.1 | 195.1 |

# UK Costs for a Range of CCS Technologies

## State of the Art Technology Results

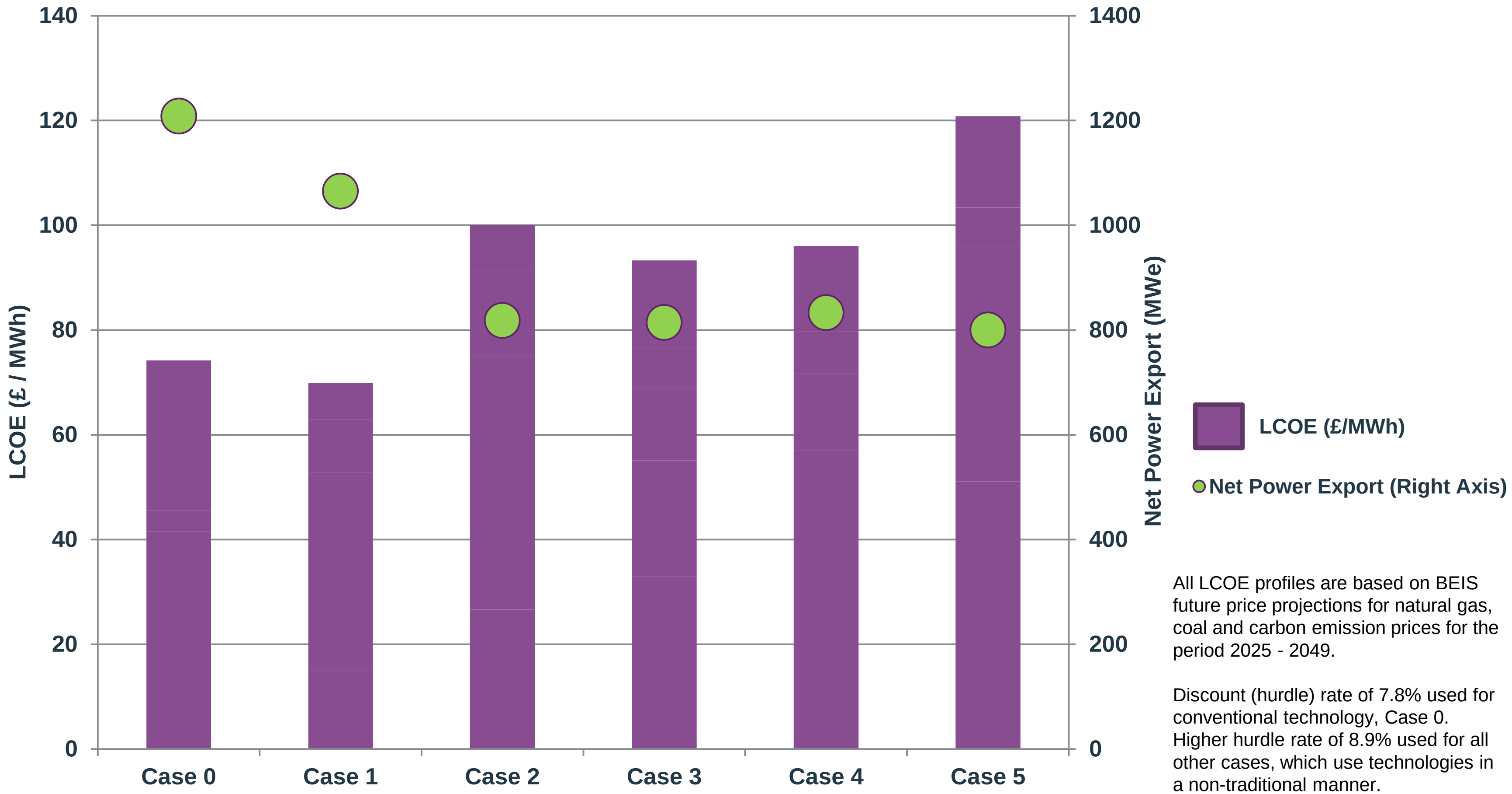



All LCOE profiles are based on BEIS future price projections for natural gas, coal and carbon emission prices for the period 2025 - 2049.

Discount (hurdle) rate of 7.8% used for conventional technology, Case 0. Higher hurdle rate of 8.9% used for all other cases, which use technologies in a non-traditional manner.

# UK Costs for a Range of CCS Technologies

## State of the Art Technology Results

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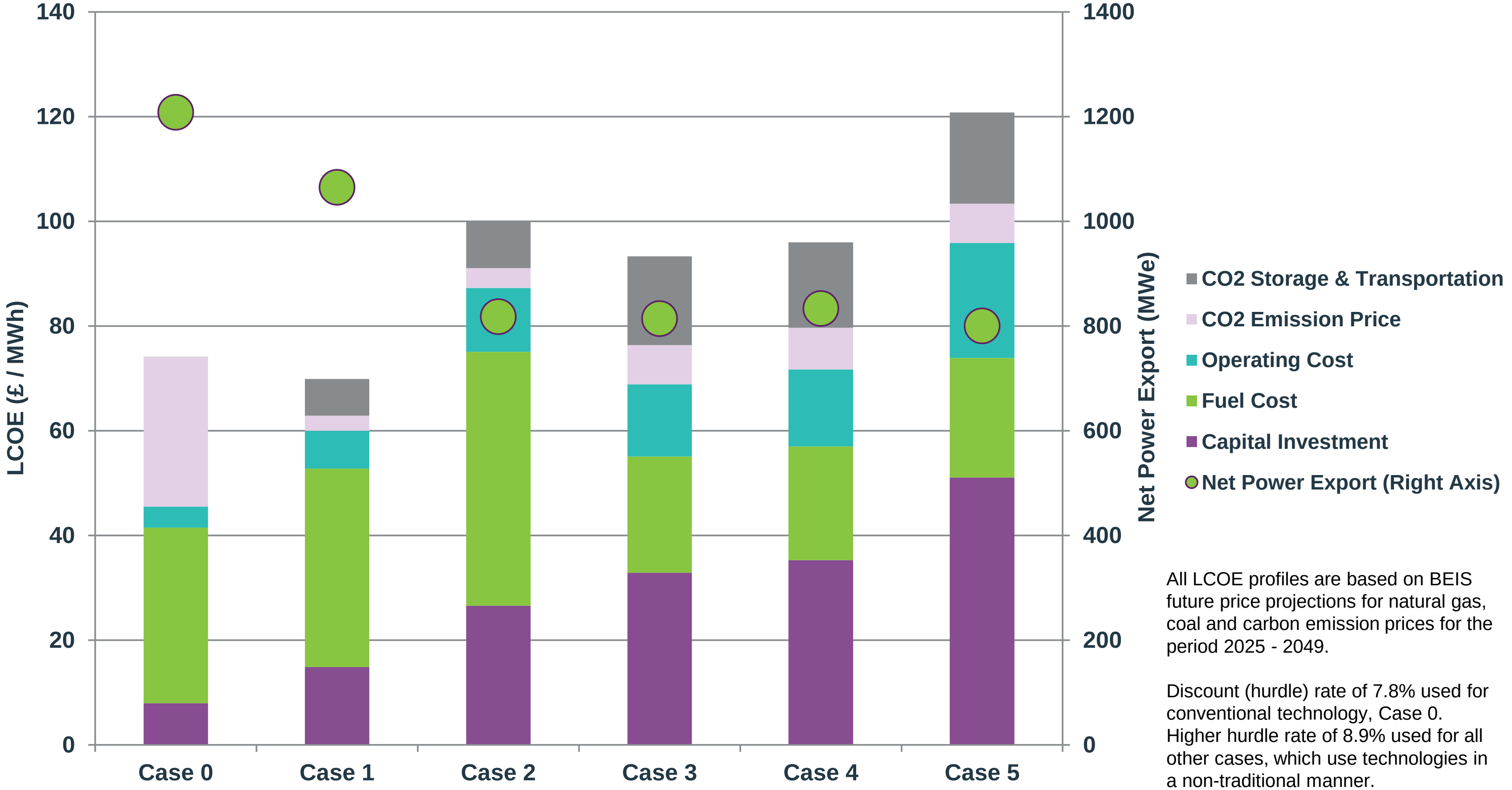


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# Novel Technology Potential – 2 Examples

# UK Costs for a Range of CCS Technologies

## Novel Technology Results – 2 Examples

- Modelled from public domain data
- Higher degree of technical risk
- Modelled as Nth of a kind to assess future potential once commercialised
  - Allam cycle natural gas oxy-combustion
    - Natural gas is combusted with oxygen at high pressure & temperature
    - Hot combustion products drive a turbine
    - Integrated heat recovery systems
    - Cryogenic ASU & $CO_2$ purification
  - Molten carbonate fuel cells for post combustion capture
    - Natural gas combined cycle power plant (2 x GE 9HA.01s)
    - Flue gas used as oxidant stream in natural gas fed MCFCs
    - MCFCs generate power while capturing $CO_2$ from the flue gas
    - Unconverted fuel returned to MCFC fuel inlet
    - Cryogenic $CO_2$ purification

# UK Costs for a Range of CCS Technologies

## Novel Technology Results – 2 Examples

| | | Unabated CCGT | Post-Combustion on Gas | Allam Cycle on Gas | MC Fuel Cell on Gas | Post-Combustion on Coal |
|---|---|---|---|---|---|---|
| | Units | 0 | 1 | 6 | 7 | 3 |
| Total gross installed capacity | MWe | 1229.4 | 1144.3 | 1263.9 | 1645.0 | 953.5 |
| Total auxiliary loads | MWe | 20.9 | 79.7 | 415.5 | 136.4 | 139.4 |
| Net Power Export | MWe | 1208.5 | 1064.6 | 848.4 | 1508.6 | 814.2 |
| Net Efficiency - Year 1 (LHV) | % | 62.3% | 54.9% | 55.2% | 59.7% | 34.9% |
| Net Efficiency - Year 1 (HHV) | % | 56.2% | 49.5% | 50.2% | 43.2% | 33.3% |
| Total $CO_2$ captured | kg/h | 0 | 361539 | 283546 | 477597 | 692310 |
| Carbon capture rate | % | 0.0% | 90.8% | 90.0% | 92.1% | 90.0% |
| Carbon Footprint | kg $CO_2$/MWh | 329.4 | 34.3 | 37.1 | 27.1 | 94.6 |
| Direct Materials Cost | £M | 335.3 | 493.5 | 583.2 | 815.8 | 853.1 |
| EPC Contract Cost | £M | 583.6 | 845.3 | 1067.9 | 1392.0 | 1547.4 |
| **Total Project Cost** | **£M** | **672.2** | **968.2** | **1,213.2** | **1,569.6** | **1,732.2** |
| Total Operating Cost (excl. Fuel & Carbon) | £M pa | 36.4 | 109.8 | 98.8 | 180.4 | 188.6 |
| Income from Elec Export | £M pa | 730.6 | 586.9 | 535.5 | 840.4 | 598.8 |
| **Levelised Cost of Electricity** | **£/MWh** | **74.2** | **69.9** | **80.1** | **70.7** | **93.3** |
| Cost of CO2 Avoided | £/t$CO_2$ | 0 | -14.5 | 20.0 | -11.7 | 81.3 |

# UK Costs for a Range of CCS Technologies

## Novel Technology Results – 2 Examples


All LCOE profiles are based on BEIS future price projections for natural gas, coal and carbon emission prices for the period 2025 - 2049.

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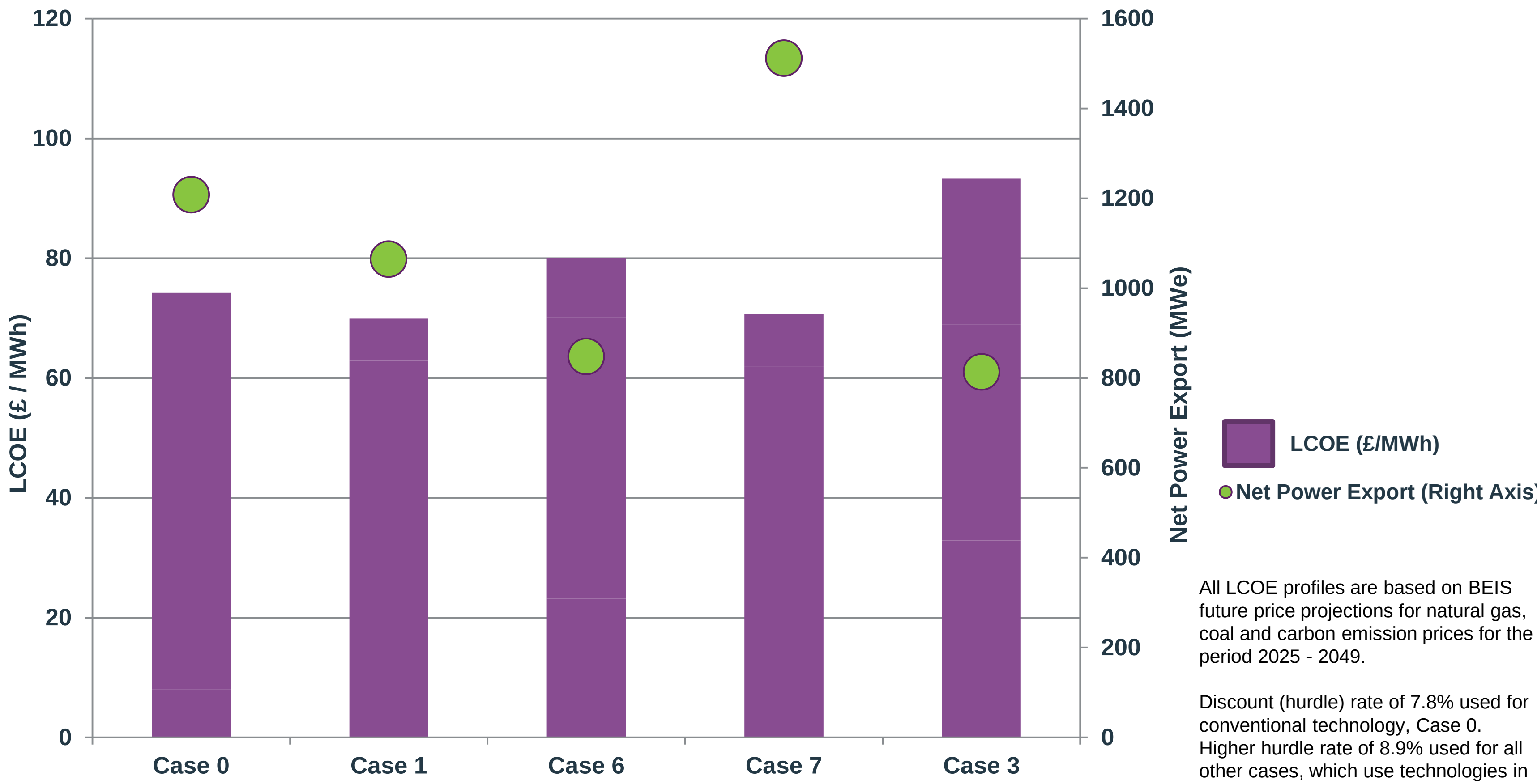
## Novel Technology Results – 2 Examples

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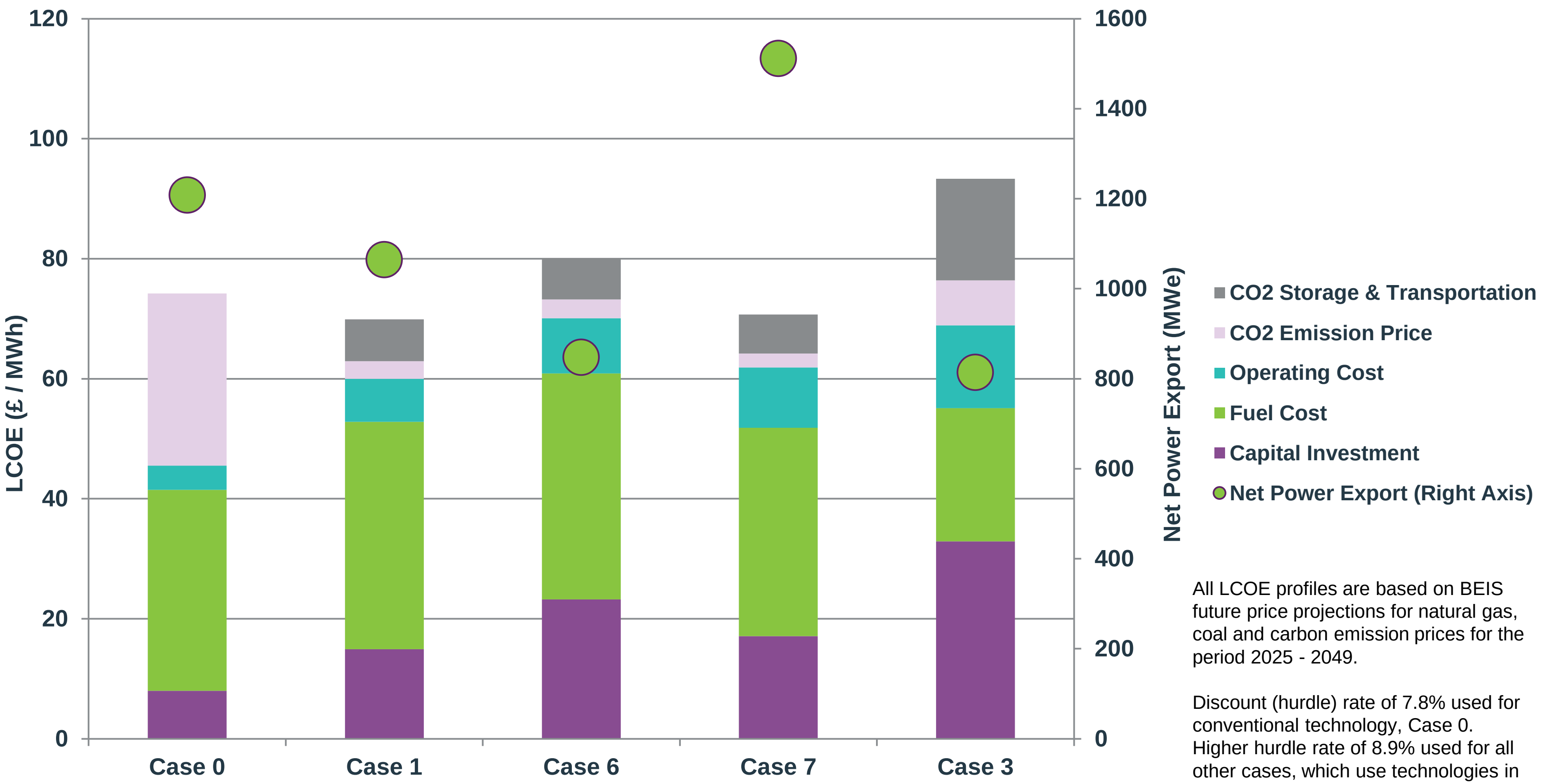
## Novel Technology Results – 2 Examples

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# Conclusions

# UK Costs for a Range of CCS Technologies

## Conclusions

- Lowest cost LCOE with carbon capture is still CCGT with proprietary solvent by a significant margin, results suggest this is due to;
  - high efficiency & low capital cost of base plant
  - clean fuel results in $CO_2$ capture conditions less challenging than some
  - less carbon to be captured and compressed per unit of electricity generated
- Post combustion routes appear most attractive (with oxy not far behind)
  - For baseload operation producing power, flexibility advantages of pre-combustion routes (e.g. hydrogen production) cannot be quantified.
- Two of the leading novel technologies appear well positioned to compete with proprietary solvents for base load power generation if they can reduce their capital costs or improve efficiencies further.
- **LCOE with carbon capture could be achieved at:**
  - **£69.9/MWh on gas at a carbon footprint of 34 kg $CO_2$/MWh**
  - **£93.3/MWh on coal at a carbon footprint of 95 kg $CO_2$/MWh**

# Thank you!

# Questions?

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