Carbon Capture and Storage Workshop
University of Sheffield
December 2019

CCS – same basic purpose but a lot of different technologies

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The UKCCSRC is supported by the Engineering and Physical Sciences Research Council as part of the Research Councils UK Energy Programme

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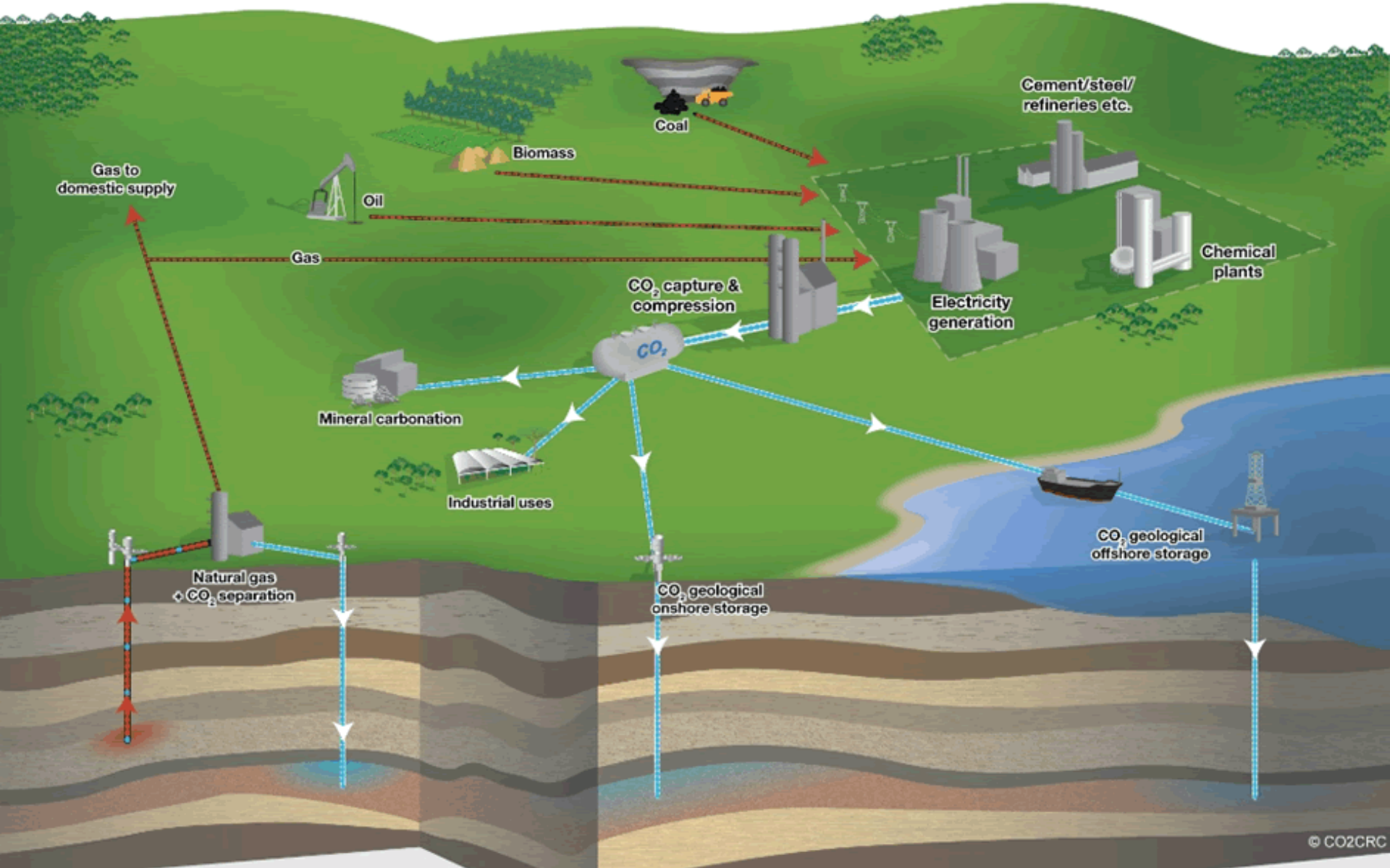
Pioneering research and skills

1. Overview of Carbon Capture and Storage (CCS) (from point sources)



In global modelling CCS is much more critical than solar and wind for delivering two degrees, but is less important in weaker scenarios

IPCC WGII AR5 Summary for Policymakers - *Climate Change 2014: Impacts, Adaptation, and Vulnerability.*

Mitigation cost increases in scenarios with limited availability of technologies

[% increase in total discounted mitigation costs (2015–2100) relative to default technology assumptions]

2100 concentrations (ppm CO_2-eq)	no CCS	nuclear phase out	limited solar/wind	limited bioenergy
450 (430 to 480)	138% (29 to 297%) 4	7% (4 to 18%) 8	6% (2 to 29%) 8	64% (44 to 78%) 8
550 (530 to 580)	39% (18 to 78%) 11	13% (2 to 23%) 10	8% (5 to 15%) 10	18% (4 to 66%) 12

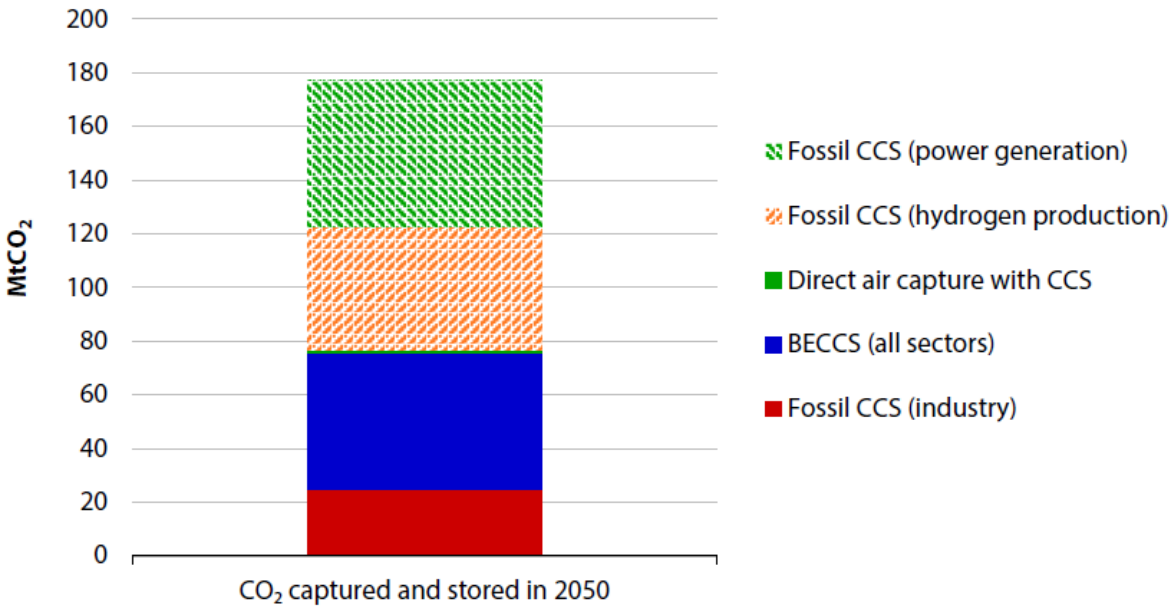
Symbol legend—fraction of models successful in producing scenarios (numbers indicate the number of successful models)

- : all models successful
- : between 80 and 100% of models successful
- : between 50 and 80% of models successful
- : less than 50% of models successful

Committee on Climate Change Net Zero report, May 2019

https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

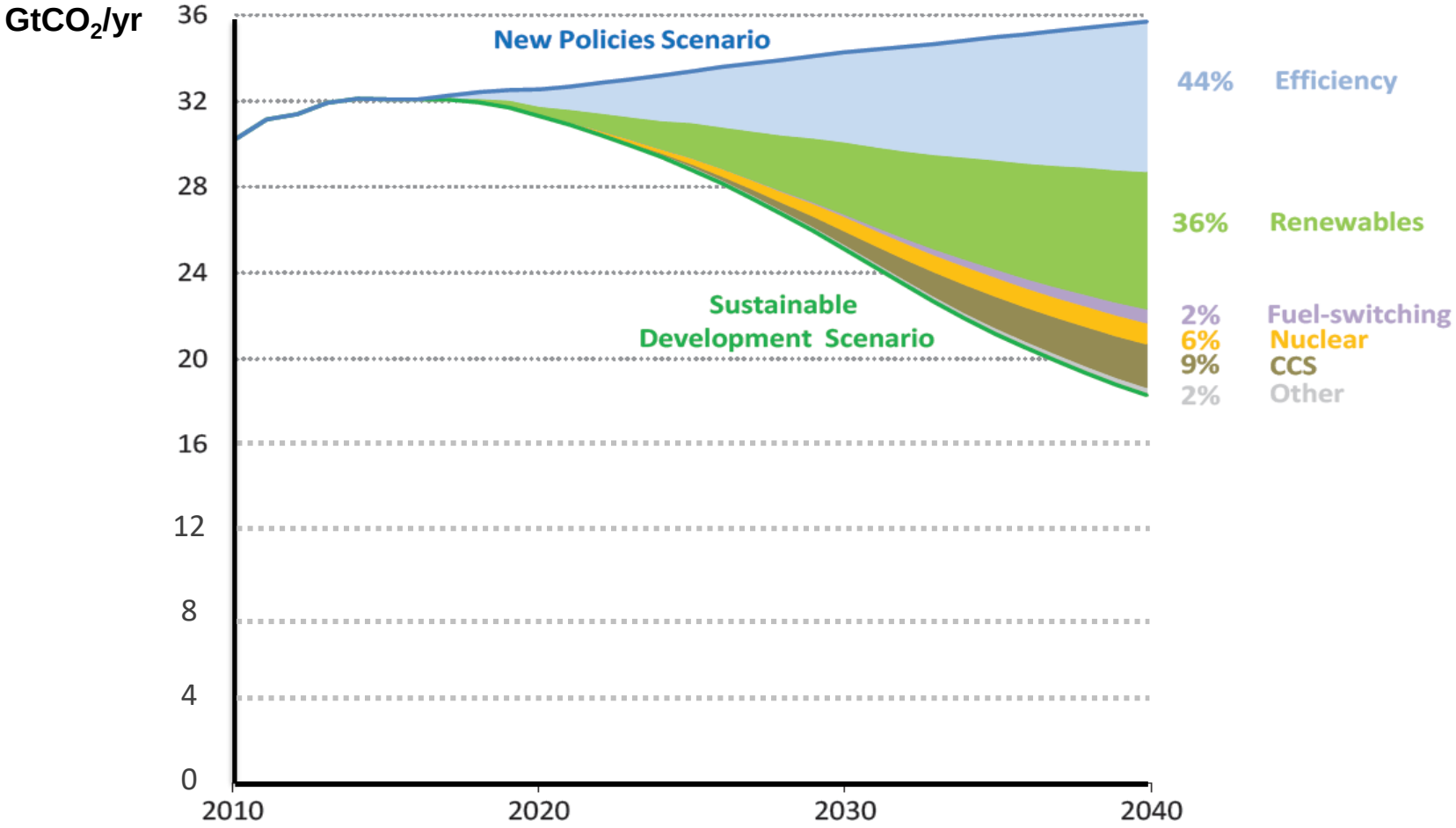
Carbon capture and storage (CCS) in industry, with bioenergy (for GHG removal from the atmosphere), and very likely for hydrogen and electricity production. **CCS is a necessity not an option.** The scenarios involve aggregate annual capture and storage of 75-175 $MtCO_2$ in 2050, which would require a major CO_2 transport and storage infrastructure servicing at least five clusters and with some CO_2 transported by ships or heavy goods vehicles.



CCS has a much smaller role than renewables to 2040, but this is still a very significant increase from essentially zero CCS now, to CCS on 10% of total fossil fuel use in 20 years

http://www.iea.org/weo2017/

- 2040 storage of ~ 1.6 $GtCO_2$/yr is 40 times current amount* - this would need perhaps 100 large sources or clusters each taking 5-10 years to develop, even in China
- Larger amounts of CCS by 2040 have also been considered in previous IEA studies+



* http://www.globalccsinstitute.com/news/institute-updates/paris-climate-change-targets-cannot-be-met-without-ccs-cop23

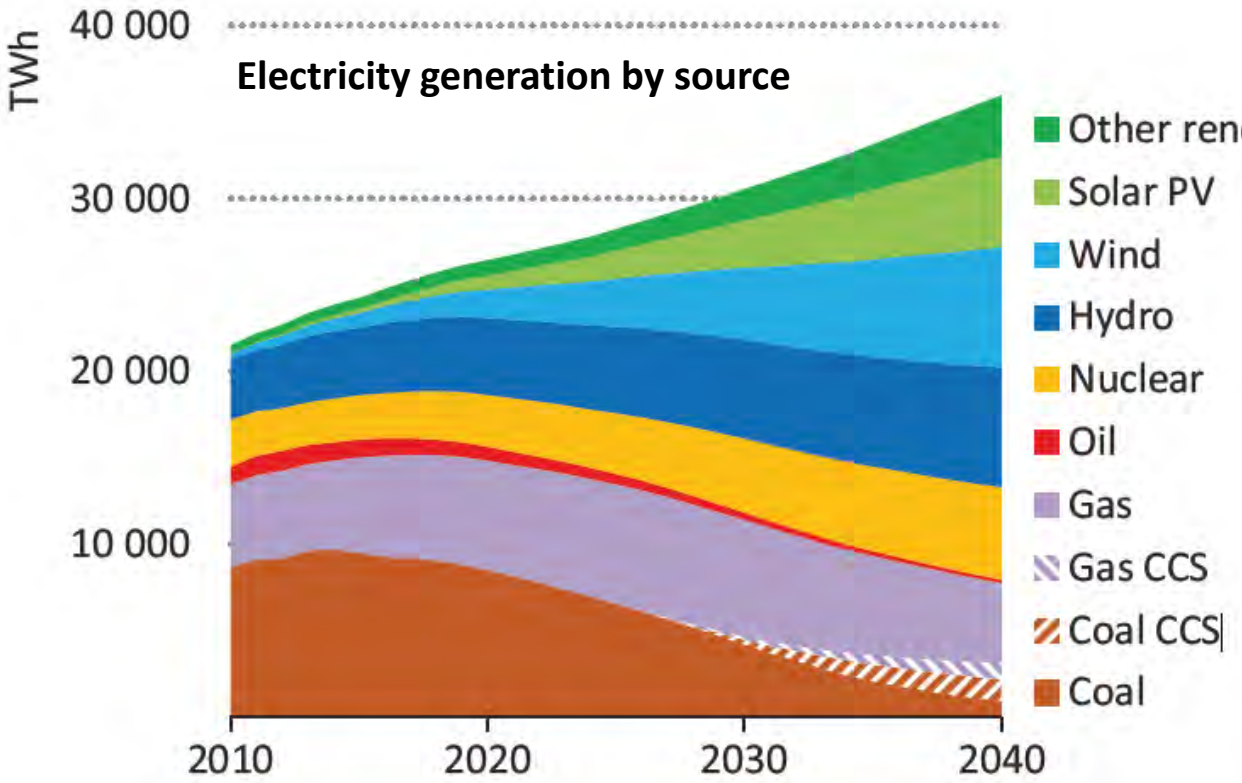
+ https://www.iea.org/publications/freepublications/publication/20-years-of-carbon-capture-and-storage.html

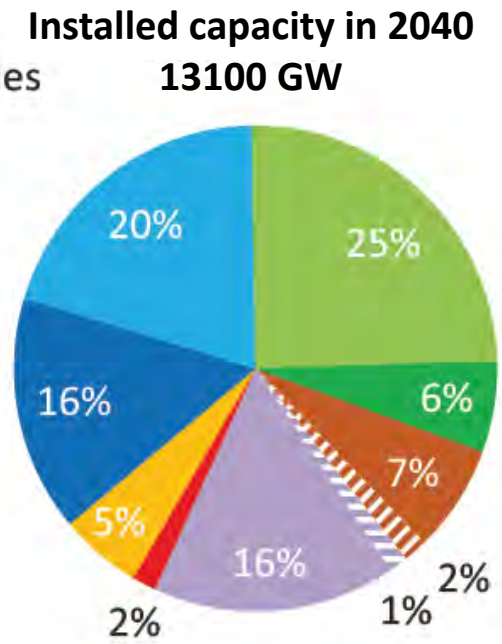
By 2040 in the Sustainable Development Scenario CCS is 6% of electricity generation vs. renewables over 60% and nuclear power 15%

http://www.iea.org/weo2017/

2040 power CCS capacity is 375GW vs 360MW now* (plus capture from industry)

- 210 GW of coal power capacity with CCS
- 150 GW of this is in China (~15% of current Chinese power plant capacity)+
- 165 GW of gas power capacity with CCS worldwide





* Boundary Dam 3 120MW, Petra Nova 240MW

+ https://www.iea.org/publications/insights/insightpublications/ThePotentialforEquippingChinasExistingCoalFleetwithCarbonCaptureandStorage.pdf

2. CCS at the UoS - the UK CCS Research Centre

The Centre brings together over 280 of the UK's world-class CCS academics from more than 40 UK universities and research institutes and provides a national focal point for CCS research and development at its regular six monthly meetings (see below).

Over 250 Early Career Researchers in an active capacity development ECR programme.

Now in its second phase, hosted by the University of Sheffield, UKCCSRC is funded by £6M from the Engineering & Physical Sciences Research Council (EPSRC) and £1.2M from partners.

The UKCCSRC links to all CCS stakeholders through its CCS Community Network.
https://ukccsrc.ac.uk/membership/ccs-community-network

CCS at the UoS -PACT: Pilot-Scale Advanced Capture Technology

https://pact.group.shef.ac.uk/

PACT is coordinating the ITCN for 2 years

https://itcn-global.org/

PACT

The University Of Sheffield.

ITCN INTERNATIONAL TEST CENTER NETWORK

Home About ITCN

ITCN partners

VIEW on MAP VIEW by COUNTRY

SaskPower Powering the future

EERC

U.S. DEPARTMENT OF ENERGY

NATIONAL CARBON

TECHNOLOGY CENTRE MONGSTAD

SINTEF

PACT

e·on

中国华能 CHINA HUANENG

RITE Research Institute of Innovative Technology for the Earth

KIER

International post-combustion capture retrofit workshop held in Sheffield, 9-12 April 2019

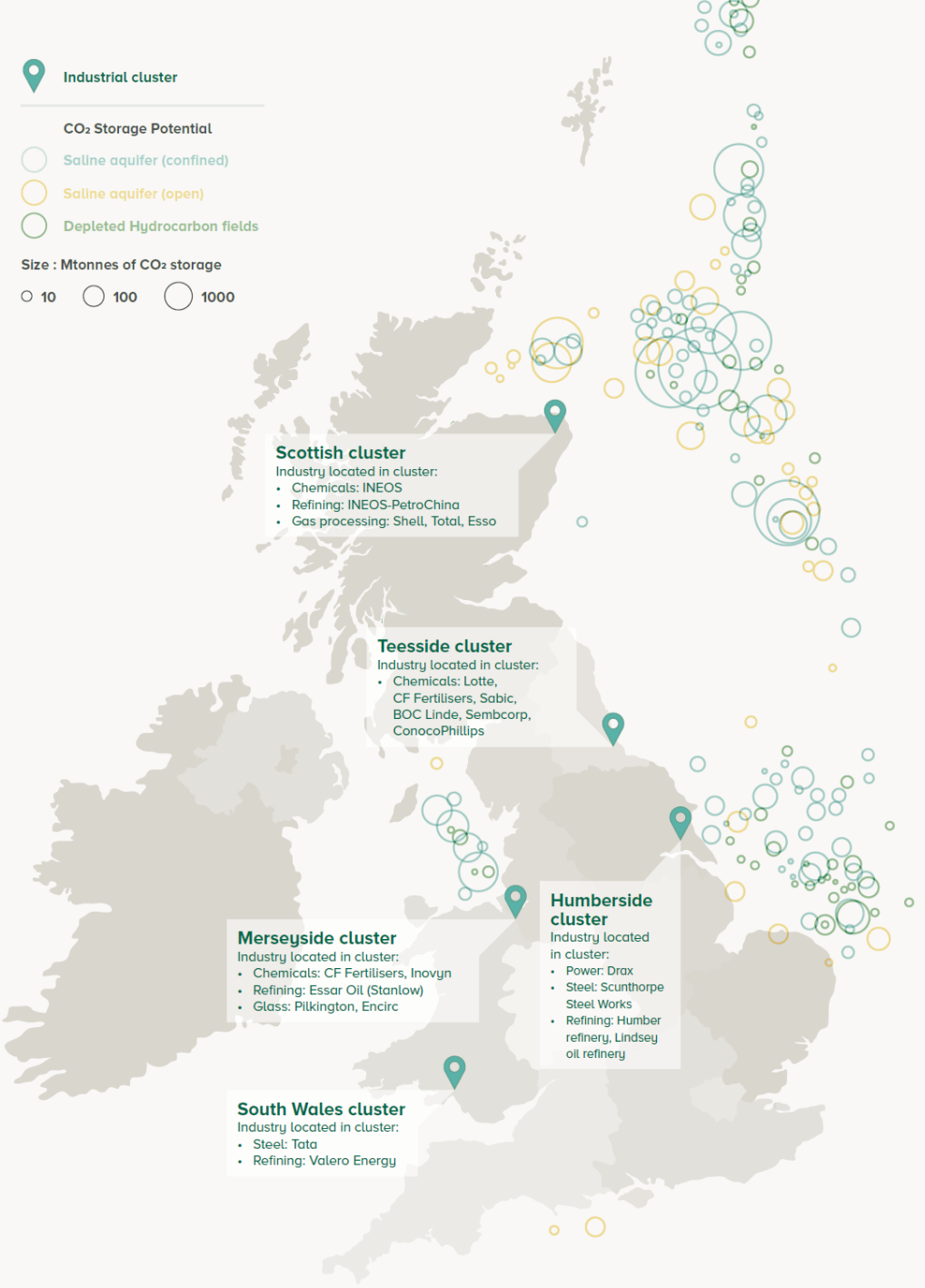
CCUS specialists from the UK CCS Research Centre and the University of Sheffield's PACT facilities together with Bechtel (US), TNO (NL), Test Centre Mongstad (Norway) and the Universities of Edinburgh and Leeds held an international workshop on post-combustion capture (PCC) retrofit. Together with application experts from China, Ireland, South Africa and Thailand, the workshop examined past open-access PCC studies and potential future practical applications from across the world.

https://ukccsrc.ac.uk/news-events/news/international-post-combustion-capture-retrofit-workshop

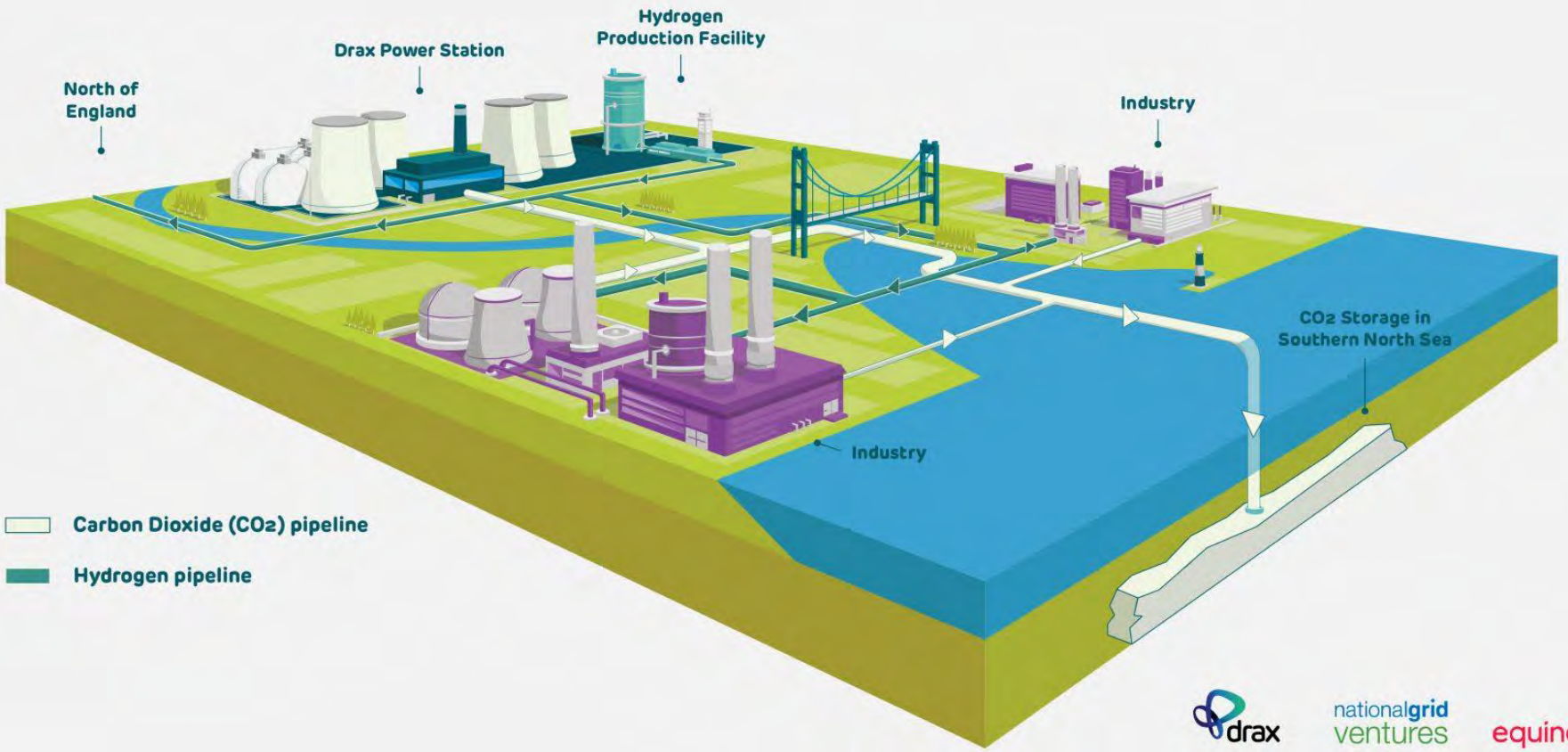
https://www.gov.uk/government/publications/delivering-clean-growth-ccus-cost-challenge-taskforce-report

3. UK's potential CCUS clusters: CO_2 sources share transport and storage infrastructure

- Industries
- Power – from gas and biomass
- Greenhouse Gas Removal Technologies – biomass and direct air capture
- Hydrogen



WHAT A ZERO CARBON CLUSTER COULD LOOK LIKE IN THE HUMBER REGION



https://www.drax.com/press_release/energy-companies-announce-new-zero-carbon-uk-partnership-ccus-hydrogen-beccs-humber-equinor-national-grid/

HyNet North West

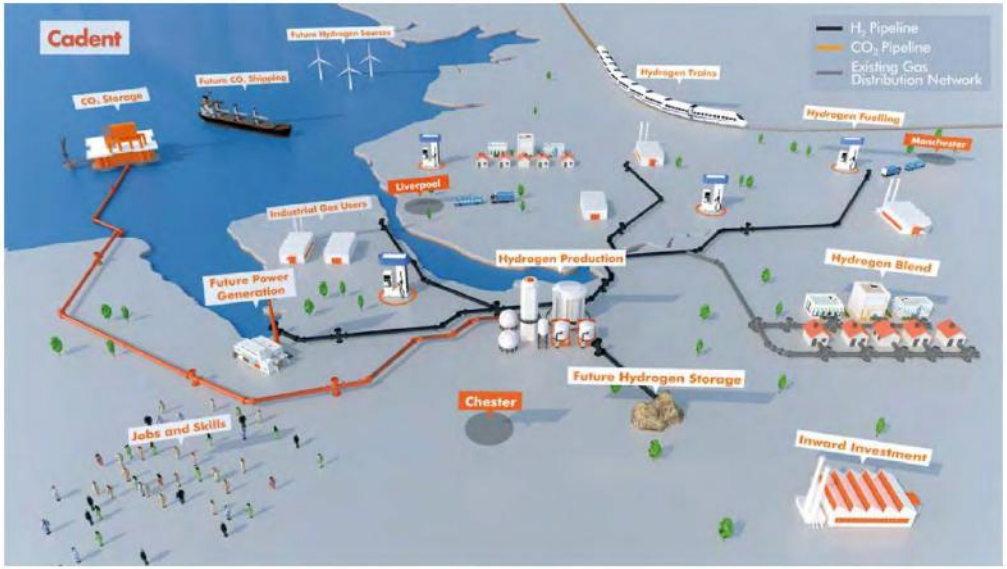
https://hynet.co.uk/

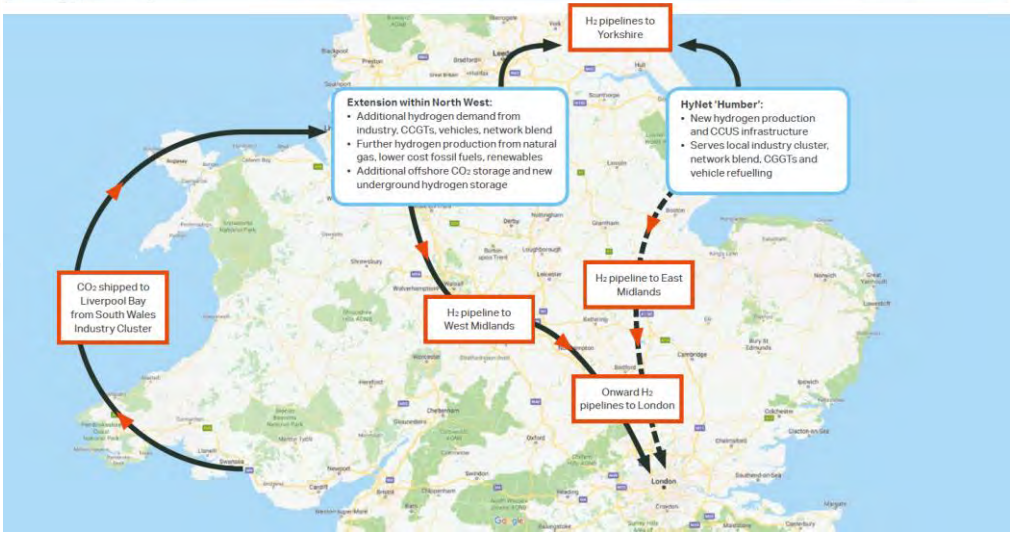
Table 2.2: HyNet Capex Data

Project Element[1]	Related Information	Average Unit Cost (£M)	Total Cost (£M)
Hydrogen Production and CO_2 Capture	HPCC plant comprises two ATRs, producing around 890 MW of hydrogen at pressure[2]	£256/unit	£513
Hydrogen Transport	Transport of 890 MW of hydrogen in new 109km onshore hydrogen pipeline from HPCC plant to industrial cluster and blend injection points	£1.65/km	£178
Hydrogen Compression and Injection to LTS	No compression required at HPCC plant, but additional equipment needed to inject hydrogen into the four LTS injection sites	£5/site	£20
Conversion of Industry to Hydrogen	Modifications to boilers, kilns and furnaces at 10 large industrial sites	£7.8/site	£78
CO_2 Transport	New 31km onshore pipeline from ATR plant to existing pipeline at Connah's Quay[3]	£2.03/km	£63
CO_2 Facilities	Modifications to existing Hamilton platform	n/a	£27
CO_2 Storage	Includes design, procurement, construction and commissioning of wells, licensing and permitting	n/a	£31
		TOTAL	£920

Notes:

1. The battery limit for CCUS costs is from the inlet to the CO_2 compressor at the HPCC plant
2. Includes costs of CO_2 compression
3. Also includes costs for modifications to existing gas pipelines which are repurposed for CO_2





‘South Wales’ + ‘HyNet’ form ‘West Coast cluster’

15Mt CO_2/yr injection capacity

1.5bt CO_2 storage - sufficient for 100 years

5Mt CO_2/yr from South Wales

Developing a South Wales Cluster

nationalgrid

Progressive energy

RICE

Reducing Industrial Carbon Emissions
Lleihau Allyriadau Carbon Diwydiannol

FLEXIS

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
ABERYSTWYTH
BANGOR
University of South Wales
Swansea University
Prifysgol Abertawe

WALES&WEST UTILITIES

WESTERN POWER DISTRIBUTION

Dŵr Cymru Welsh Water

Cadent

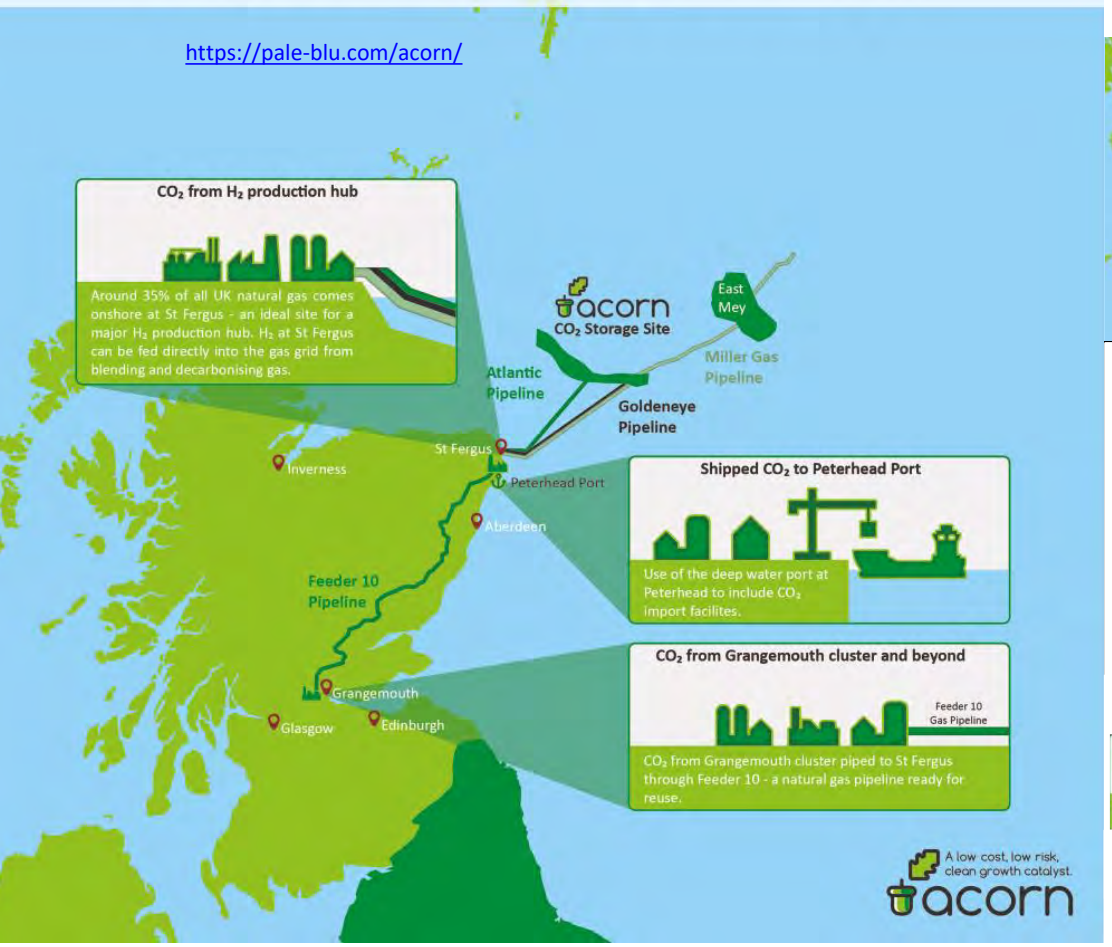
UKCCS RESEARCH CENTRE

CO2 Chem

Thanks to Google Maps

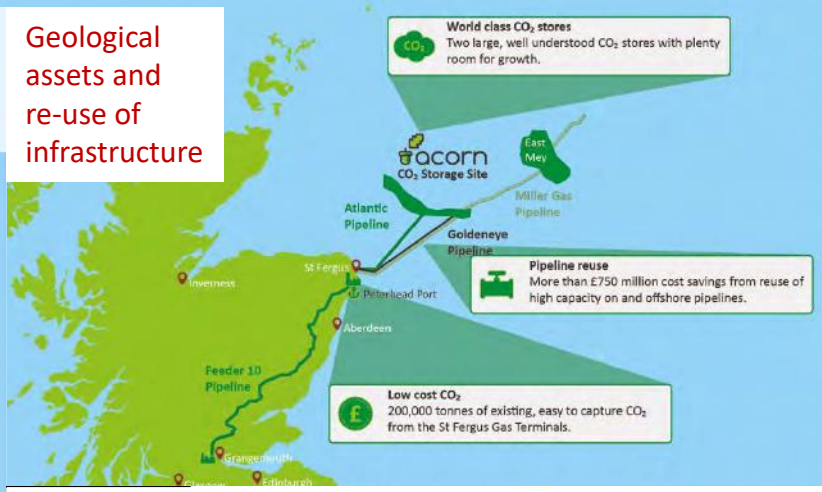
acorn: a major clean growth catalyst

https://pale-blu.com/acorn/

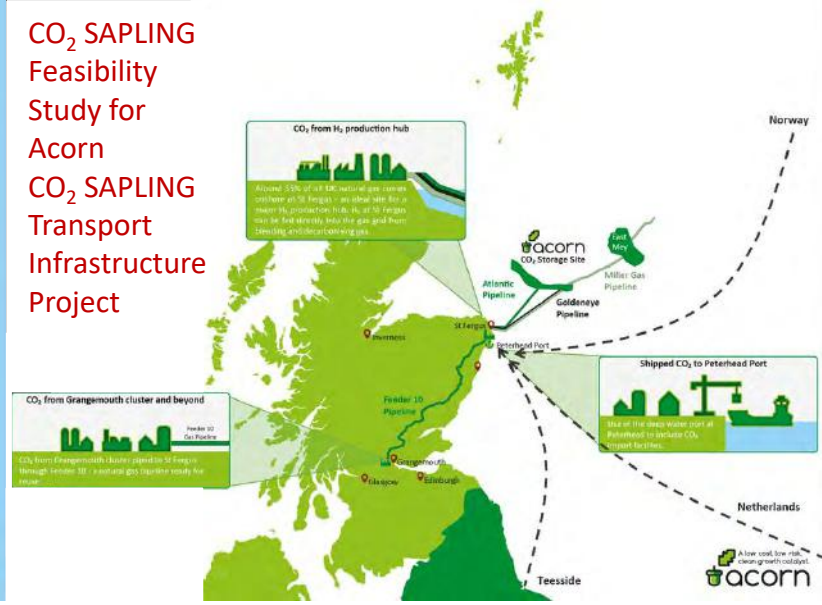


acorn: making best use of the UK's built and natural assets

Geological assets and re-use of infrastructure



CO_2 SAPLING Feasibility Study for Acorn CO_2 SAPLING Transport Infrastructure Project



Net Zero Teesside Project

https://oilandgasclimateinitiative.com/climate-investments-announces-progression-of-the-uks-first-commercial-full-chain-carbon-capture-utilization-and-storage-project/

November 28, 2018, London, UK:
OGCI Climate Investments announced that it is entering into a strategic partnership with BP, ENI, Equinor, Occidental Petroleum, Shell and Total to progress the Clean Gas Project, the UK's first commercial full-chain Carbon Capture Utilization and Storage (CCUS) project in Teesside. The Clean Gas Project could form the heart of the Tees Valley CCUS Cluster that will deploy commercially viable, safe, environmentally responsible CCUS at scale. It will combine CO_2 capture from new efficient low-carbon power generation and local industrial emitters in Teesside.

ETI gas power with CCS project

https://www.eti.co.uk/programmes/carbon-capture-storage/thermal-power-with-ccs

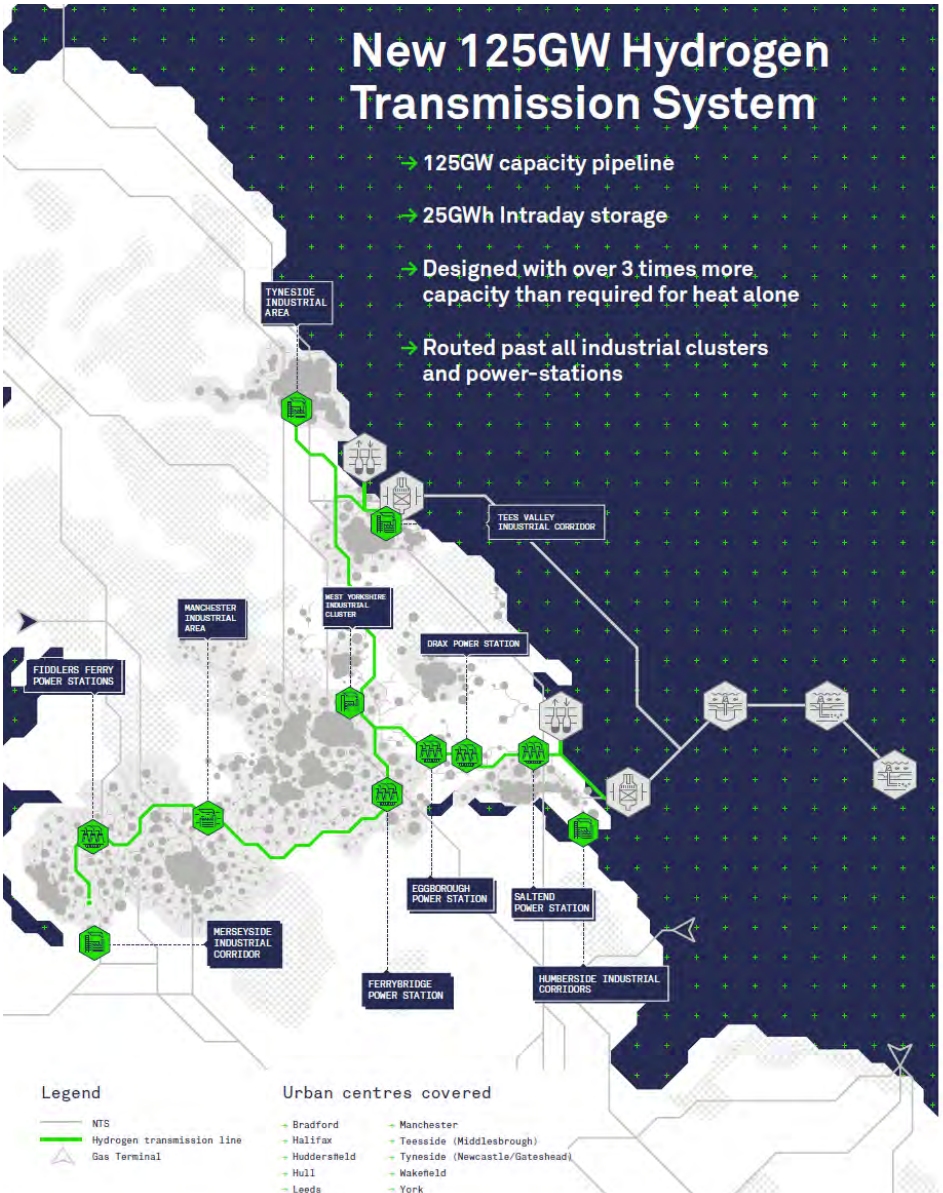
energy technologies institute

The University Of Sheffield.

AECOM

SNC·LAVALIN

Conversion of the North of England

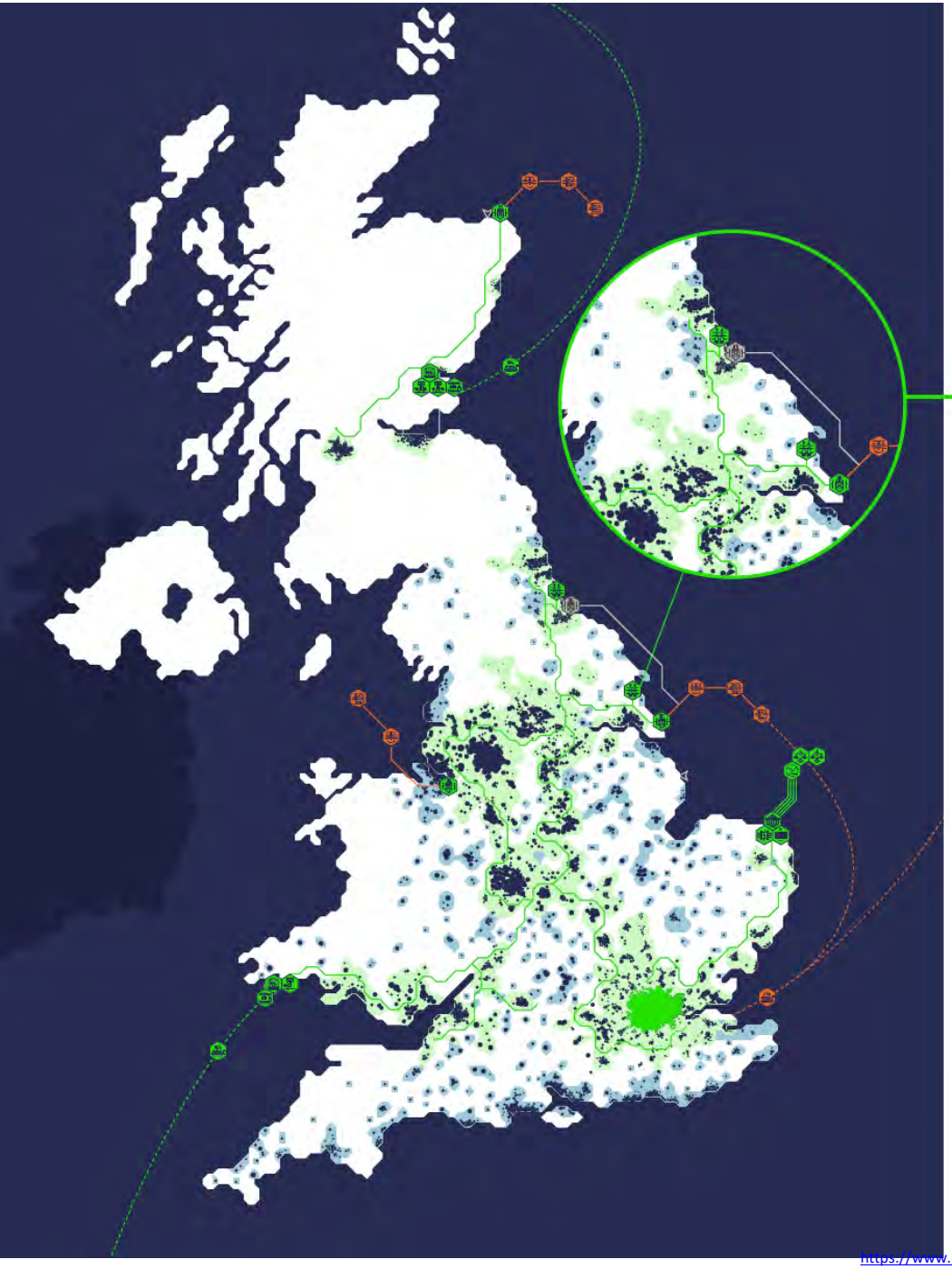


Capital costs (£bn)	
H_2 production	8.52
H_2 storage	1.99
CO_2 T&S	1.34
H_2 transport	3.43
Conversion	7.50
Total	22.78

→ Conversion 2028 – 2034
→ Max time off gas 1-5 days
→ Vulnerable customers less than 1 day off gas
→ Supply and demand managed through engineering design.

↑ Conversion areas, 2028 year one position

https://www.northerngasnetworks.co.uk/wp-content/uploads/2018/11/H21-Meeting-UK-Climate-Change-Obligations.pdf



UK Hydrogen Conversion Position in 2050

Phase 1
H21 NoE
Conversion 2028 - 2034
14% UK heat
30% Power (H21 XL) for North of England

Phase 2
H21 South Yorkshire & East/ West Midlands
2033-2038

Phase 3
H21 Scotland
2030-2032

Phase 4
H21 South Wales & South West
2036-2037

Phase 5
H21 East Anglia & Home Counties
2040-2045

Phase 6
H21 London
2045-2050

https://www.northerngasnetworks.co.uk/wp-content/uploads/2018/11/H21-Meeting-UK-Climate-Change-Obligations.pdf

4. CO_2 storage example: Sleipner, 1Mt/yr CO_2 separated from natural gas, now been operating for 20 years

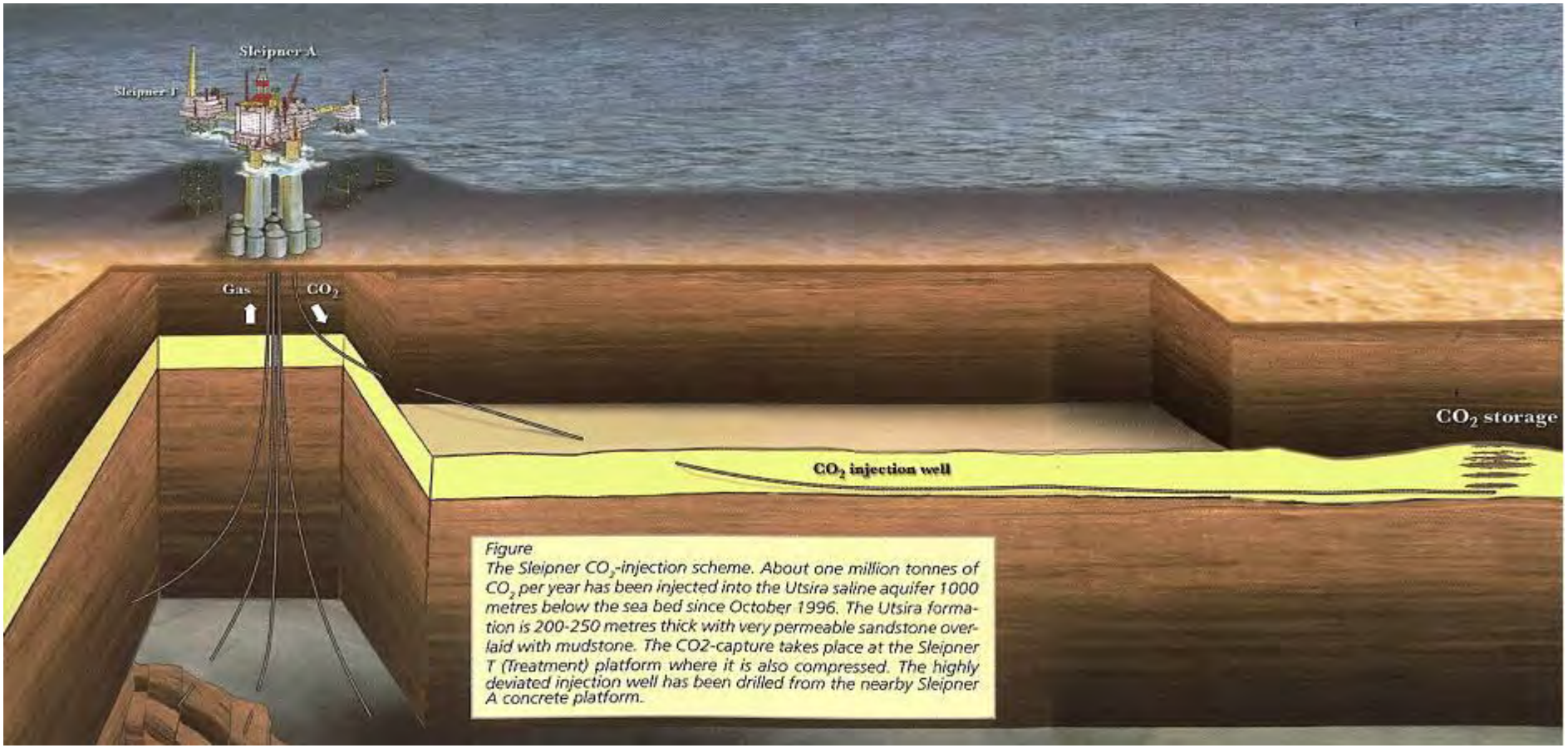
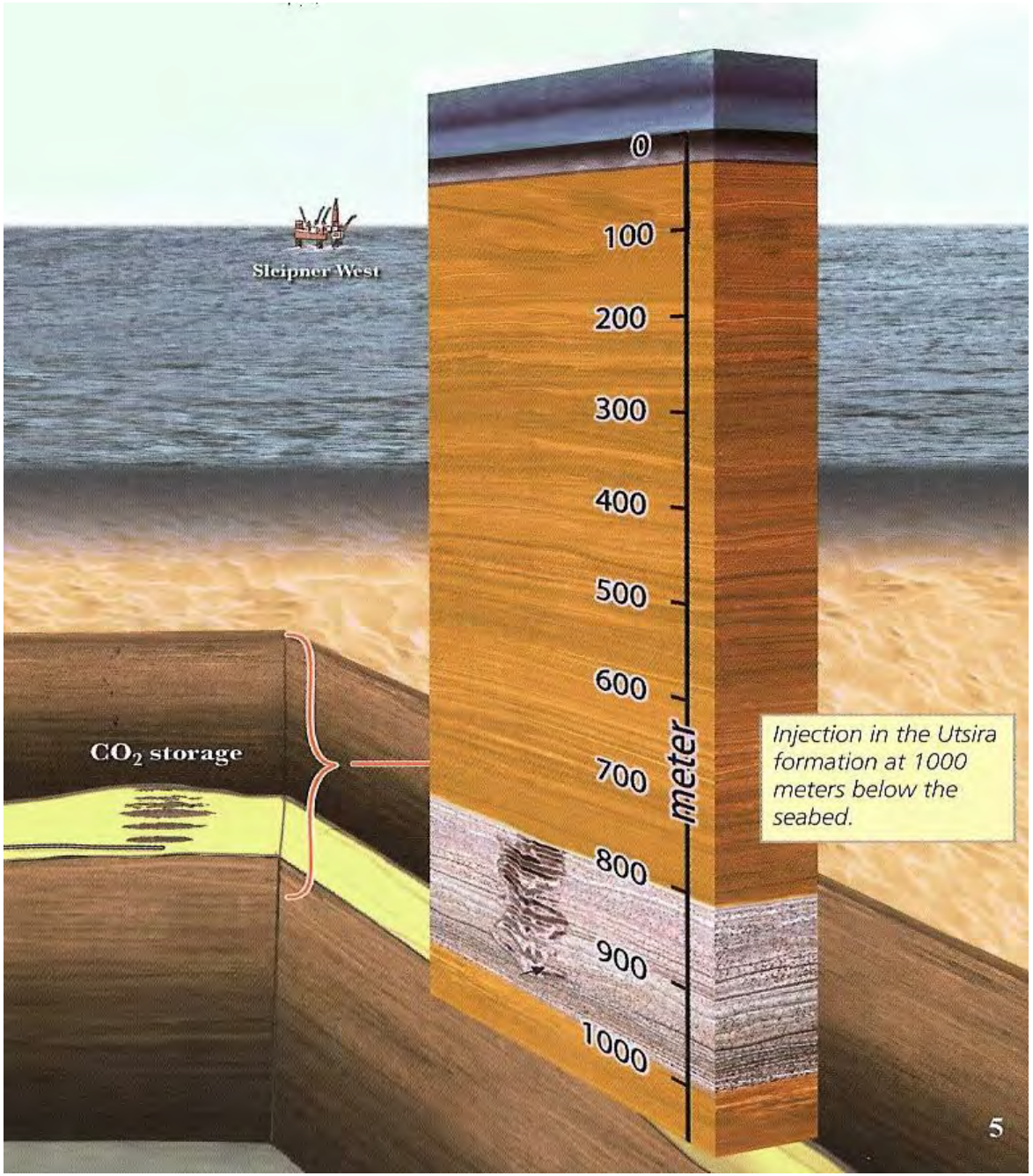


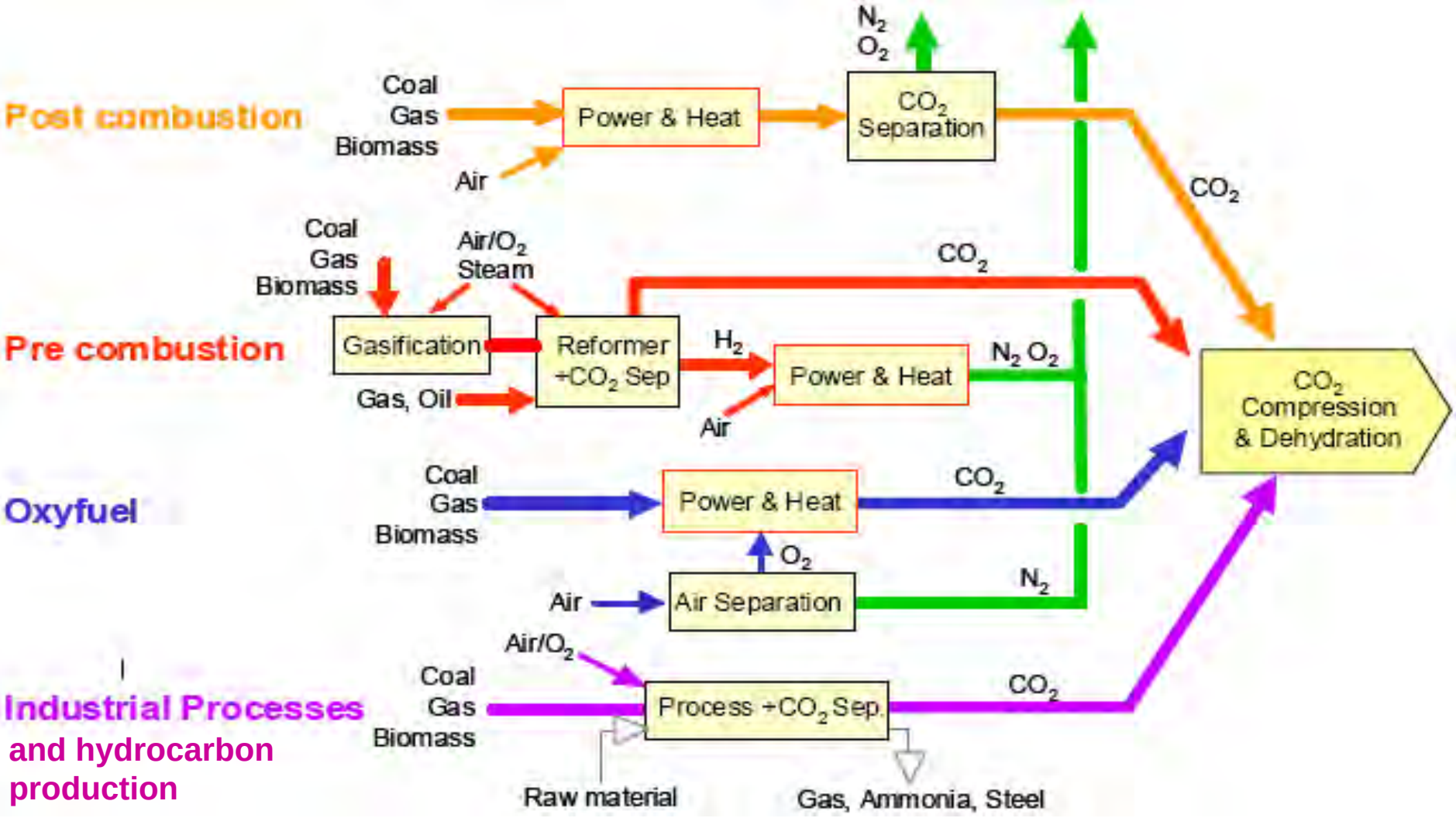
Figure
The Sleipner CO_2-injection scheme. About one million tonnes of CO_2 per year has been injected into the Utsira saline aquifer 1000 metres below the sea bed since October 1996. The Utsira formation is 200-250 metres thick with very permeable sandstone overlaid with mudstone. The CO2-capture takes place at the Sleipner T (Treatment) platform where it is also compressed. The highly deviated injection well has been drilled from the nearby Sleipner A concrete platform.

www.statoil.com, 2002



www.statoil.com, 2002

4. Types of Carbon Capture Technology

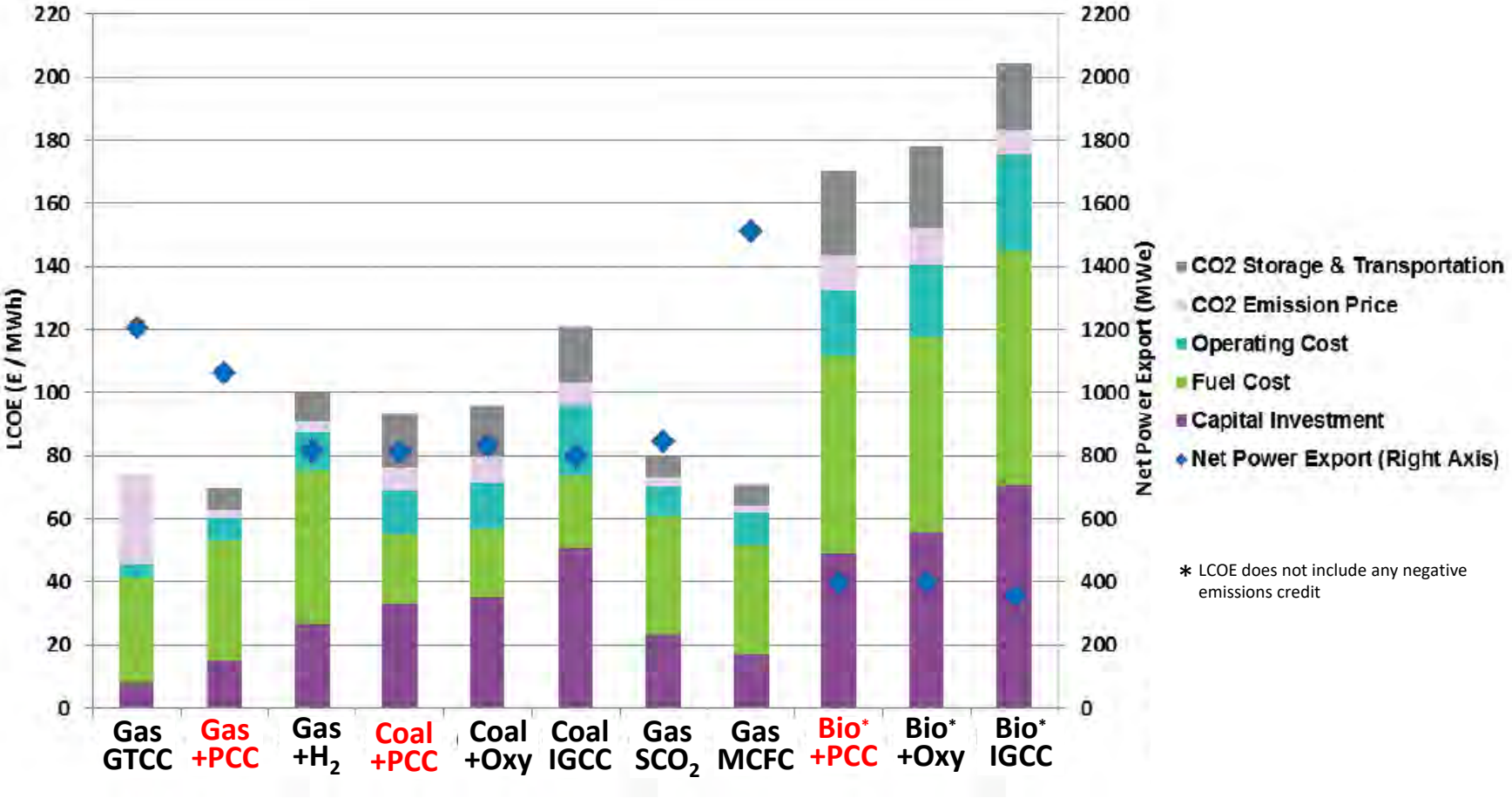


IPCC Special Report on CCS

UK cost estimates for a range of fuels and technologies

Study for BEIS by Wood, formerly Amec-FW https://www.gov.uk/guidance/funding-for-low-carbon-industry

- Post-combustion capture appears competitive – also allows retrofit
- Supercritical CO_2 cycles also being developed
- Urgent to accelerate learning by doing for all technologies to reduce costs



* LCOE does not include any negative emissions credit

SaskPower Boundary Dam Unit 3 CO_2 capture project

- Final approval in April 2011
- First CCS power project in the world
- $1.4-billion project
- Refurbish sub-critical unit
- Capturing ~ 1Mt CO_2 /yr

- EOR opportunities in Saskatchewan
- Officially opened October 2014
- Cansolv (Shell subsidiary) post-combustion capture
- Hitachi Canada boiler, modified steam turbine , air quality control system

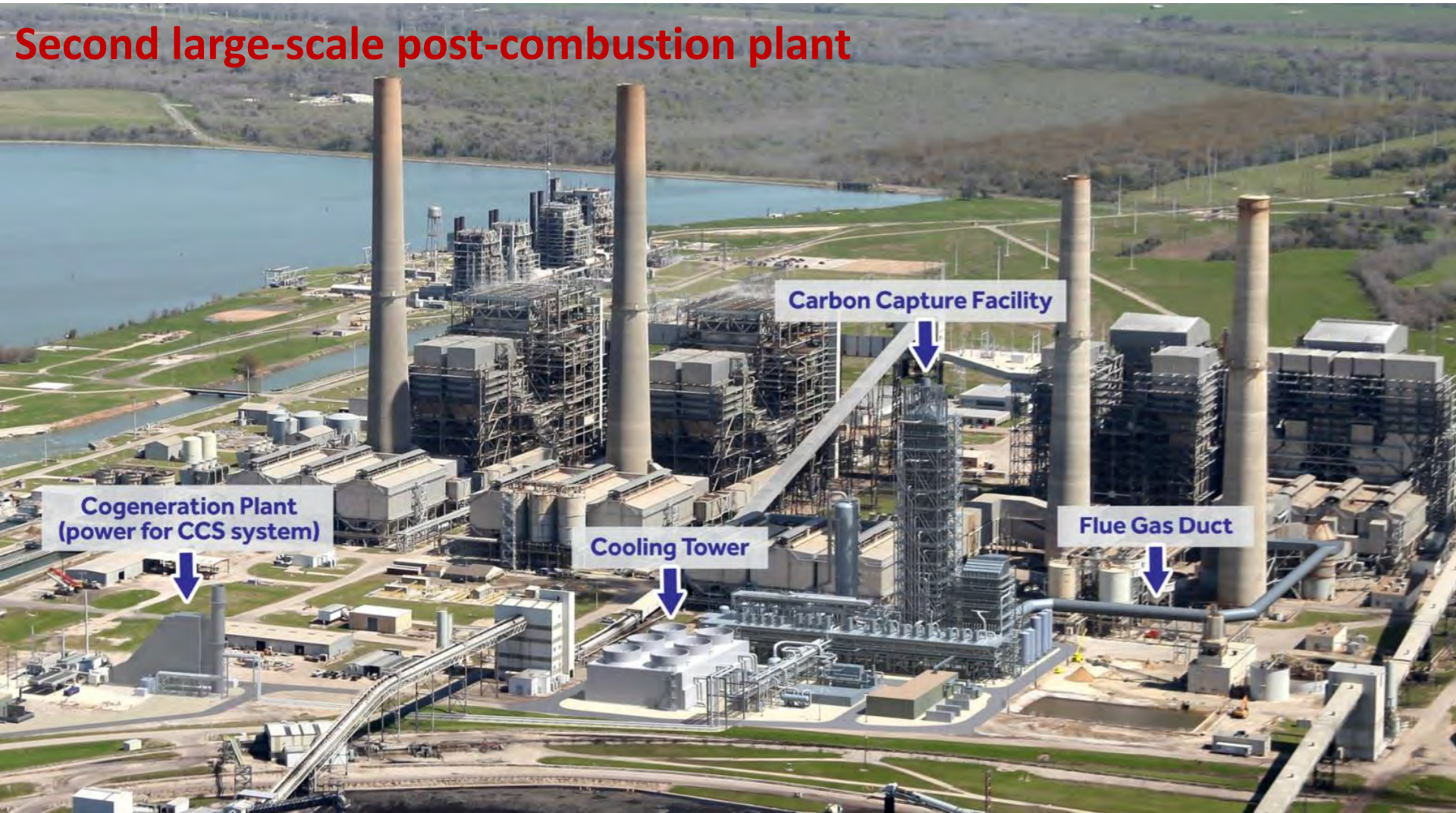
http://ieaghg.org/publications/technical-reports/2015-technical-reports/603-2015-06

Petra Nova is a joint venture between NRG Energy and JX Nippon Oil & Gas Exploration that became operational in early January 2017

http://www.ourworldofenergy.com/vignettes.php?type=coal-power&id=11

The largest post-combustion CCS project installed on an existing coal-fired power plant in the world. The project is designed to capture approximately 90 percent, or 1.6 million tons annually, of the CO_2 from NRG Energy's W.A. Parish 240 MW generating station southwest of Houston, Texas.

Second large-scale post-combustion plant



Carbon Capture System Site Layout

https://2w4set5pkcc374jjw3jbdf15-wpengine.netdna-ssl.com/wp-content/uploads/2017/10/5-Armpriester-Petra-Nova.pdf

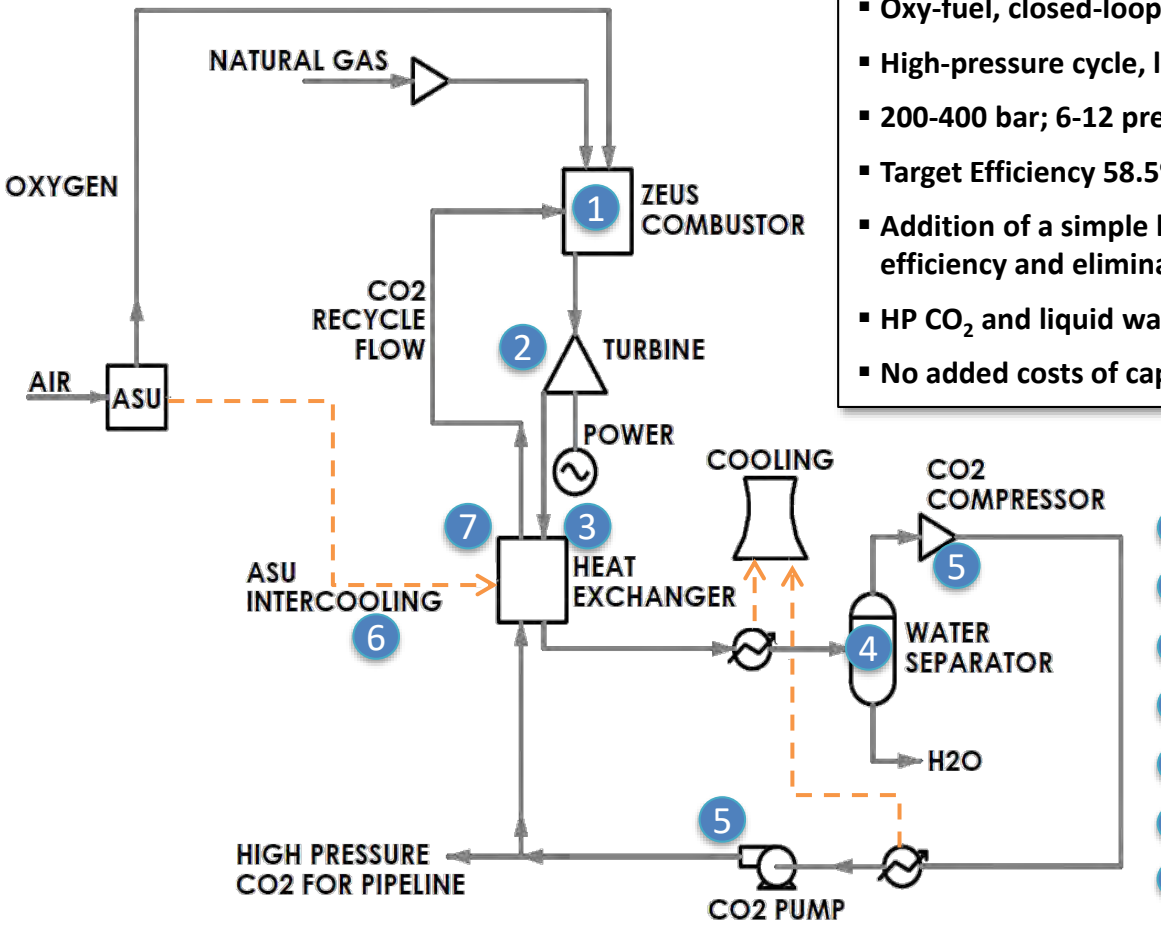
Petra Nova Carbon Capture Site

nrg | JX
PETRA NOVA Carbon Capture

Wet flue gas cooling rather than dry cooling as at BD3, also has a conventional wet FGD upstream that will not be affected by fly ash

6. The Allam Cycle

The NET Power natural gas system



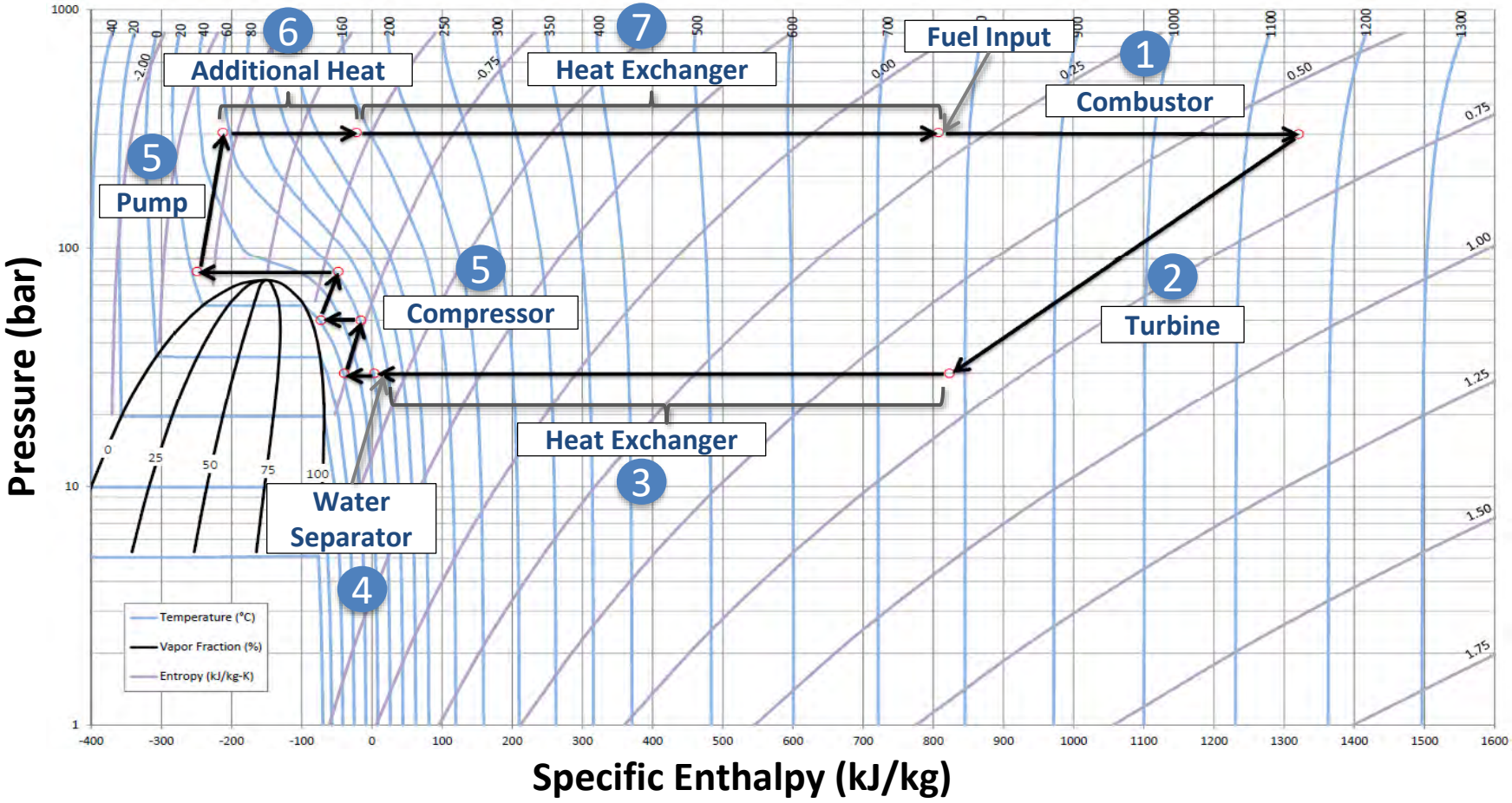
- Oxy-fuel, closed-loop, CO_2 working fluid
- High-pressure cycle, low pressure ratio turbine
- 200-400 bar; 6-12 pressure ratio
- Target Efficiency 58.5% (LHV with 100% CC at 300 bar)
- Addition of a simple hot compression cycle maintains efficiency and eliminates the need for ASU side heat
- HP CO_2 and liquid water are the only byproducts
- No added costs of capture, separation or compression of CO_2

1. Fuel Combustion
2. CO_2 Turbine
3. Heat Rejection
4. Water Separation
5. Compression and Pumping
6. Additional Heat Input
7. Heat Recuperation

Hideo Nomoto, Toshiba Corporation, Rodney Allam, NET Power, Presentation to 7th Trondheim Carbon Capture and Sequestration Conference, June 5, 2013

NET Power natural gas cycle

- Internal combustion – fuel burnt in the working fluid – like a gas turbine
- But compression using a pump as well as a compressor, so much higher peak pressures possible than with a gas turbine
- Uses a large heat exchanger to recycle heat from turbine exhaust to turbine inlet



Hideo Nomoto, Toshiba Corporation, Rodney Allam, NET Power, Presentation to 7th Trondheim Carbon Capture and Sequestration Conference, June 5, 2013

Contains the intellectual property of 8 Rivers Capital, NET Power and Toshiba.

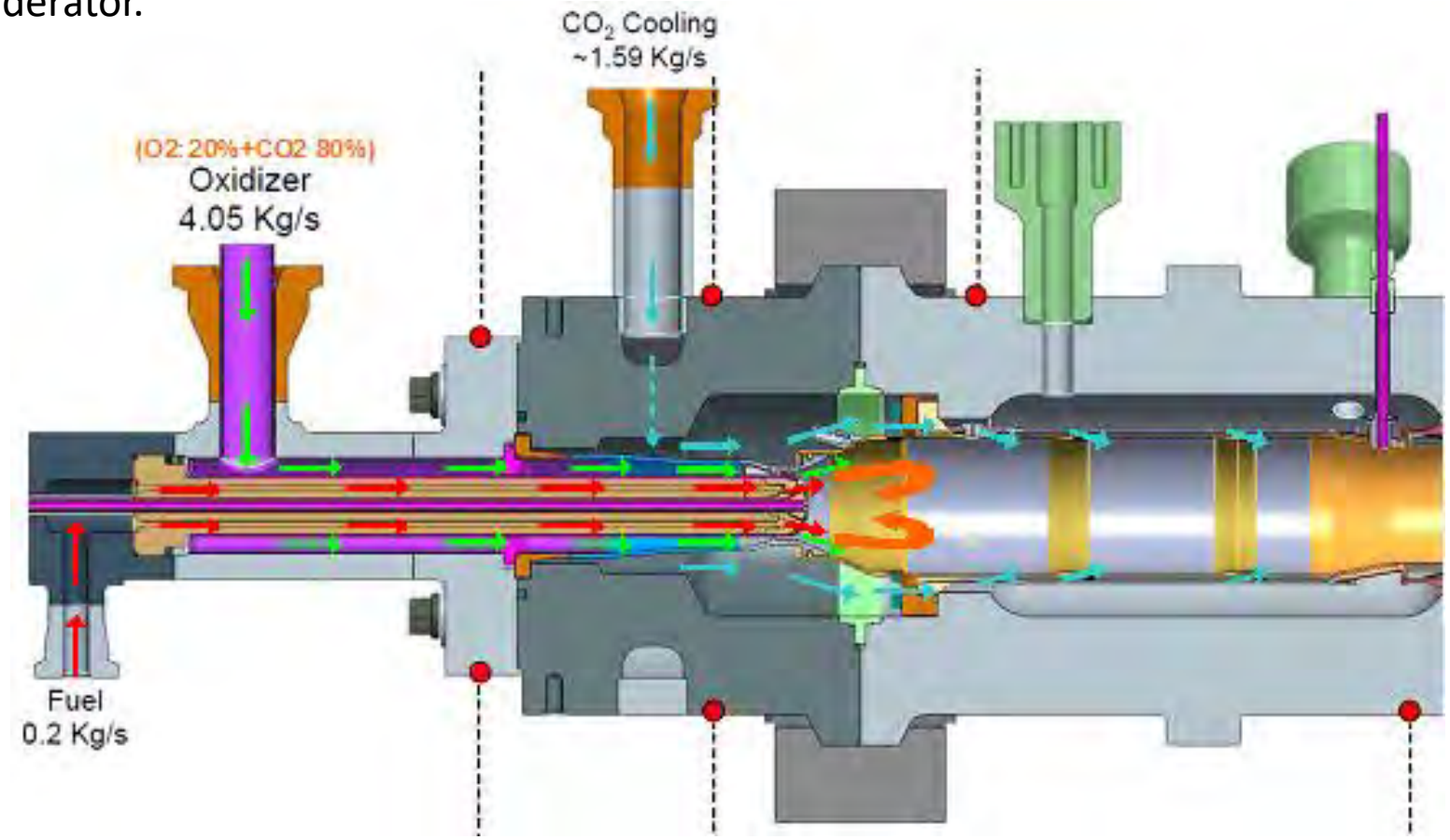
Natural gas cycle target efficiencies

Natural Gas Platform Target Efficiencies (100% CO_2 Capture at 300 bar)		
Energy Components	**HHV**	**LHV**
Gross Turbine Output	75%	83%
CO_2 Compressor Power	-11%	-12%
Plant Parasitic Power (primarily ASU)	-11%	-12%
Net Efficiency	**53%**	**59%**

Hideo Nomoto, Toshiba Corporation, Rodney Allam, NET Power, Presentation to 7th Trondheim Carbon Capture and Sequestration Conference, June 5, 2013

Pressurized Oxy-Combustion for High Pressure Cycles

Pressurized oxy-combustors use purified oxygen combined with a temperature moderator to burn fuels at high pressure. In place of the nitrogen found in air, CO_2 and/or steam are used as the temperature moderator and also subsequently as a working fluid that is expanded through a turbine to generate power. The combustor pictured here is a high-pressure (300 bar) oxy-combustor for use with gaseous fuels using CO_2 as the temperature moderator.



7. Two ‘engineering’ technologies for greenhouse gas removal (GGR) from the air: BECCS and DACCS

Direct Air Capture (DACS/DACCS) and Bioenergy with CCS (BECCS) can capture CO_2 for storage to offset fossil fuel emissions or for synthesis of hydrocarbon fuels using non-fossil energy sources

- BECCS is 'conventional' CCS using biomass as the fuel, but there is concern about biomass availability at the scales required

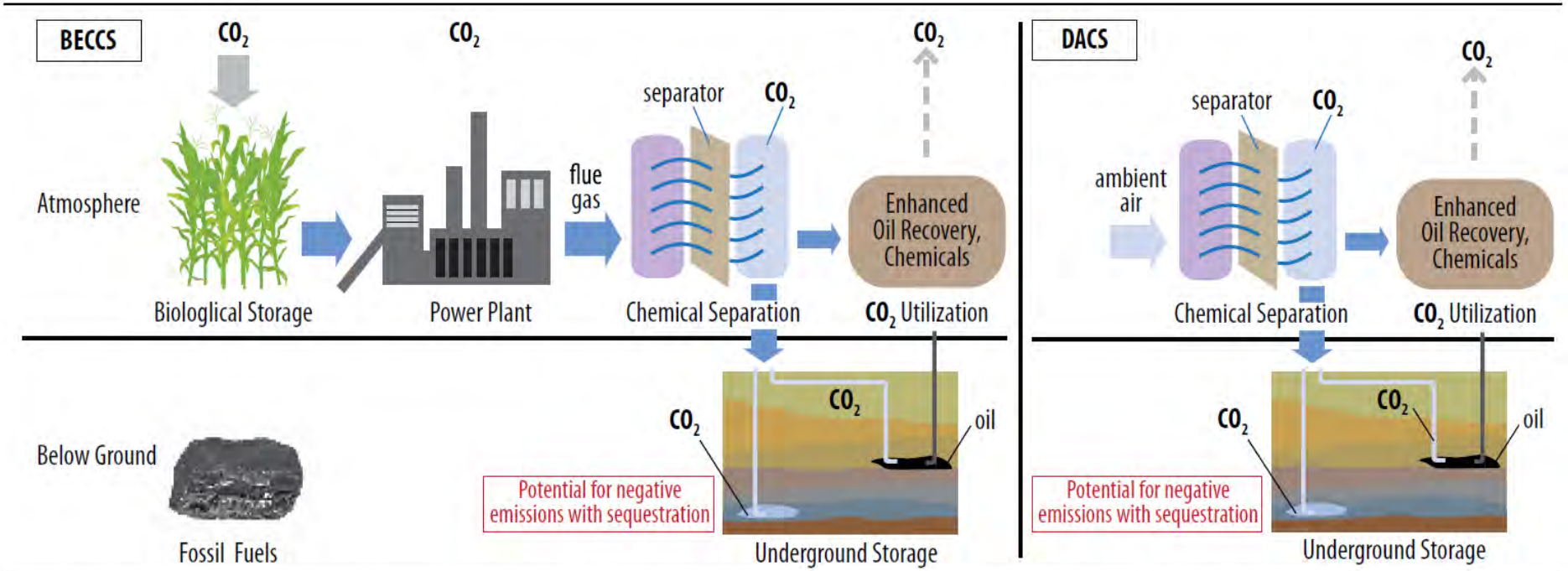
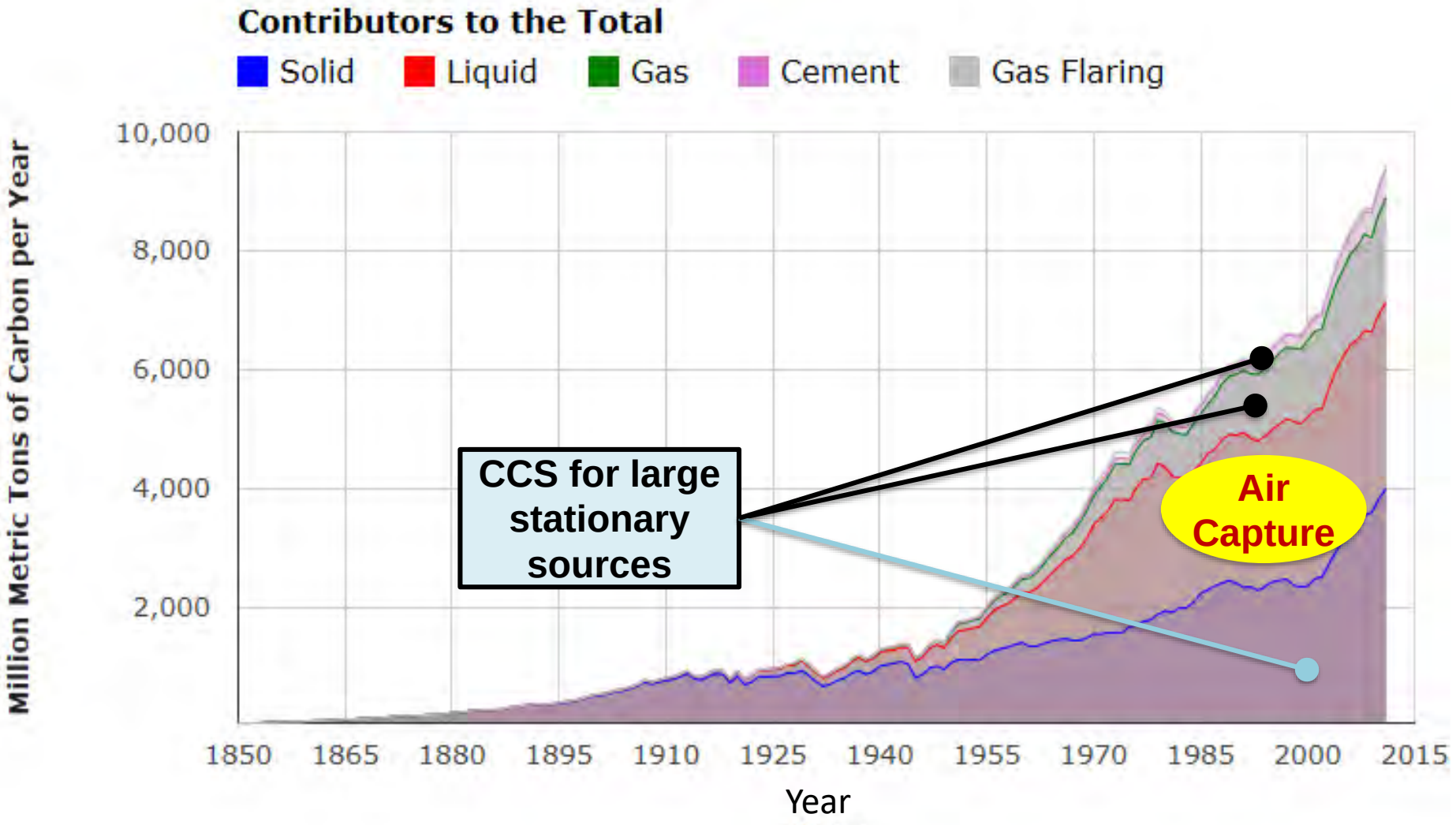


Figure 1. *In Bioenergy with Carbon Capture and Sequestration (BECCS, shown on left), crops such as corn or switchgrass take up carbon dioxide from the atmosphere as they grow. The crops can be burned in power plants to produce electricity, and the carbon dioxide generated is captured and sequestered underground. In Direct Air Capture and Sequestration (DACS, shown on right), carbon dioxide can be removed from the atmosphere as air passes through air filtering structures and is sequestered underground. Block arrows represent fluxes of carbon (as fuel or as carbon dioxide); dashed arrows indicate residual carbon dioxide emissions.*

http://nas-sites.org/americasclimatechoices/

Significant fraction of fossil fuel use requires air capture

http://cdiac.ess-dive.lbl.gov/trends/emis/glo_2014.html

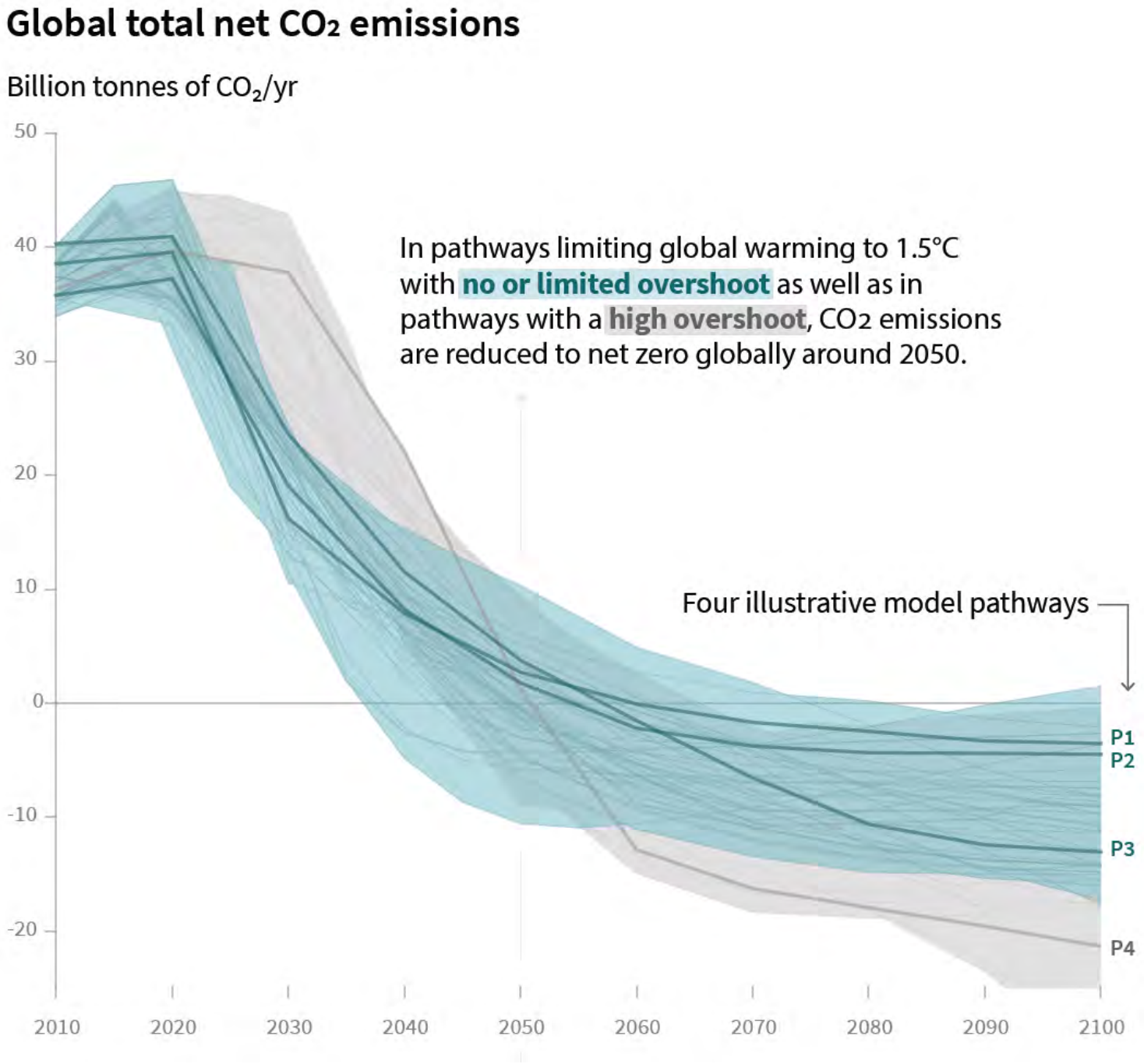


Source: Boden, T.A., G. Marland, and R. J. Andres. 2015. Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi: 10.3334/CDIAC/00001_V2015.

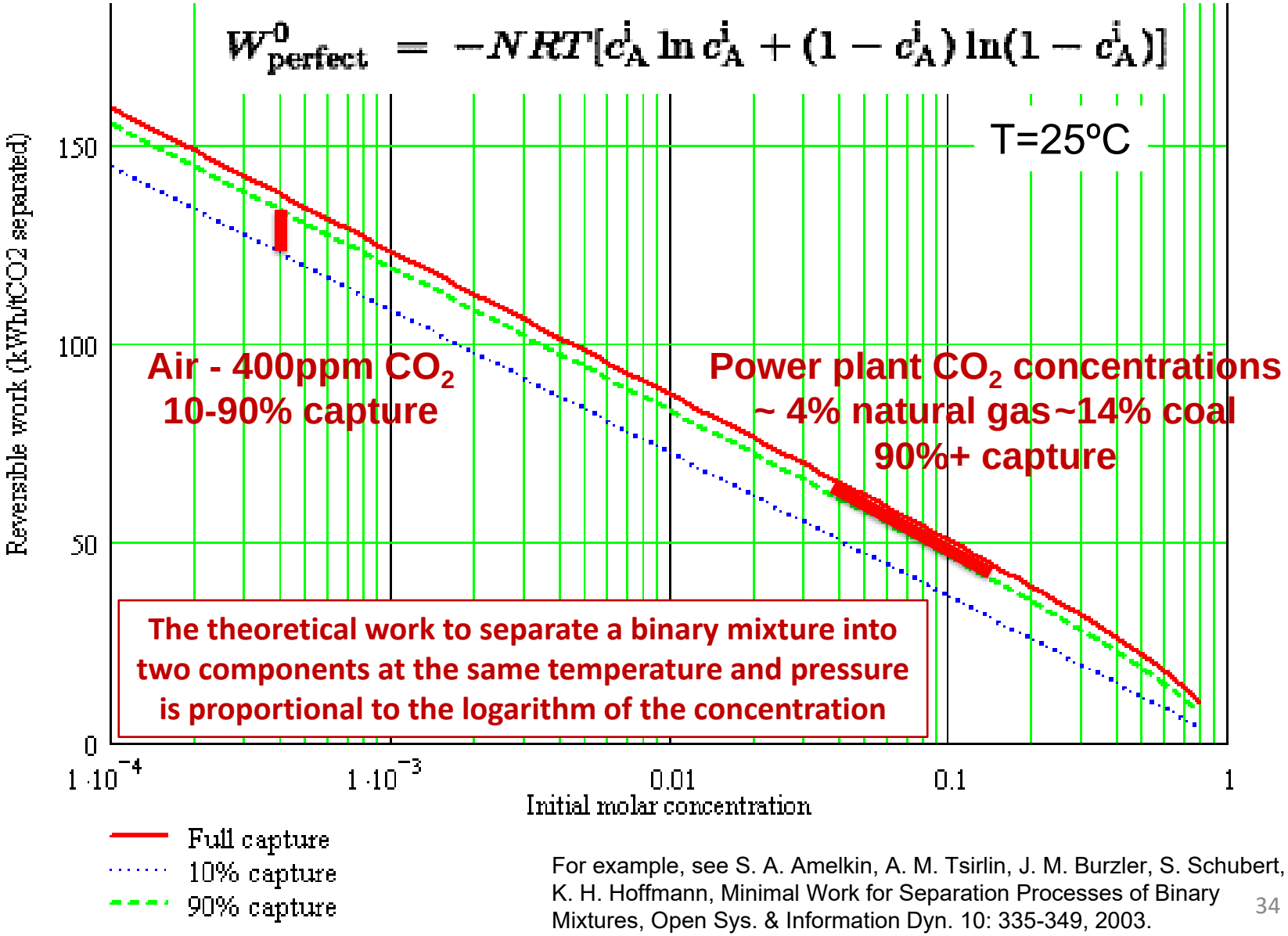
IPCC special report on global warming of 1.5°C, October 2018

GGR technologies required to achieve even net zero emissions, as well as net negative CO_2 emissions.

Technically feasible but what about inter-generational equity?



Direct air capture requires only about twice the theoretical energy input of conventional CO_2 capture from power plants

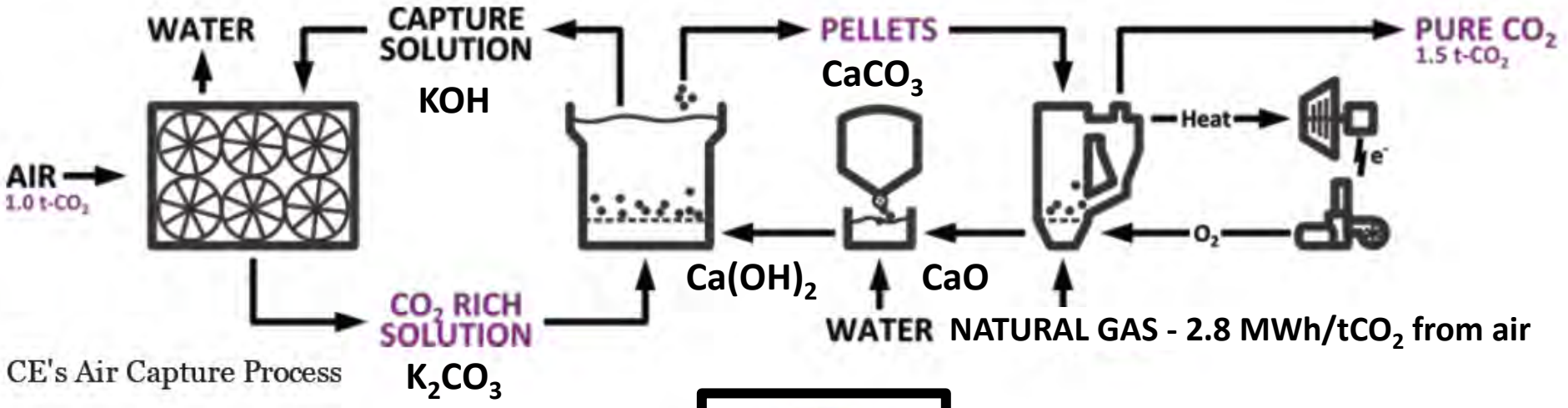


For example, see S. A. Amelkin, A. M. Tsirlin, J. M. Burzler, S. Schubert, K. H. Hoffmann, Minimal Work for Separation Processes of Binary Mixtures, Open Sys. & Information Dyn. 10: 335-349, 2003.

Example 1: Carbon Engineering air capture process

Carbon Engineering

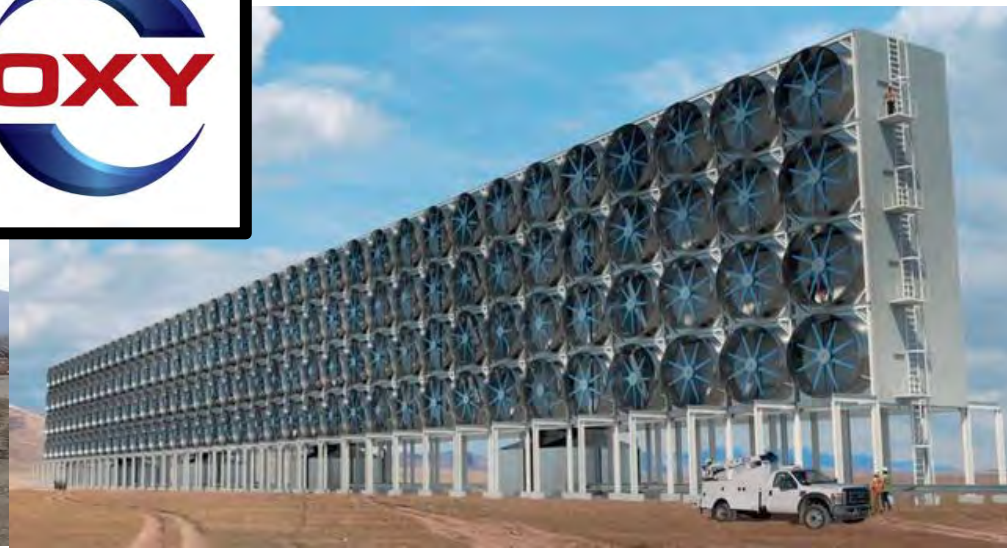
http://carbonengineering.com/



Squamish demo plant site construction

Running 2015, ~500 tCO_2/yr scale

OXY



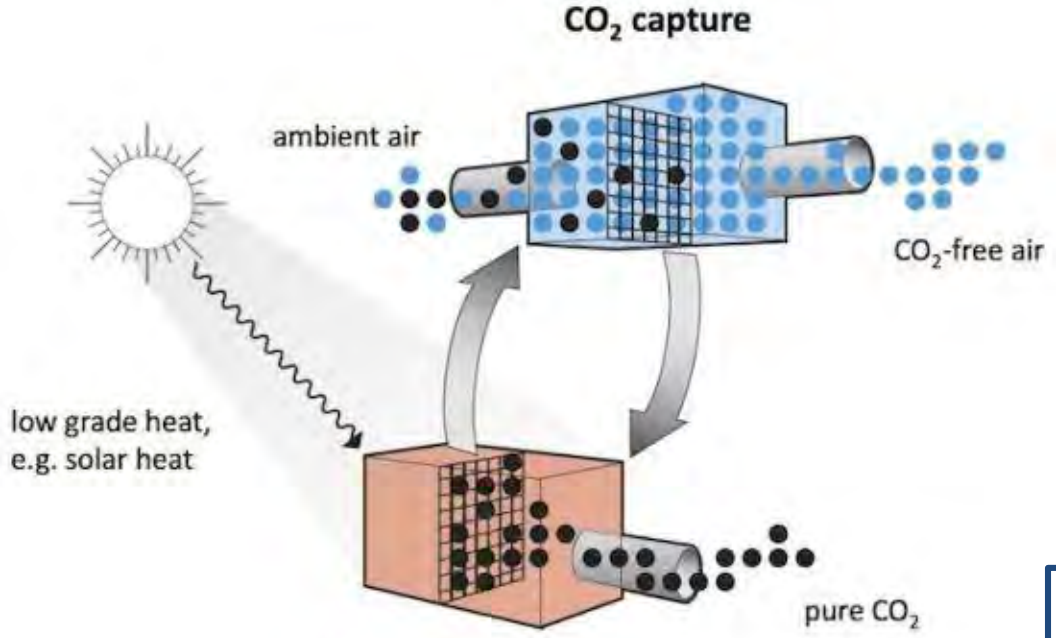
Design for 'slab' air contactor

100,000tCO_2/yr scale image, now 1MtCO_2/yr project

Example 2: Climeworks air capture process

CLIMEWORKS

http://www.climeworks.com



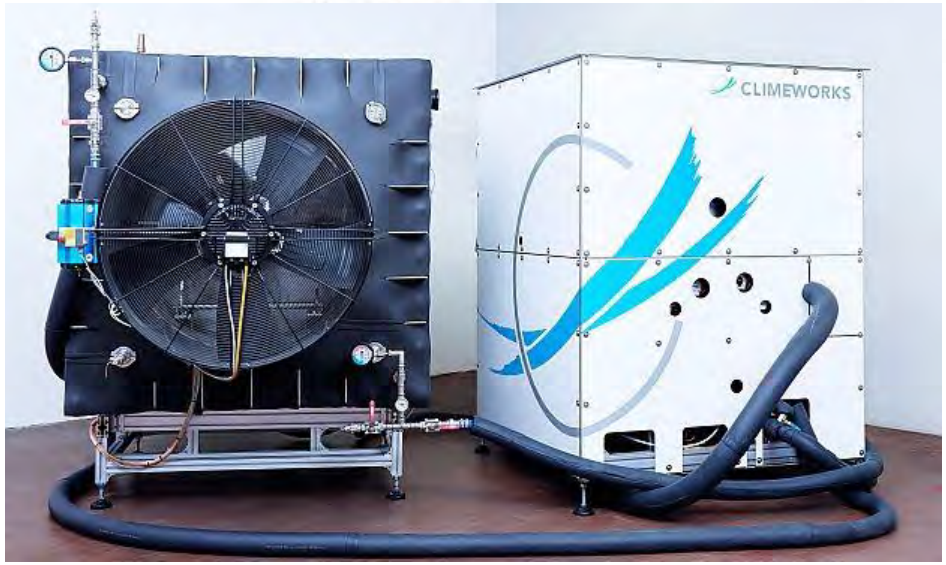
Based on a cyclic adsorption / desorption process on a novel filter material ("sorbent"). Scalable in multiples of 300 tCO_2/yr, in shipping container sized units.

Energy demand per ton of CO_2 :

1.5 – 2.0 MWh heat at 100 °C

0.2 – 0.3 MWh electricity

Climeworks has raised a total of SFr50m ($50.1m) and has 14 plants, operating around the world.



Climeworks CO_2 Kollektor

Design for Climeworks CO_2 Capture Plant

Direct Air Capture Overview

- Examples of working DAC/DACCS technologies now being developed
- Initial independent* cost estimate in 2011 was ~ \$600/tCO_2
- Detailed 2018 engineering and cost analysis** for a 1 Mt-CO_2/year direct air capture plant by Carbon Engineering reported levelized costs of \$94 to \$232 per ton CO_2 from the atmosphere (\$42 to \$102 on a barrel of oil).
- High marginal costs of abatement have been paid via Feed in Tariffs etc. for renewables, with the expectation of reducing costs as a result of experience.
- But even \$600/tCO_2 would add only ~ \$1.50 per litre of gasoline (i.e. less than doubling pump price in Europe).
- And for any stationary source operating at low load factors (e.g. natural gas plant filling in for wind) the point source CCS cost per tonne of CO_2 has to be a LOT lower to beat a DAC unit that is operating all the time.
- DAC technologies can be developed and proven relatively cheaply as individual units that are then mass-produced to reduce costs for deployment.
- **VERY important for countries to commit within ~ 10 years to finite future emission budgets and hence, eventually, to net zero emissions - demonstration of viable DAC options as a back-stop could be a deal-maker.**

* http://www.aps.org/policy/reports/assessments/upload/dac2011.pdf ** https://www.cell.com/joule/fulltext/S2542-4351(18)30225-3

Katowice Airport, COP24, December 2018

https://twitter.com/jadehameister