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KAUST Research Conference
Near Zero-Carbon Combustion Technology
21-23, June, 2021

Global Picture on CO_2 Capture from Power Generation

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Three phases for CO_2 emissions management

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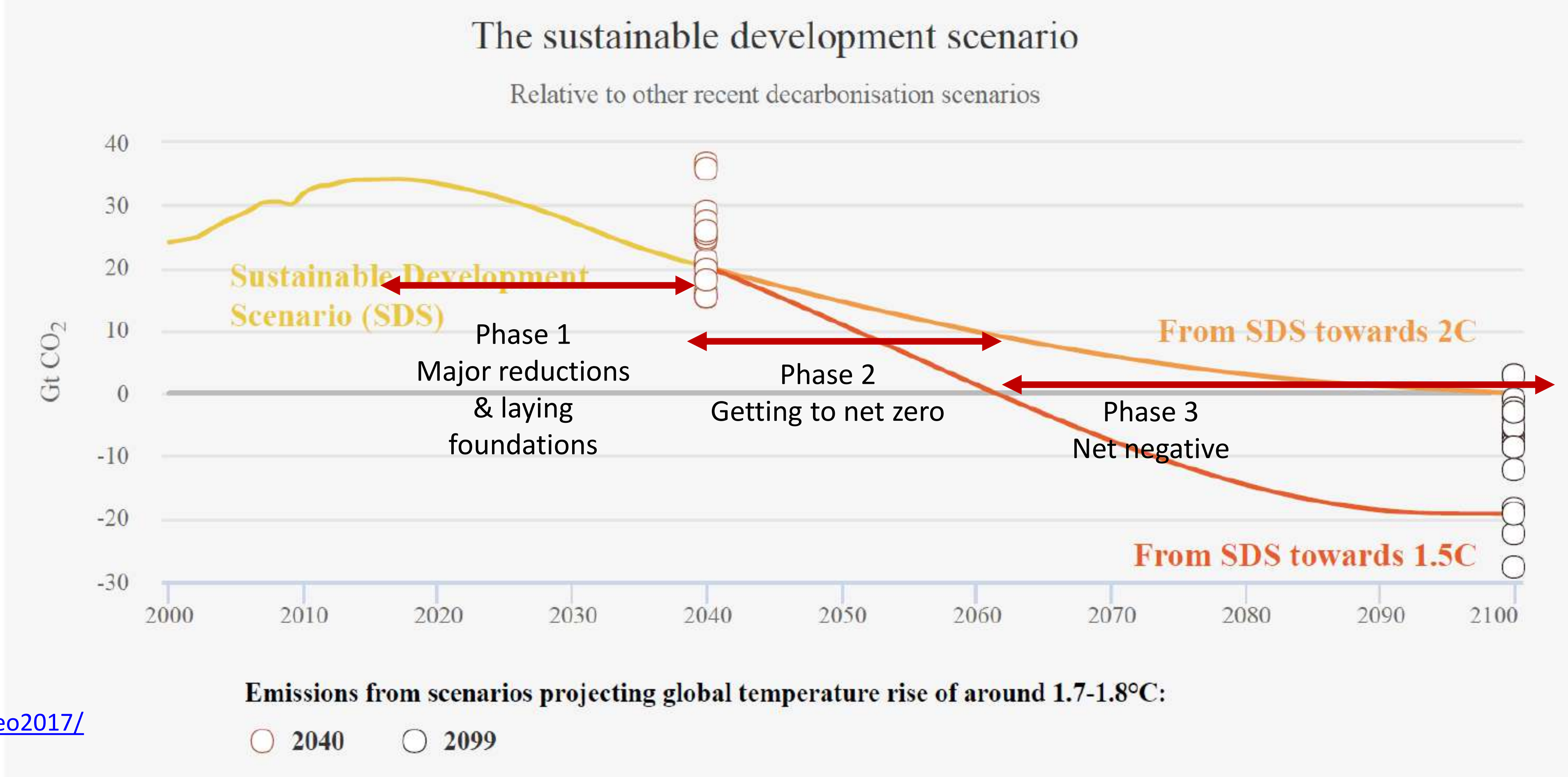
- IEA Sustainable Development Scenario 2017 reduces global emissions to 20GtCO_2/yr
- Would need to be accelerated e.g. to 2035, for global net-zero by 2050 (instead of 2060)
- But trends still expected to be relevant for a track that includes CCS
- The first of three phases from now to the end of the century



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

IEA Sustainable Development Scenario 2017 achieves global Phase 1 CO_2 emission target by cutting coal and oil use while increasing gas only slightly

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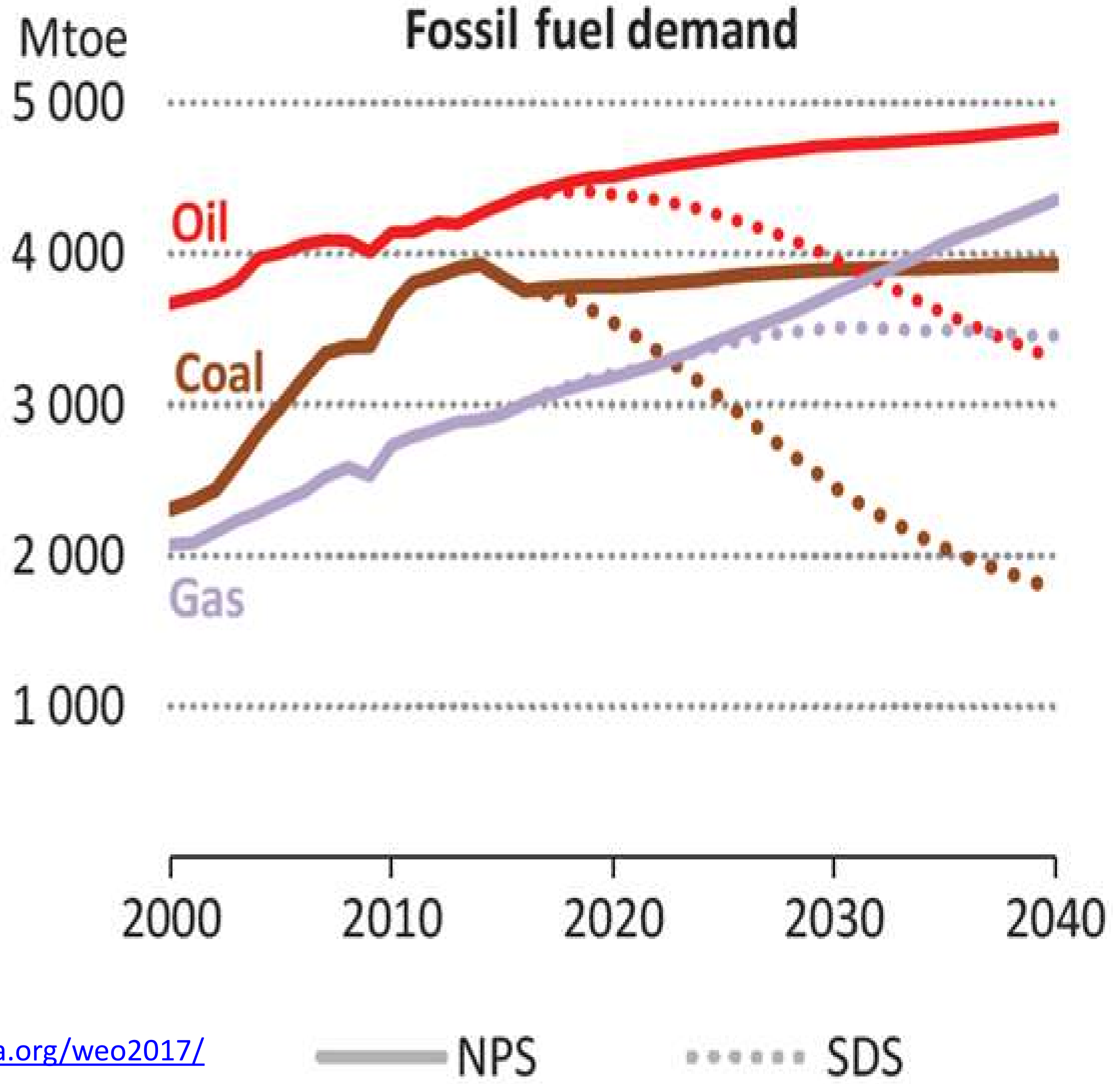

http://www.iea.org/weo2017/

Fossil fuel prices fall or stabilise in SDS

Real terms ($2016)	New Policies 2025	New Policies 2040	Sustainable Development 2025	Sustainable Development 2040
IEA crude oil ($/barrel)	83	111	72	64
Natural gas ($/MBtu)				
United States	3.7	5.6	3.4	3.9
European Union	7.9	9.6	7.0	7.9
China	9.4	10.2	8.2	8.5
Japan	10.3	10.6	8.6	9.0
Steam coal ($/tonne)				
United States	61	62	56	55
European Union	77	82	67	64
Japan	82	87	71	68
Coastal China	87	91	78	77

The Sustainable Development Scenario proposes extremely rapid growth for CCS in Phase 1 and implies a lot more CCS after that

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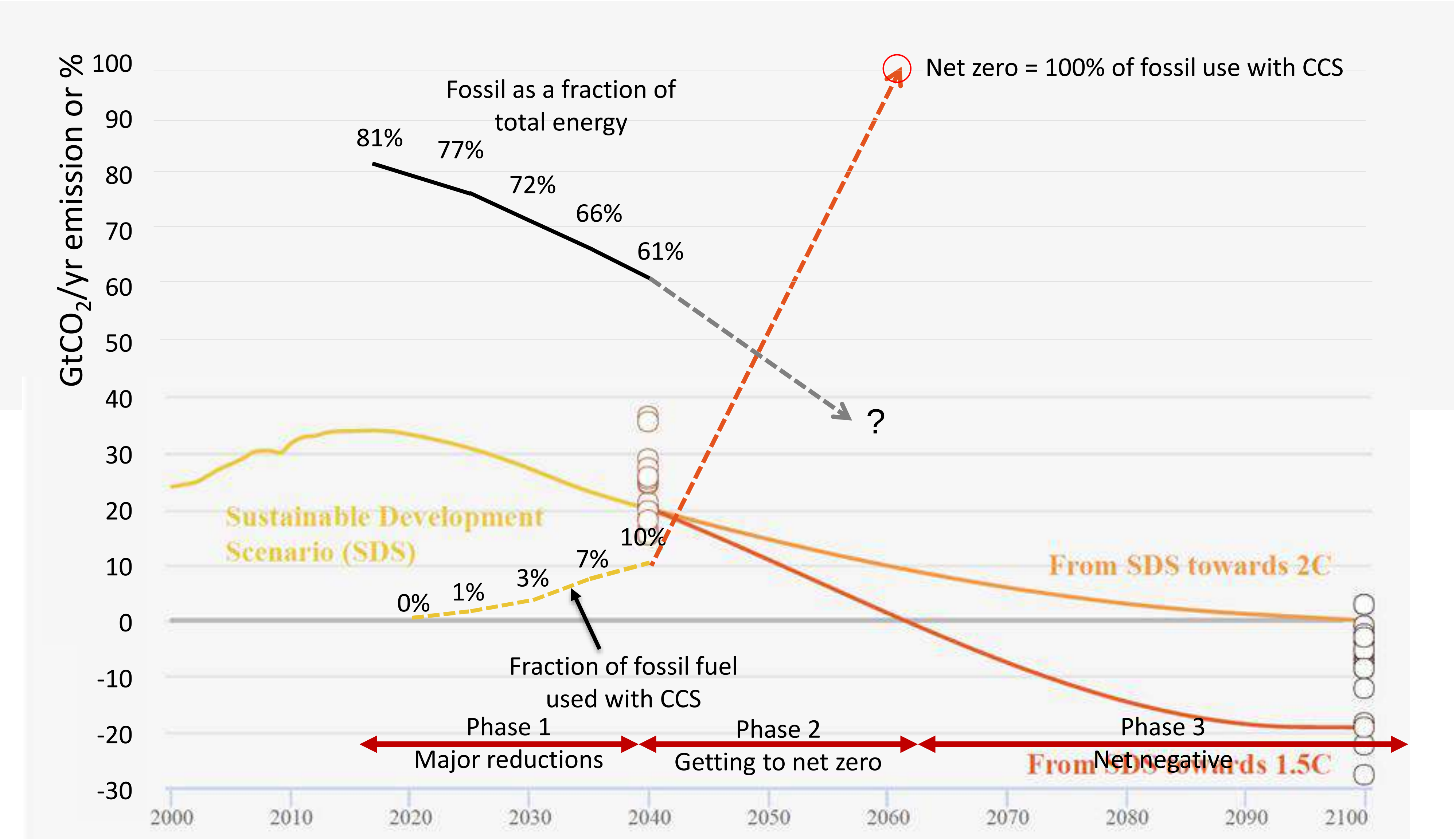
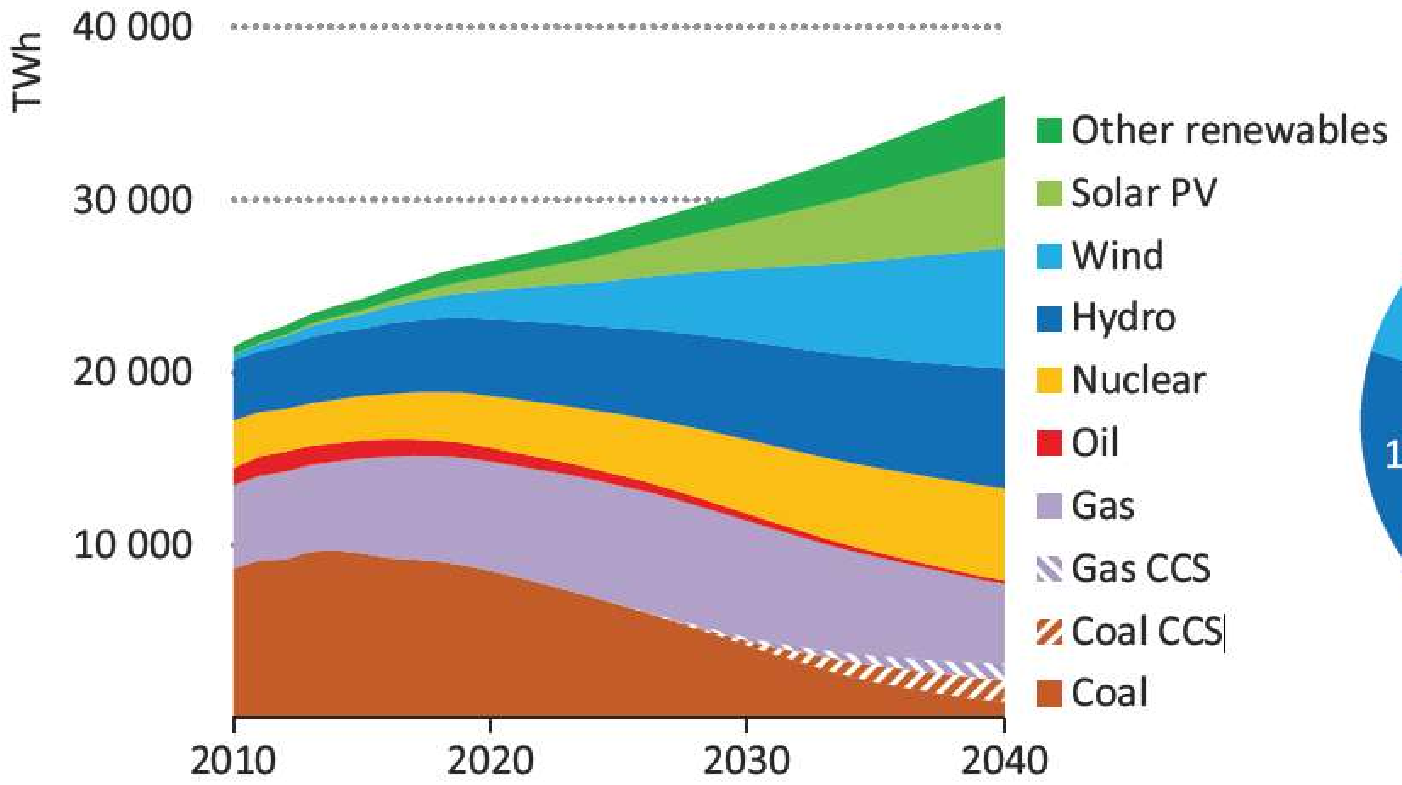
- 2040 Storage: ~ 1.6 $GtCO_2$/yr (x40 current), perhaps 100 large sources or clusters
- 2040 Capture: ~ 375 GW of power plant capacity (x1000 current) plus industrial sources



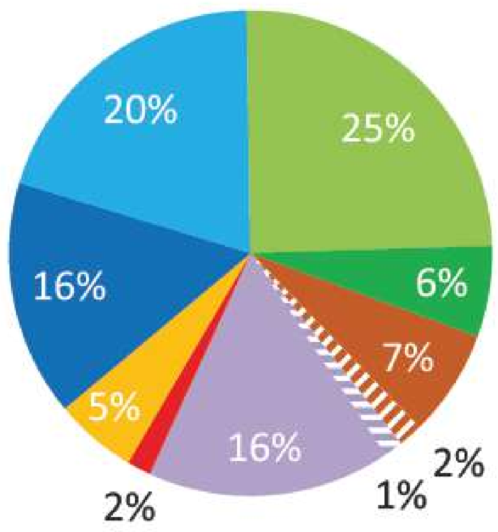
SDS has CCS as 6% of global electricity generation, with renewables over 60% and nuclear 15%

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

Annual Electricity generation by source



Installed capacity 13100 GW

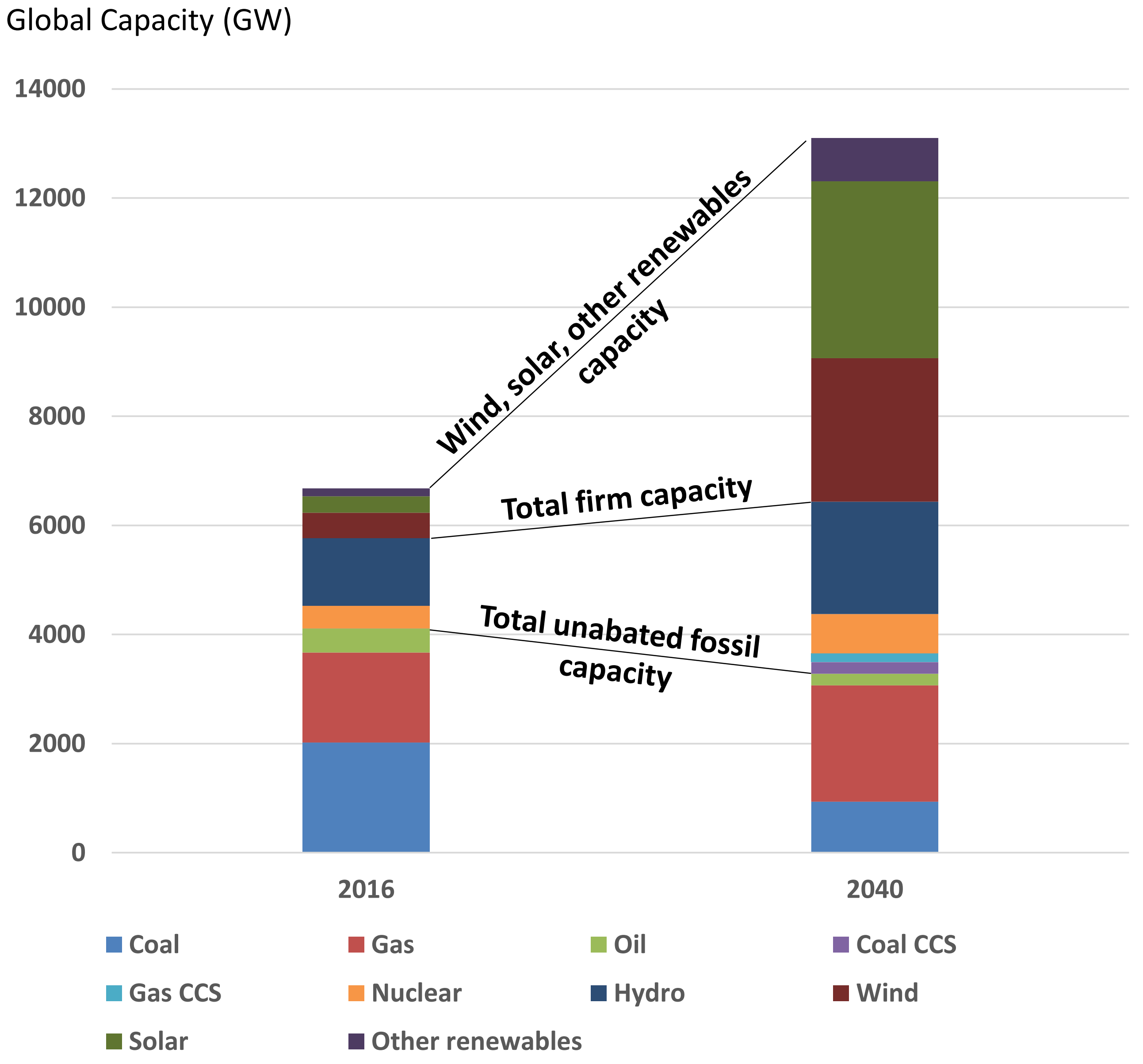


* Boundary Dam 3 120MW, Petra Nova 240MW

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

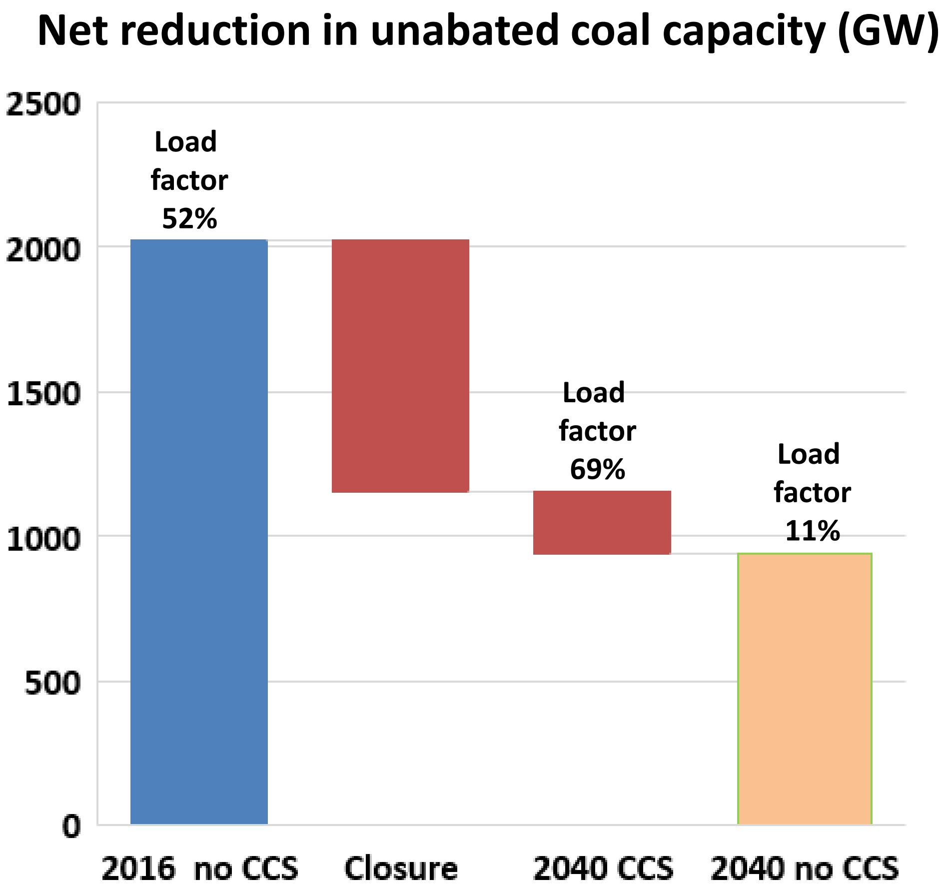
Global electricity generation capacity trends in the SDS

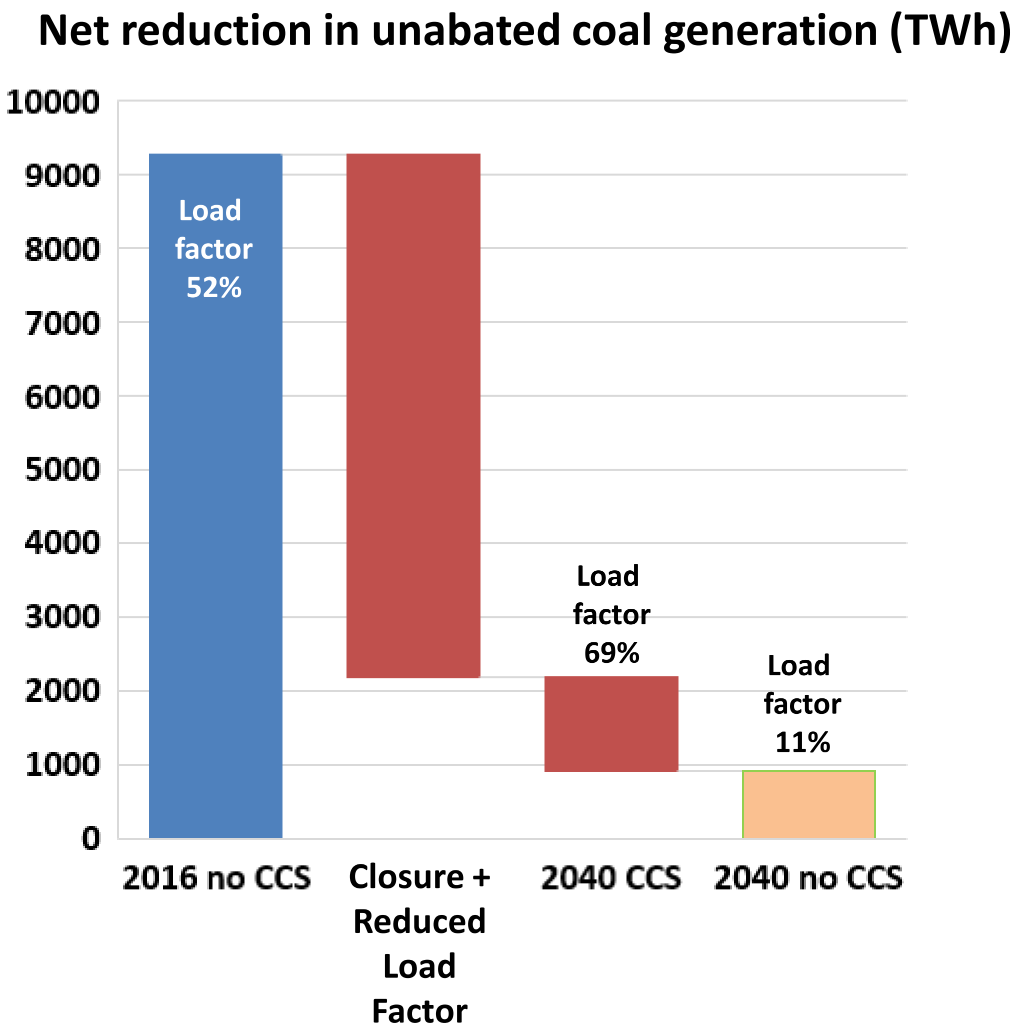
- Total electricity generation (TWh) increases by 42%, nominal capacity (GW) doubles
- Total wind+solar capacity increases by 670%
- Total fossil+nuclear+hydro firm capacity increases by 12%
- Total unabated fossil capacity decreases by 20%
- 37% of the decrease in unabated coal and oil capacity is replaced by unabated natural gas capacity
- 29% of the decrease in unabated coal and oil capacity is replaced by CCS capacity using coal or natural gas



A lot of coal capacity is retained in the SDS

- But coal power plants without CCS run at very low load factors
- Effectively being used as peaking plant





More detailed illustration of CCS power plant roles

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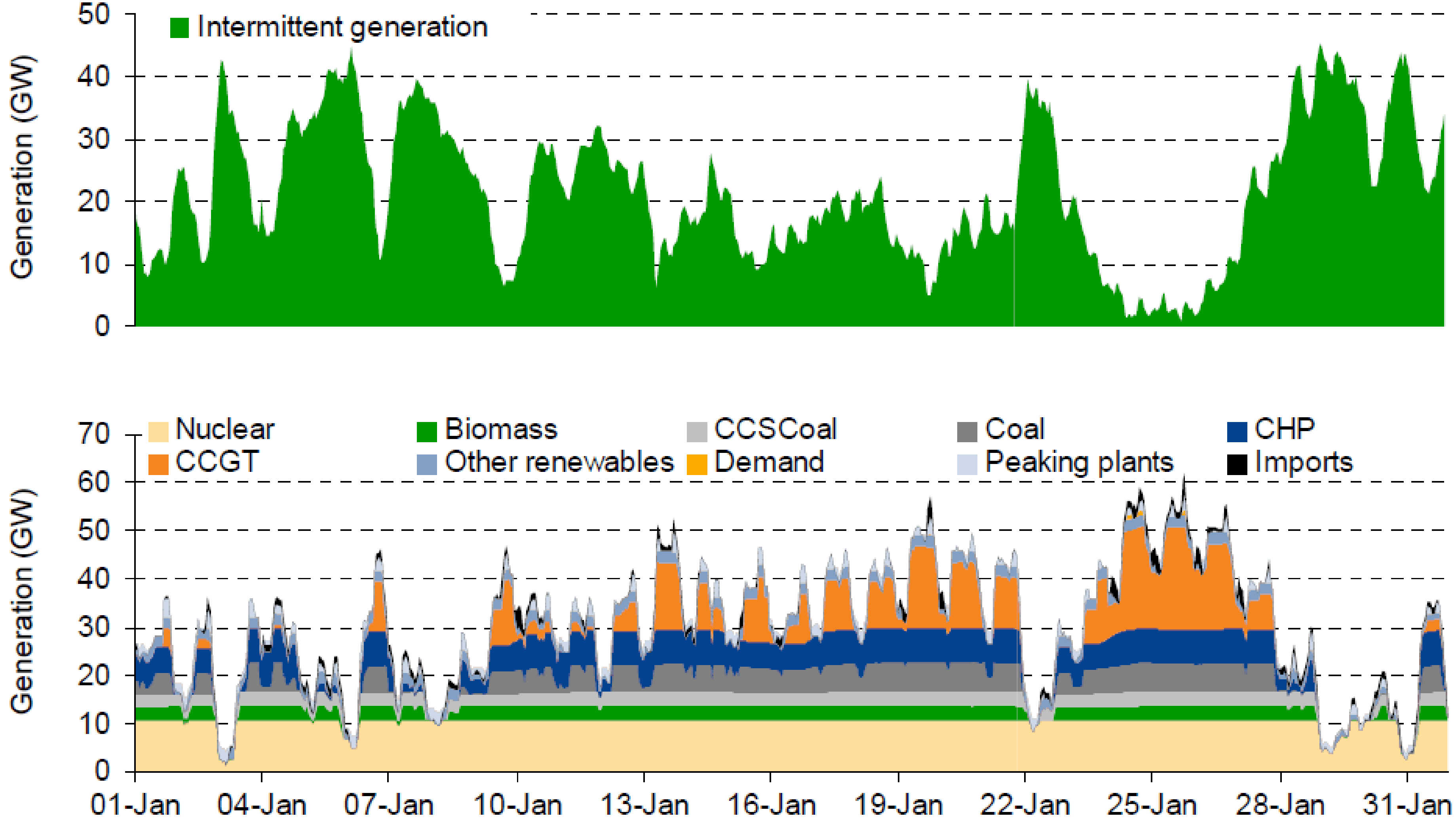
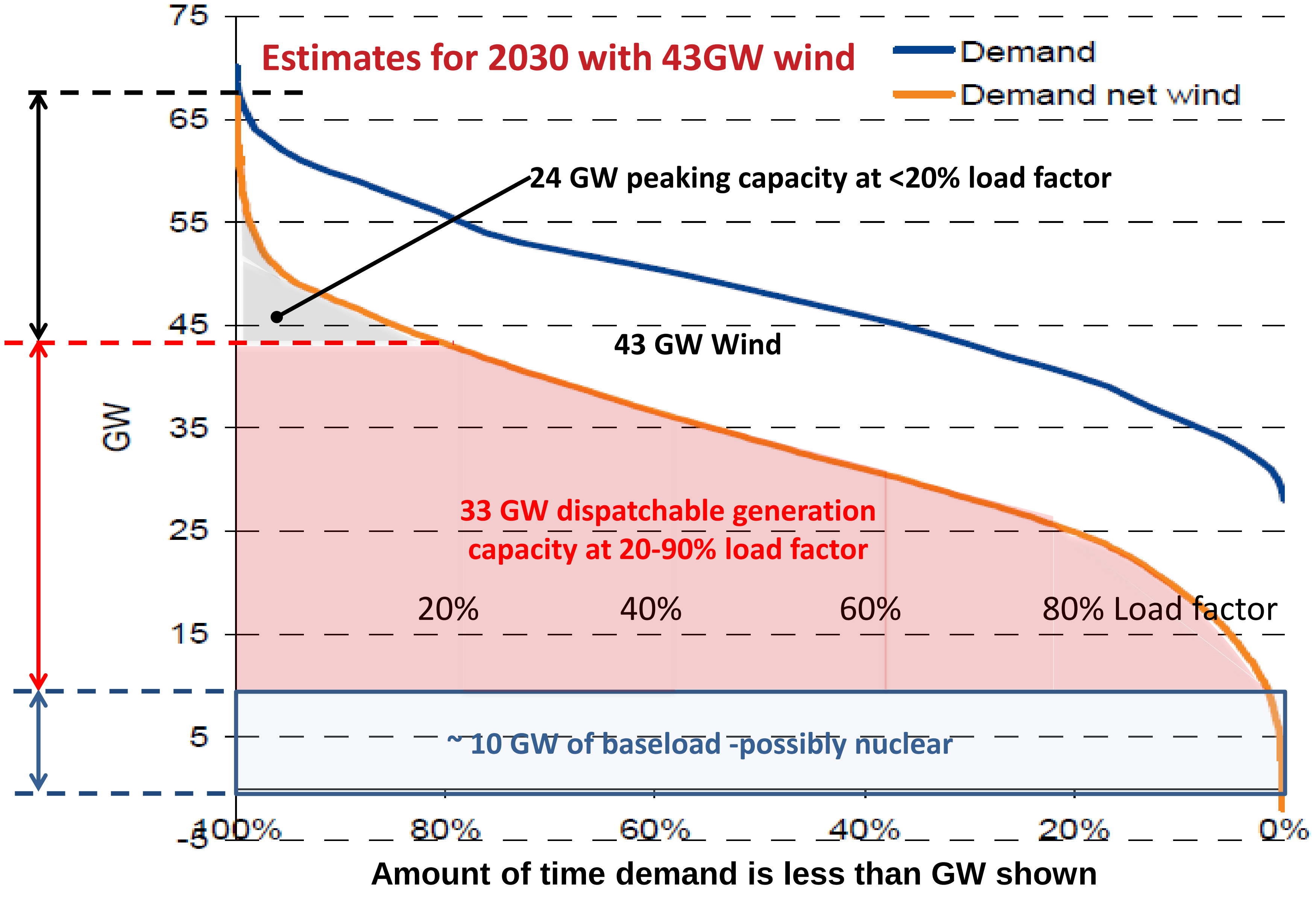
- Wind and thermal generation in January 2030 with the UK wind patterns from 2000 and 43GW of wind capacity
- UK 2030 target now is 40GW of offshore wind plus there is ~14GW existing onshore



- Expected 2030 mix of generation now differs in detail
- But a similar trend expected for any dispatchable power plants
- Demand management and electricity storage also expected to have an effect.

Poyry, Impact of intermittency: how wind variability could change the shape of the British and Irish electricity markets, Summary report, July 2009



- Trends are only illustrative.
- Lower dispatchable power plant load factors now expected for 2030
- And these will reduce over time as more renewables, storage and demand management enter the market

Poyry, Impact of intermittency: how wind variability could change the shape of the British and Irish electricity markets, Summary report, July 2009, http://www.poyry.com/linked/group/study

Capture from Power Generation in CO_2 Management Phases

Phase 1: Major reductions & laying foundations

- Capture on dispatchable power plants, all fuels (gas, oil, coal, biomass, wastes)
- Probably limited baseload and a range of load factors
- Capture may be stopped for short periods to allow more power to be sent out

Phase 2: Getting to net zero

- Address CO_2 emissions from peaking power plants – but probably not capture them at source
- Low load factors, running costs can be high but capital costs must be kept low
- Options including:
    - Hydrogen
    - Ammonia
    - Biofuels
    - Synthetic fuels made from DAC CO_2
    - Fossil fuels + CDR from BECCS or DACCS

Phase 3: Net negative

- CDR may be required at very large scales, affecting power generation as follows:
    - BECCS on as much biomass as available – the electricity generated becomes a by-product
    - May be able to integrate electricity production and DACCS, e.g. provide heat, share CO_2 transport and storage system

Key Features for Capture from Power Generation in Phase 1

- Plant has to be dispatchable – able to stop and start as required, while capturing CO_2
- Capital cost dominates economics as load factor reduces
- Thermal efficiency has only a secondary impact, especially at lower fuel costs
- Have to be able to meet periods of peak/emergency demand – may be very high electricity prices at these times
- May be some benefit for time-shifting the capture penalty
- Plant has to capture ~99% of the CO_2 or be able to be upgraded to do so for net zero future
- Other pollutant emissions and environmental impacts are also a factor
- CCS also raises questions about water demand in some areas

CCS power plant characteristics from a UK study

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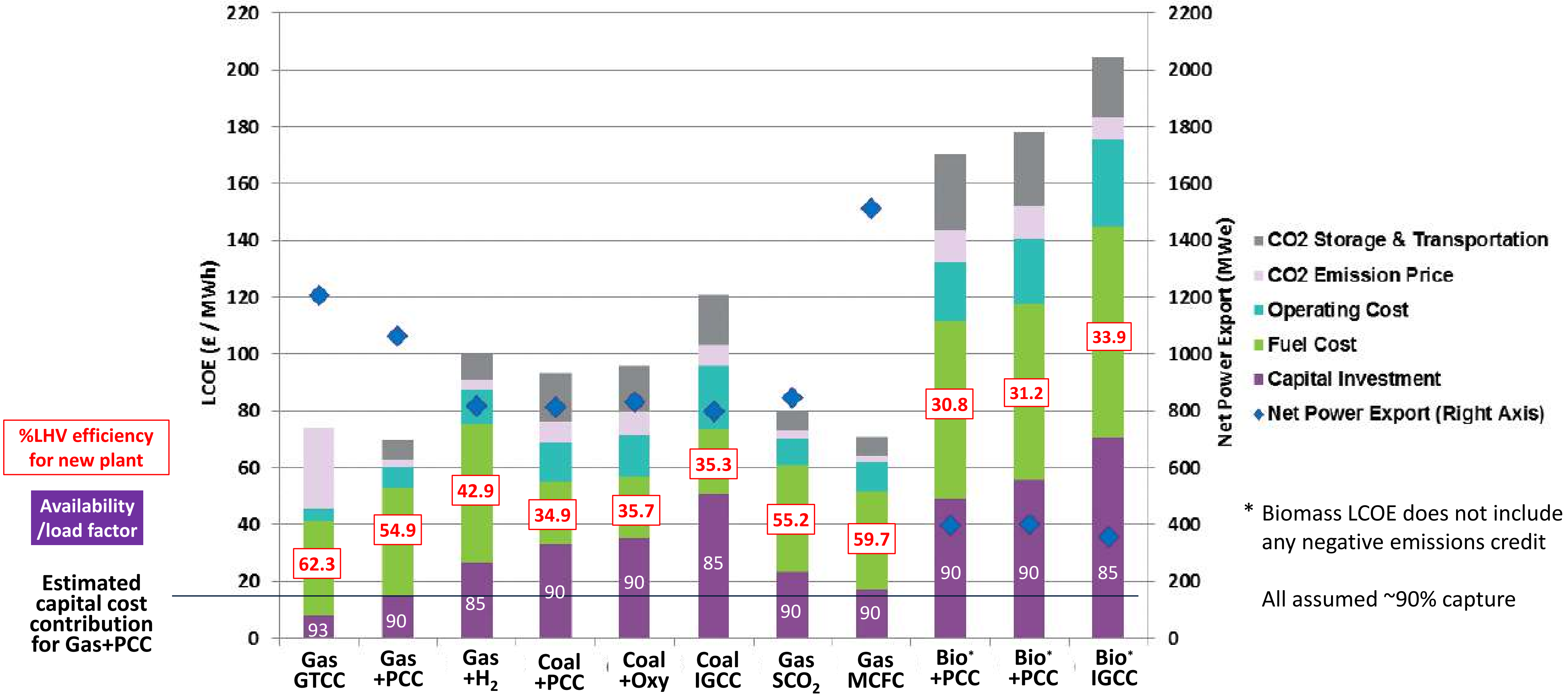
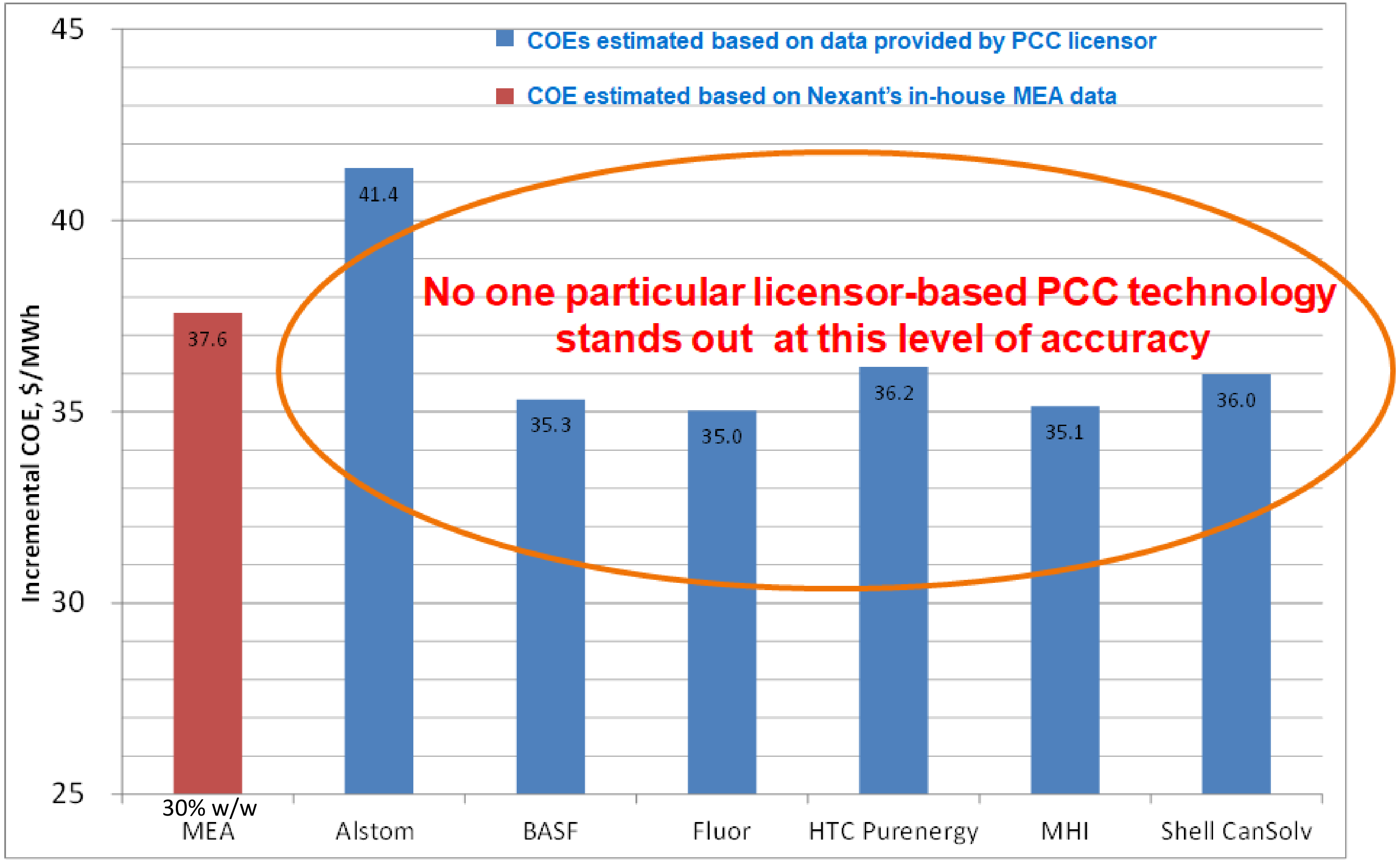
Study for BEIS by Wood, formerly Amec-FW https://www.gov.uk/guidance/funding-for-low-carbon-industry. Detailed report and cost calculation spreadsheet available



Natural gas CCGT PCC retrofit study for World Bank found similar costs for a range of proprietary amine solvents (and similar to first-generation 30% MEA)

https://www.netl.doe.gov/File%20Library/Events/2016/c02%20cap%20review/1-Monday/H-Lu-Nexant-NGCC-Applications-in-Mexico.pdf + full details in final Mexico World Bank project report
https://www.gob.mx/cms/uploads/attachment/file/107318/CCPP_Final_Report.pdf



CO_2 Capture Facility at Kårstø, Norway

Front-End Engineering and Design (FEED) Study Report

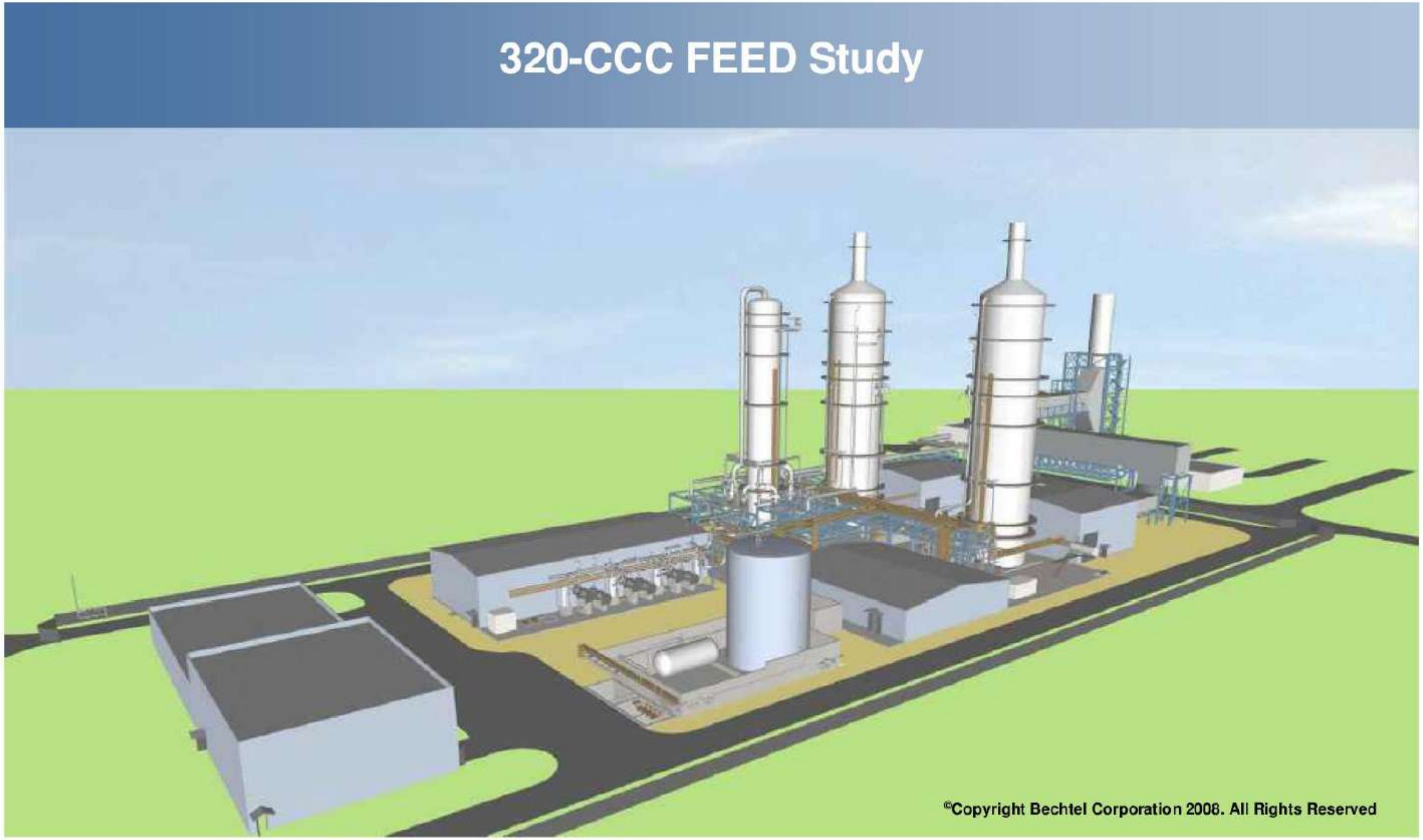
Submittal to GASSNOVA

13 January 2009, Revision 1

Redacted for Distribution as per Gassnova Instructions
3 April 2019

25474-000-30R-G04G-00001

10112936-PB-G-DOC-0005



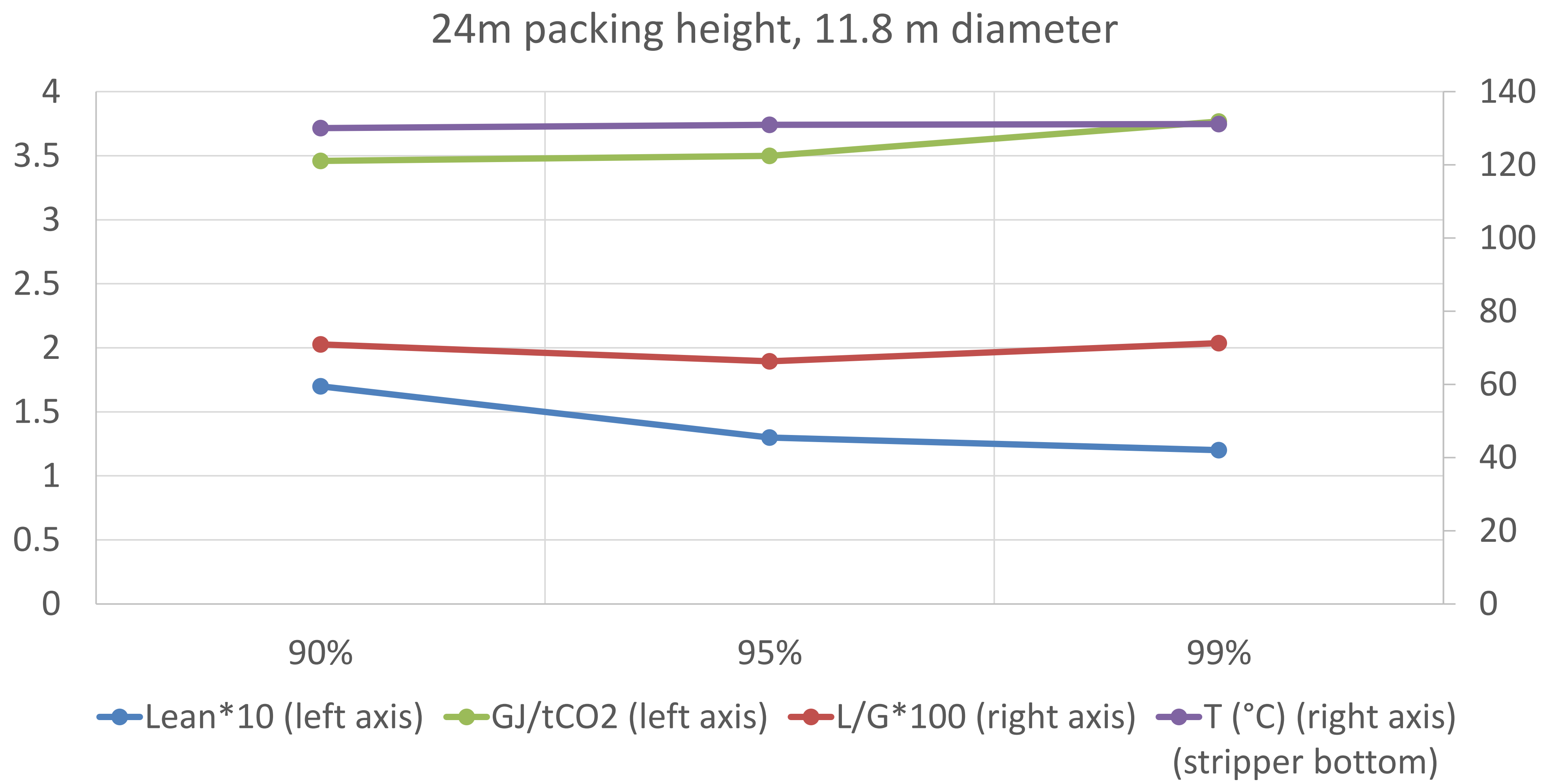
https://ukccsrc.ac.uk/open-access-carbon-capture-and-storage-at-karsto-norway/

Open-technology study based on 35%w/w MEA

Modelling results – 24 m packing (+60% packing vs 85% capture)

L/G and lean loading varied together to give 90, 95 and 99% capture on GT flue gas, with minimum reboiler heat input

https://terc.ac.uk/news-events/register-here-a-webinar-on-delivering-ultra-high-post-combustion-co2-capture/



Some examples of other published work on 95-99% capture levels

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Fluor examples: ‘85-95% capture’ including on GT flue gases
http://www.zeroco2.no/projects/bellingham
https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.204.8298&rep=rep1&type=pdf

‘A 95% CO_2 capture rate was achieved and found to be optimum when studying cases at 85, 90 & 95% CO_2 capture from coal-fired boiler flue gases.’
Application of the Econamine FG Plus process to Canadian Coal-based Power Plant, Shakir Khambaty, Satish Reddy (Fluor), Robert Stobbs (Saskpower), Clean Coal Session of Combustion Canada Conference, Vancouver, Canada, September 22-24, 2003.
Previously available on https://origin-www.fluor.com/SiteCollectionDocuments/ApplofEFG-ProcesstoCanadianCoal-basedPowerPlant-CombCanadaConf-Sep2003.pdf

MHI example, for up to 99.5% capture on coal flue gases
Takuya Hirata, Tatsuya Tsujiuchi, Takashi Kamijo, Shinya Kishimoto, Masayuki Inui, Shimpei Kawasaki, Yu-Jeng Lin, Yasuhide Nakagami, Takashi Nojo (2020) Near-zero emission coal-fired power plant using advanced KM CDR process™, International Journal of Greenhouse Gas Control, Volume 92. http://www.sciencedirect.com/science/article/pii/S1750583618307527)

IEAGHG study: up to 99.1% capture, including on natural gas
Paul Feron, Ashleigh Cousins, Kaiqi Jiang, Rongrong Zhai, San Shwe Hla, Ramesh Thiruvenkatachari, Keith Burnard (2019), *Towards Zero Emissions from Fossil Fuel Power Stations*, International Journal of Greenhouse Gas Control, Volume 87, 2019, Pages 188-202.
https://www.sciencedirect.com/science/article/pii/S1750583618308934

Patrick Brandl, Mai Bui, Jason P. Hallett, Niall Mac Dowell, *Beyond 90% capture: Possible, but at what cost?*,
International Journal of Greenhouse Gas Control, Volume 105, 2021, 103239,
https://doi.org/10.1016/j.ijggc.2020.103239 ; https://www.sciencedirect.com/science/article/pii/S1750583620306642

Shah, M.I., da Silva, E.F., Gjernes, E. and Åsen, K.I. (2021) , *CO_2 capture cost reduction study for CCGT flue gas, based on MEA at TCM*, GHGT15
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3821061
Pilot scale trials achieving 95-99% capture using ~35% w/w MEA from ~4% v/v CO_2 flue gas, 3.7-4.0 GJ/tCO_2.

AECOM (2020) for BEIS, *Start-up and Shut-down times of Power CCUS Facilities*. https://www.gov.uk/government/publications/start-up-and-shut-down-times-of-power-carbon-capture-usage-and-storage-ccus-facilities

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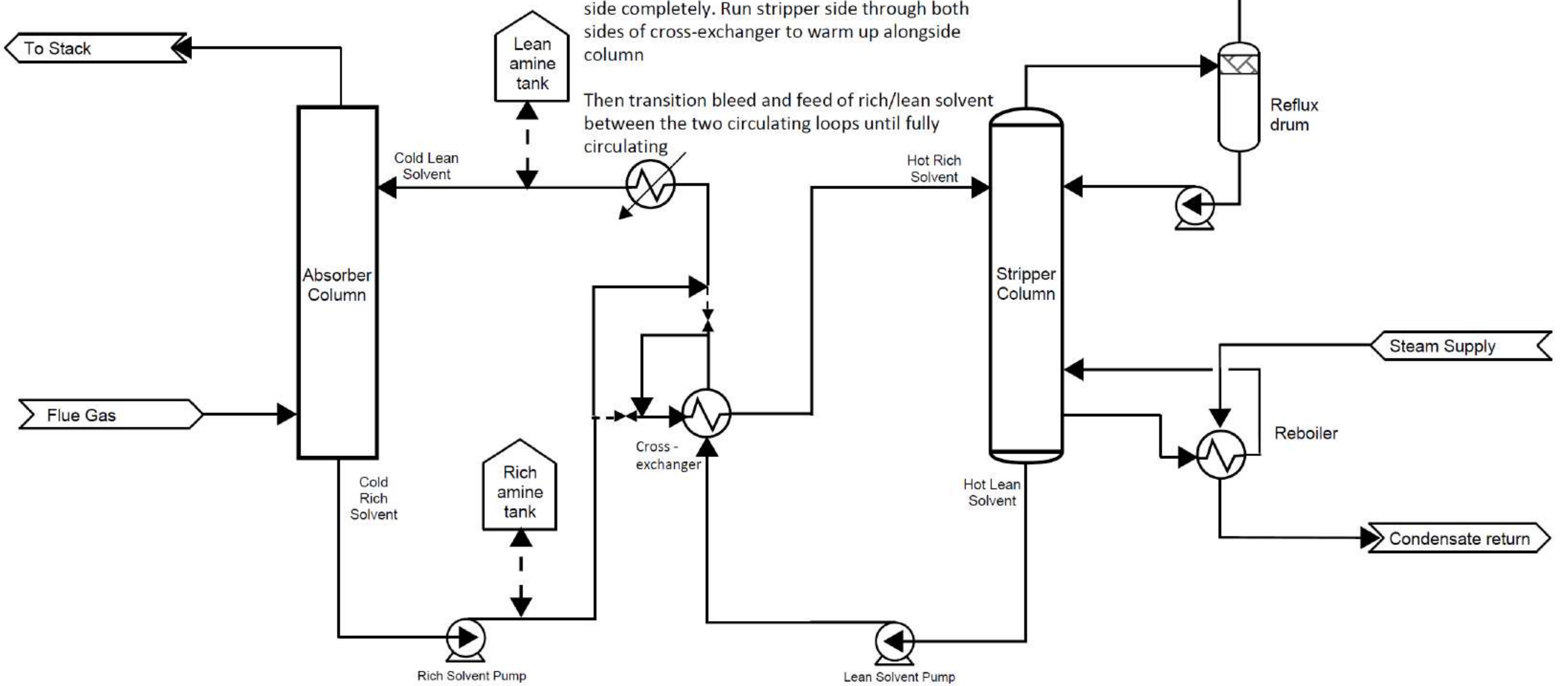
AECOM

Simplified process flow diagram of base case at start-up - hybrid of segregated inventory start with two storage tanks

At start-up: Bypass cross-exchanger on absorber side completely. Run stripper side through both sides of cross-exchanger to warm up alongside column

Then transition bleed and feed of rich/lean solvent between the two circulating loops until fully circulating



Issue being addressed is GT starting up and running for extended periods (especially on warm or cold starts) before steam is available to regenerate PCC solvent.

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Some CCS power plant initiatives globally – but hard to keep up to date!

- UK – multiple CCGT plus PCC plant and biomass+PCC FEED studies planned within the CCS clusters, also hydrogen for CCGT (possibly partial firing only) FEEDs and feasibility study for Allam-Fetvedt Cycle power plant
- US - multiple FEED studies for CCGT and coal PCC plants, also membranes, plus coal retrofit projects being developed. Petra Nova slipstream PCC plant run but now not operating, Kemper County IGCC+CCS plant never ran properly and $BNs over budget
- Canada – Boundary Dam 3 operating
- NL – PCC retrofits on waste incinerator plants exporting power, hydrogen power being considered
- China – coal PCC retrofits being considered
- Australia – coal PCC retrofits being considered
- Japan – 500 tpd PCC on biomass power plant

UK:https://ukccsrc.ac.uk/web-series/ukccsrc-summer-2021-web-series/ ; US https://www.energy.gov/fe/foa-2058-front-end-engineering-design-feed-studies-carbon-capture-systems-coal-and-natural-gas ; Canada https://www.saskpower.com/Our-Power-Future/Infrastructure-Projects/Carbon-Capture-and-Storage/Boundary-Dam-Carbon-Capture-Project ; NL https://ukccsrc.ac.uk/wp-content/uploads/2020/06/Jan-Hopman-CCUS-Developments-in-the-Netherlands.pdf ; China https://www.modernpowersystems.com/features/featureccus-becoming-a-commercial-reality-in-china-8770880/ ; Australia https://www.spglobal.com/platts/en/market-insights/latest-news/coal/041221-glencore-china-huaneng-sign-deal-to-fit-carbon-capture-to-australian-coal-plant ; Japan https://www.toshiba-energy.com/en/info/info2020_1031.htm

Final words

- Power plants with CCS being planned to help deliver net net-zero global emissions
- Dispatchable power with range of load factors, determined by intermittent renewable build
- Retrofits on existing coal, gas and biomass power plants
- New-build gas and biomass power plants, limited new coal with CCS
- Currently mostly post-combustion capture using amines, but any technology that can offer reduced capital costs could be competitive; efficiency becoming less important as load factor expectations reduce
- Capture level also important, for net zero emissions, plus overall environmental performance
- BECCS, including waste incinerators, likely to become important for CO_2 removal (CDR), with electricity as a by-product
- Pre-combustion capture for power has had some unsuccessful examples, appears to be more expensive so combustion-based technologies expected to dominate in the power sector, except:
    - H_2 with storage for future peaking plants
    - Locations where H_2 supply is cheaper than CO_2 transport and storage