Imperial College
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20 years of CCS – what have we learned?

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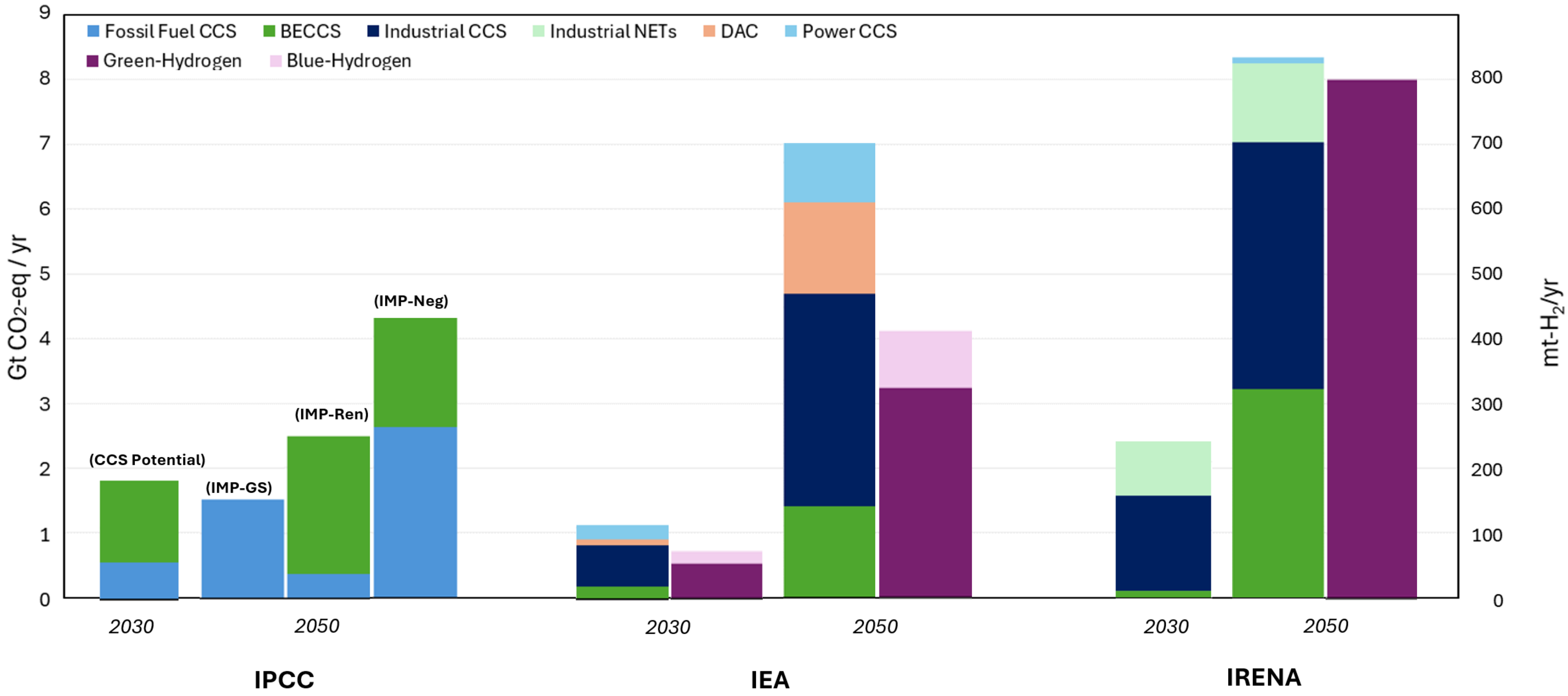
Questions when I started

- What is CCS?
- Do we need this?
- Does it work?
- What does it do?
- Is it safe?
- Which technology is best?
- What does it cost?
- How much CO_2 can you capture?
- …

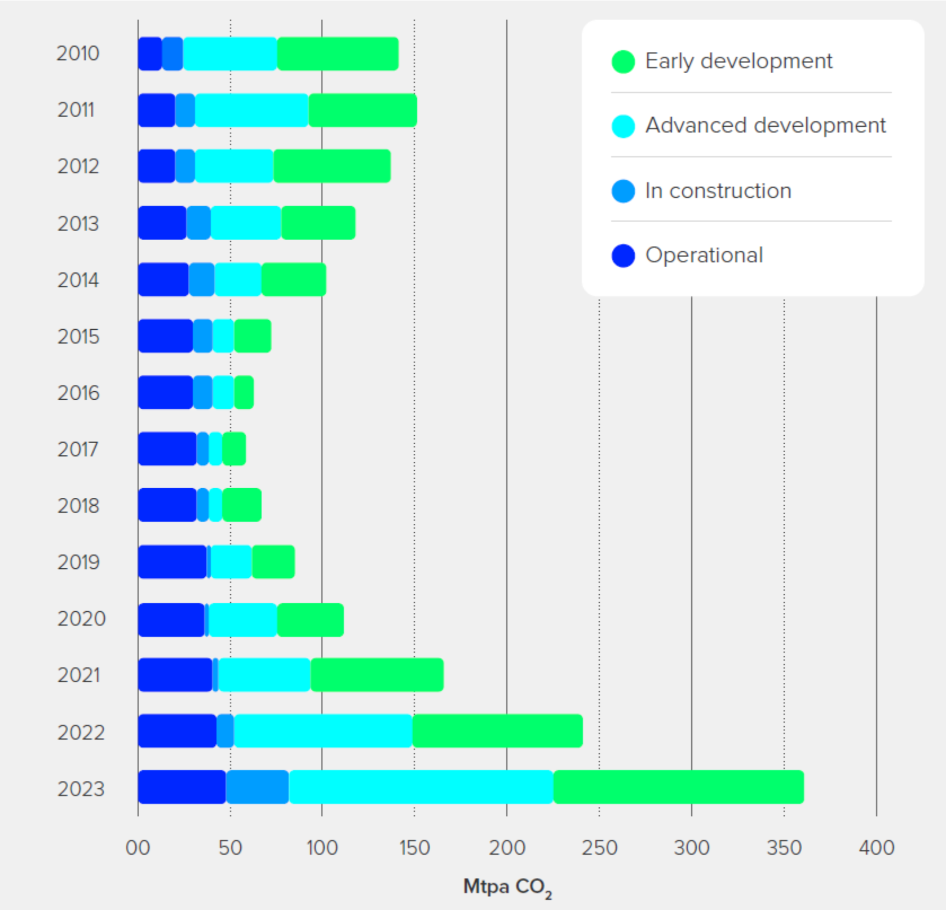
Unanimity on the need for CCS and CDR



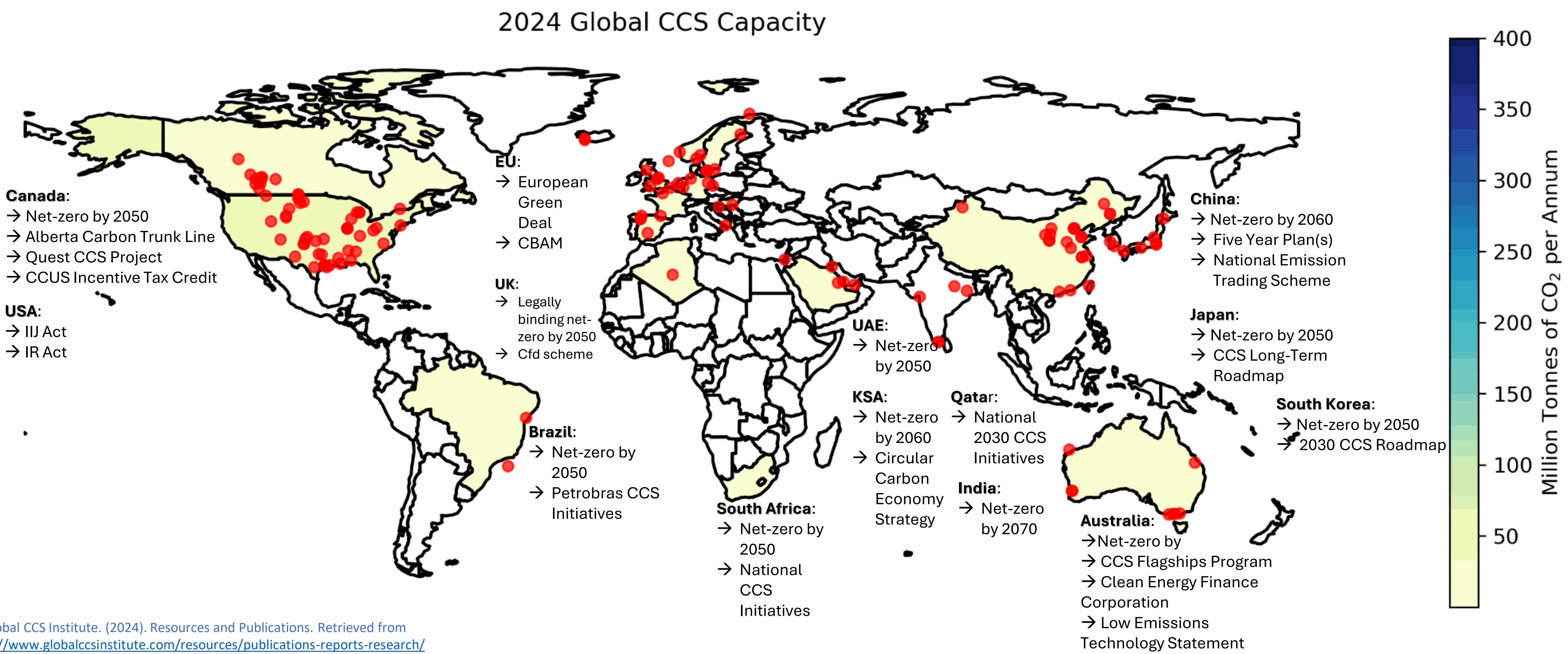
1 Intergovernmental Panel on Climate Change. (2022). Sixth Assessment Report: Working Group III. Retrieved from https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/
2 Intergovernmental Panel on Climate Change. (2023). AR6 Synthesis Report: Climate Change 2023. Retrieved from https://www.ipcc.ch/report/ar6/syr/
3 International Energy Agency. (2021). Net Zero by 2050: A Global Roadmap for the Energy Sector. Retrieved from https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reachl
4 International Renewable Energy Agency. (2022). Hydrogen. Retrieved from https://www.irena.org/Energy-Transition/Technology/Hydrogen
5 International Renewable Energy Agency. (2021). Capturing Carbon: The Role of Carbon Dioxide Removal in Reaching Net-Zero. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA_Capturing_Carbon_2021.pdf

Significant commercial pipeline emerging

- In 2023, there were 392 CCS projects:
  - All these projects have a capture capacity of 361 $MtCO_2$ pa
  - the 41 in operation captured and stored 49 $MtCO_2$ pa
  - 26 in construction which will capture and store 32 $MtCO_2$ pa
- This is still significantly below the required levels of CCS in the IPCC scenarios

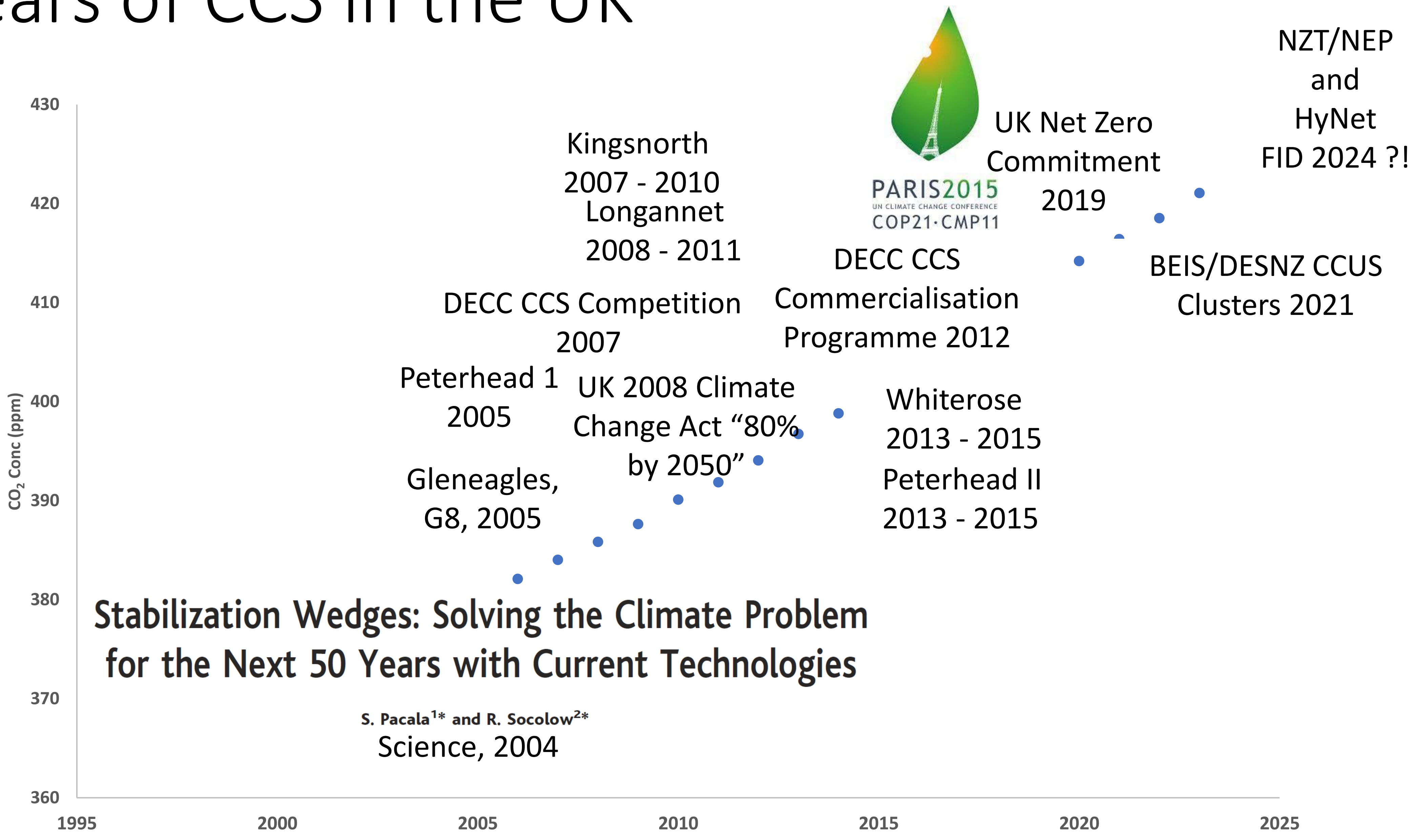


Global policy tailwinds driving deployment



(1) Global CCS Institute. (2024). Resources and Publications. Retrieved from https://www.globalccsinstitute.com/resources/publications-reports-research/
(2) International Energy Agency (IEA). (2024). Reports and Analysis. Retrieved from https://www.iea.org/analysis?type=report

20 years of CCS in the UK



Data: NOAA, https://www.esrl.noaa.gov/gmd/ccgg/trends/index.html

20 years of CCS in the UK

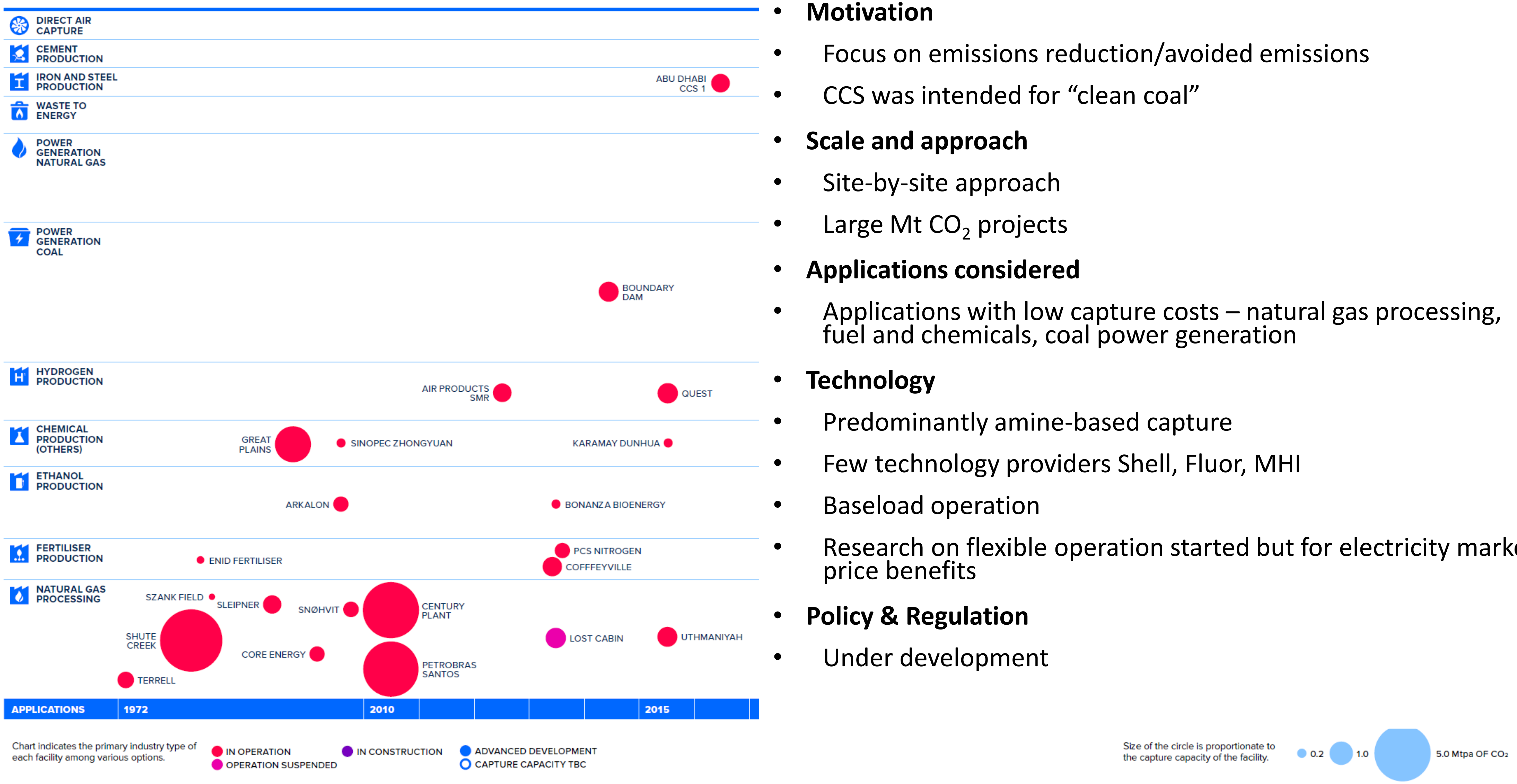
- The UK has been trying to deliver CCS for almost two decades
- Final Investment Decision (FID) imminent*, but what have we learned?
- How has how we think about CCS changed?
- What are the remaining challenges and next steps?

I hope…

What has changed?

Then	Now
“Clean Coal”	“Net Zero”
Policy vacuum	Global policy tailwinds
Avoided emissions	Net Zero, 1.5C, and CDR
Ambiguity of value of CCS	Indispensability of CCS
Point source to sink	Hubs, clusters, and networks
Baseload	Flexibility
Whole value chain	Split value chain
Pipelines	Multiple transport modes
“30 wt% MEA”	Diverse portfolio of capture technologies
Large scale, bespoke application	Modular, “cookie cutter” technologies
Technology “demonstration”	Technology “commercialisation”

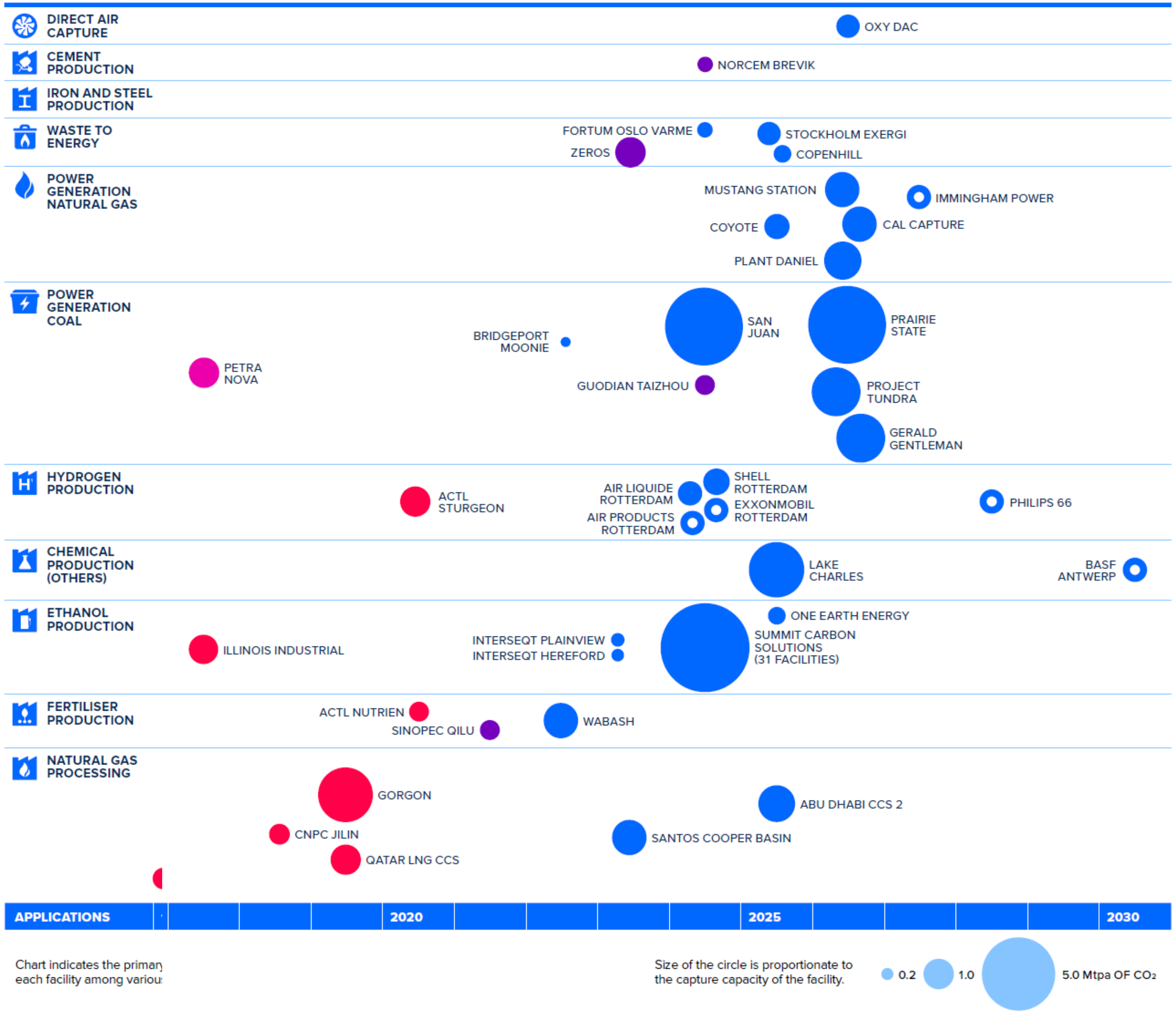
CCS then…



- **Motivation**
- Focus on emissions reduction/avoided emissions
- CCS was intended for “clean coal”
- **Scale and approach**
- Site-by-site approach
- Large Mt CO_2 projects
- **Applications considered**
- Applications with low capture costs – natural gas processing, fuel and chemicals, coal power generation
- **Technology**
- Predominantly amine-based capture
- Few technology providers Shell, Fluor, MHI
- Baseload operation
- Research on flexible operation started but for electricity market price benefits
- **Policy & Regulation**
- Under development

GCCSI, 2021. Global Status of CCS. https://www.globalccsinstitute.com/wp-content/uploads/2021/10/2021-Global-Status-of-CCS-Report_Global_CCS_Institute.pdf

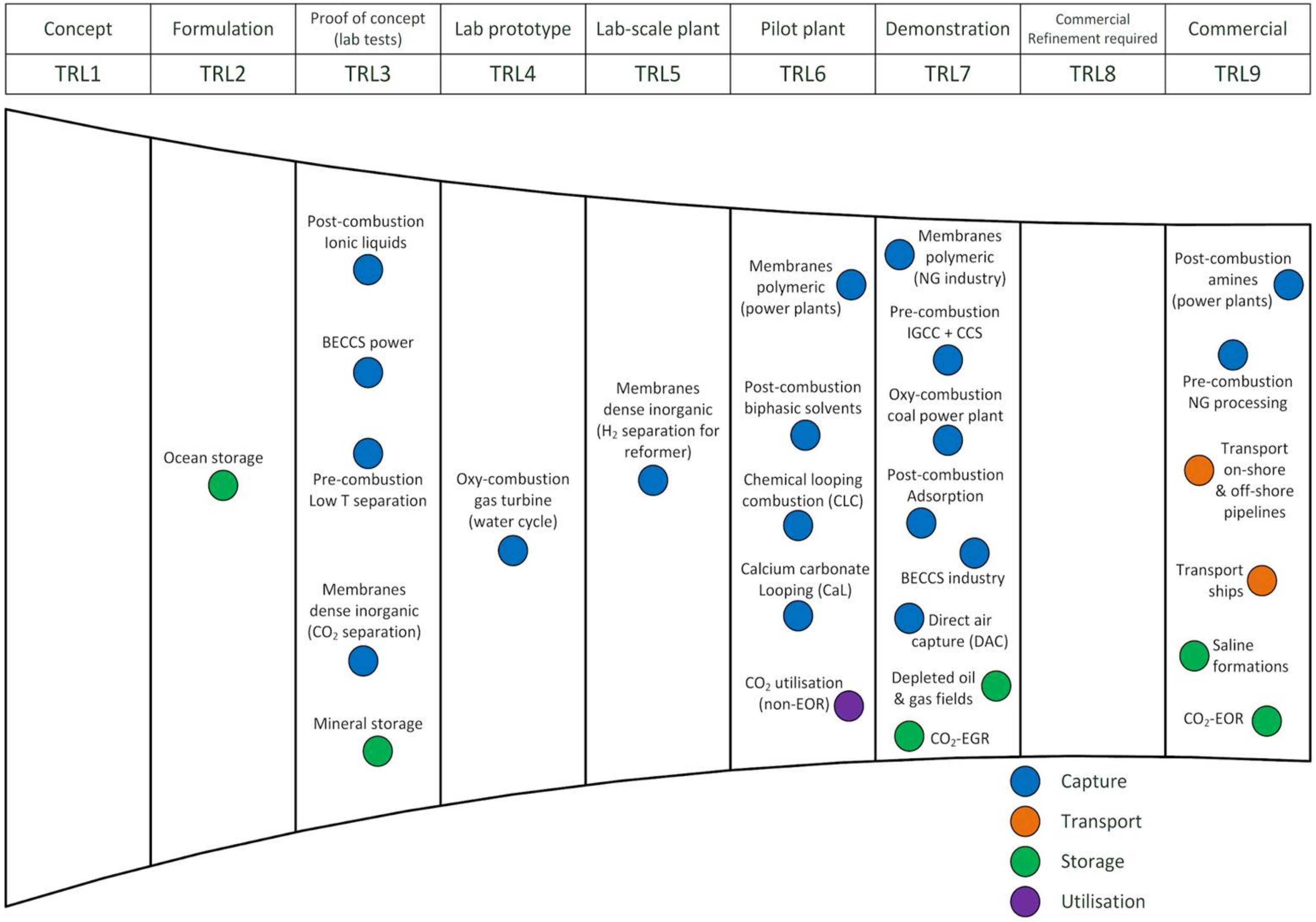
CCS now…



- **Motivation**
- Transition to focus on industrial applications and hubs and cluster approach. Driven by the narrative of "industrial decarbonisation" rather than "demonstrate CCS"
- **Scale and approach**
- Large and small point sources
- Modular construction ideal for distributed point sources (modularity)
- **Applications being considered**
- Power, industrial processes and blue hydrogen
- Carbon dioxide removal – BECCS and DACCS
- **Technology**
- More technology diversity (e.g., membranes, water lean solvents, solid sorbents)
- Flexible operation
- Multiple technology suppliers and vendors
- **Policy & Regulation**
- CCS policy and regulations is much more developed in the US (e.g., IRA), the UK, Norway and the EU (e.g., CBAM)
- Business models developed with input from private sector

GCCSI, 2021. Global Status of CCS. https://www.globalccsinstitute.com/wp-content/uploads/2021/10/2021-Global-Status-of-CCS-Report_Global_CCS_Institute.pdf

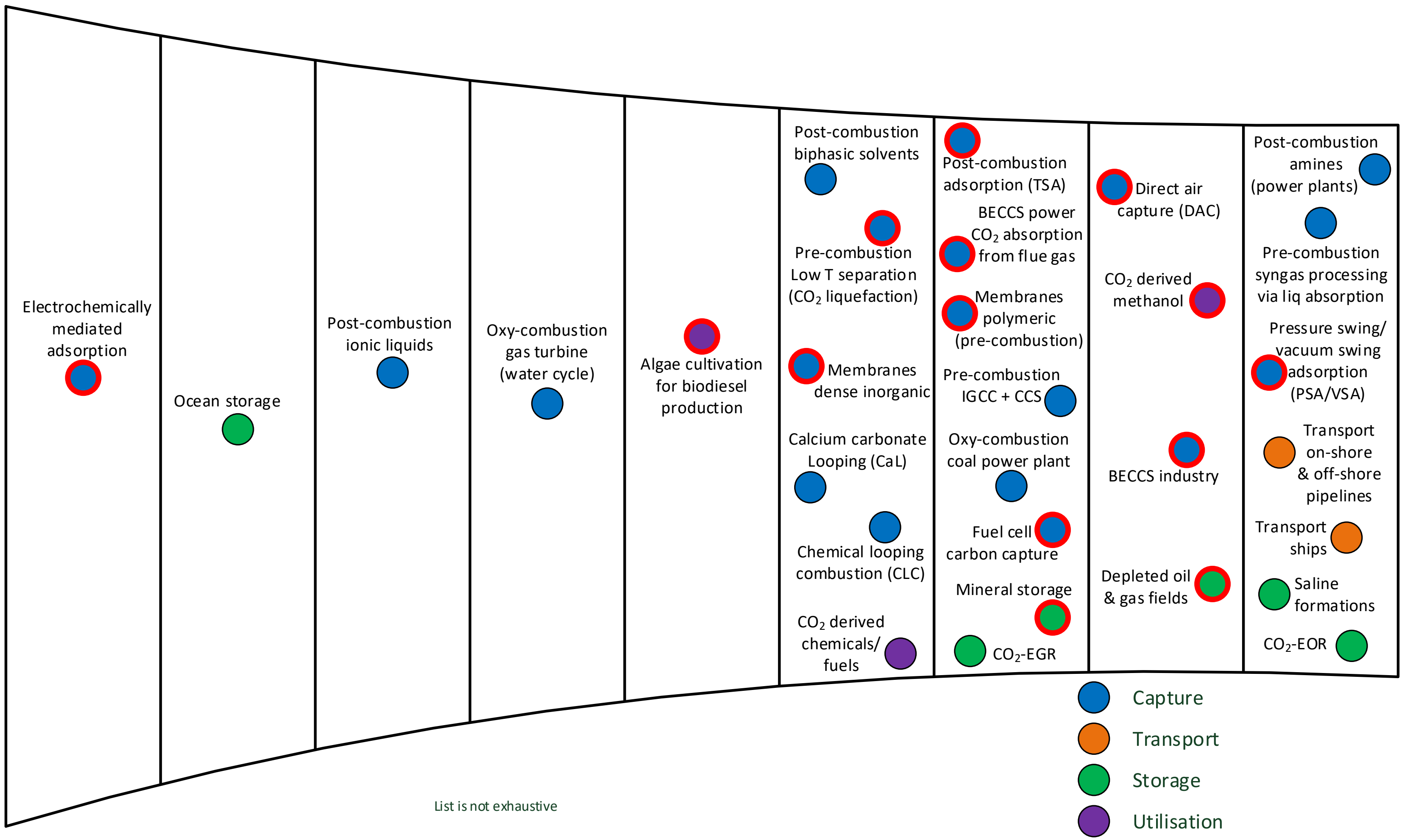
CCS technology pipeline - 2018



Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176

CCS technology pipeline - 2024

Concept	Formulation	Proof of concept (lab tests)	Lab prototype	Lab-scale plant	Pilot plant	Demonstration	Commercial Refinement required	Commercial
TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9



Adapted from Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176

Updated from data in:

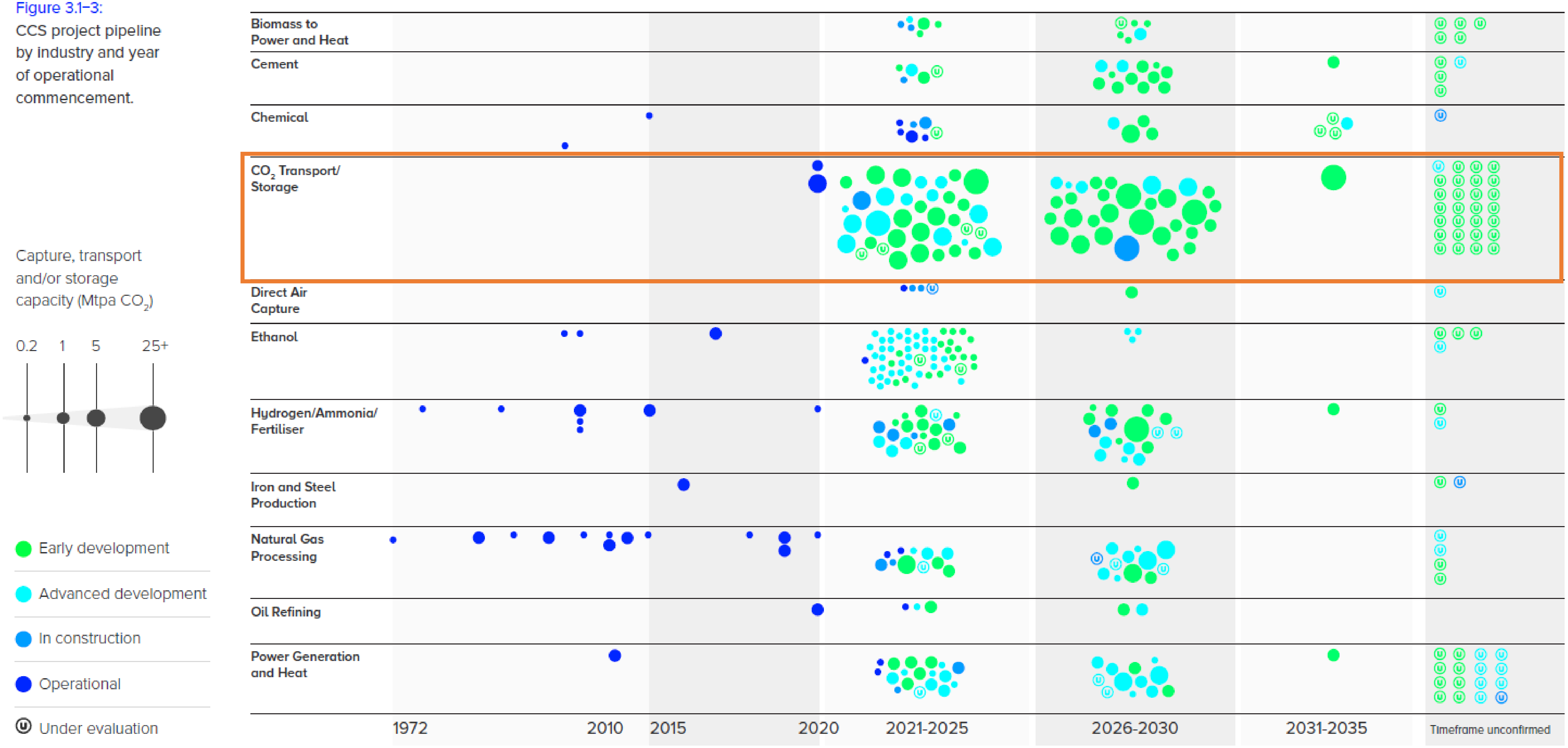
1) Bukar & Asif (2024). https://doi.org/10.1016/j.rser.2024.114578
2) GCCSI (2023). https://www.globalccsinstitute.com/wp-content/uploads/2023/08/State-of-the-Art-CCS-Technologies-2023-Global-CCS-Institute.pdf
3) Rezaei et al. (2023). Emerging technologies in post-combustion carbon dioxide capture & removal. https://doi.org/10.1016/j.cattod.2023.114286
4) Raganati, F. & Ammendola, P. (2024). CO_2 Post-combustion Capture: A Critical Review of Current Technologies and Future Directions. Energy & Fuels. 10.1021/acs.energyfuels.4c02513
5) Raganati, F., Miccio, F. & Ammendola, P. (2021). Energy & Fuels, 35 (16), 12845-12868. 10.1021/acs.energyfuels.1c01618
6) Roussanaly, S. et al. (2020). Front. Chem. Sci. Eng., 14(3): 436–452. https://doi.org/10.1007/s11705-019-1870-8
7) Mulk et al. (2023). Journal of CO_2 Utilization, 75, 102555. https://doi.org/10.1016/j.jcou.2023.102555

CCS starts with a store

GCCSI, 2023. Global Status of CCS. https://www.globalccsinstitute.com/wp-content/uploads/2024/01/Global-Status-of-CCS-Report-1.pdf

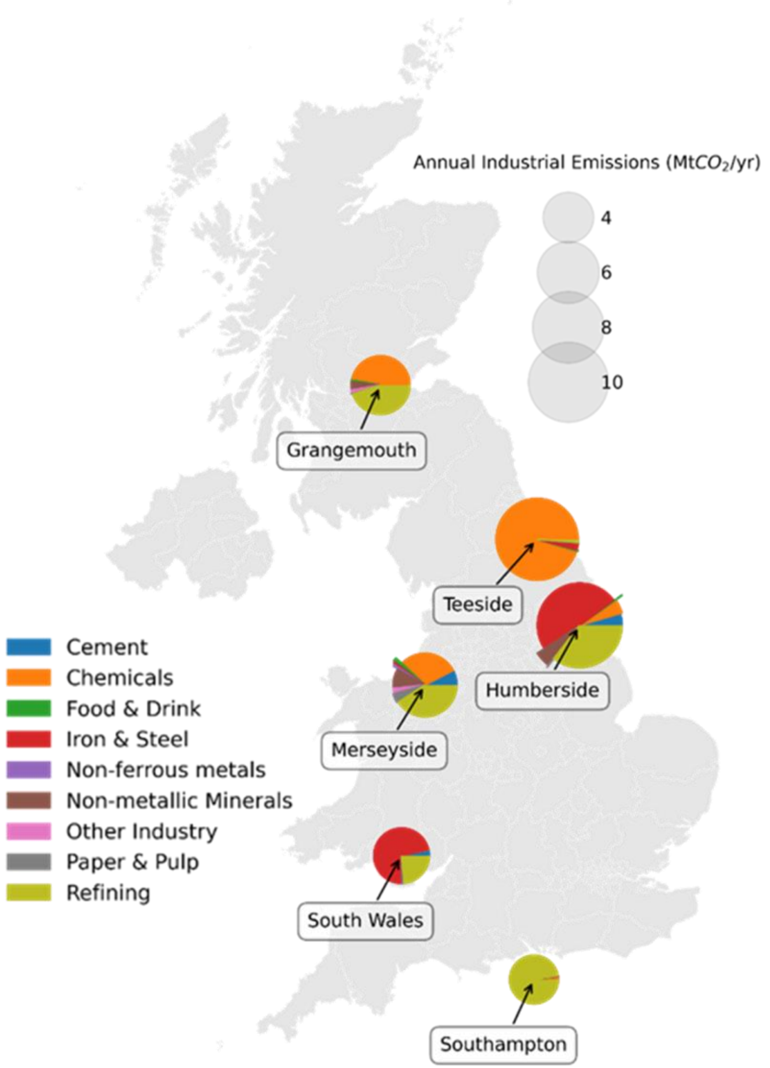
CCS starts with a store

Figure 3.1–3:
CCS project pipeline by industry and year of operational commencement.



GCCSI, 2023. Global Status of CCS. https://www.globalccsinstitute.com/wp-content/uploads/2024/01/Global-Status-of-CCS-Report-1.pdf

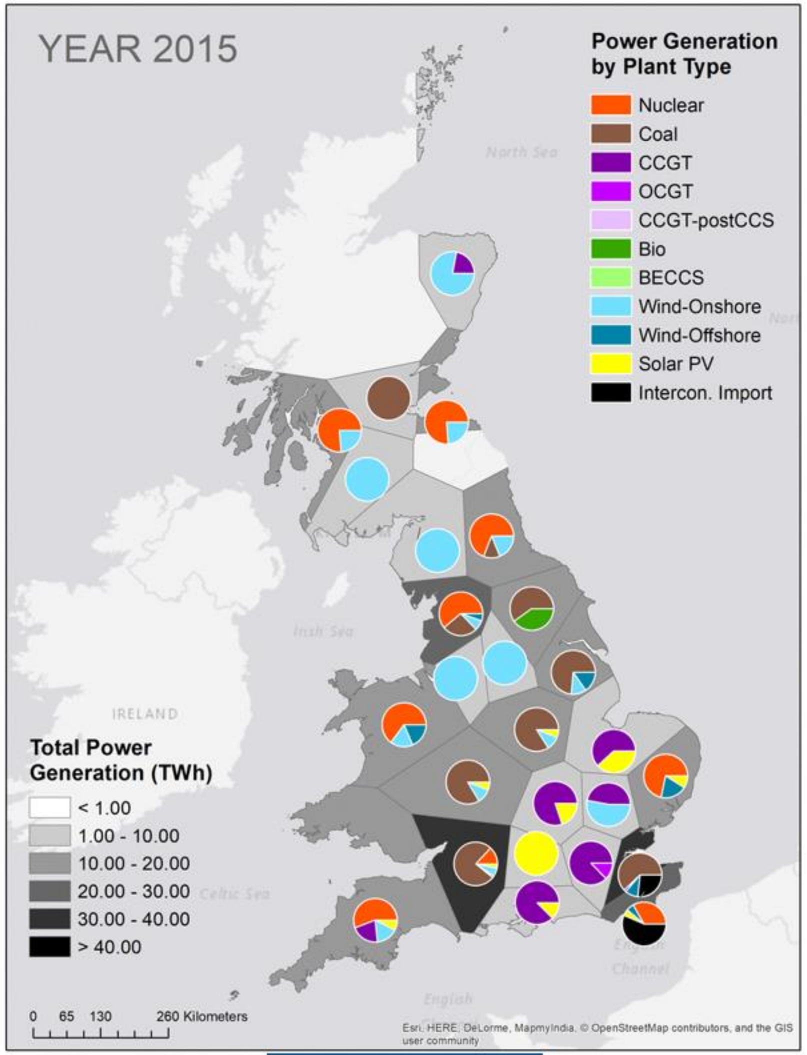
UK strategy for CCS deployment



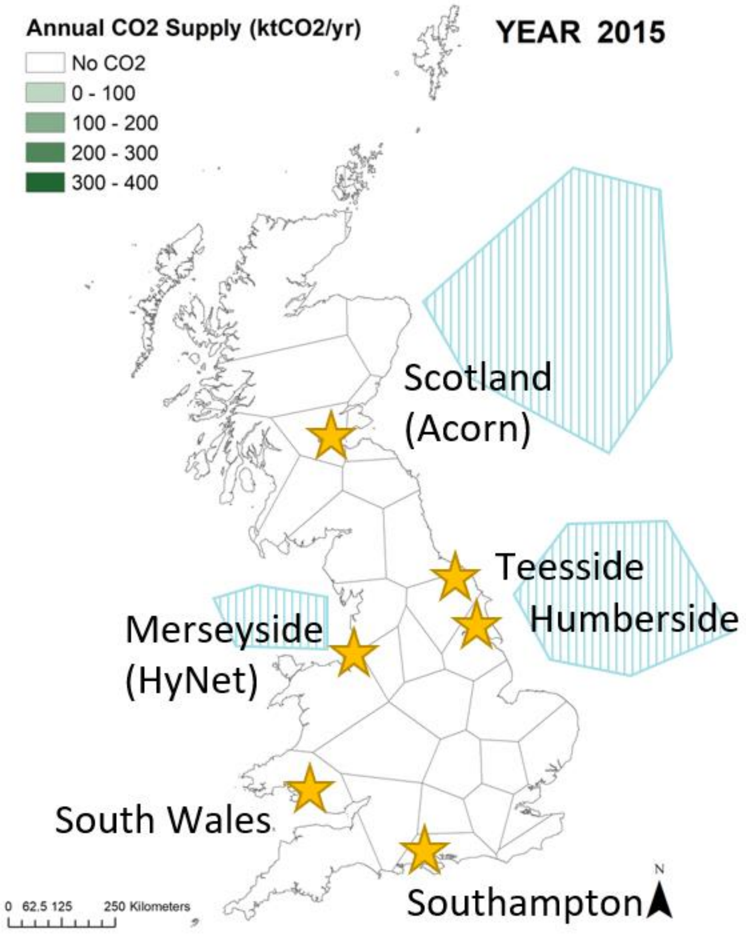
- UK's industrial decarbonisation challenge ran from 2019 – 2024
- Provided £210M of public funding, leveraged £261M of industrial funding to support FEED studies
- HMG has adopted a "Cluster Sequencing" process with a combination of power and industry projects selected for Track 1
  - HyNet North West: hydrogen and industry
  - East Coast Cluster: power and hydrogen
- Track 2: Scottish and Humber clusters

a UKRI, 2024. Industrial Decarbonisation. https://www.ukri.org/what-we-do/browse-our-areas-of-investment-and-support/industrial-decarbonisation
b https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-deployment-phase-1-expressions-of-interest/october-2021-update-track-1-clusters-confirmed
c https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-track-2/ccus-cluster-sequencing-track-2-market-update-december-2023

Sector coupling across power, industry & transport



Base case



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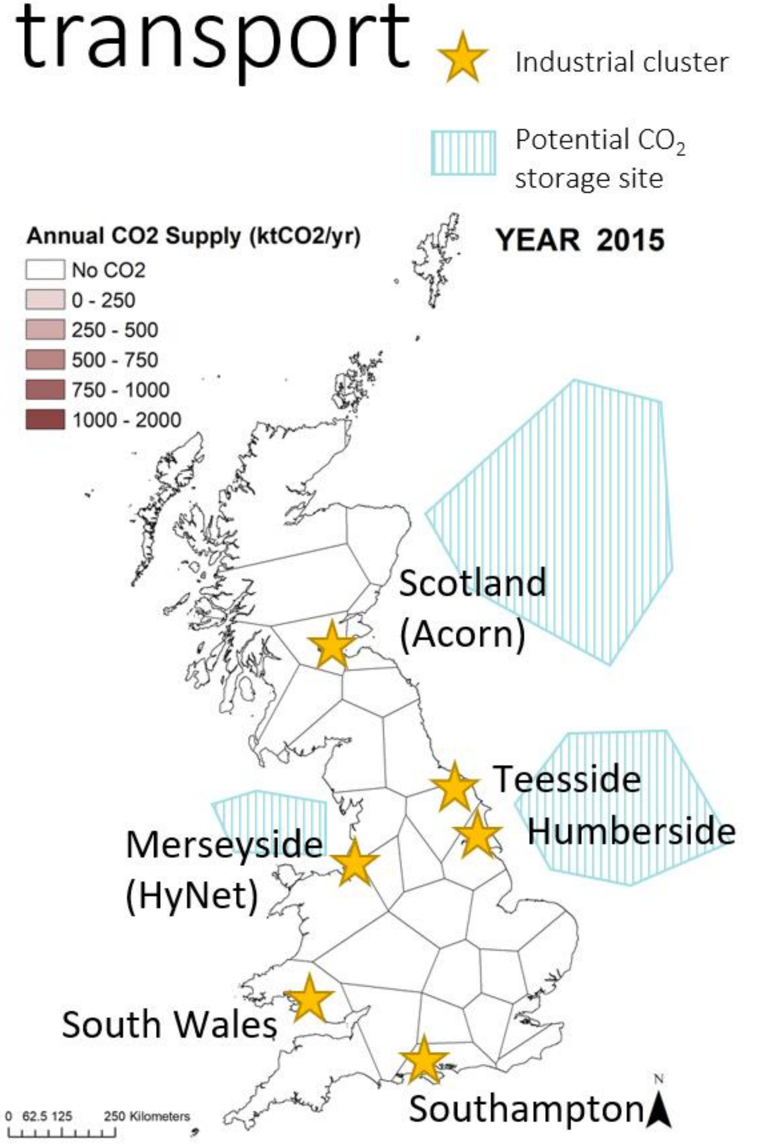


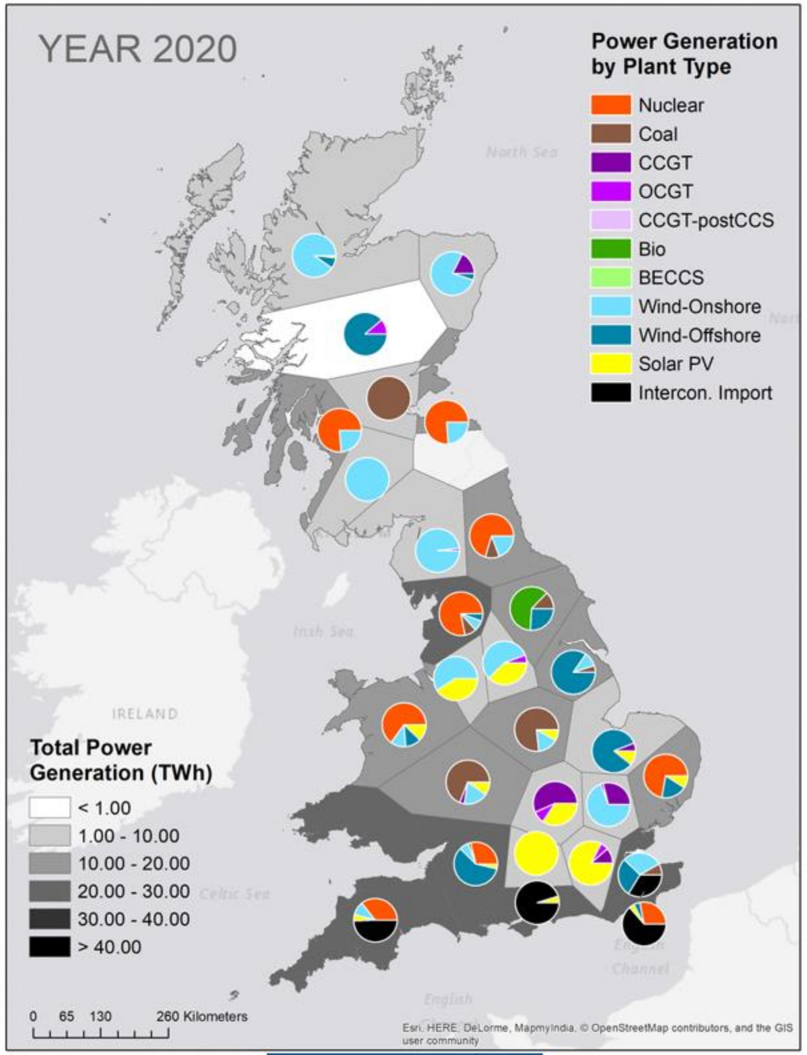
CO_2 supplied from CCS

Heuberger, C. F., Bains, P. K. & Mac Dowell, N. (2020) Applied Energy, 257, 113715. https://doi.org/10.1016/j.apenergy.2019.113715

Sector coupling across power, industry & transport

★ Industrial cluster

Potential CO_2 storage site



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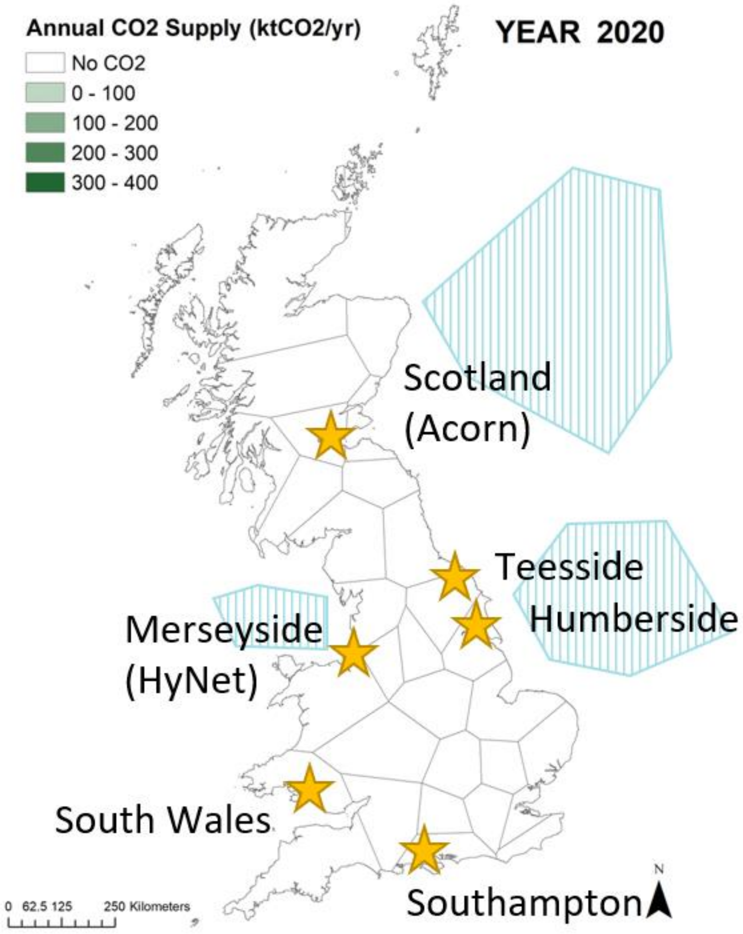

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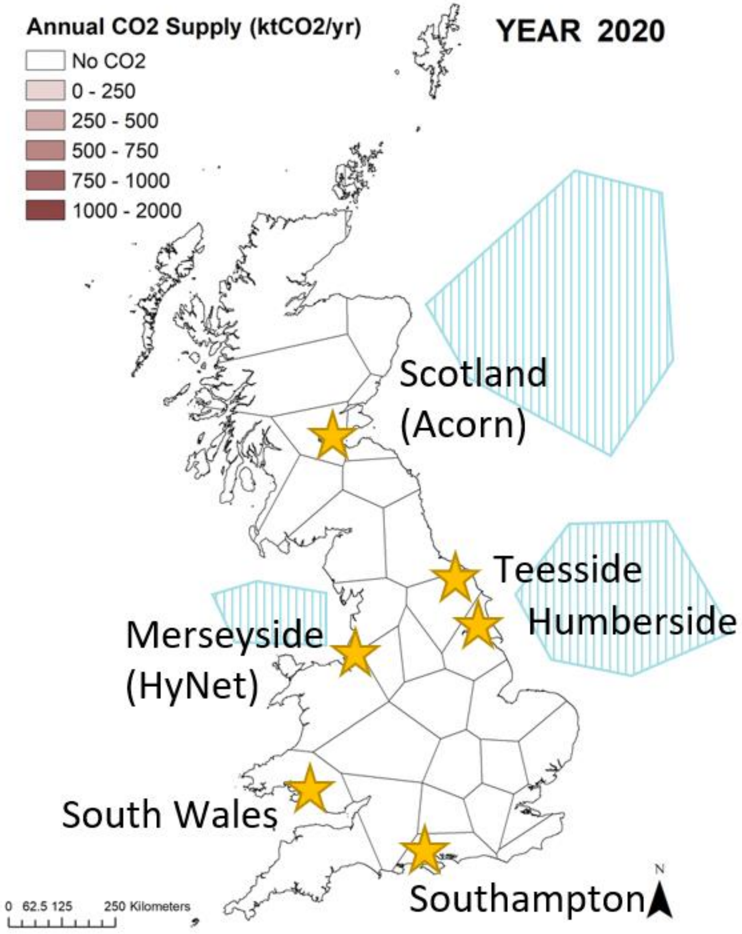

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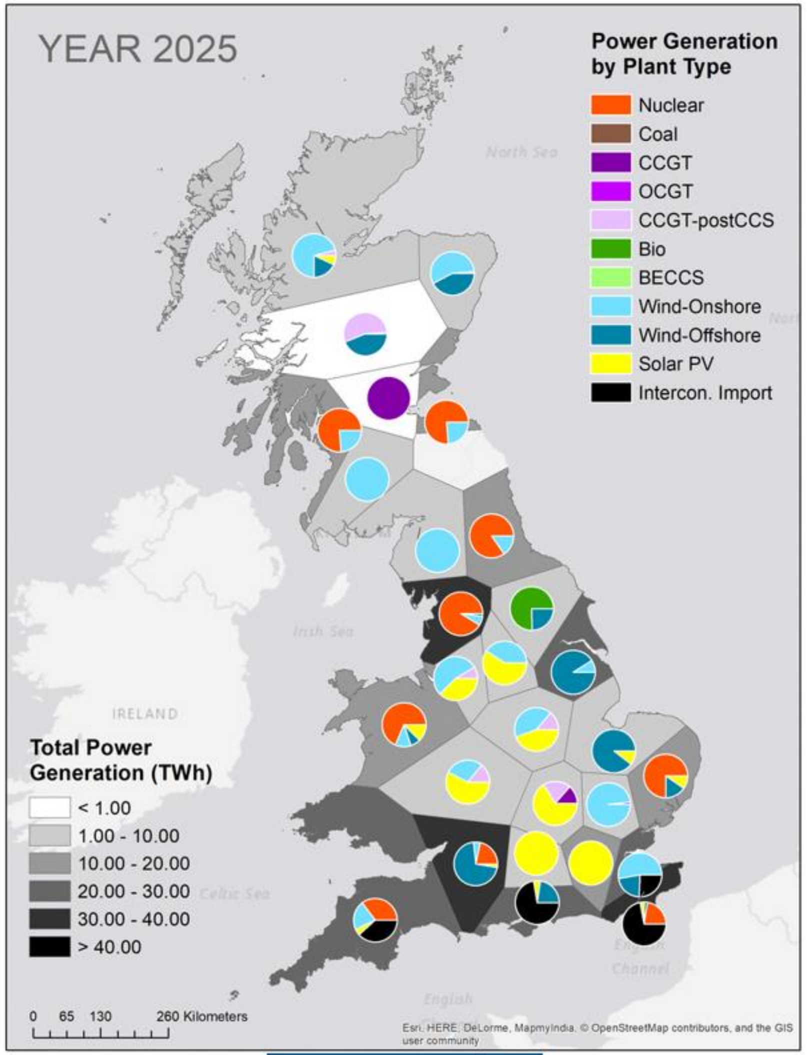

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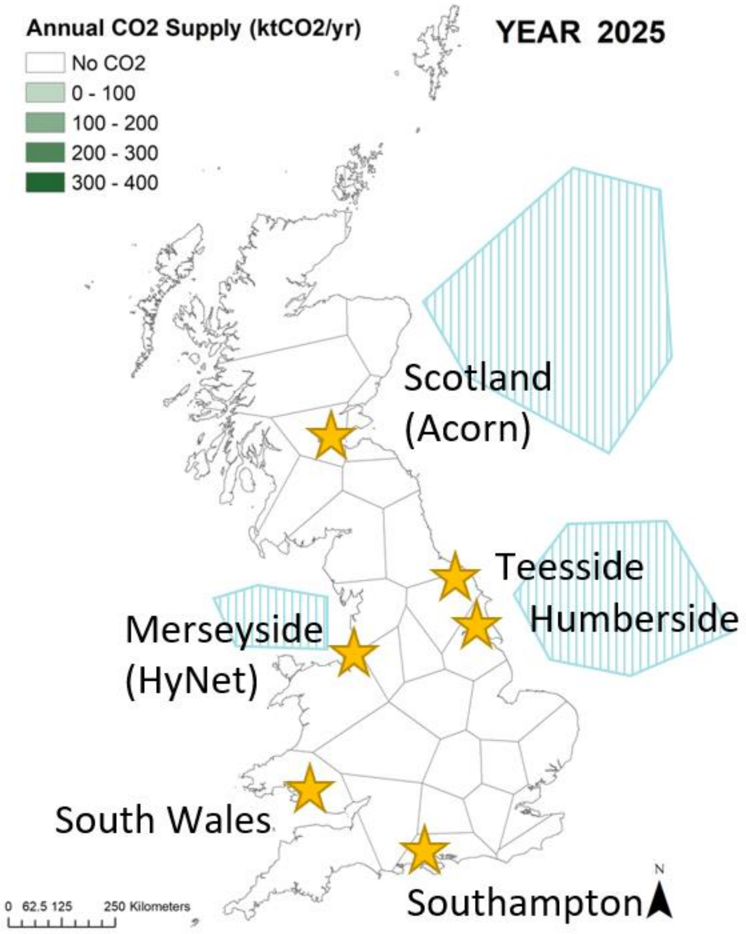

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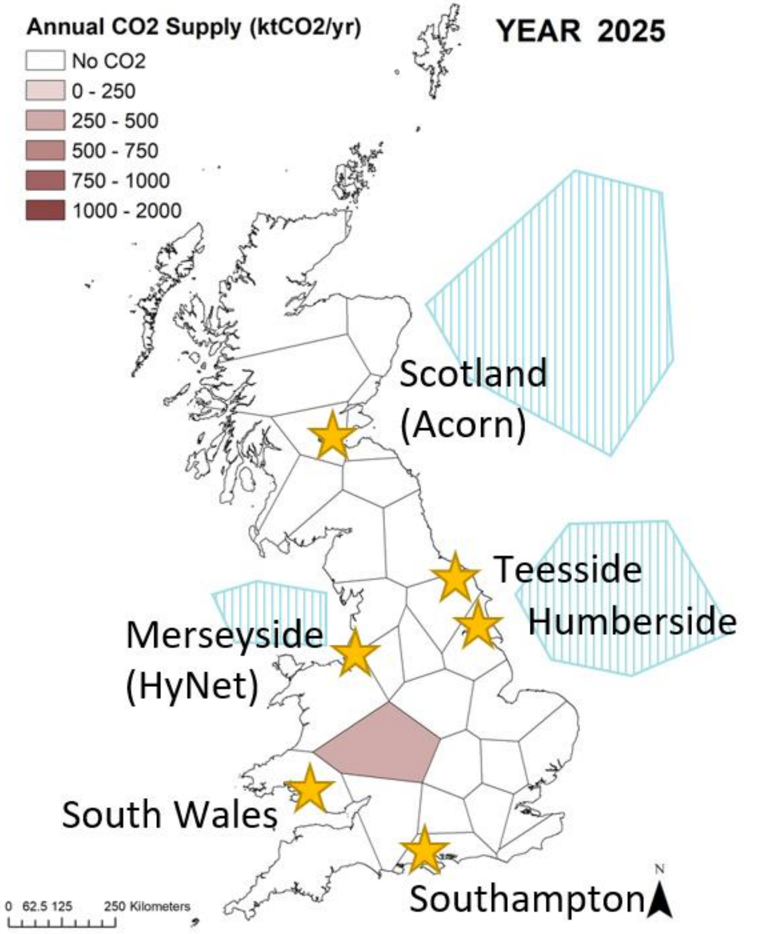

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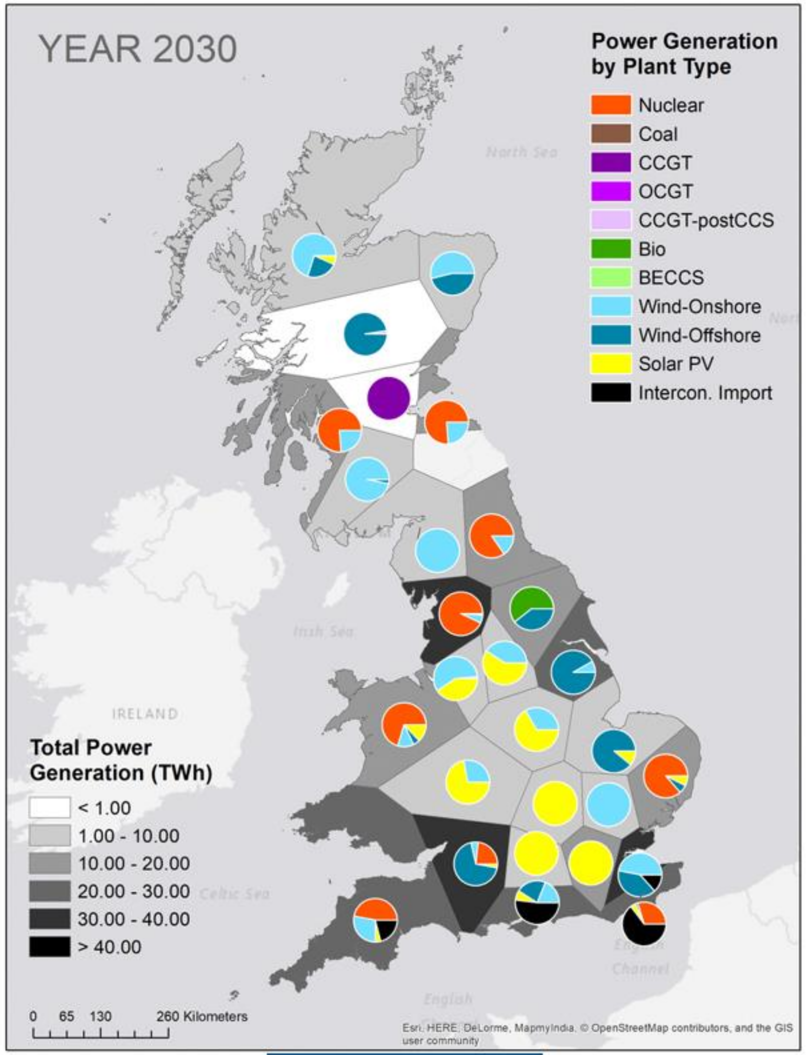

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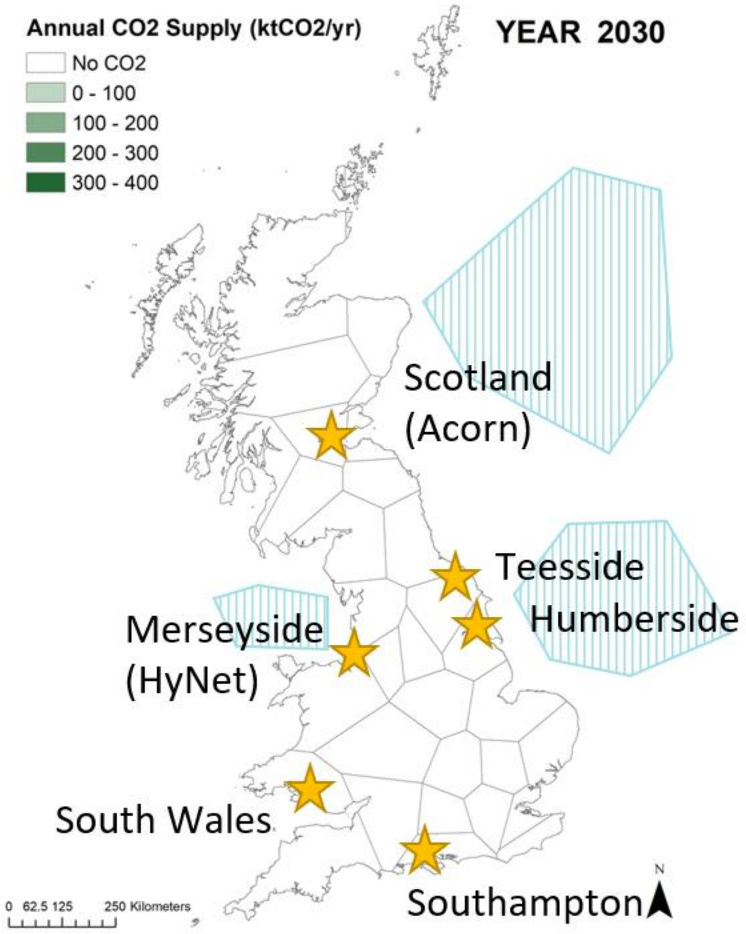

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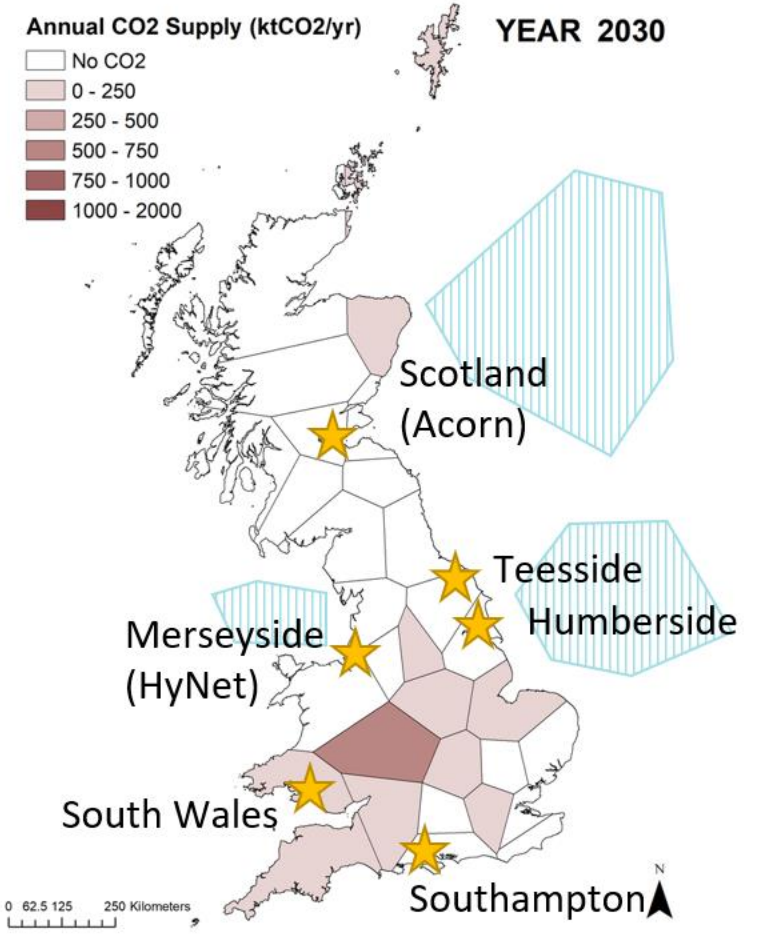

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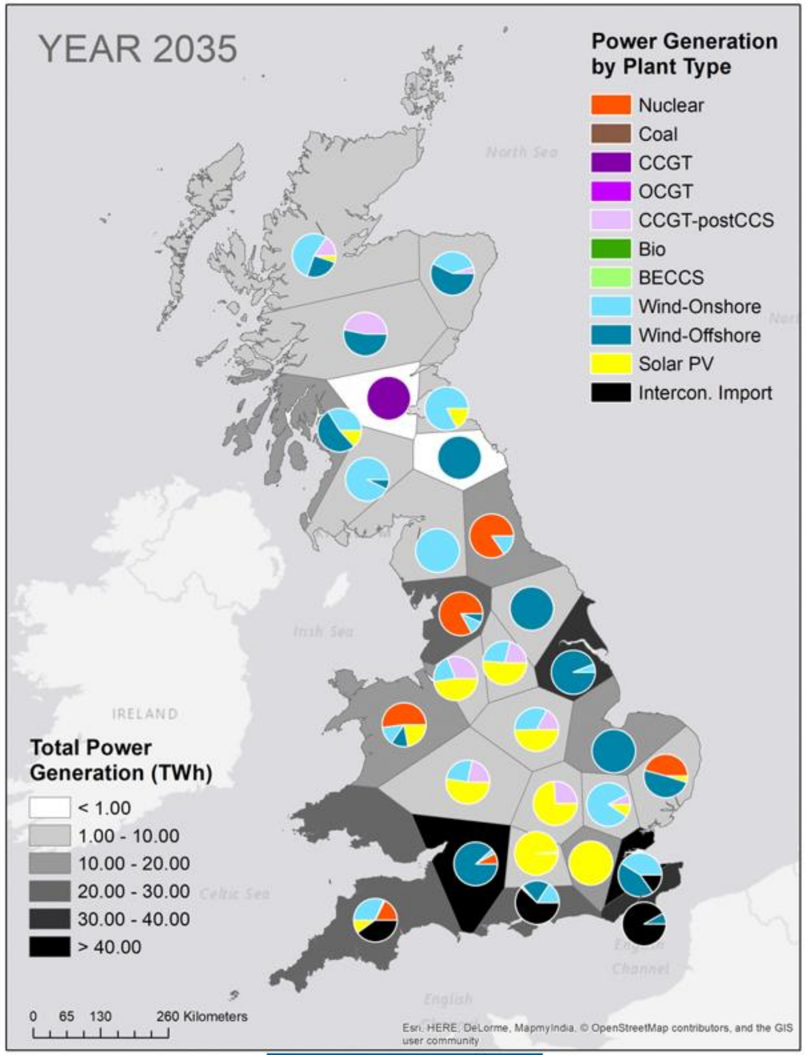

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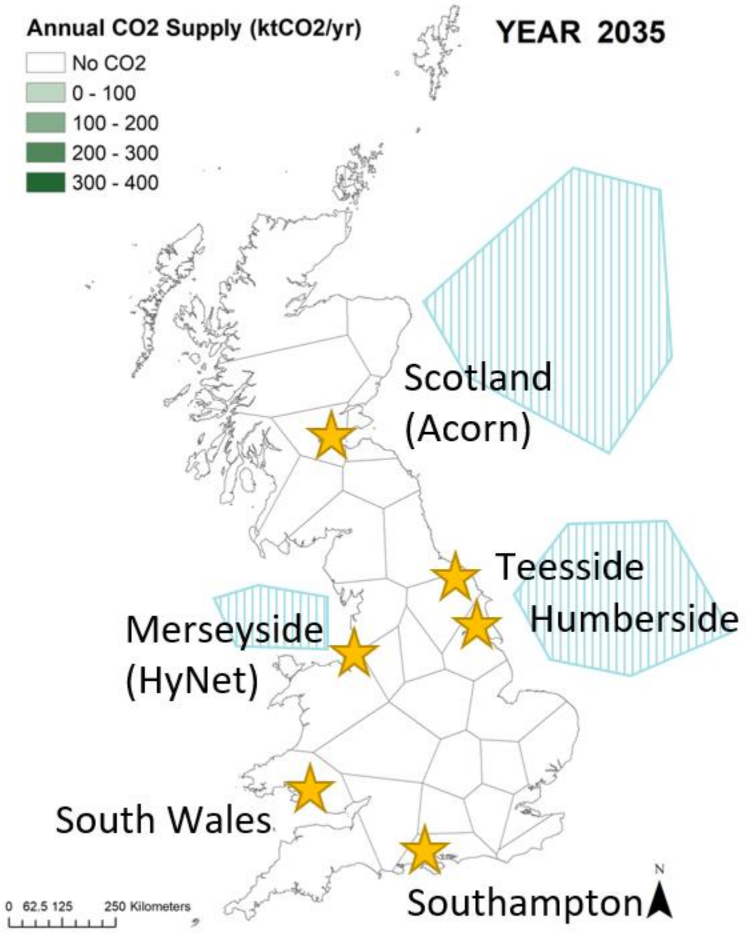

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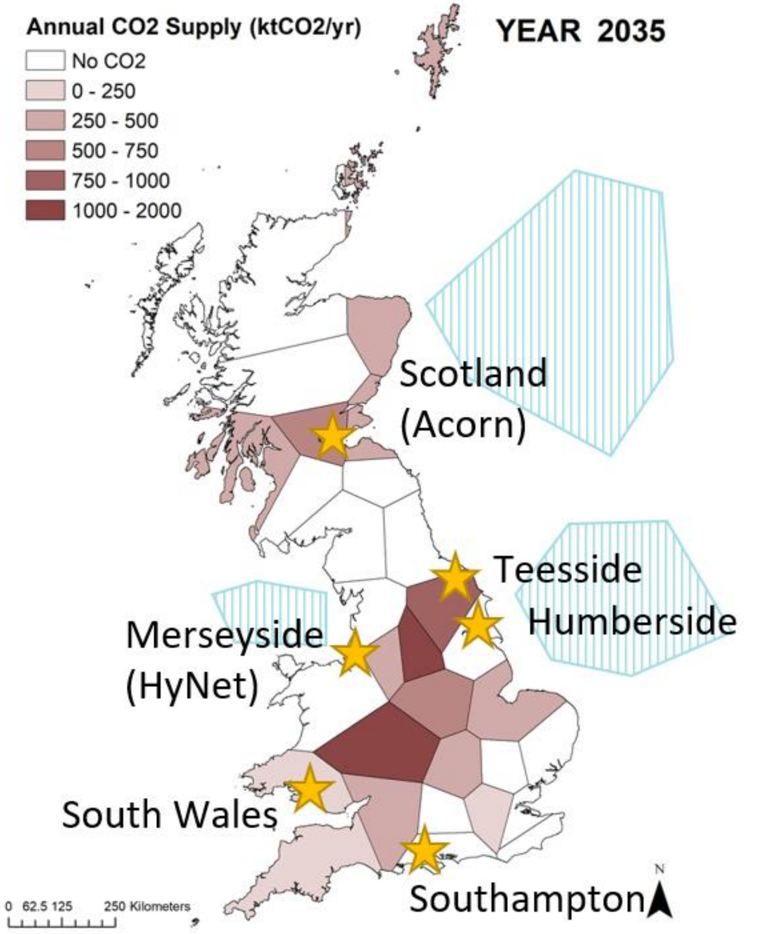

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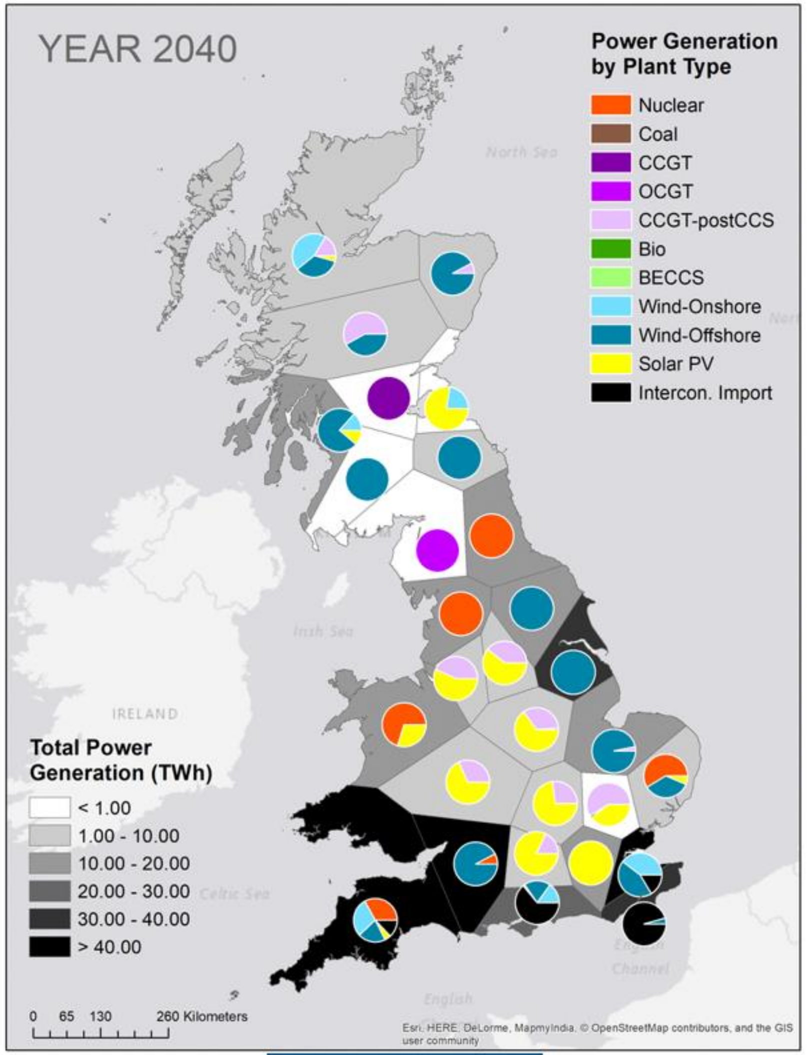

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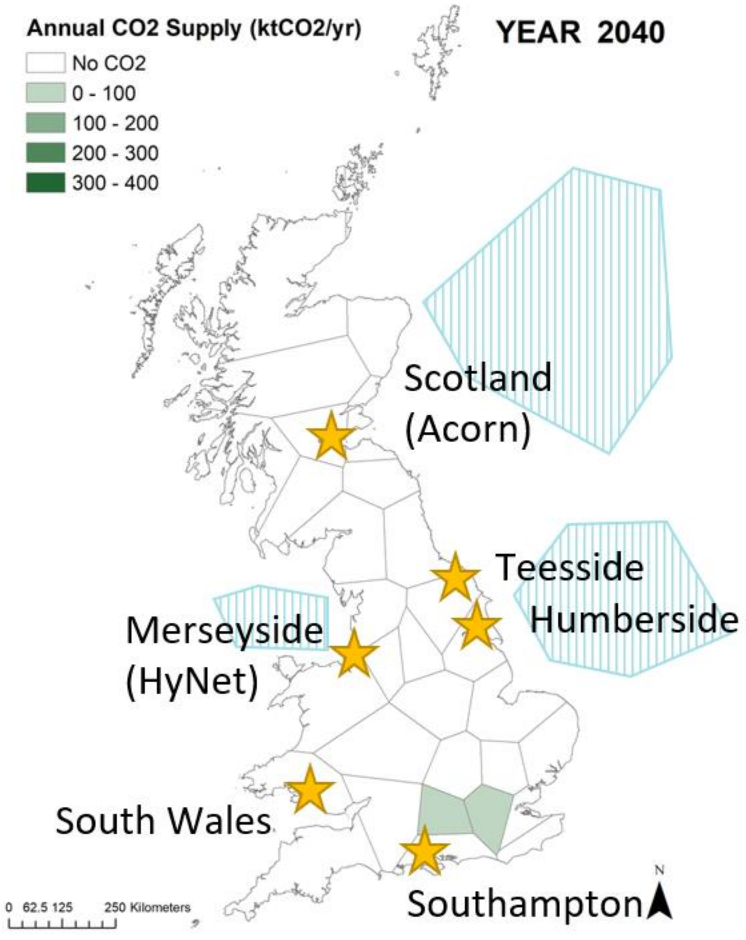

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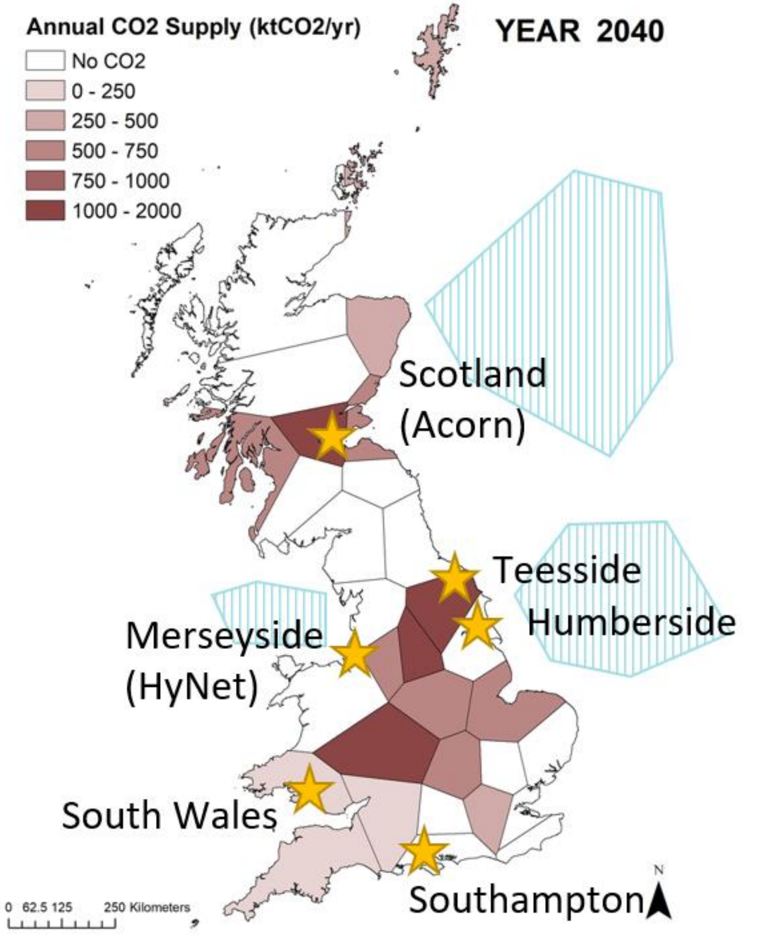

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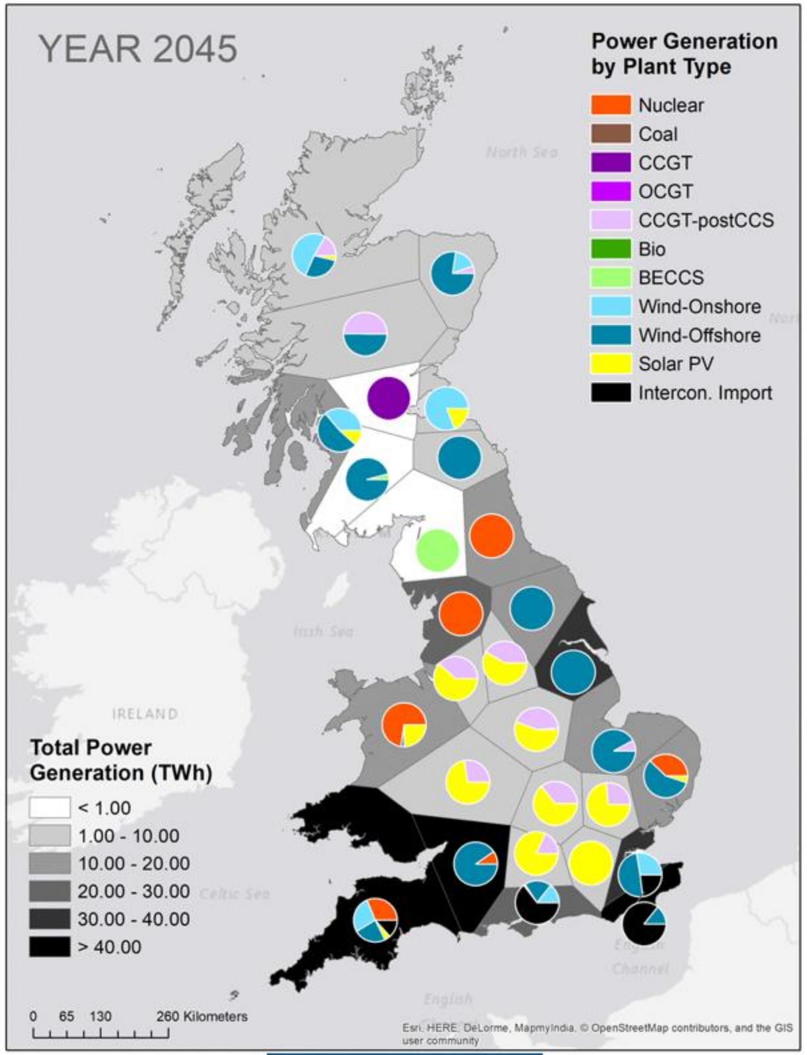

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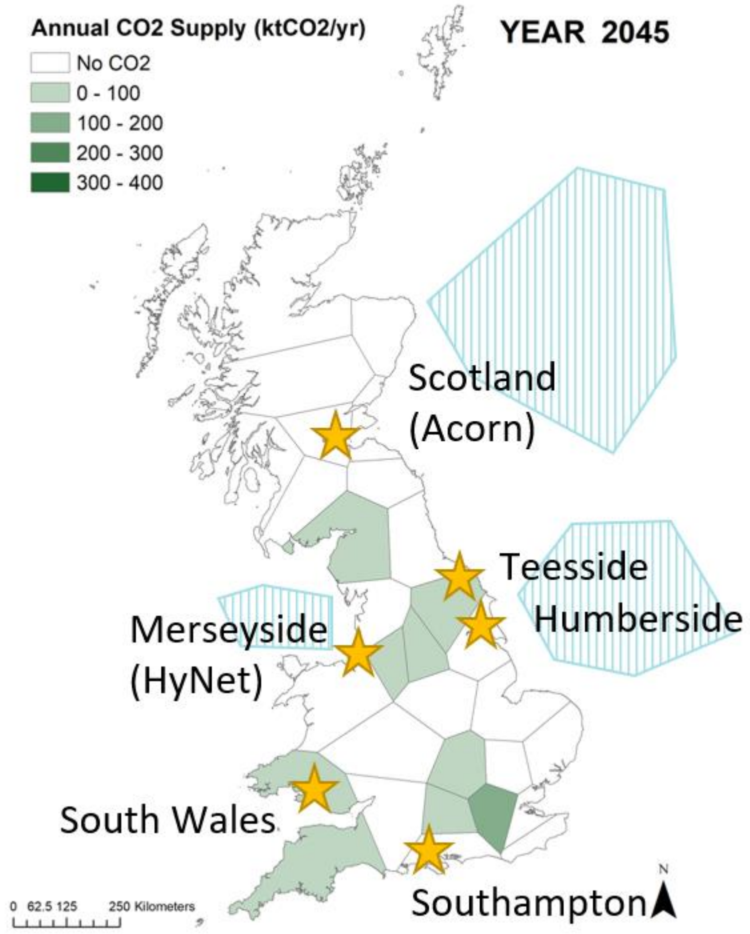

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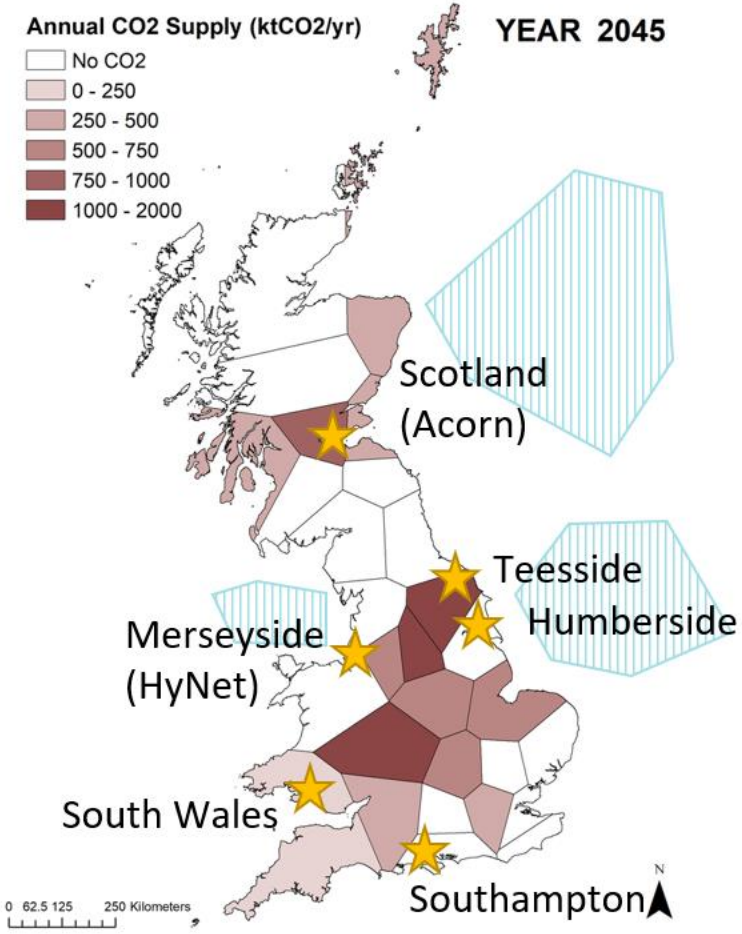

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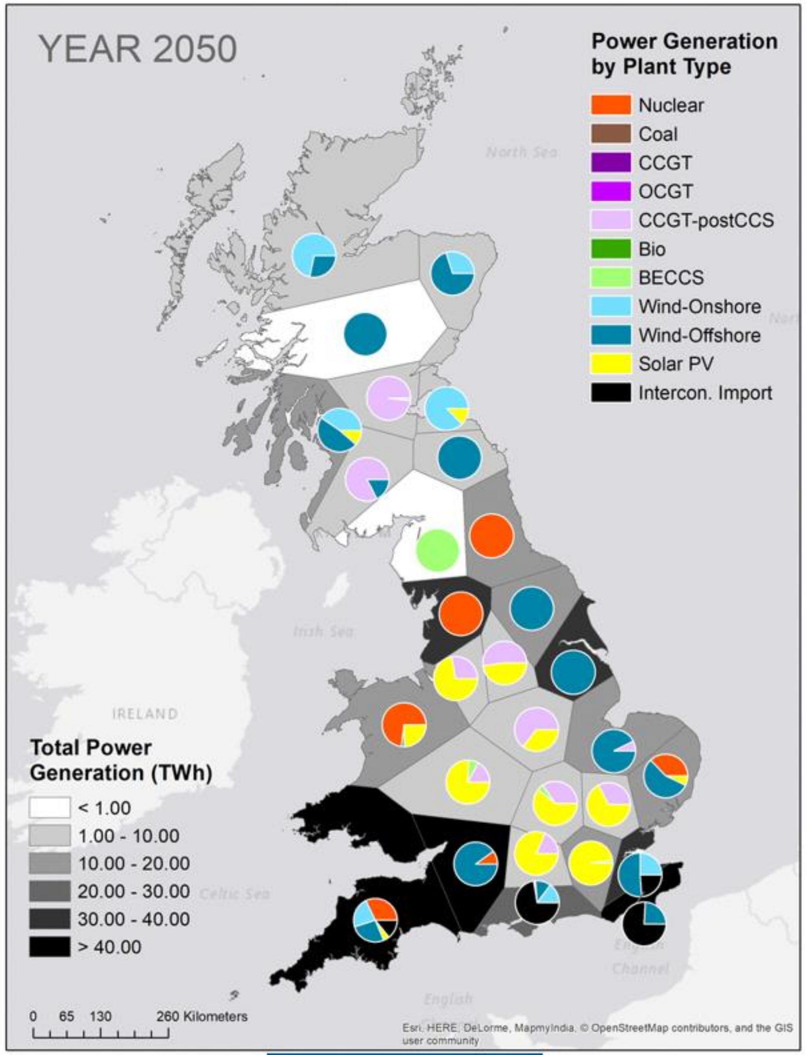

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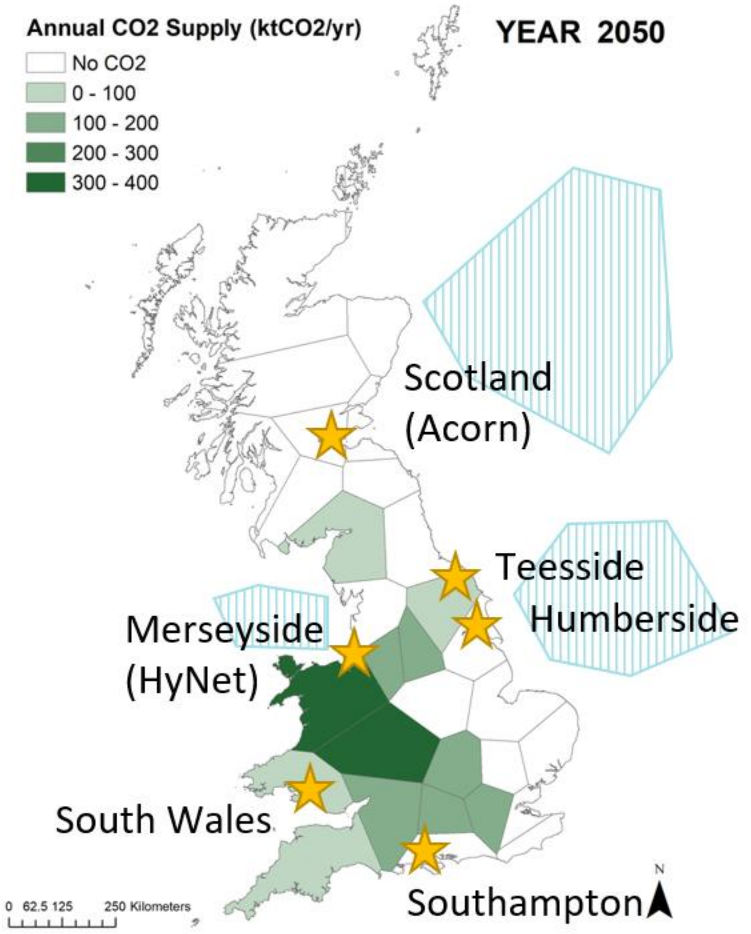

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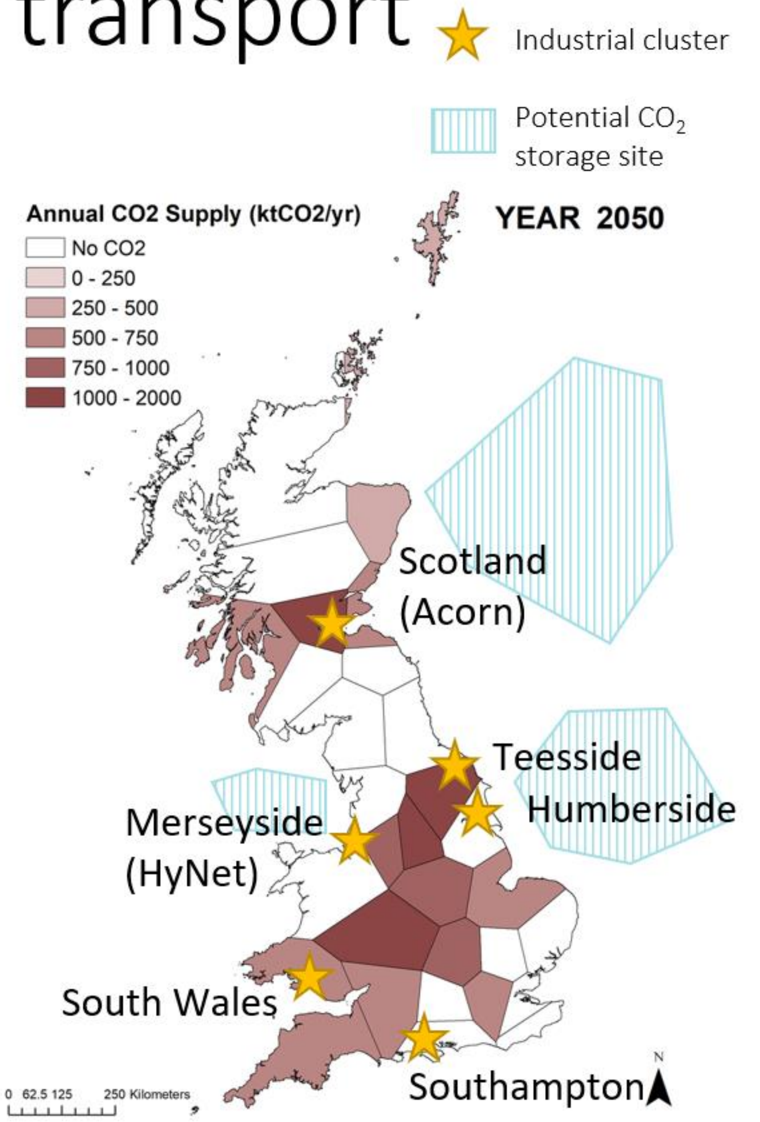

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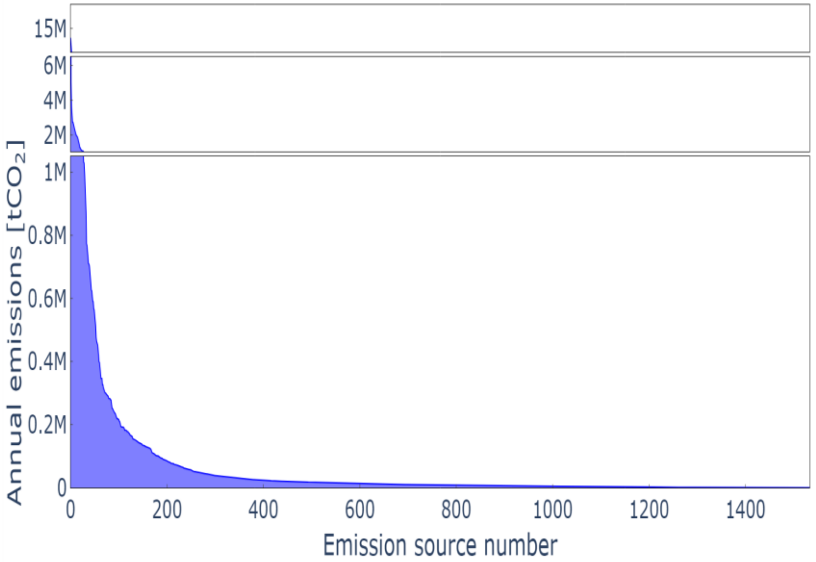
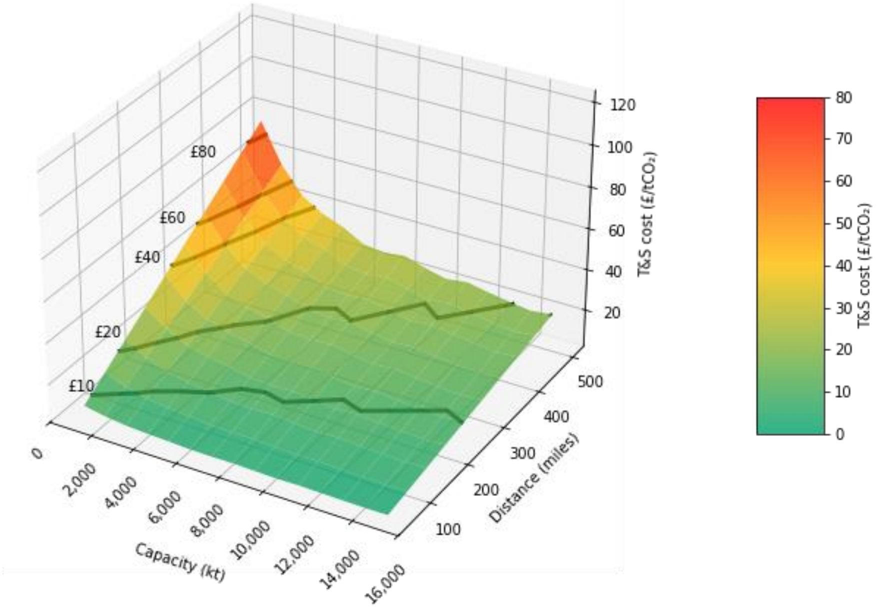
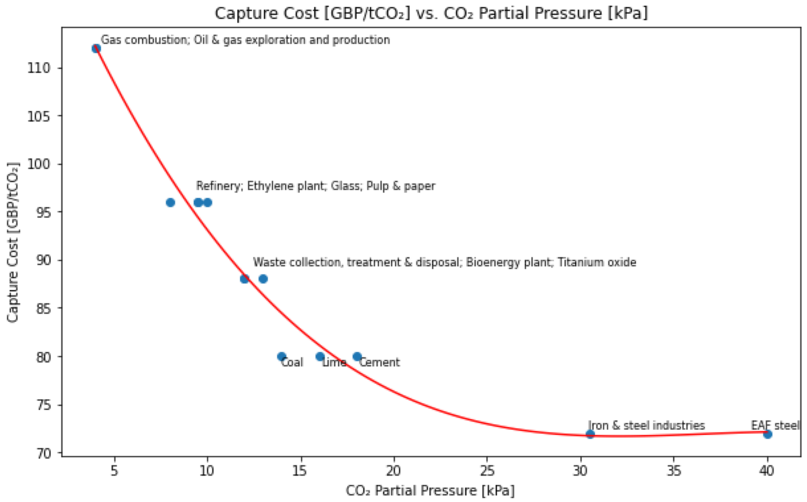
Evolution of UK's CCS infrastructure

- Industrial clusters only account for 16% of total UK emissions
- 88% of the UK's point source emitters are "small", i.e., < 100 ktpa and dispersed
- Thus, key questions remain
  - How will the UK's CO_2 T&S infrastructure evolve?
  - What are the cost vs. scale trade-offs?

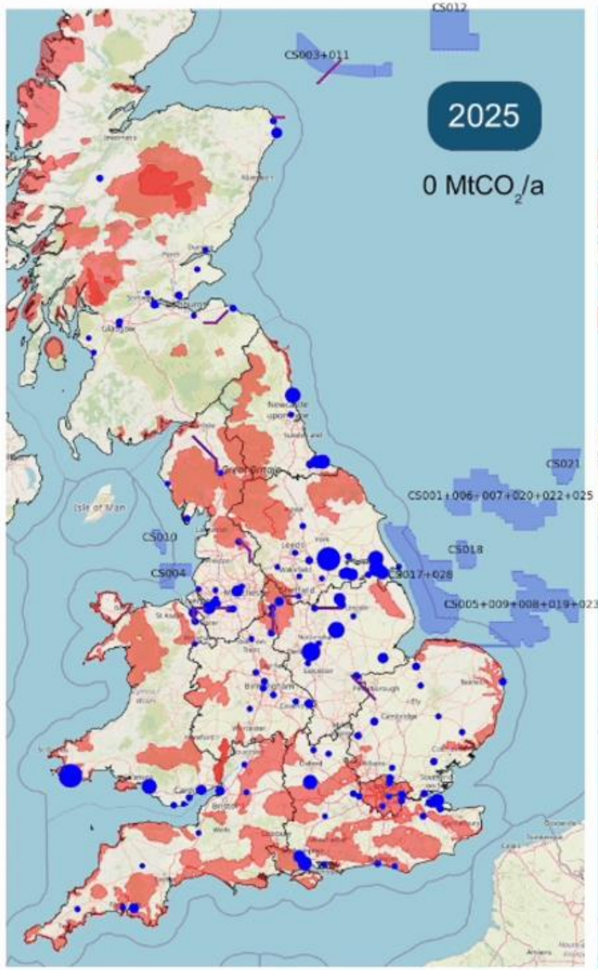




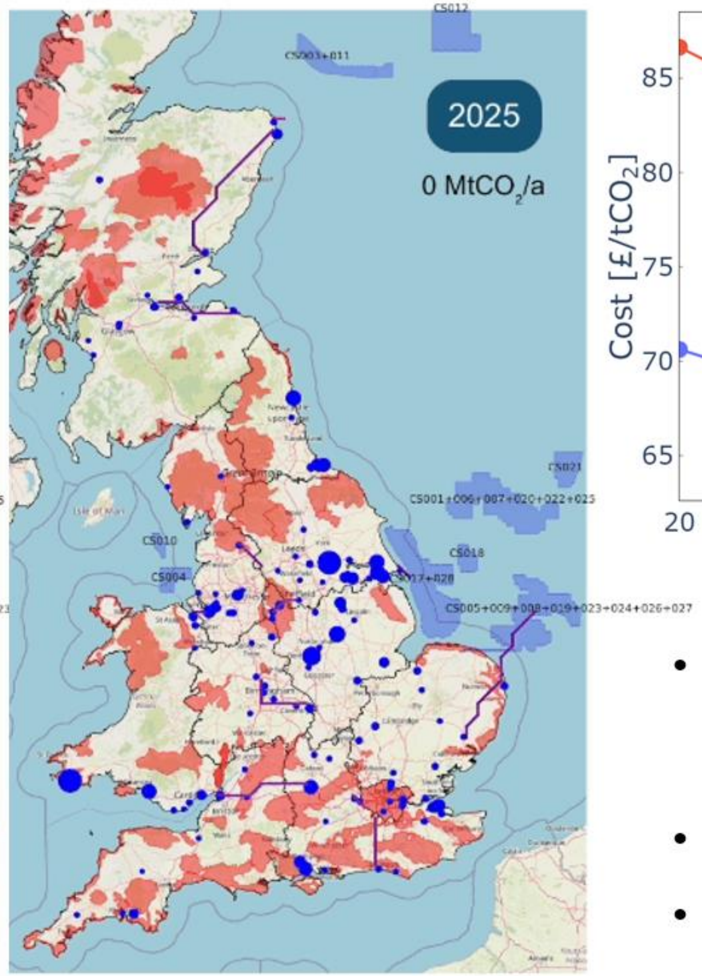


Different approaches to CCS development

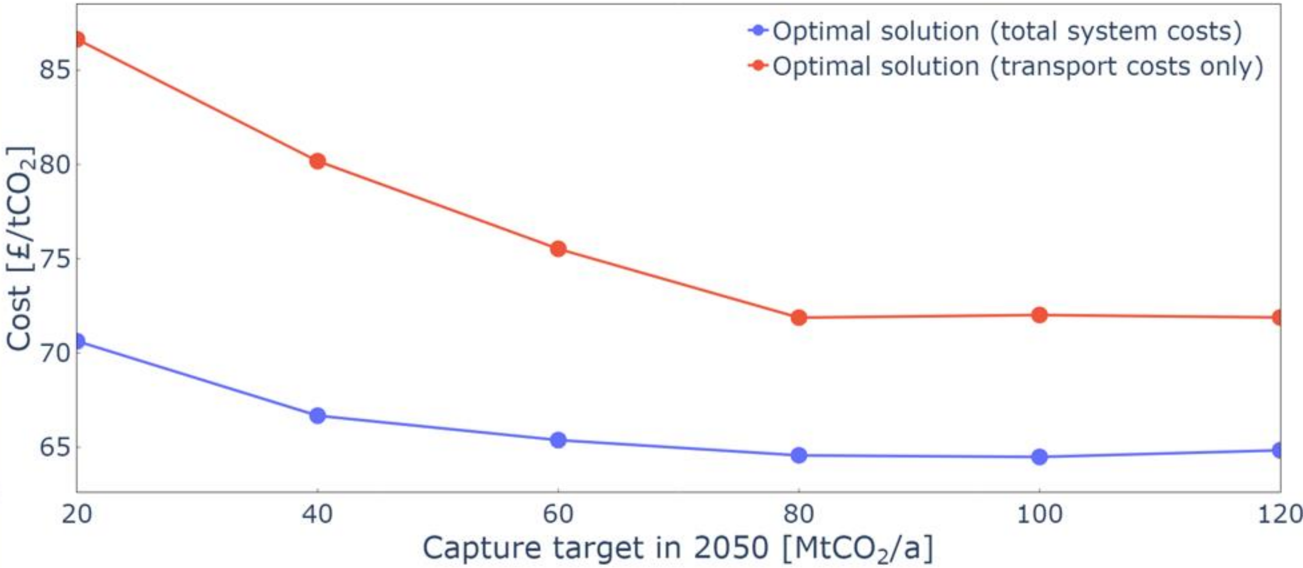
Central planning



Project by project approach



Value of strategic planning



- The current "cluster by cluster" approach to CCS development in the UK is closer to the red line than the blue
- As CCS deployment grows, the cost ratio approaches unity.
- Ensure that all pipelines are using a similar CO_2 specification so future system integration can occur

Mersch et al. (2024). Study for DESNZ, HMG

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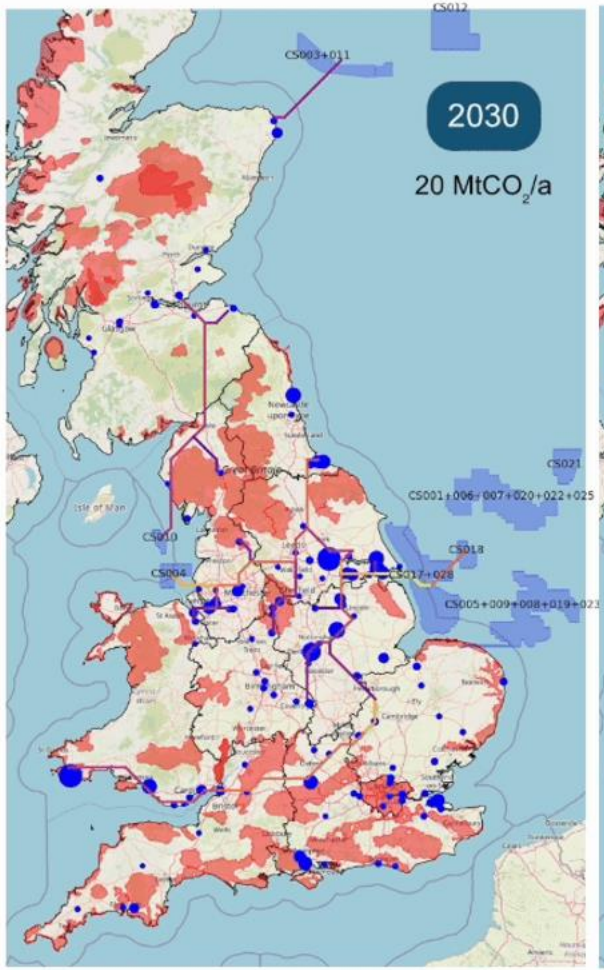

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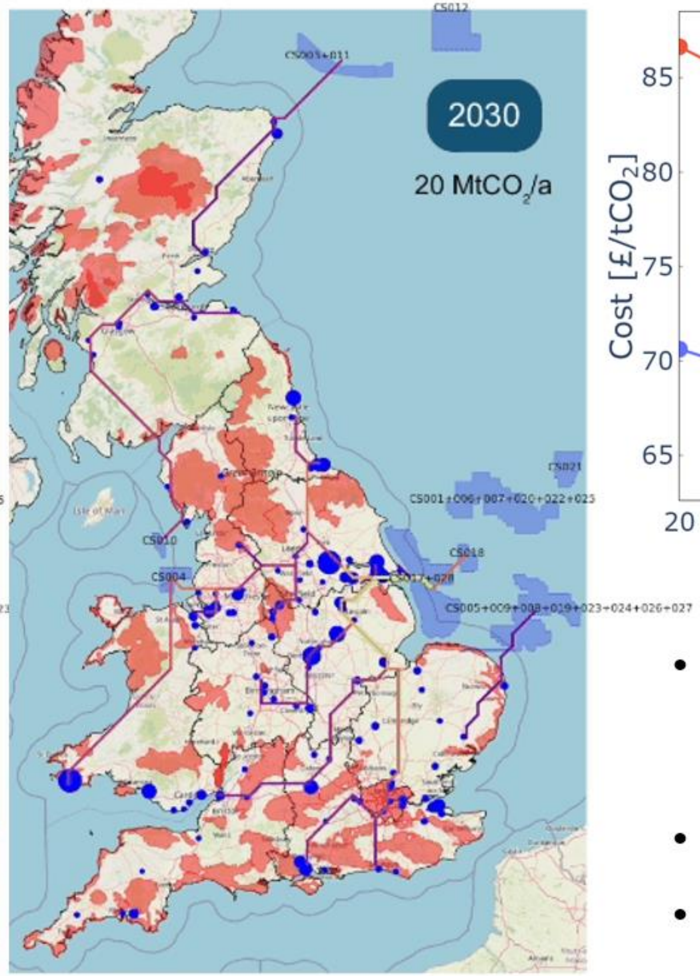

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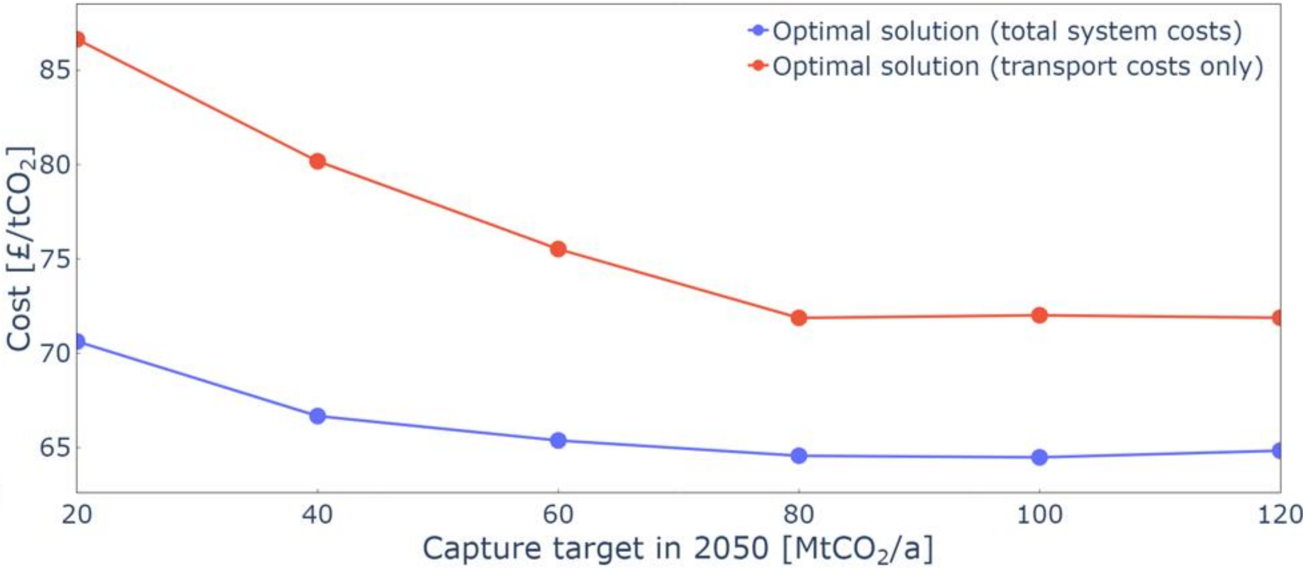

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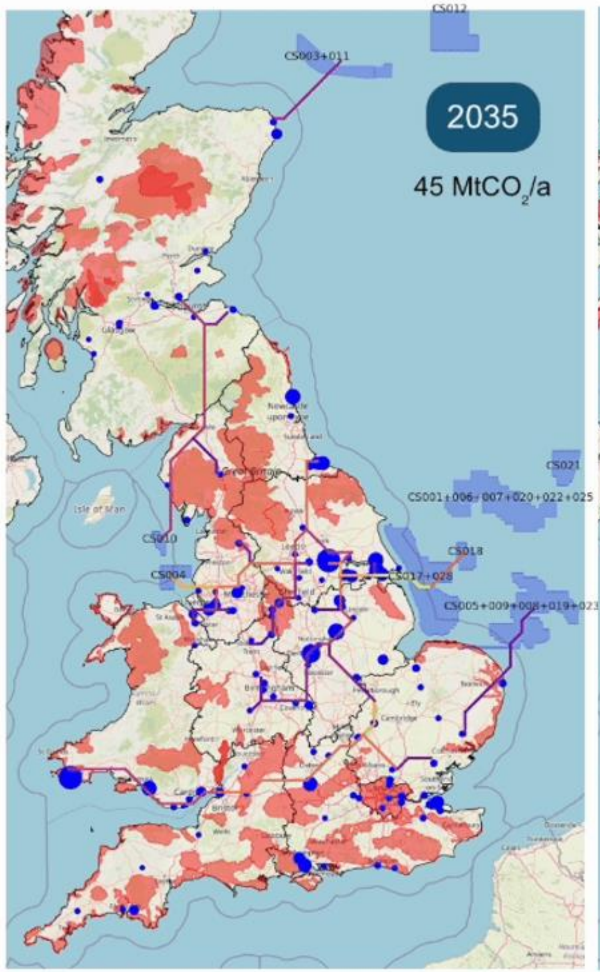

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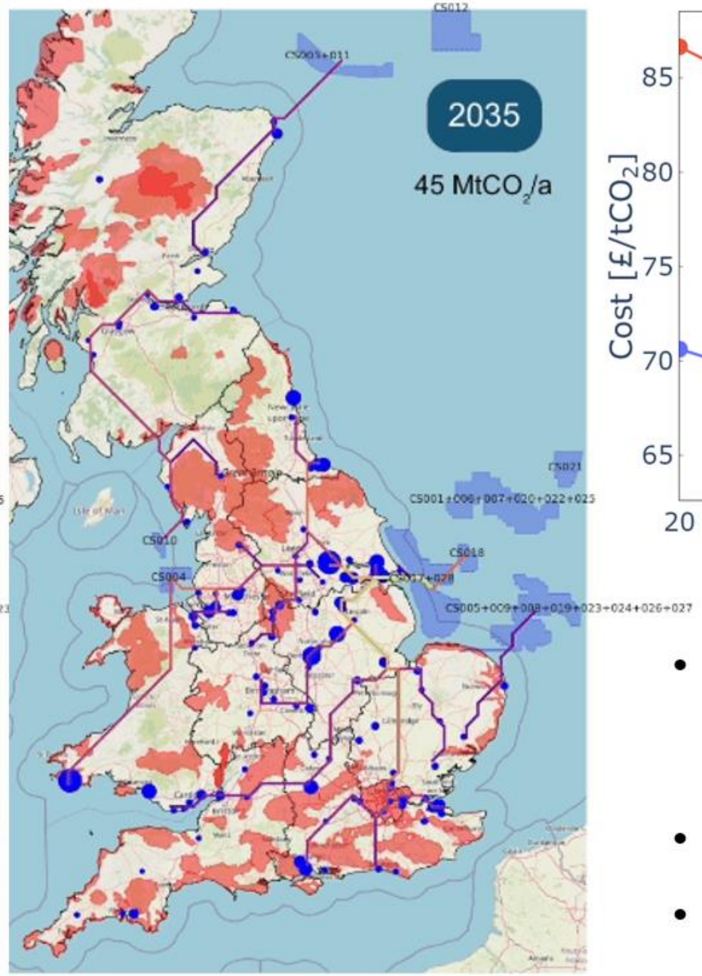
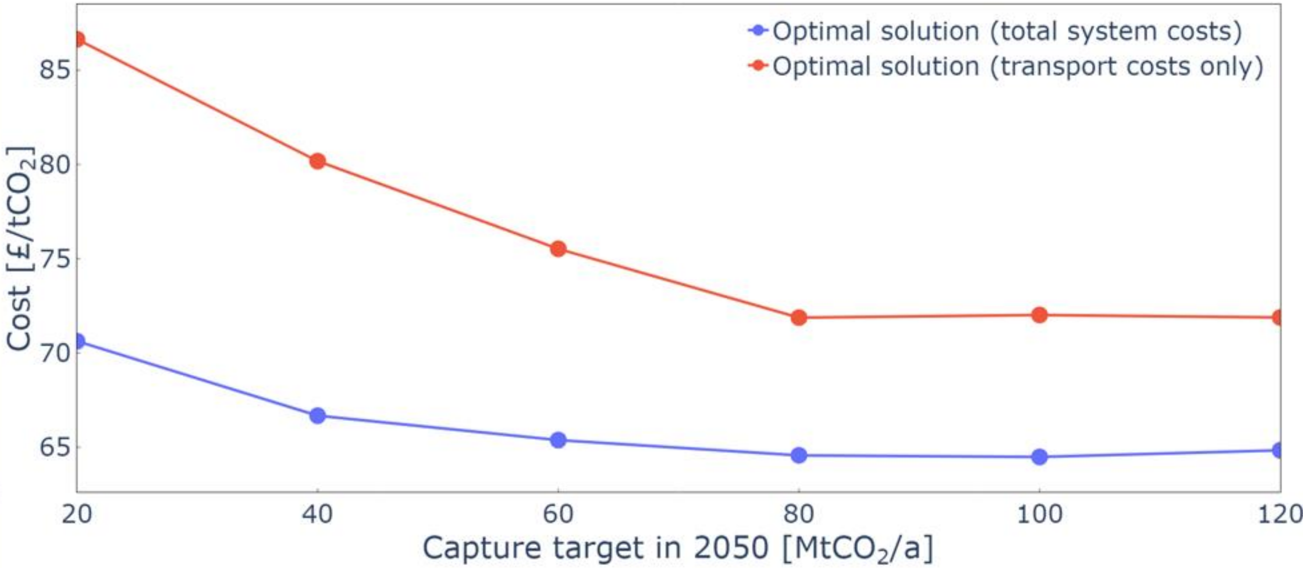


Value of strategic planning

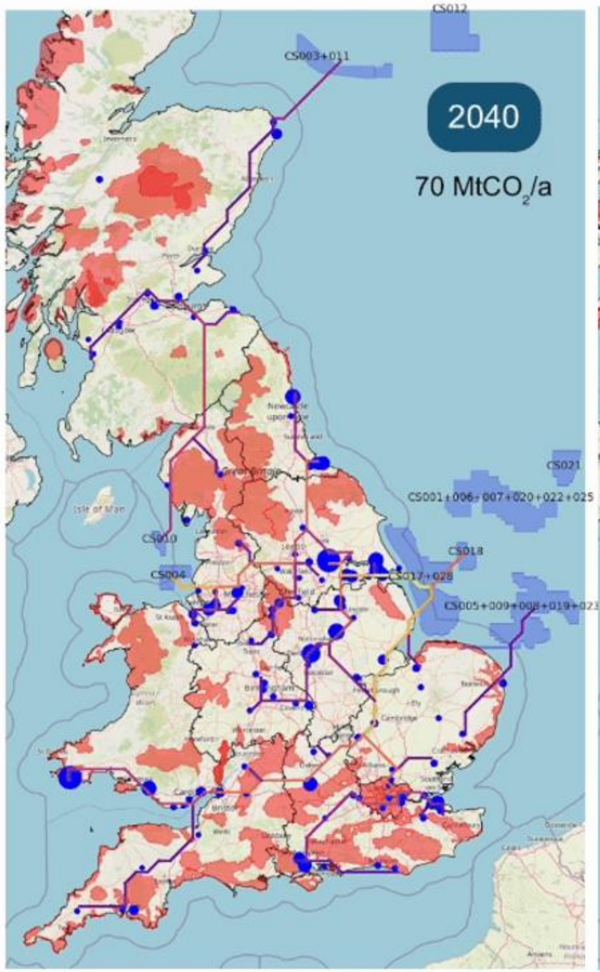


- The current “cluster by cluster” approach to CCS development in the UK is closer to the red line than the blue
- As CCS deployment grows, the cost ratio approaches unity.
- Ensure that all pipelines are using a similar CO_2 specification so future system integration can occur

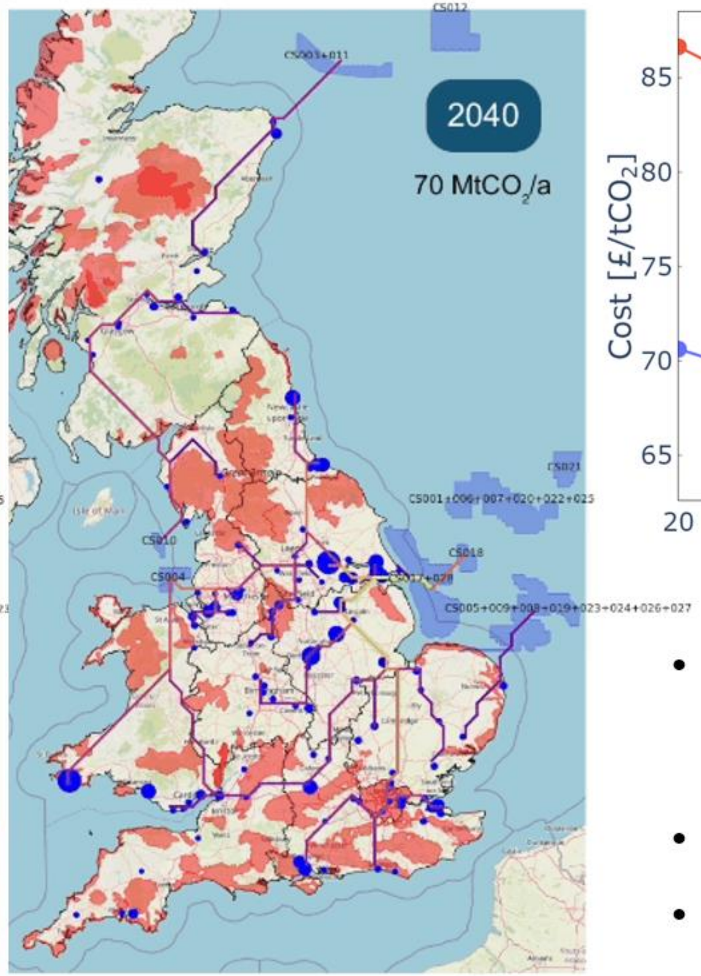
Mersch et al. (2024). Study for DESNZ, HMG

Different approaches to CCS development

Central planning



Project by project approach



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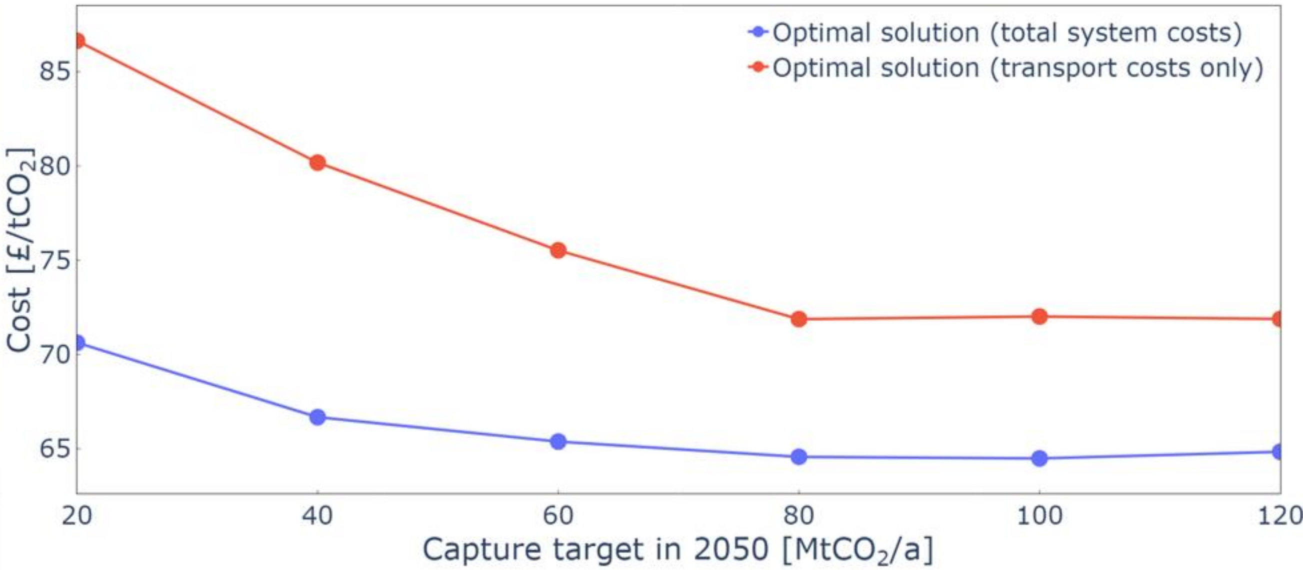

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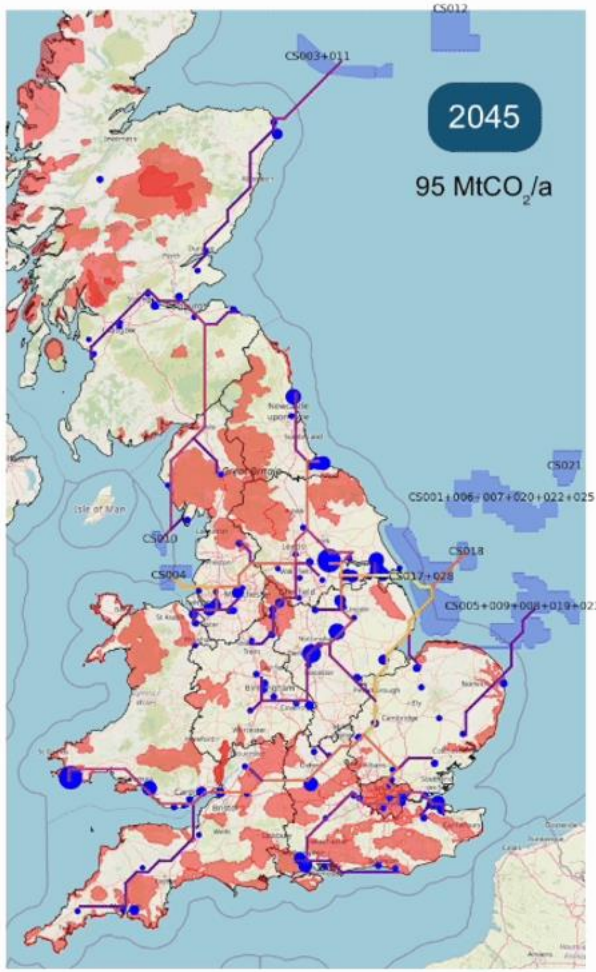

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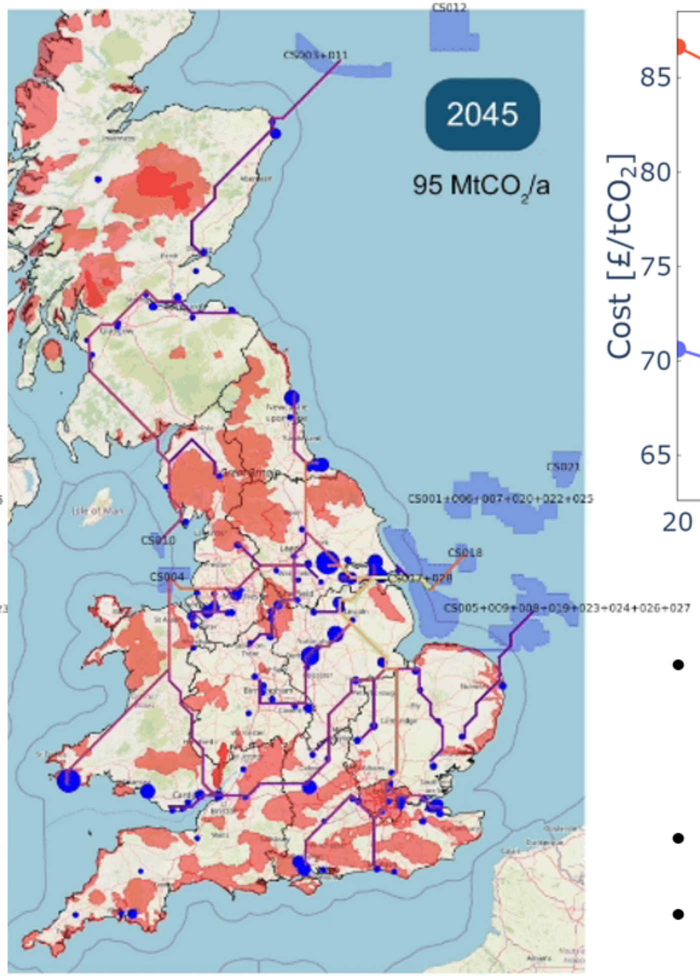

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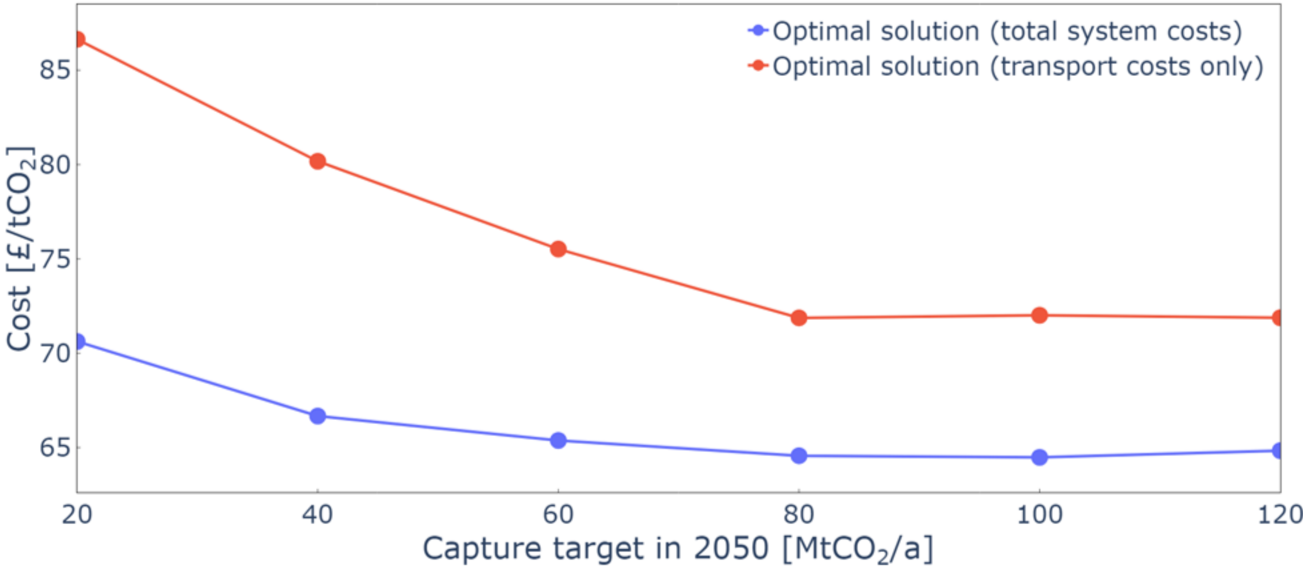

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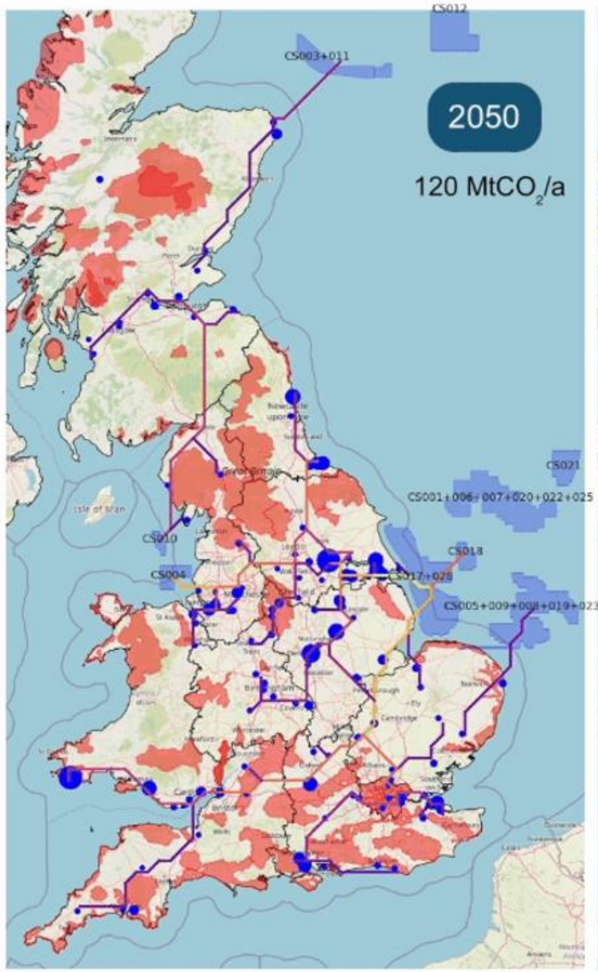

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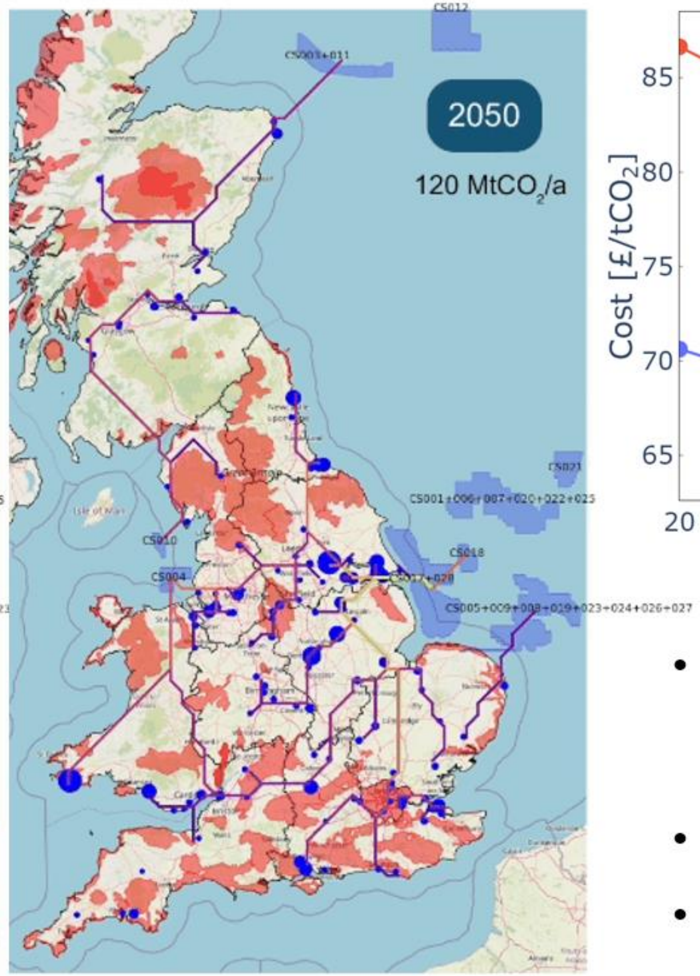

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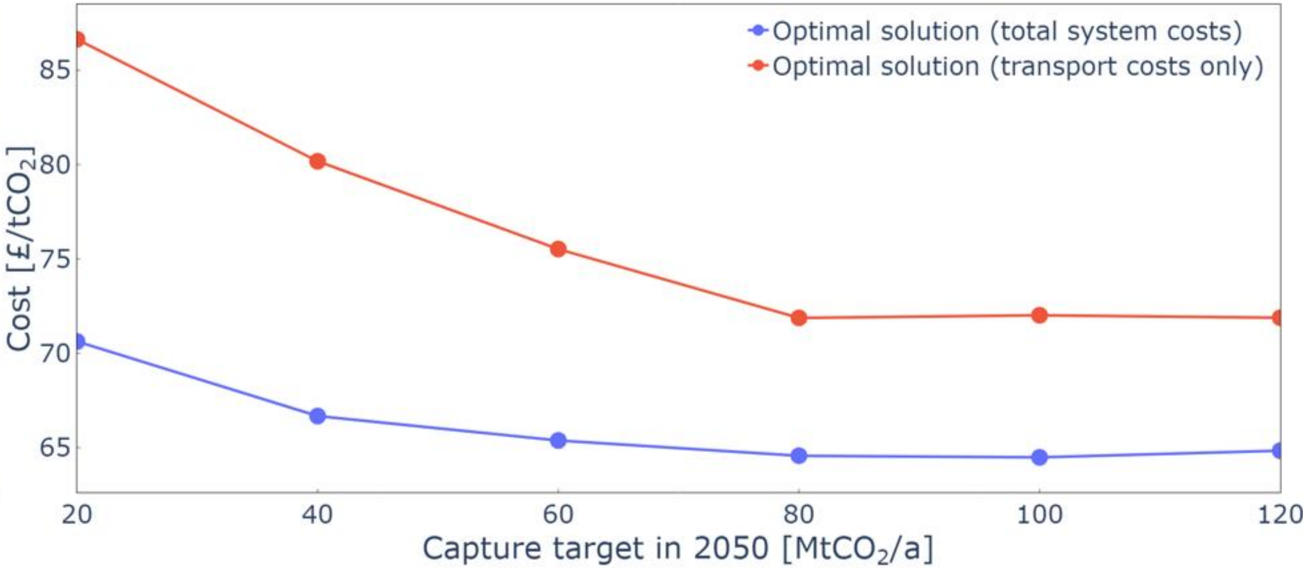

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Mersch et al. (2024). Study for DESNZ, HMG

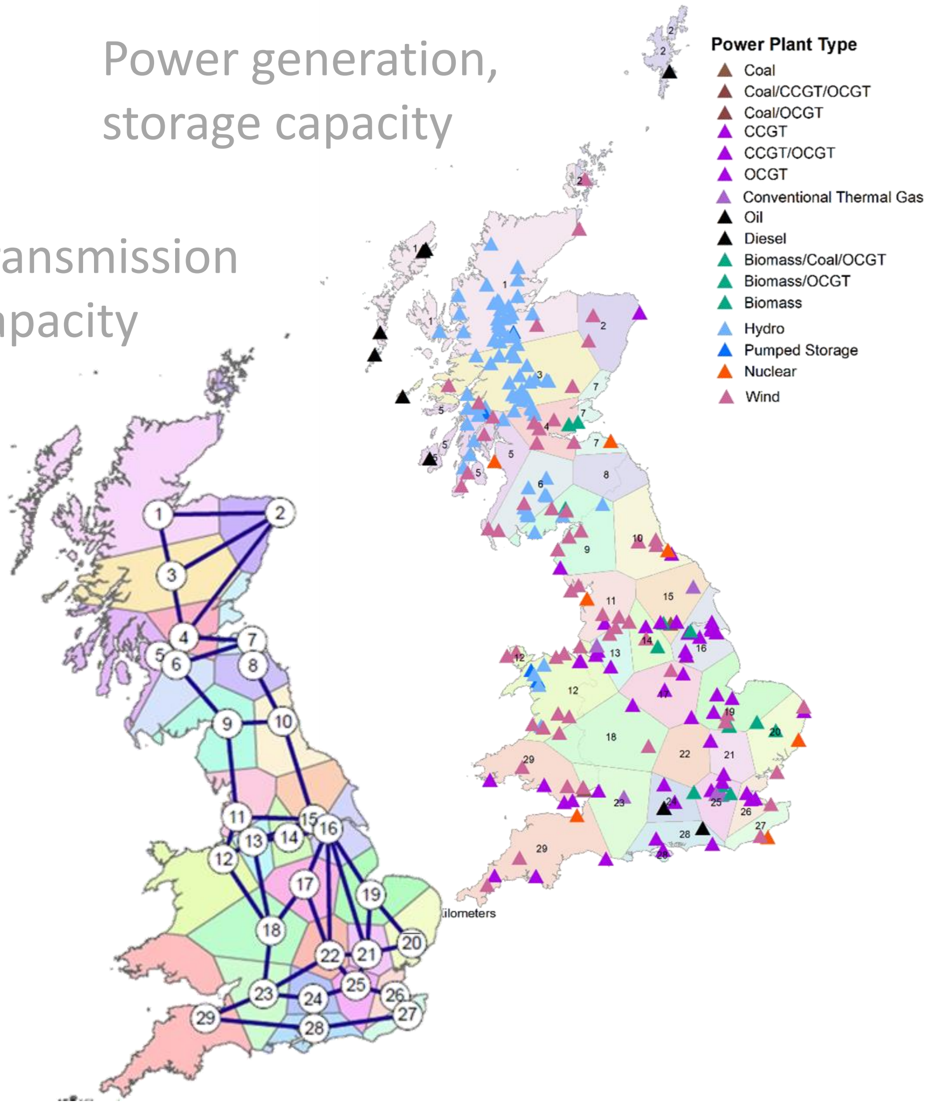
What does CCS “do”?

- CCS started out as a “clean coal” technology, and coal was (mostly) a baseload power generation asset
- CCS was also interpreted as being costly to build and costly to operate
- Therefore, baseload operation was deemed the obvious operating strategy
- However…

Energy system optimisation (ESO) framework

Power generation, storage capacity

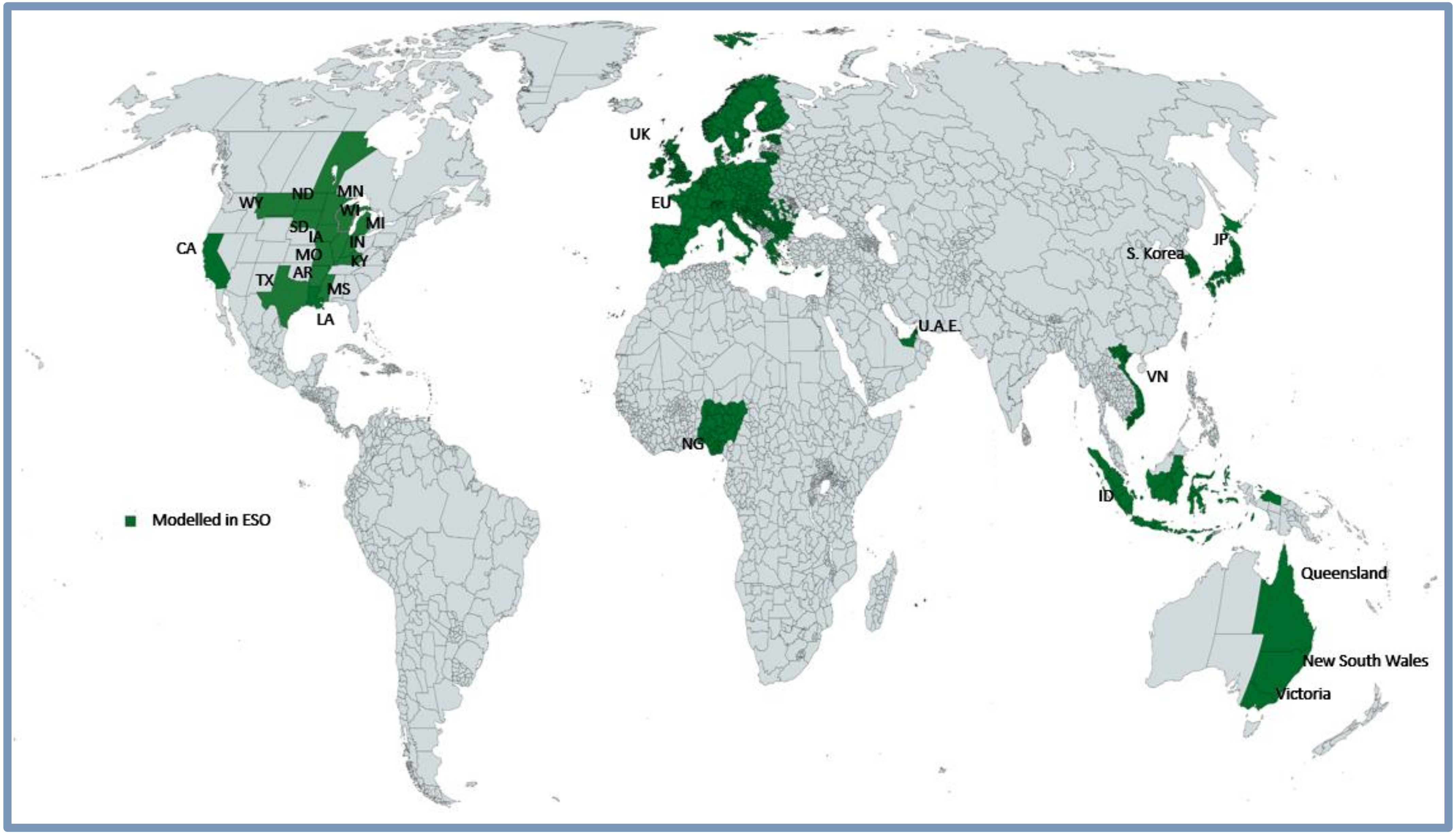
Transmission capacity



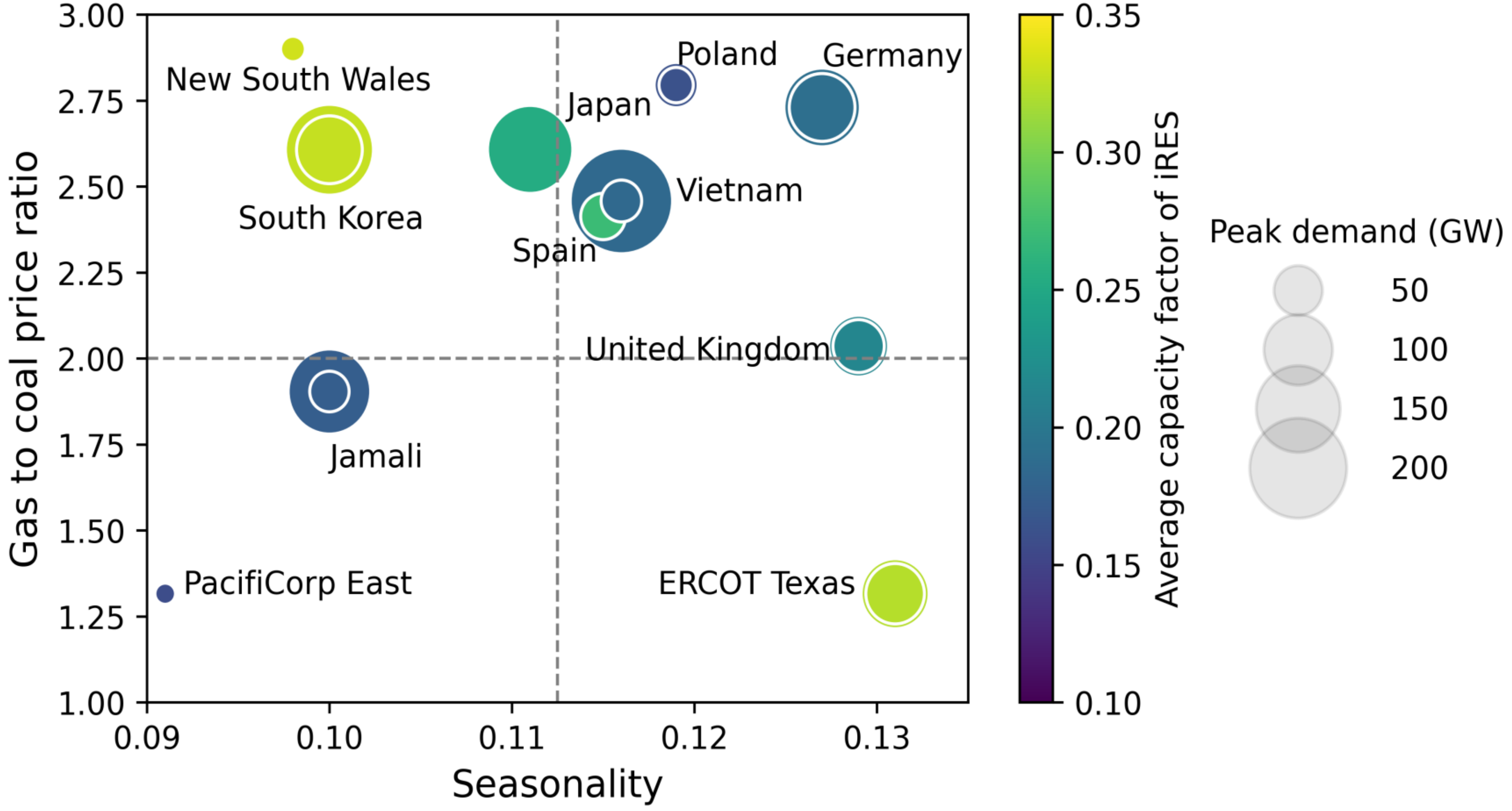
$\forall i \in I$ $\forall a \in A$	Capacity expansion	• Initial supply and transmission capacity • Build rate constraints (supply, store, transmission) • Life time constraints • Maximum resource constraints
$\forall c \in C$	System-wide constraints	• Electricity demand • Reserve requirements • Inertia requirements • Emission target
$\forall z \in Z$	Transmission	• Transmission between zones
$\forall t \in T$	Tech.-wise constraints Integer scheduling	• Power, Reserve, inertia provision • Flexibility of generation/storage units • Carbon emissions by technology • Uptime and downtime
sum	Objective	min { CAPEX + mode-specific OPEX }

Heuberger, C. F., et al. (2016). Energy & Environmental Science, 9 (8), 2497-2510, Heuberger, C. F. & Mac Dowell, N. (2018). Joule, 2 (3), 367-370, Heuberger, C. F., et al. (2018). Nature Energy, 3 (8), 634-640.

Energy system optimisation (ESO) framework



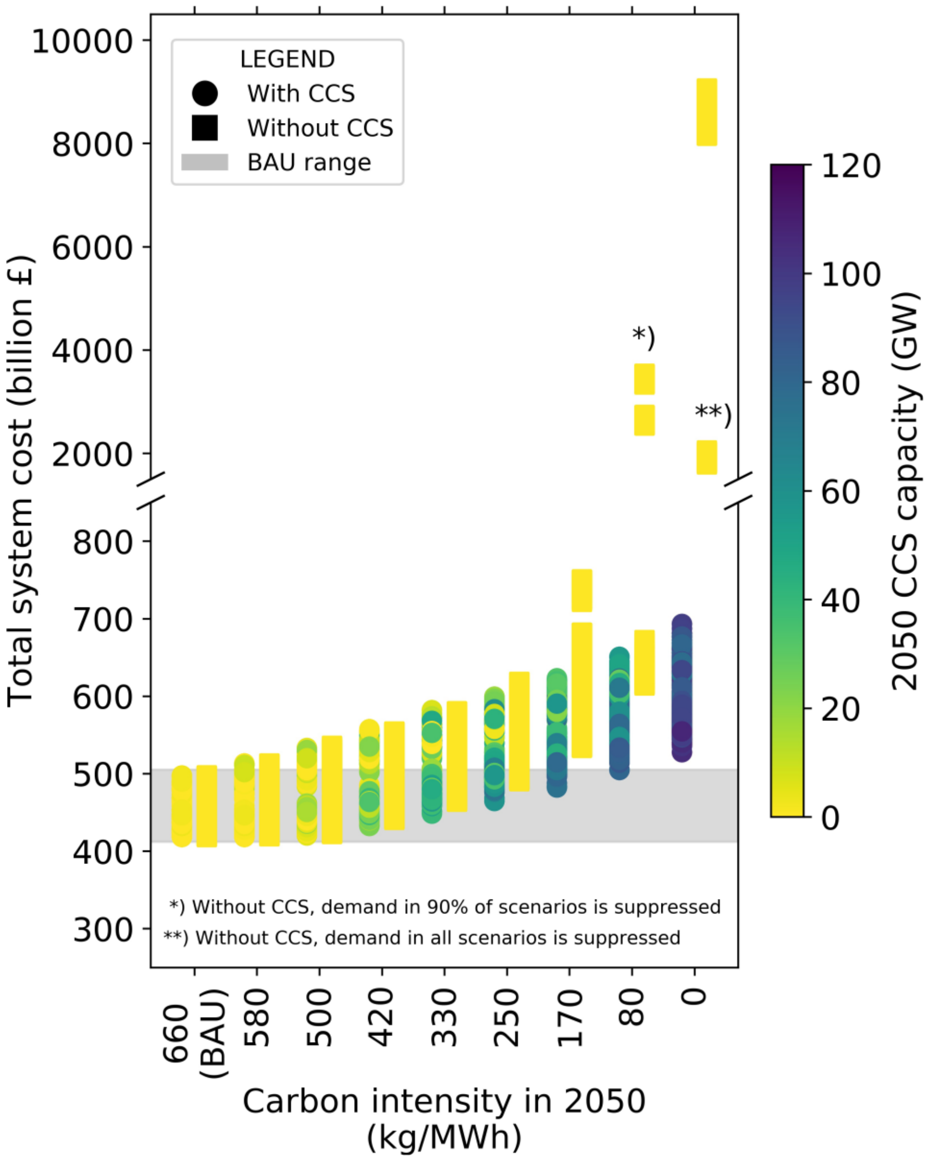
No one size fits all



**) Seasonality is defined as the standard deviation of the hourly electricity demand*
Inner and outer circles are 2020 and 2050 peak demand, respectively

Pratama, Patrizio, and Mac Dowell, iScience, 2022

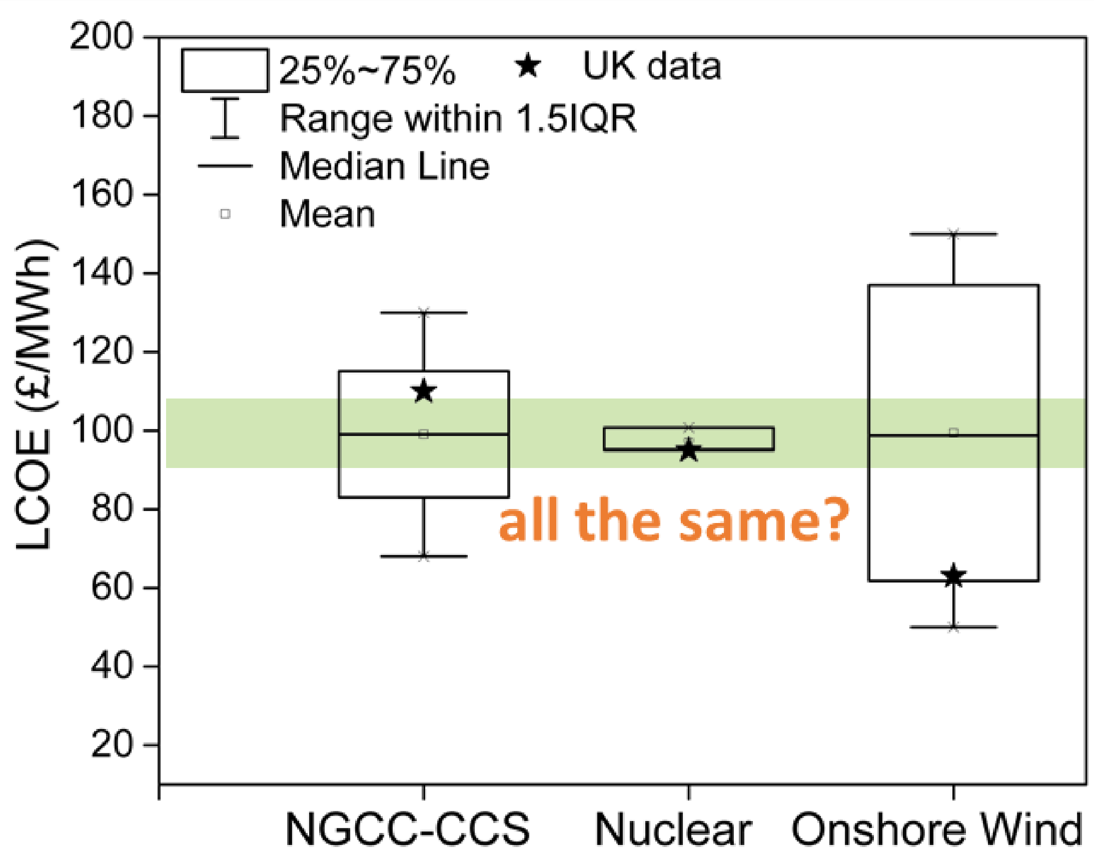
Quantifying the value of CCS (JAMALI)



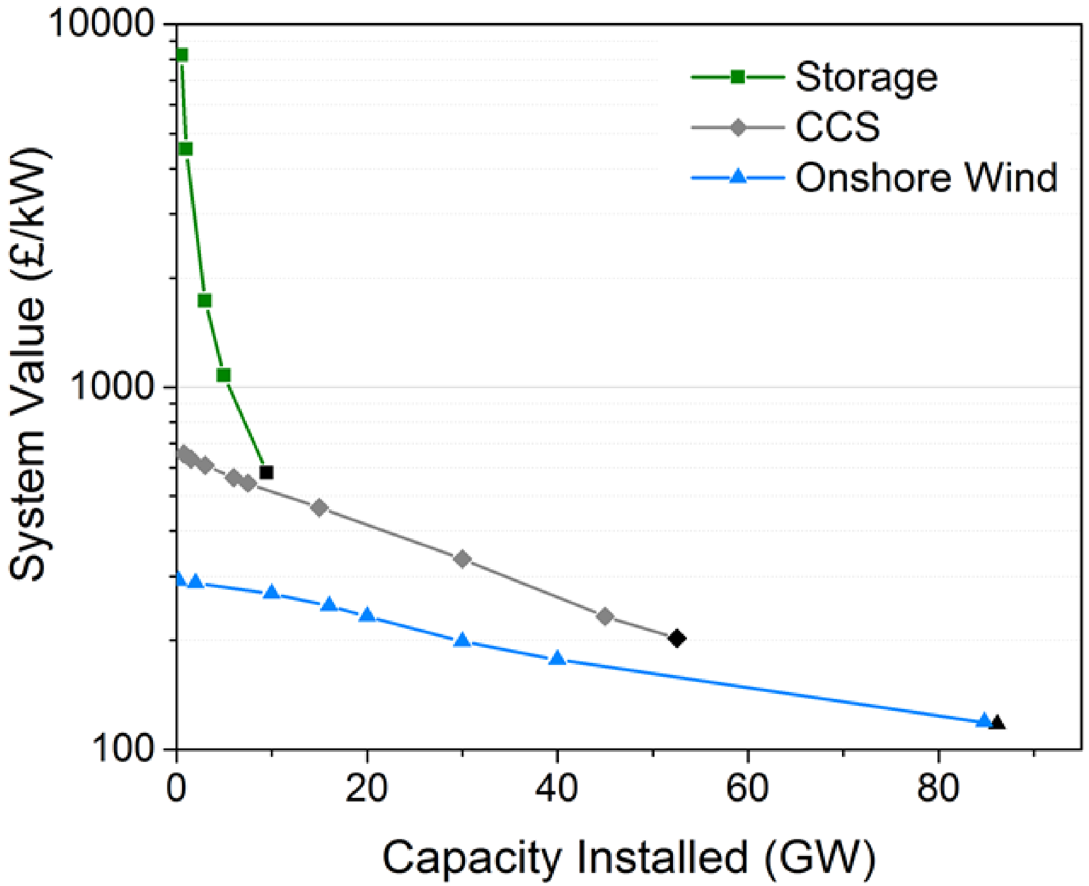
Pratama and Mac Dowell, IEA CCC, 2021

Value ≠ cost

LCOE

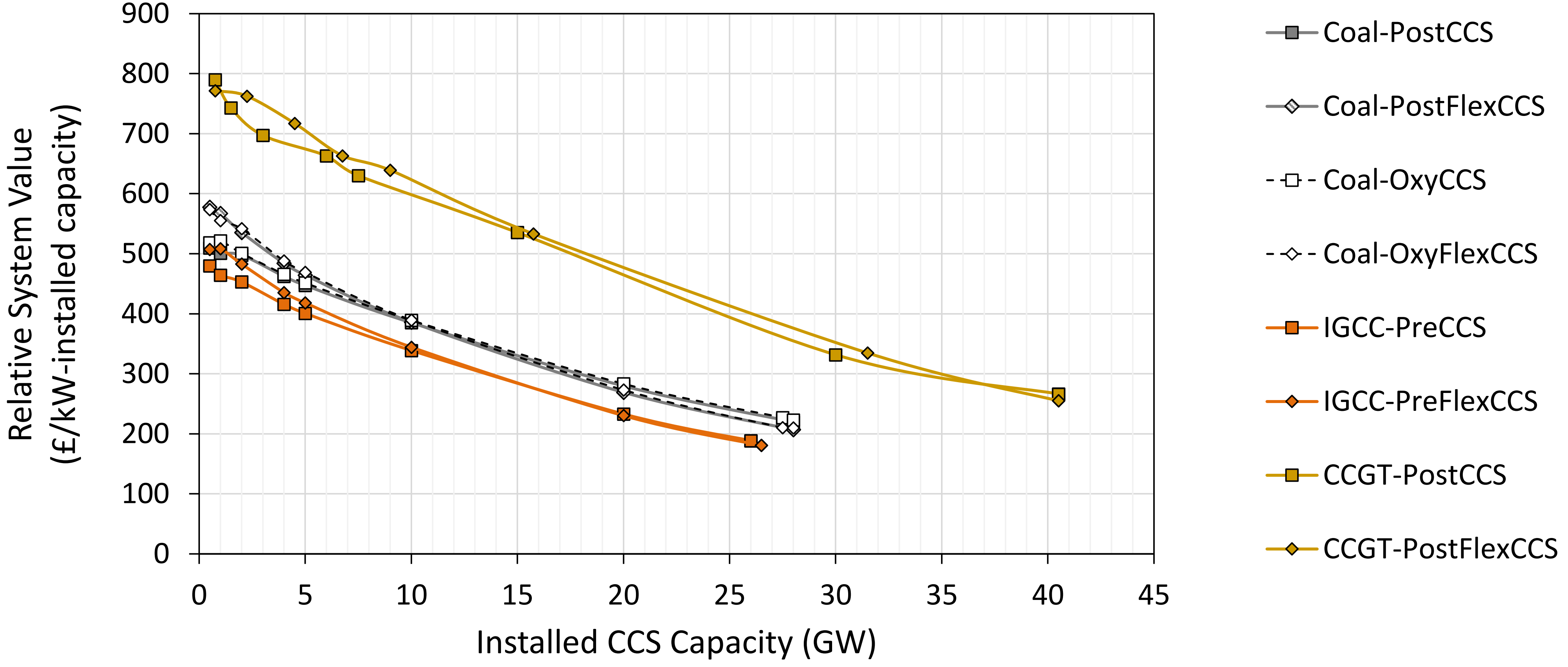


System Value



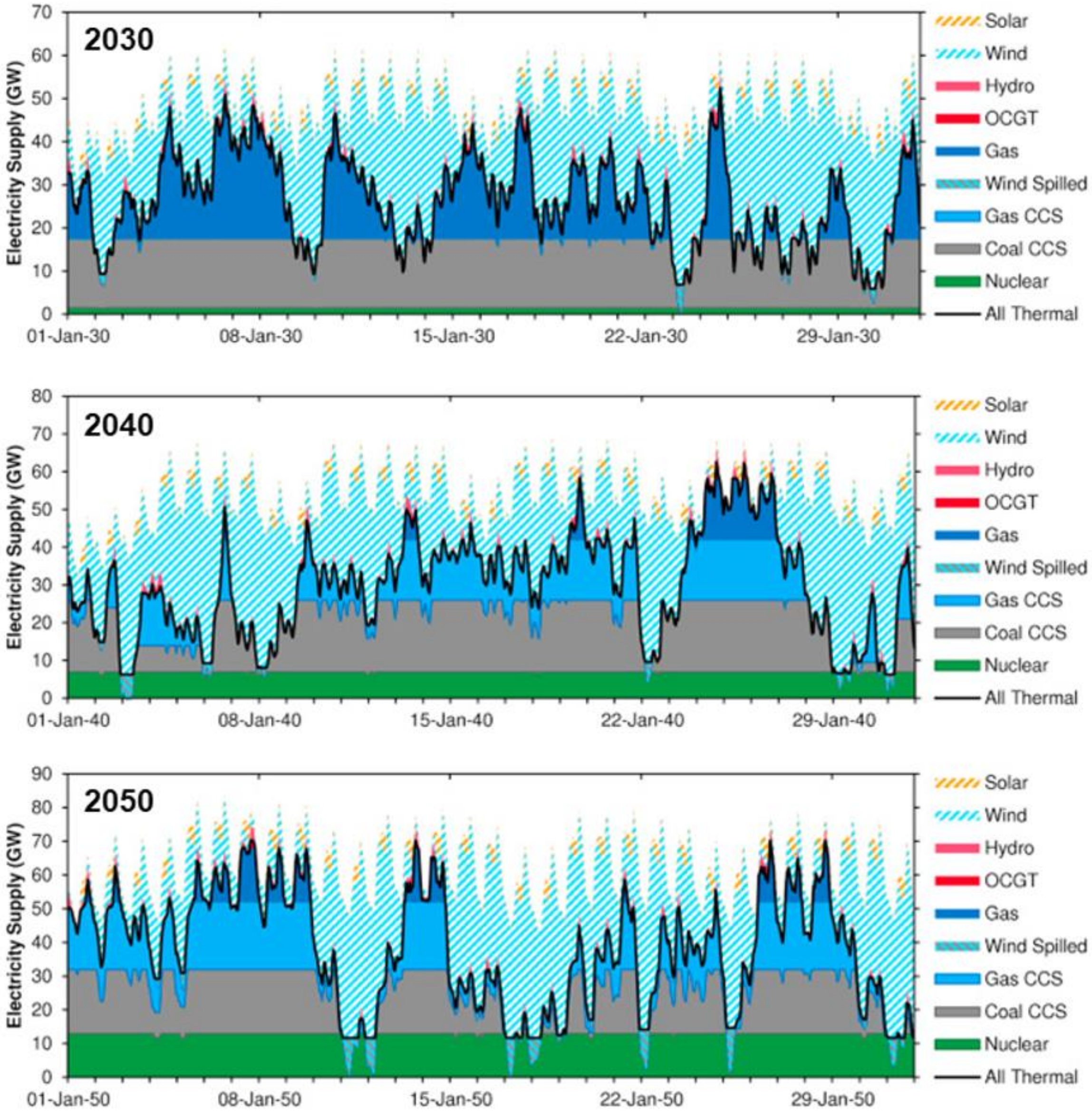
CF Heuberger, *et al*, Computers and Chemical Engineering, 2017

Flexible CCS technologies provide the greatest value



CF Heuberger, *et al*, Computers and Chemical Engineering, 2017

Increasing understanding of the role of flexible CCS

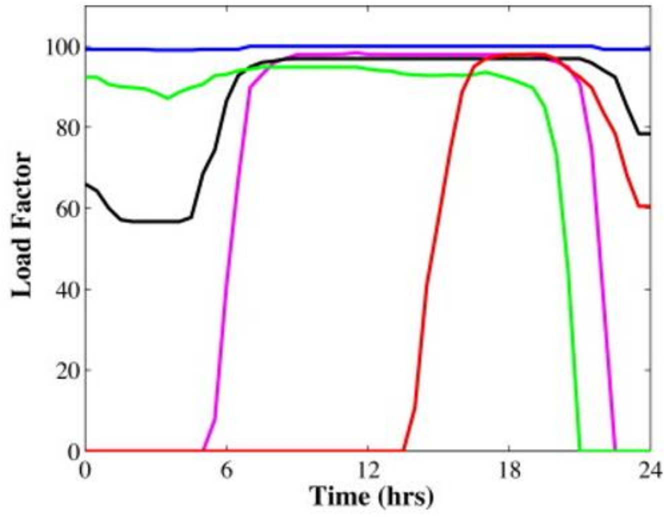


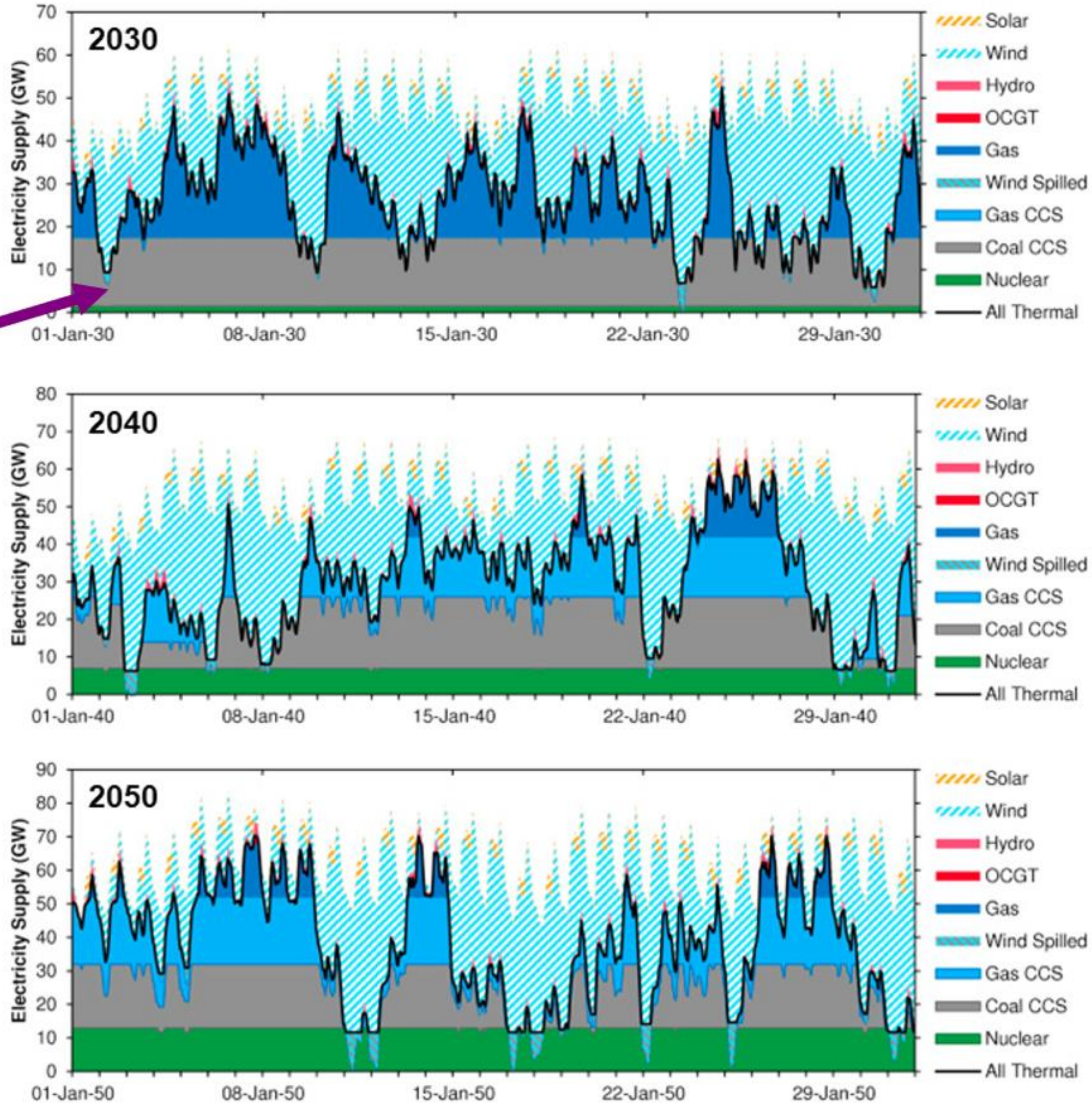
Mac Dowell, N. & Staffell, I. (2016). International Journal of Greenhouse Gas Control, 48, Part 2 (Flexible operation of carbon capture plants), 327–344.
Mac Dowell, N. & Shah, N. (2015). Computers & Chemical Engineering, 74, 169–183.

Increasing understanding of the role of flexible CCS

To accommodate intermittent renewables, fossil fuel power plants will need to operate flexibly.

Typical modes of operation for fossil fuel-fired power plants in the UK





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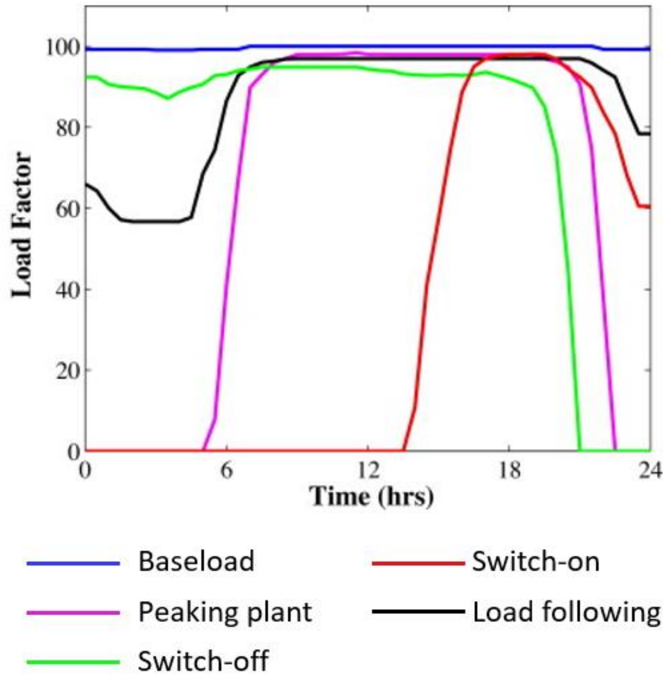
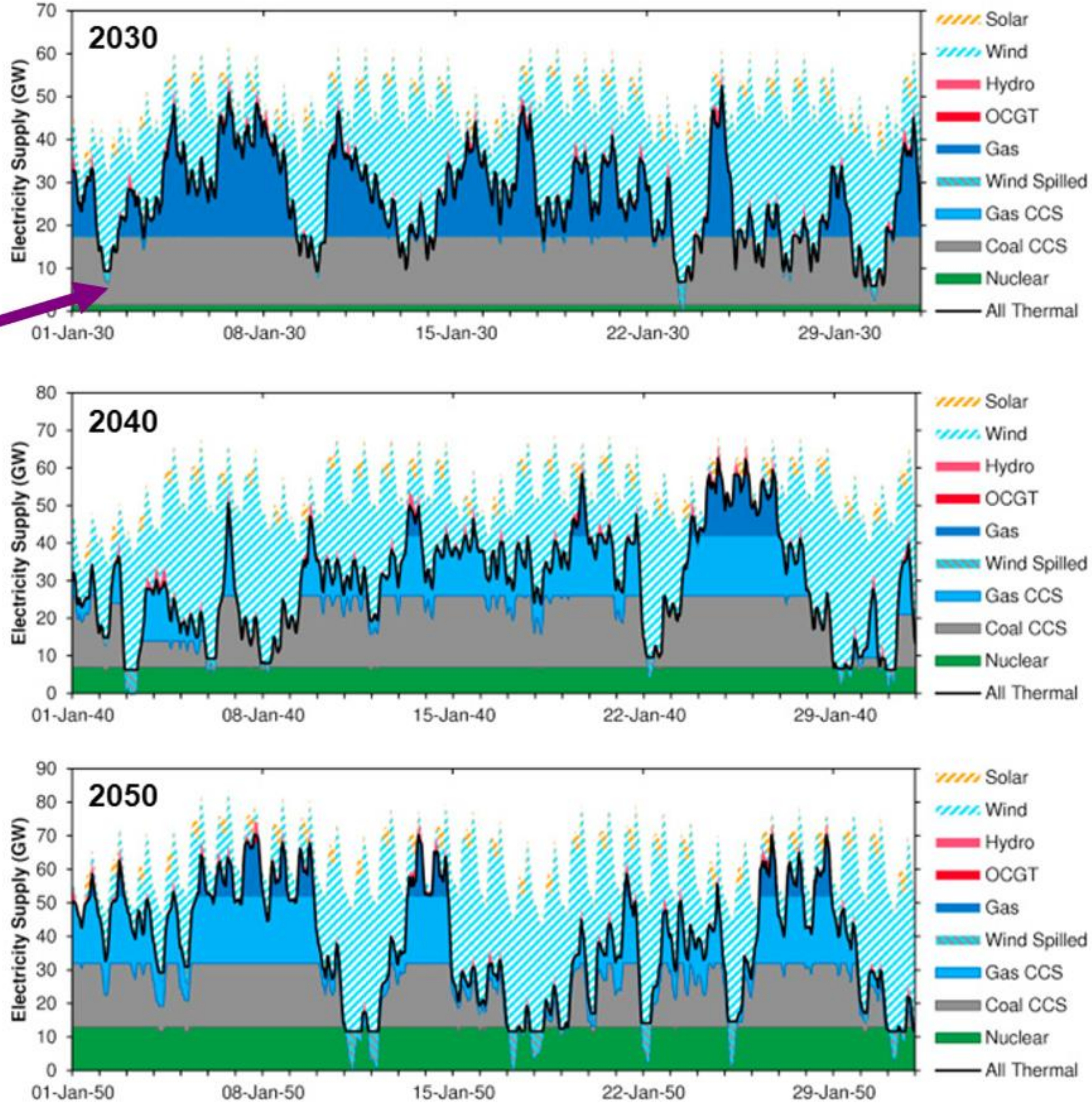
Increasing understanding of the role of flexible CCS

To accommodate intermittent renewables, fossil fuel power plants will need to operate flexibly.

Coordinate the balance between electricity demand and CO_2 capture requirements.

Typical modes of operation for fossil fuel-fired power plants in the UK





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Mac Dowell, N. & Shah, N. (2015). Computers & Chemical Engineering, 74, 169–183.

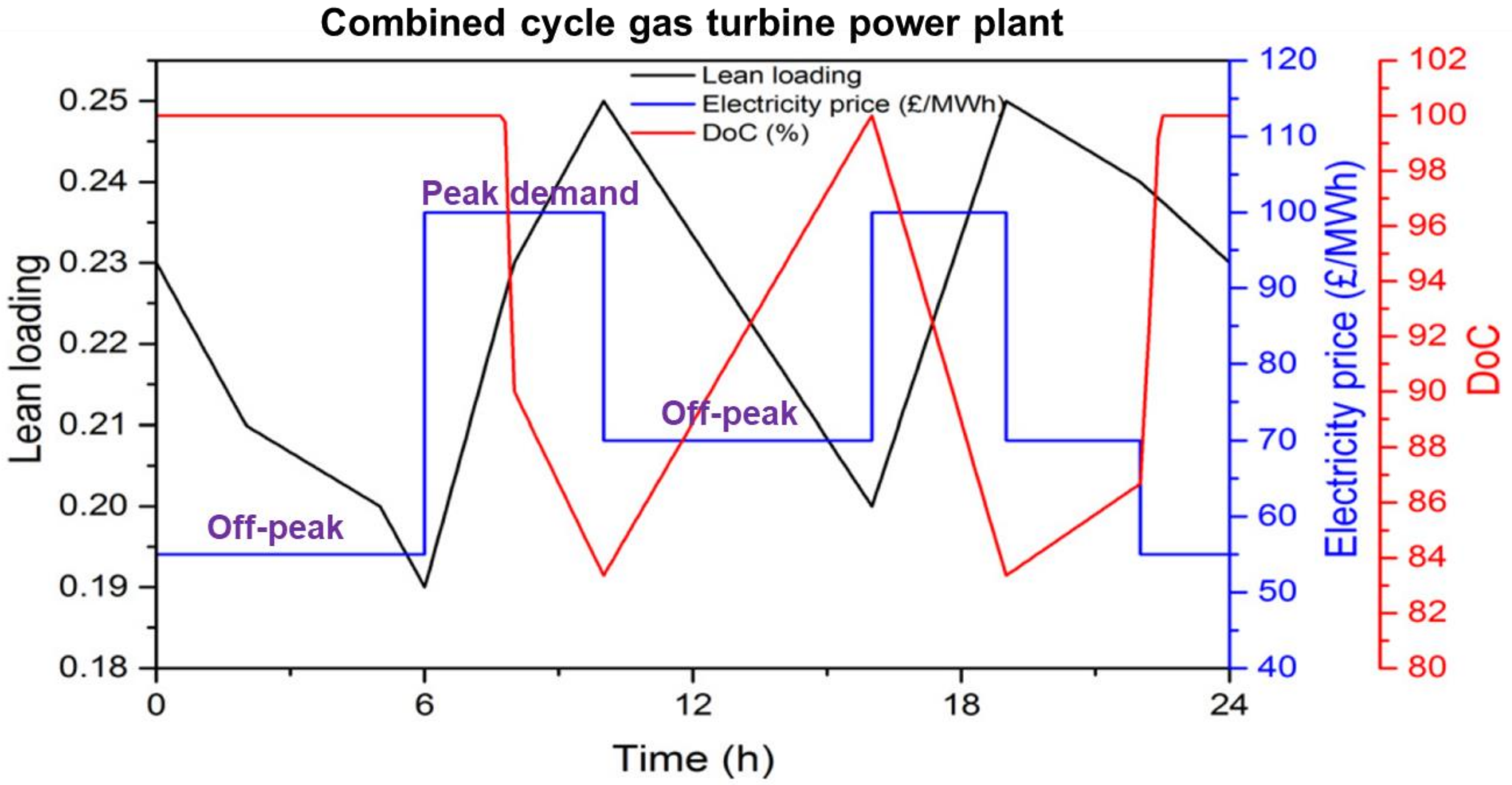
Development of optimal operation strategies

The use of solvent storage tanks involves high capital cost.

Alternatively, CO_2 can be "stored" within the amine liquid.

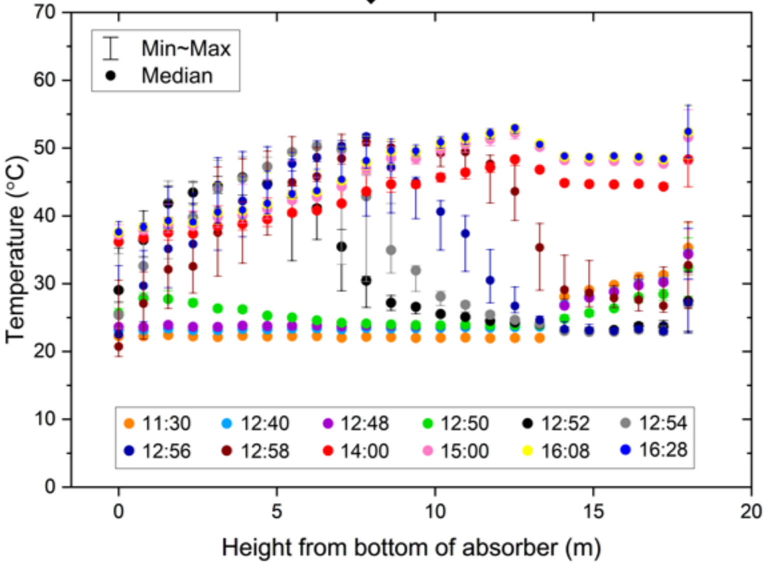
The **time-varying solvent regeneration** approach can be used to coordinate the degree of capture (DoC) with electricity price/demand.

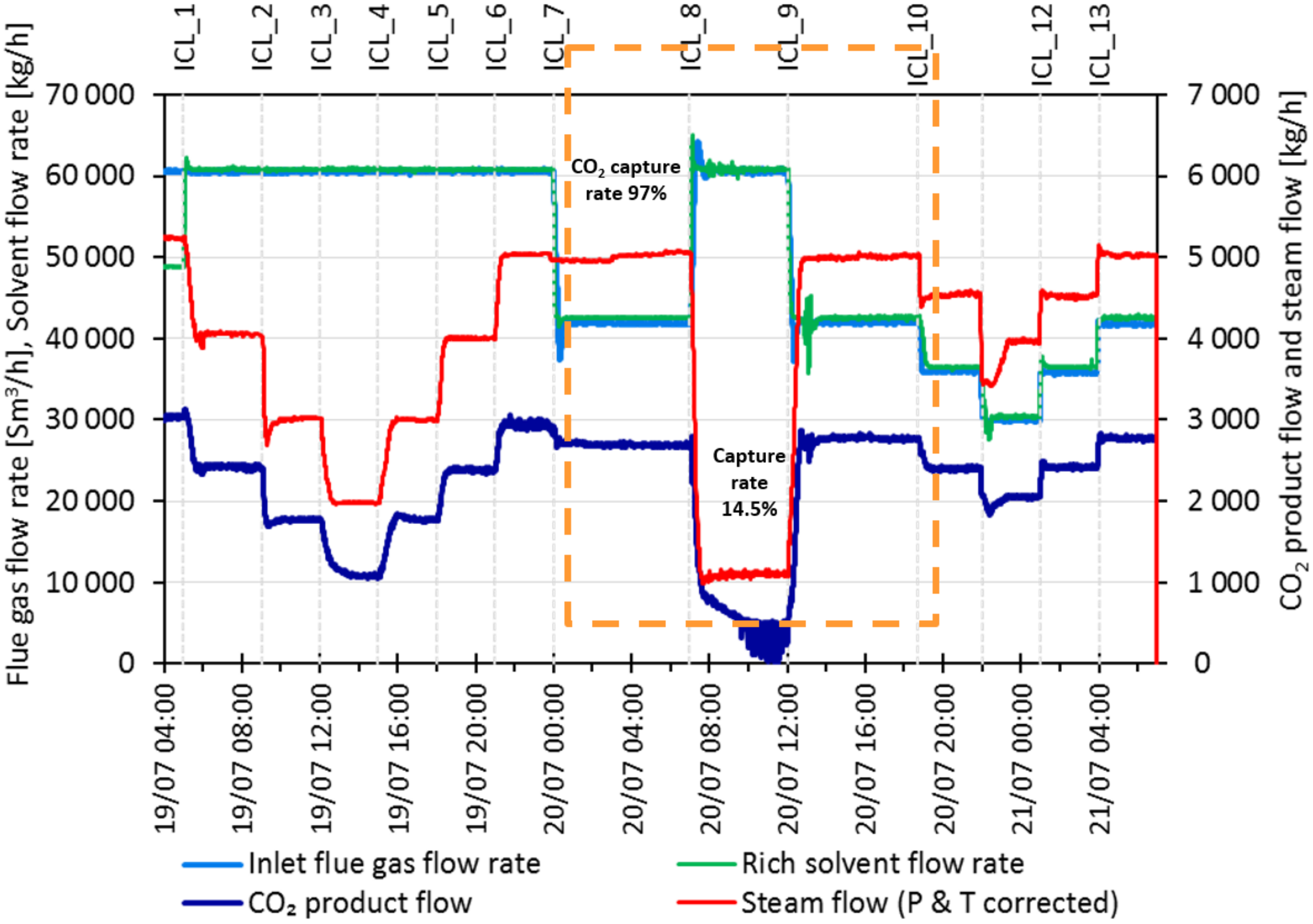
Potentially more cost effective and profitable.



References: Mechleri, E., Fennell, P. S. & Dowell, N. M. (2017). International Journal of Greenhouse Gas Control, 59, 24–39.
Mac Dowell, N. & Shah, N. (2015). Computers & Chemical Engineering, 74, 169–183.

Demonstrating flexible operation at TCM

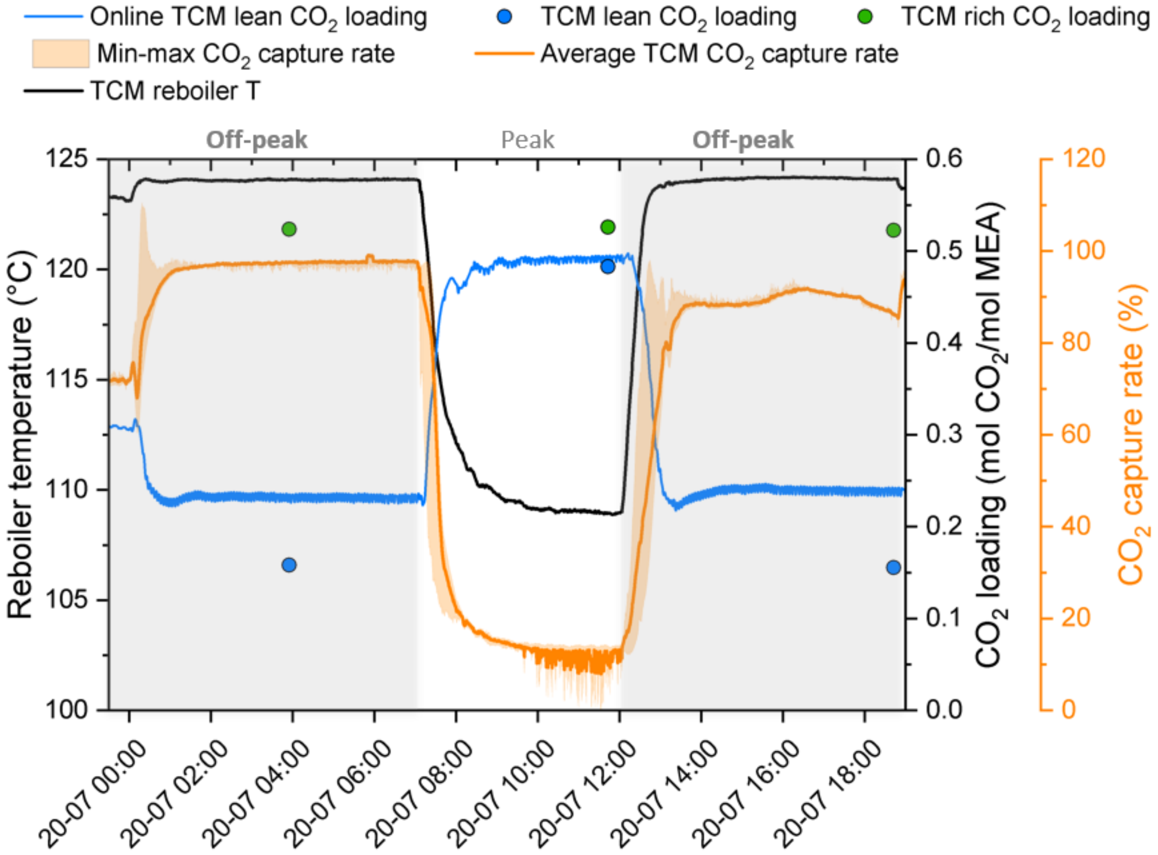


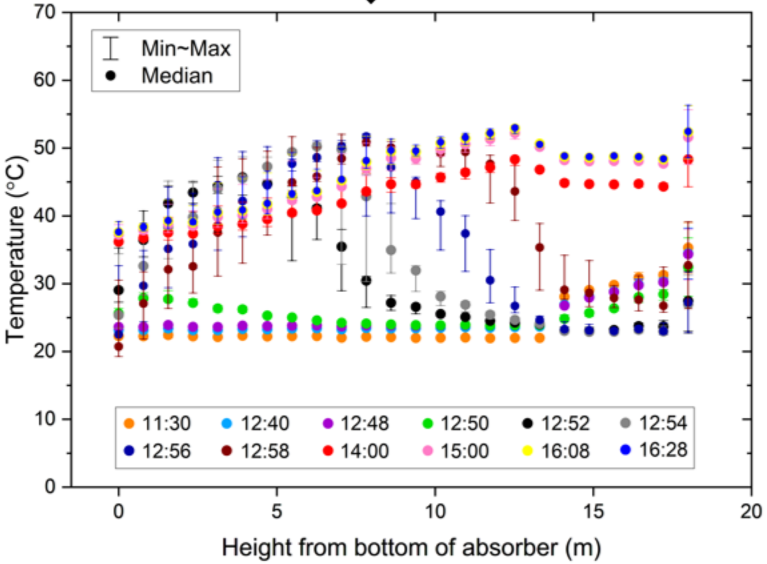


Bui, Mac Dowell, et al., (2020). Demonstrating flexible operation of the Technology Centre Mongstad (TCM) CO_2 capture plant. International Journal of Greenhouse Gas Control, 93, 102879.

Demonstrating flexible operation at TCM

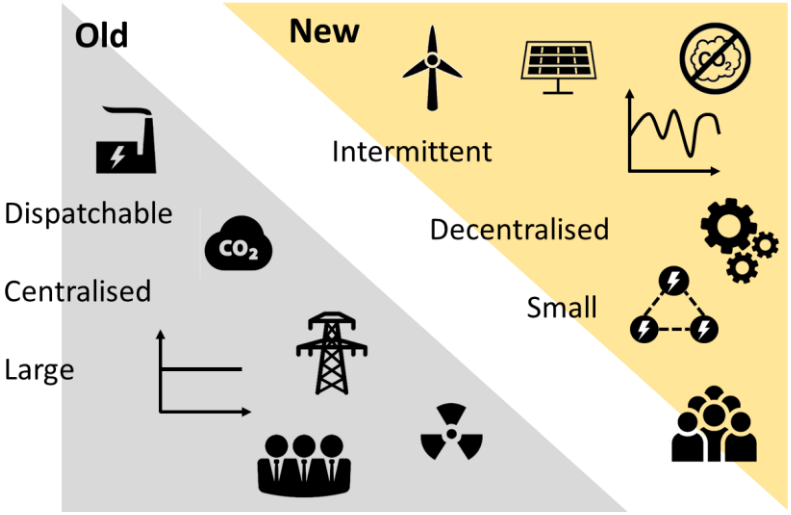
TECHNOLOGY CENTRE MONGSTAD





Bui, Mac Dowell, et al., (2020). Demonstrating flexible operation of the Technology Centre Mongstad (TCM) CO_2 capture plant. International Journal of Greenhouse Gas Control, 93, 102879.

Which technology parameters matter?



The power system is changing…

“+” → “+++” = low → high value

*modelled as minimum stable generation point, up-/down time

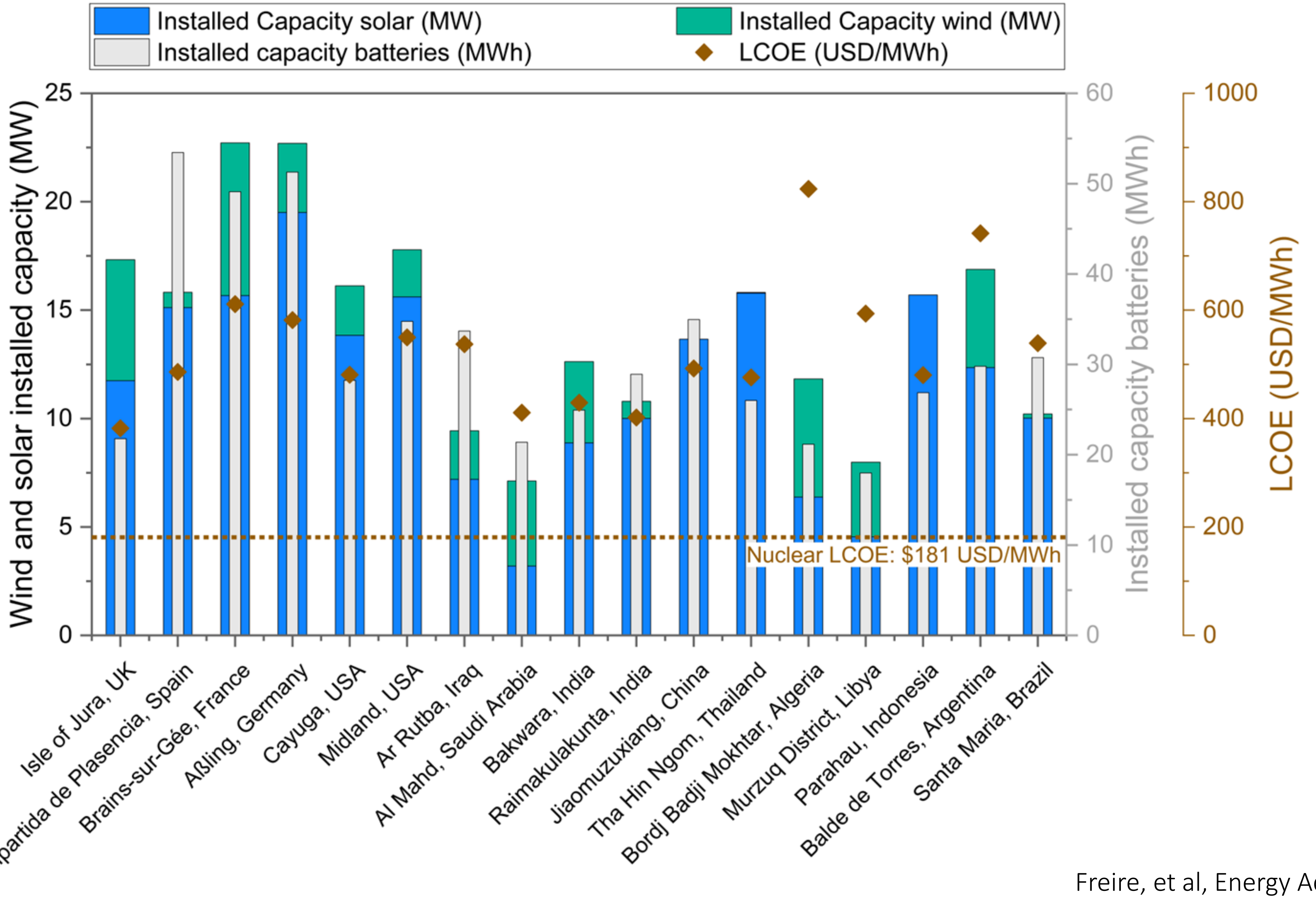
Technology Feature	Value in future power systems
High Efficiency	+
High Flexibility*	++
Low CAPEX	+++
Dispatchability	+++
Firm capacity/ancillary service provision	+++
Low OPEX	+
High Rate of Deployment	++

M Schnellmann, *et al*, Int J GHG Con, 2018

The value of reliable low CI power

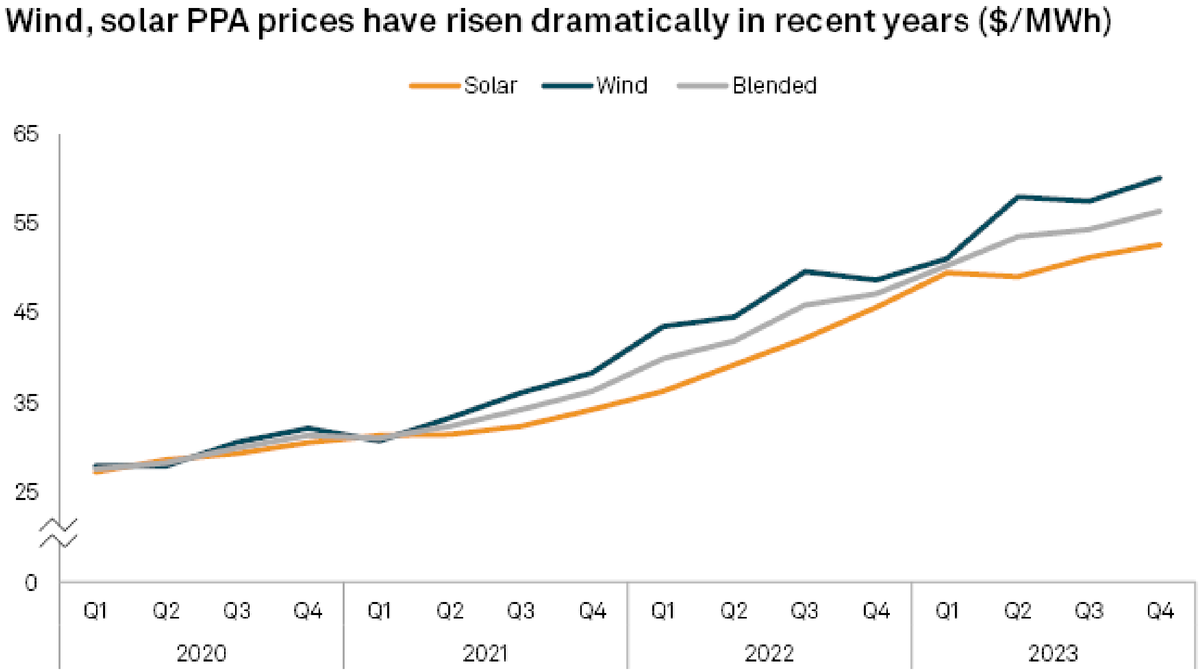
- Data centres and “AI” are very power hungry
- Getting a grid connection is increasingly difficult
- This is leading to hyperscalers (Amazon, Microsoft, etc.) seeking “direct wire” connections for power
- They are primarily seeking low/zero CI power, and this ***must*** be reliable power
- Historic preference for renewable energy
- But…

MWh ≠ MW

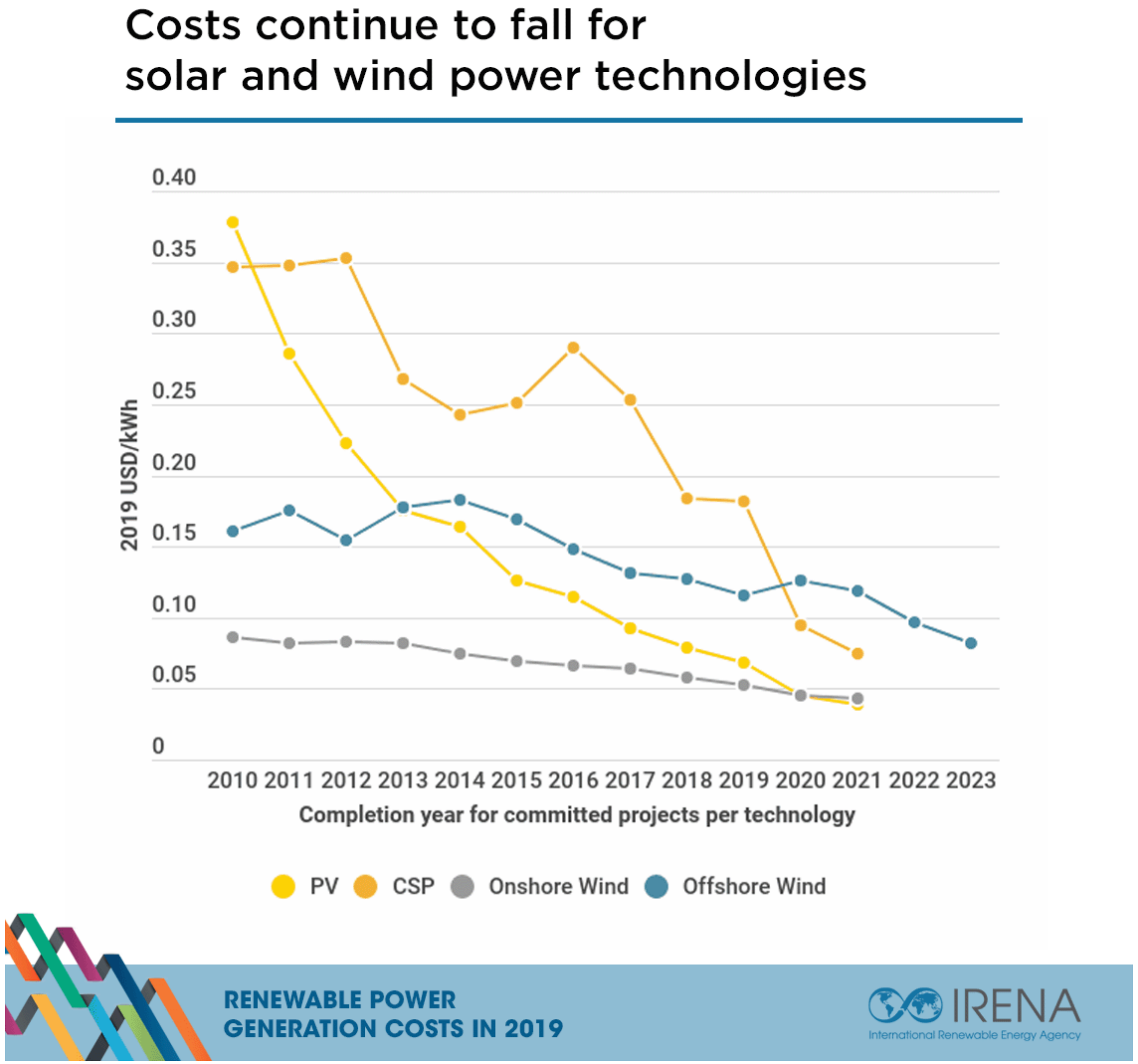


Freire, et al, Energy Advances, 2023

Renewable energy is getting cheaper…

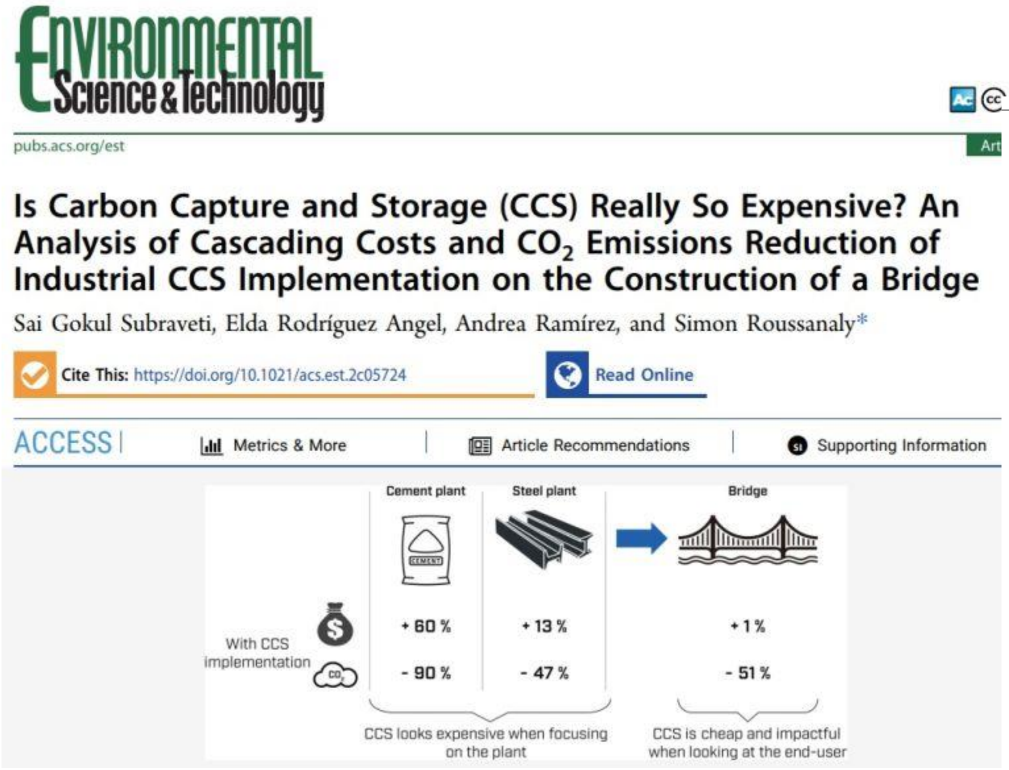


Data acessed Jan. 30, 2024.
PPA = power purchase agreement.
Shows lowest 25% of PPA offers across six wholesale energy markets in US and Canada for each technology. "Blended" is an aggregation of the lowest 25% of wind and solar PPA offers.
Source: LevelTen Energy.



Source: https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/north-american-solar-wind-power-prices-continued-ascent-in-2023-8211-report-80219261
https://www.irena.org/news/pressreleases/2020/Jun/Renewables-Increasingly-Beat-Even-Cheapest-Coal-Competitors-on-Cost

Won’t CCS be expensive?


Environmental Science & Technology

pubs.acs.org/est

Is Carbon Capture and Storage (CCS) Really So Expensive? An Analysis of Cascading Costs and CO_2 Emissions Reduction of Industrial CCS Implementation on the Construction of a Bridge

Sai Gokul Subraveti, Elda Rodríguez Angel, Andrea Ramírez, and Simon Roussanaly*

Cite This: https://doi.org/10.1021/acs.est.2c05724 | Read Online

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Energy Policy

Volume 98, November 2016, Pages 459-469

Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry

Johan Rootzén, Filip Johnsson

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Highlights

- Examines impacts downstream of investments in CO_2 abatement in the steel industry.
- Show how investing in low-CO_2 processes have marginal impacts in end-user stage.
- Increase in the retail price of a mid-sized passenger car would be well below 1%.
- Open up for complementary policies, financing mechanisms or new business models.


REGULAR SECTION

Managing the costs of CO_2 abatement in the cement industry

Johan Rootzén & Filip Johnsson

Pages 781-800 | Published online: 04 Jul 2016

Cite this article | https://doi.org/10.1080/14693062.2016.1191007

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Abstract

This article investigates how the costs associated with deep reductions in CO_2 emissions from the cement industry will influence the costs across the entire value chain from cement production to the eventual end-use, in this case a residential building. The work is motivated by the substantial difference between the pricing of CO_2 emissions and the costs of mitigation at the production sites of energy-intensive industries, such as cement manufacture. By examining how CO_2 trading and investments in low-carbon kiln systems affect costs and prices further up the supply chain of cement our analysis provides new perspectives on the costs of industry abatement of CO_2 and on the question of who could or should pay the price of such abatement. The analysis reveals that the cost impacts decrease substantially at each transformation stage, from limestone to final end-uses. The increase in total production costs for the residential building used as the case study in this work is limited to 1%, even in the cases where the cement price is assumed to be almost doubled.

- Expanding body of analysis demonstrates that, when considered across the entire value chain, the marginal cost of mitigation is negligible
- 1-2% on infrastructure, 1% on vehicles, 1% on buildings. Observed “green premium” on muni bonds is 0.023%
- See for e.g.,:
    - Rootzen and Johnsson, “Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry”, Energy Policy, 2016,
    - Rootzen and Johnsson, “Managing the costs of CO2 abatement in the cement industry”, Climate Policy, 2017,
    - Karlsson, Rootzen, and Johnsson, “Reaching net-zero carbon emissions in construction supply chains – Analysis of a Swedish road construction project”, Renewable and Sustainable Energy Reviews, 2020,
    - Subraveti, et al “Is Carbon Capture and Storage (CCS) Really So Expensive? An Analysis of Cascading Costs and CO_2 Emissions Reduction of Industrial CCS Implementation on the Construction of a Bridge”, 2023

Current questions on CCS

- Where is the store?
- What's the business model?
- Can you capture *all* the CO_2?
- Who can build it?
- Is there insurance?
- Can I finance it?

Some conclusions…

- No remaining debate as to the necessity for CCS – question is simply about financeable business models.
- The role and value of CCS recognised in power, industry, low CI hydrogen/molecules, and CDR.
- Diversity in technology vendors provides competition and promotes innovation.
- Increasing understanding of the relative affordability of CCS across energy and industry

Remaining challenges

- Need standardised CO_2 quality and pipeline specifications.
- Expediting appraisal and development of CO_2 storage capacity.
- Social license is not 100% – this leads to delays and/or rejection along the CCS chain, thus increasing costs.
- Regulatory barriers requiring IP disclosure, e.g., UK's solvent disclosure requirements by the Environmental Agency.

New opportunities for CCS

- New materials with resistance to degradation/VOC emissions, low water consumption, high purity CO_2 product stream
- Process and control technologies to support flexible operation
- "AI" is diving demand for baseload, low/zero CI power
- Modular technologies can both address terminal value risk and be applied to small point sources