Imperial College London

Challenges for a net zero transition

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Outline

- Scene setting
- CCS – where are we?
- Is CCS an R&D problem?
- The socio-economic dimension
- Thoughts on CCS project development
- Some conclusions

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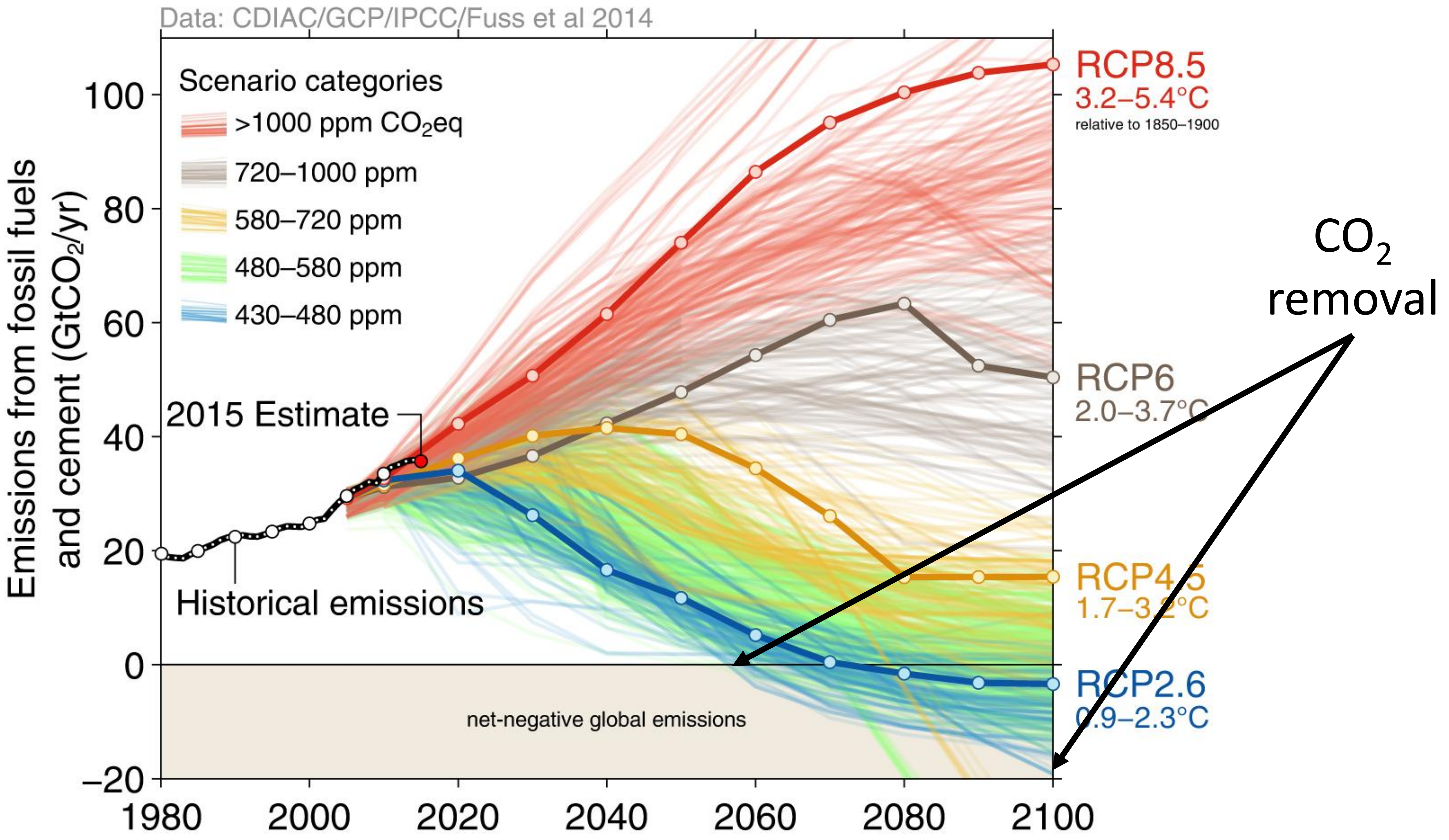


Data: CDIAC/GCP/IPCC/Fuss et al 2014
Scenario categories
>1000 ppm CO_2eq
720–1000 ppm
580–720 ppm
480–580 ppm
430–480 ppm
2015 Estimate
Historical emissions
net-negative global emissions
Emissions from fossil fuels and cement ($GtCO_2$/yr)
RCP8.5
3.2–5.4°C
relative to 1850–1900
RCP6
2.0–3.7°C
RCP4.5
1.7–3.2°C
RCP2.6
0.9–2.3°C
CO_2 removal

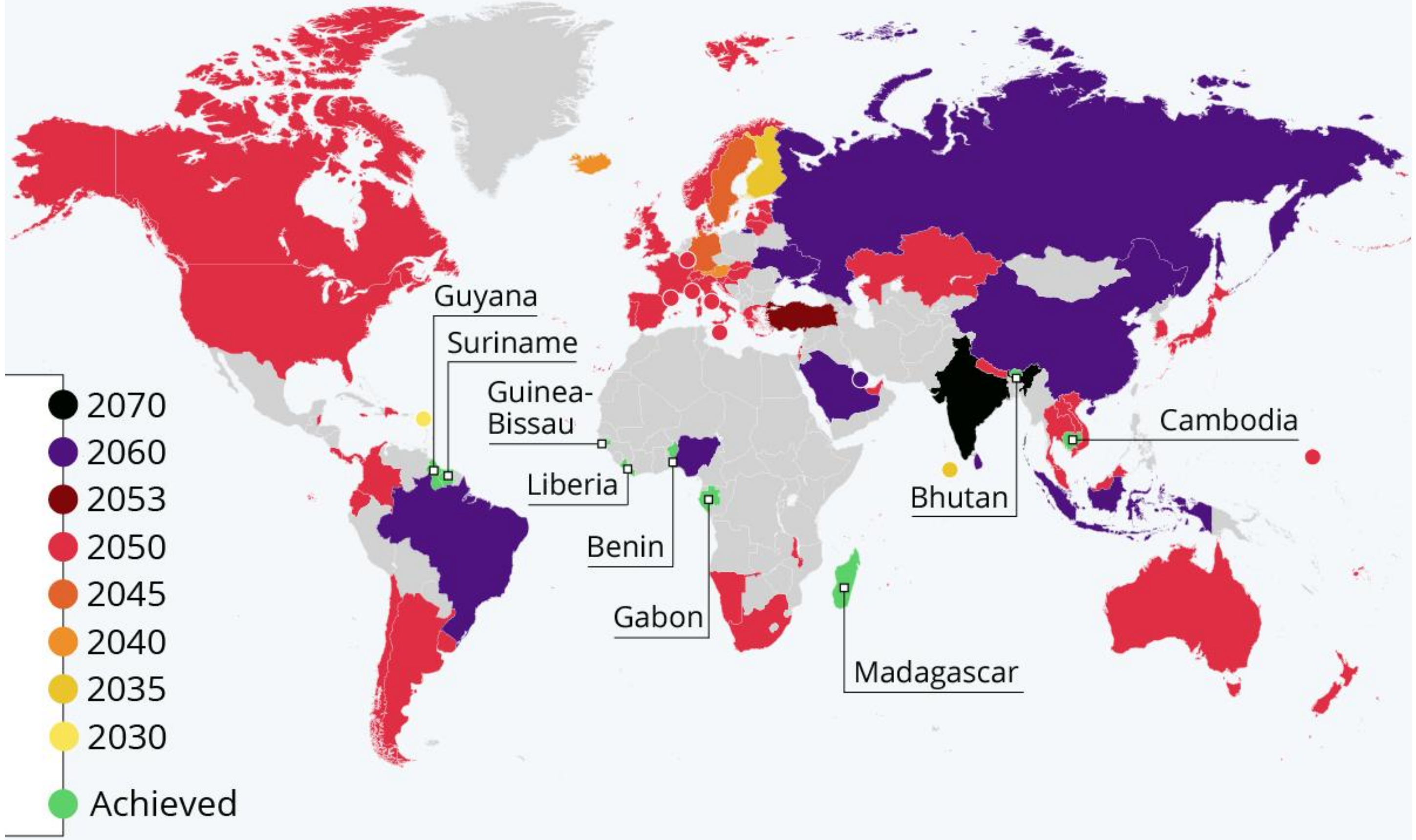
So, what does net zero mean?

The term net zero is so ubiquitous as to be meaningless

- Zero greenhouse gas emissions?
- Net zero greenhouse emissions
- No fossil carbon in the energy system?
- Only wind, water, and solar energy?

The Road to Net Zero

Countries with laws, policy documents or concrete timed pledges for carbon neutrality by target year

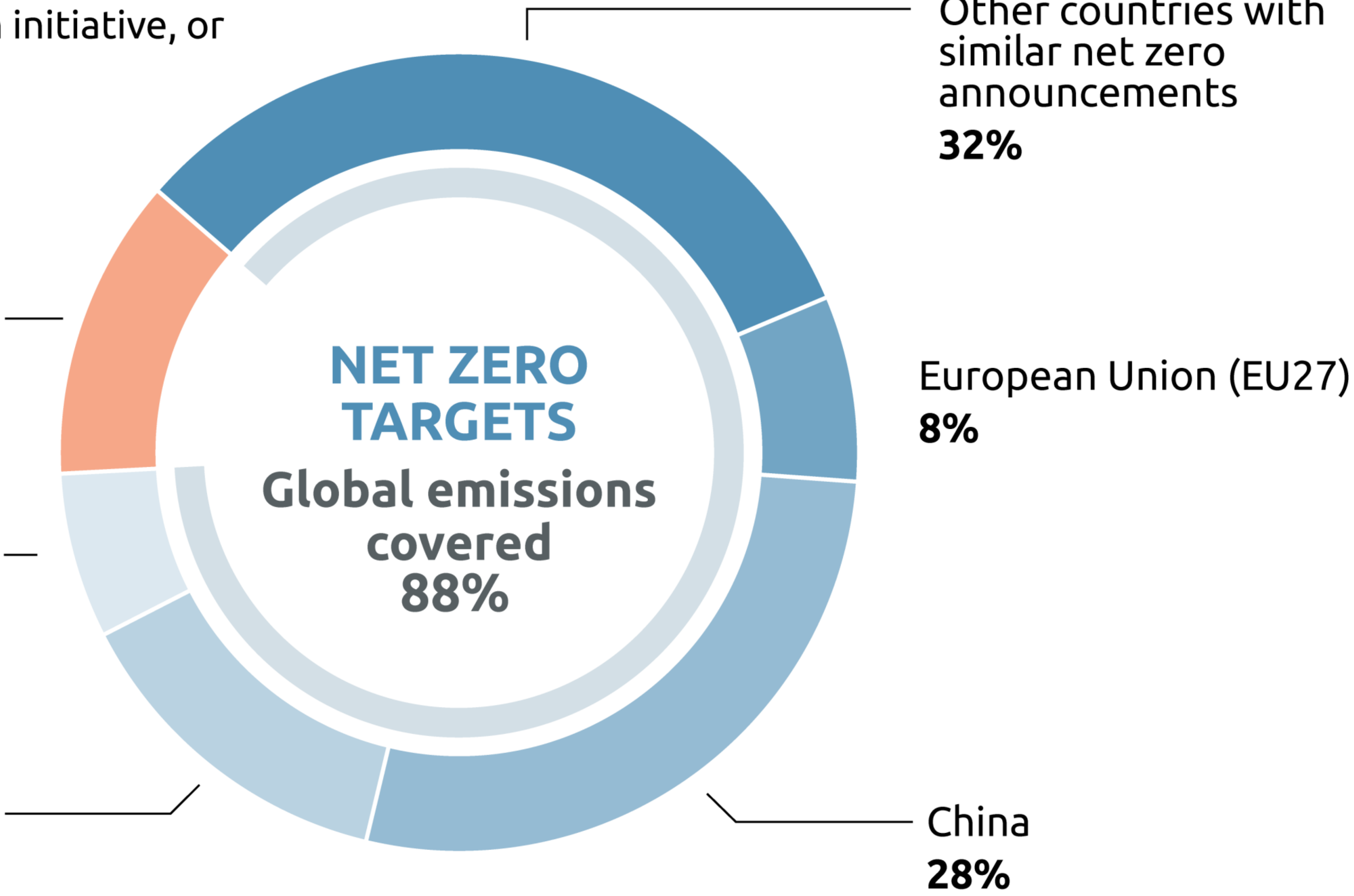


Source: Energy & Climate Intelligence Unit

Net zero emissions target announcements

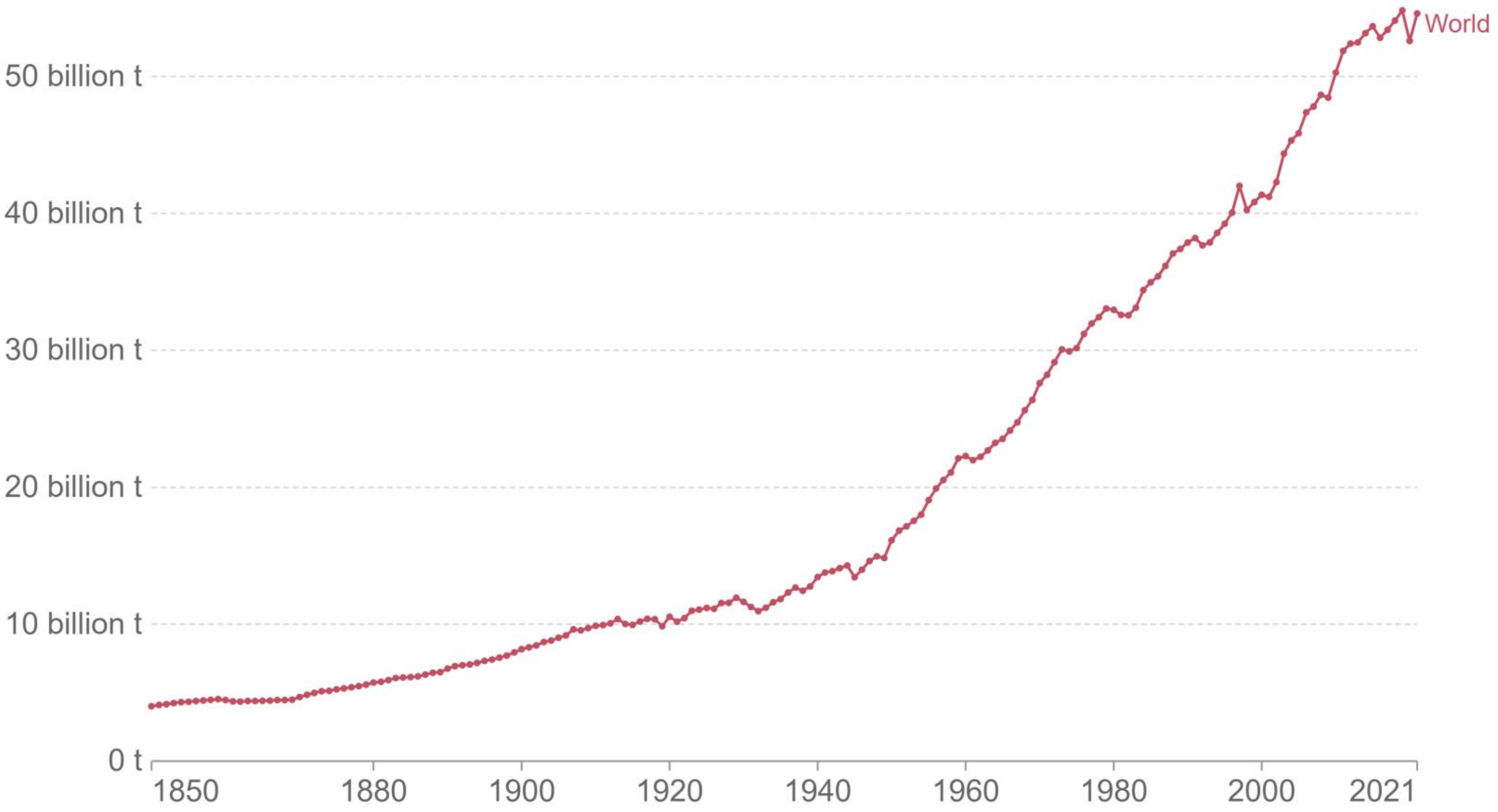
Agreed in law, as part of an initiative, or under discussion

Climate Action Tracker **Nov 2022** Update



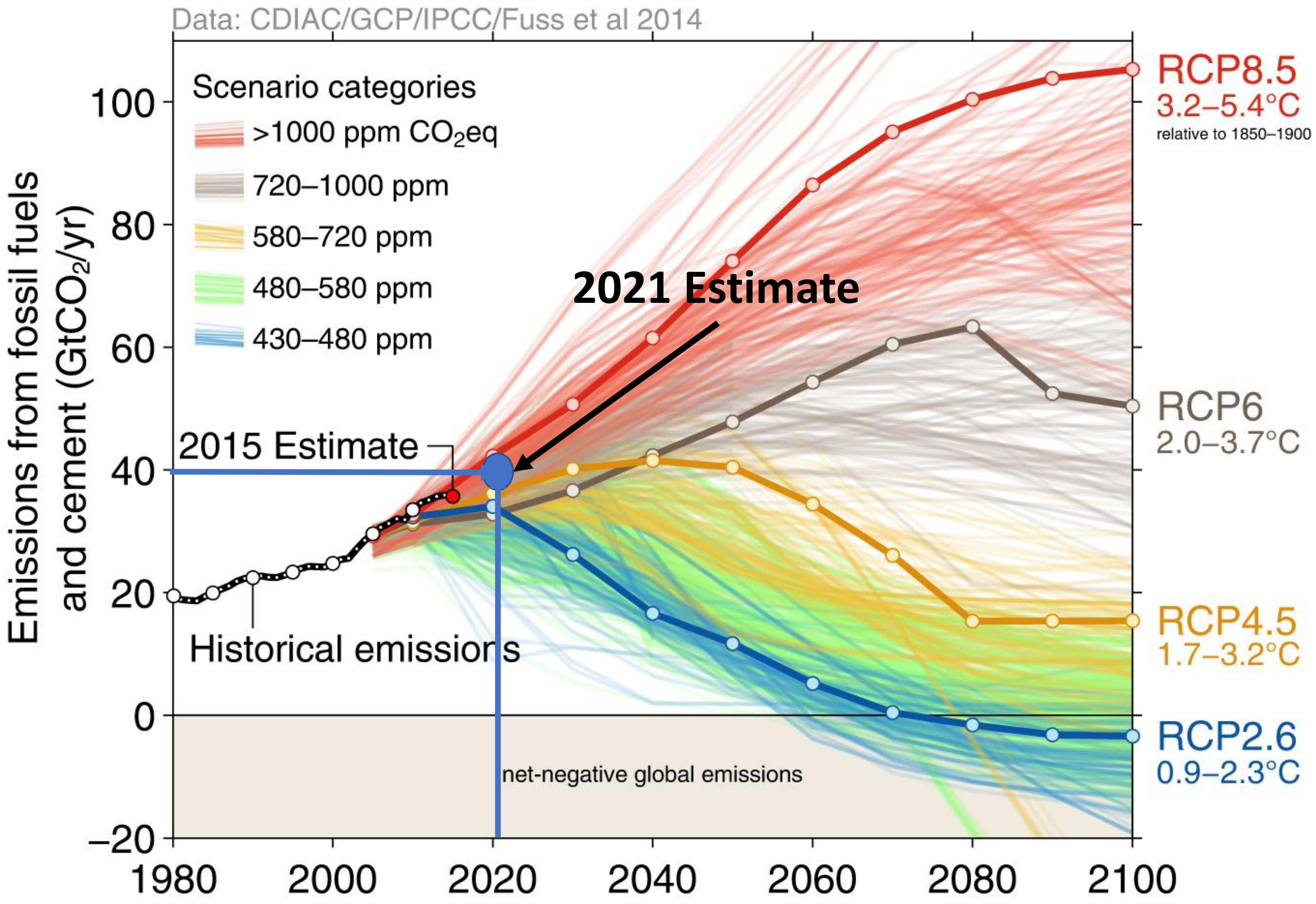
Greenhouse gas emissions

Greenhouse gas emissions include carbon dioxide, methane and nitrous oxide from all sources, including agriculture and land use change. They are measured in carbon dioxide-equivalents[1] over a 100-year timescale.



Source: Calculated by Our World in Data based on emissions data from Jones et al. (2023)
Note: Land use change emissions can be negative.

1. Carbon dioxide-equivalents (CO_2eq): Carbon dioxide is the most important greenhouse gas, but not the only one. To capture all greenhouse gas emissions, researchers express them in 'carbon dioxide-equivalents' (CO_2eq). This takes all greenhouse gases into account, not just CO_2. To express all greenhouse gases in carbon dioxide-equivalents (CO_2eq), each one is weighted by its global warming potential (GWP) value. GWP measures the amount of warming a gas creates compared to CO_2. CO_2 is given a GWP value of one. If a gas had a GWP of 10 then one kilogram of that gas would generate ten times the warming effect as one kilogram of CO_2. Carbon dioxide-equivalents are calculated for each gas by multiplying the mass of emissions of a specific greenhouse gas by its GWP factor. This warming can be stated over different timescales. To calculate CO_2eq over 100 years, we'd multiply each gas by its GWP over a 100-year timescale (GWP100). Total greenhouse gas emissions – measured in CO_2eq – are then calculated by summing each gas' CO_2eq value.



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Emissions from fossil fuels and cement ($GtCO_2$/yr)
100
80
60
40
20
0
−20
1980
2000
2020
2040
2060
2080
2100
RCP8.5
3.2–5.4°C
relative to 1850–1900
RCP6
2.0–3.7°C
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Our World in Data

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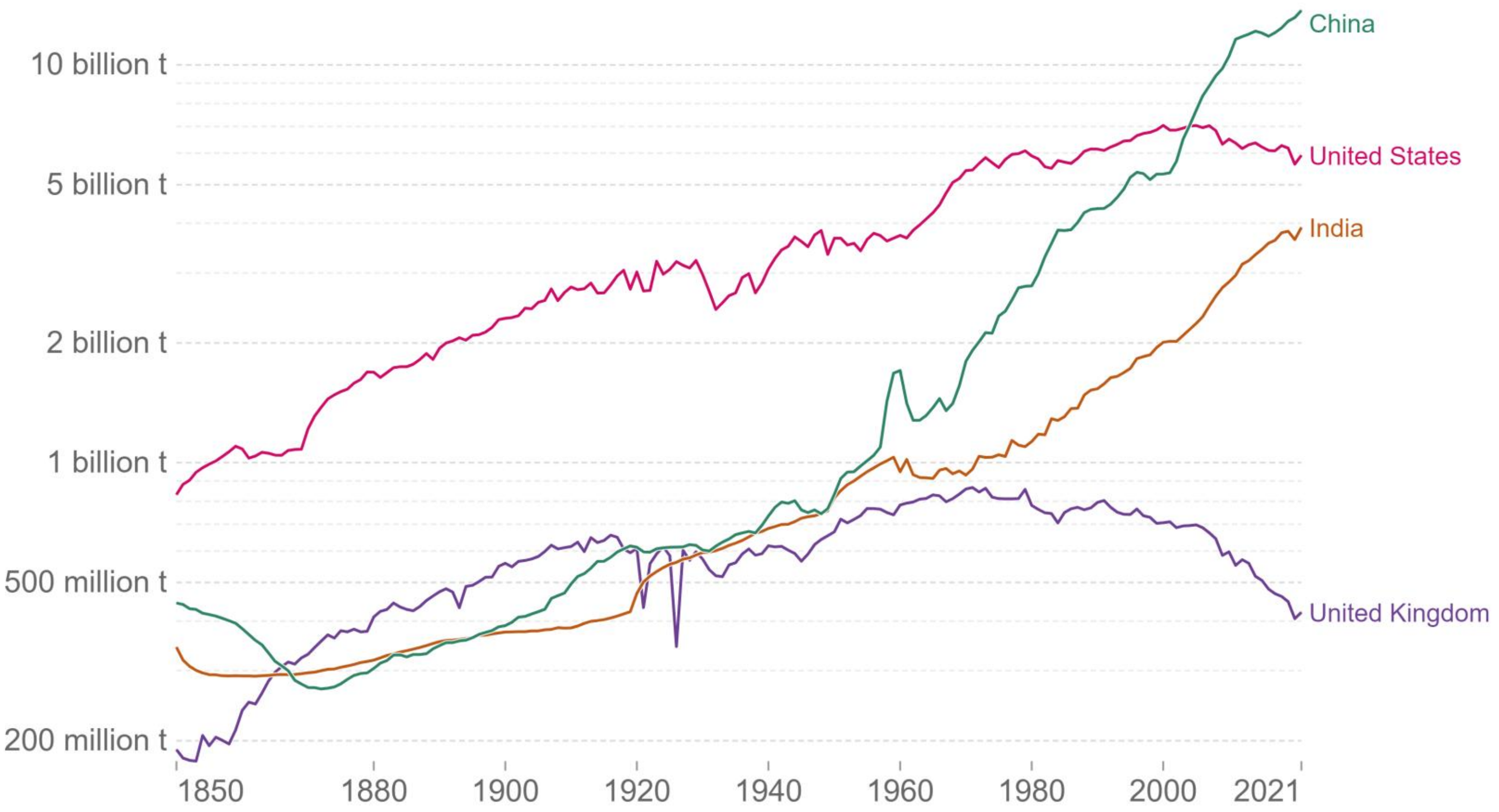

China: 8 t_{CO2}/person

USA: 18 t_{CO2}/person

India: 2.5 t_{CO2}/person

UK: 6.3 t_{CO2}/person

Source: Calculated by Our World in Data based on emissions data from Jones et al. (2023)
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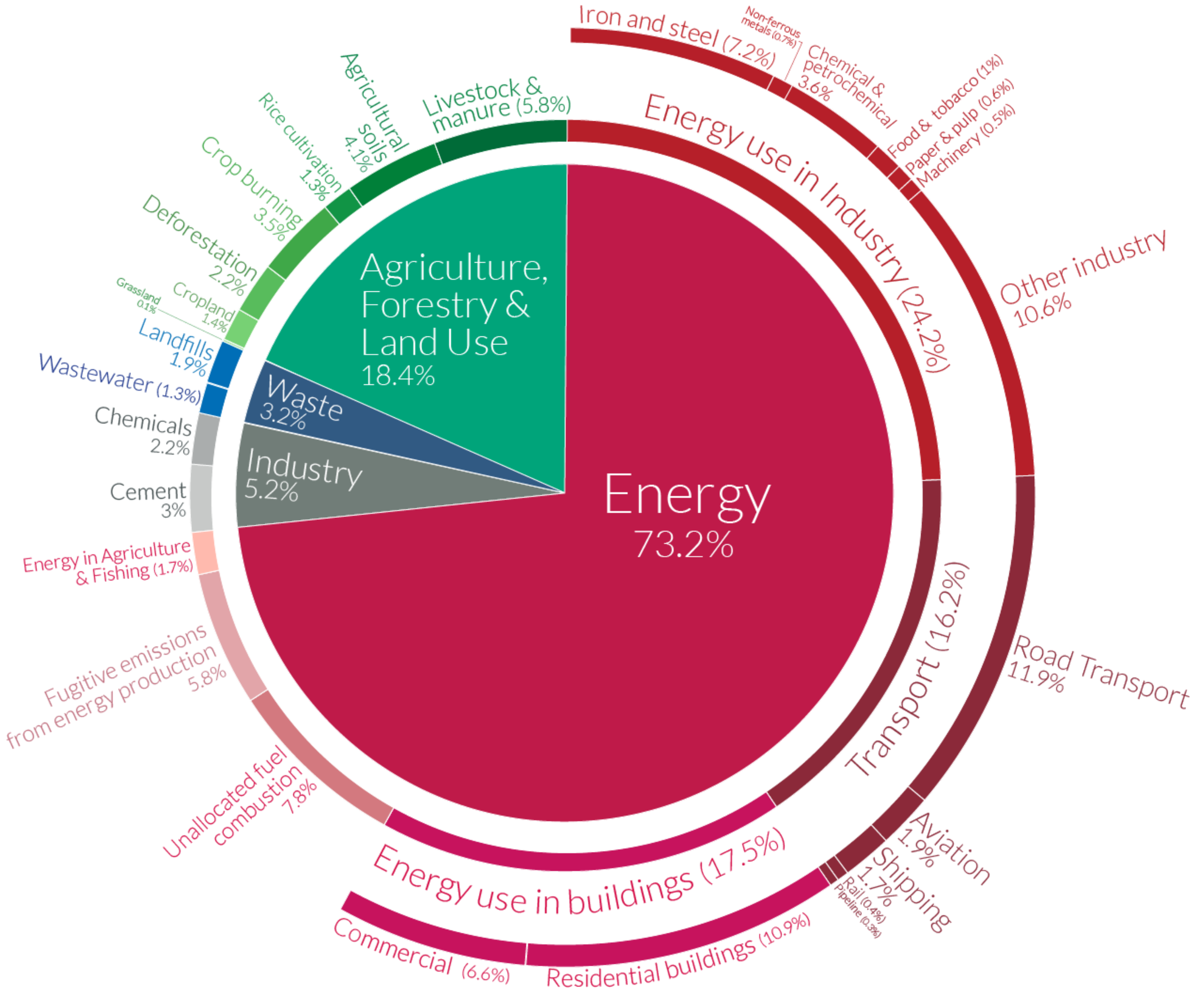
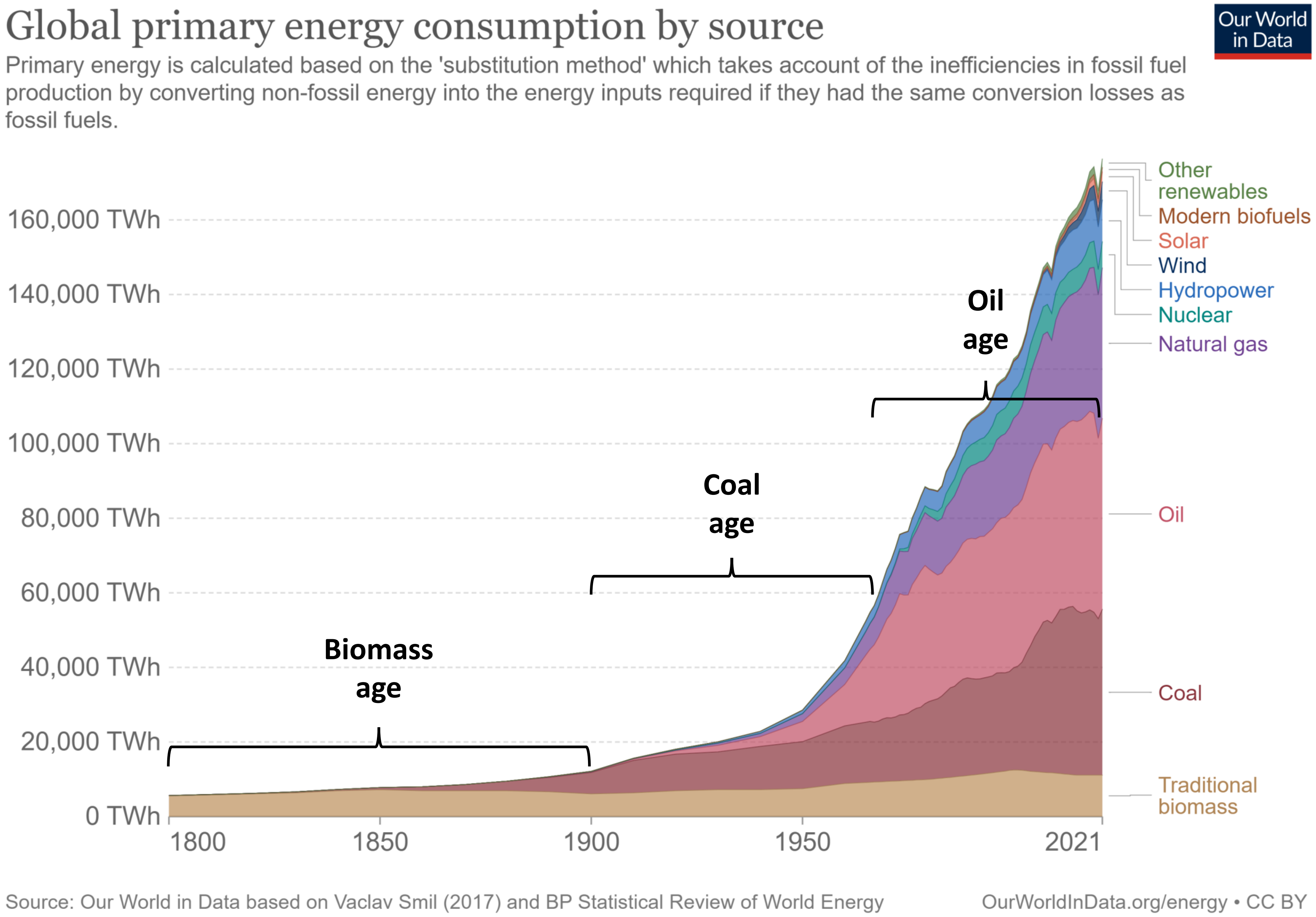
Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO_2eq.

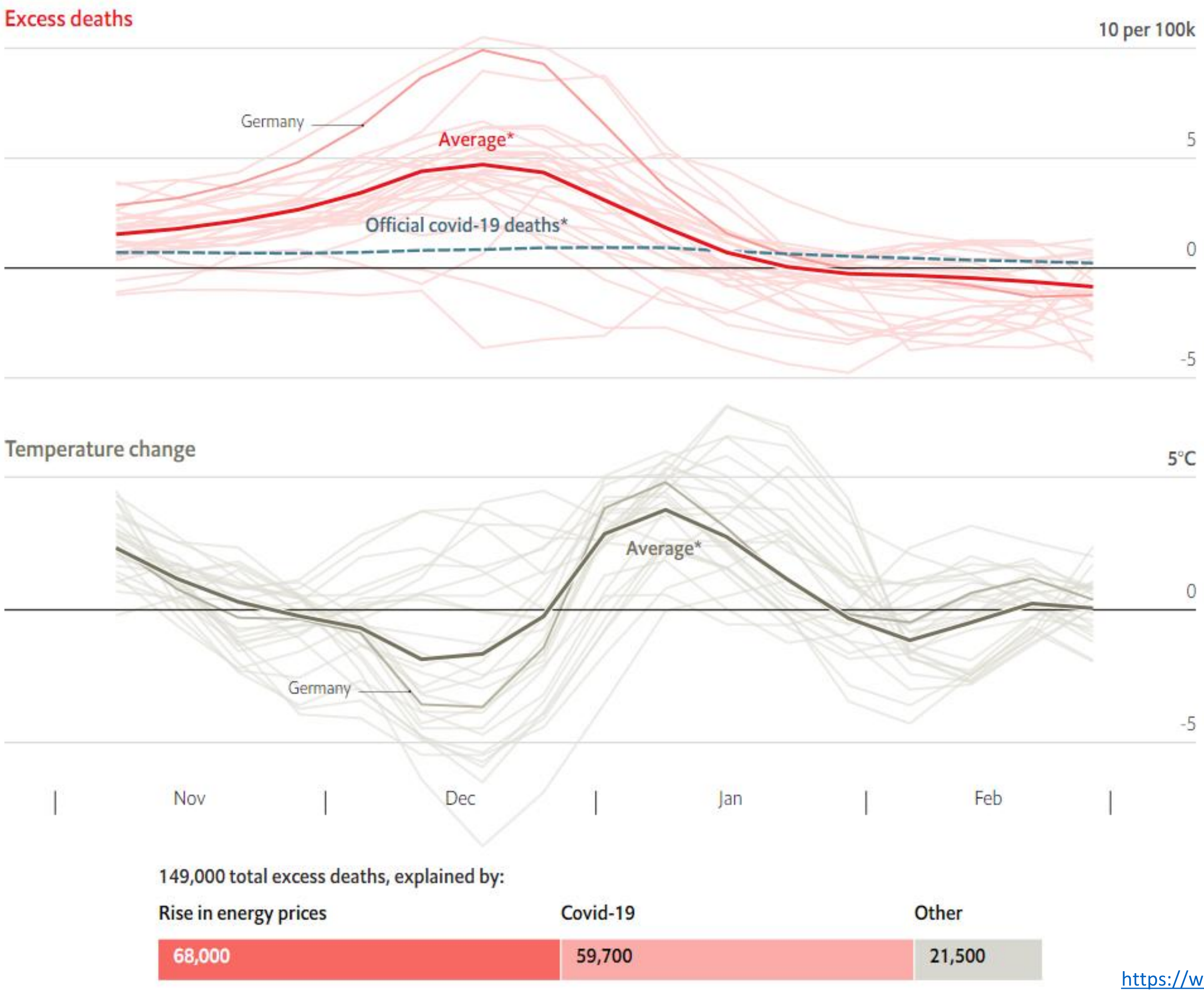


Source: Climate Watch, the World Resources Institute (2020).


Global primary energy consumption by source
Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.
Our World in Data
160,000 TWh
140,000 TWh
120,000 TWh
100,000 TWh
80,000 TWh
60,000 TWh
40,000 TWh
20,000 TWh
0 TWh
1800
1850
1900
1950
2021
Other renewables
Modern biofuels
Solar
Wind
Hydropower
Nuclear
Natural gas
Oil
Coal
Traditional biomass
Biomass age
Coal age
Oil age
Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy
OurWorldInData.org/energy • CC BY

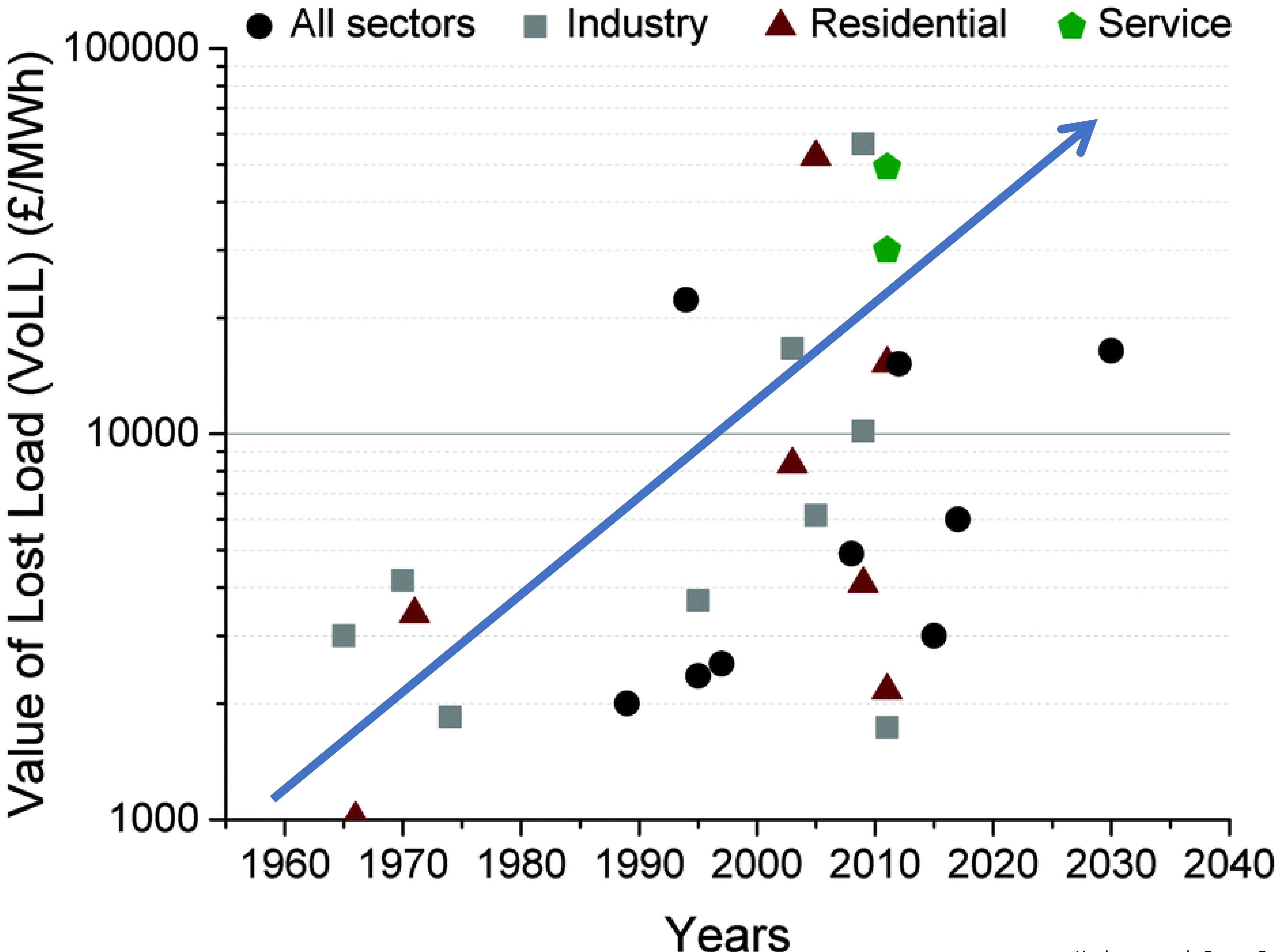
Europe, excess deaths v average temperatures

Winter 2022-23 compared with 2015-19, three-week moving average



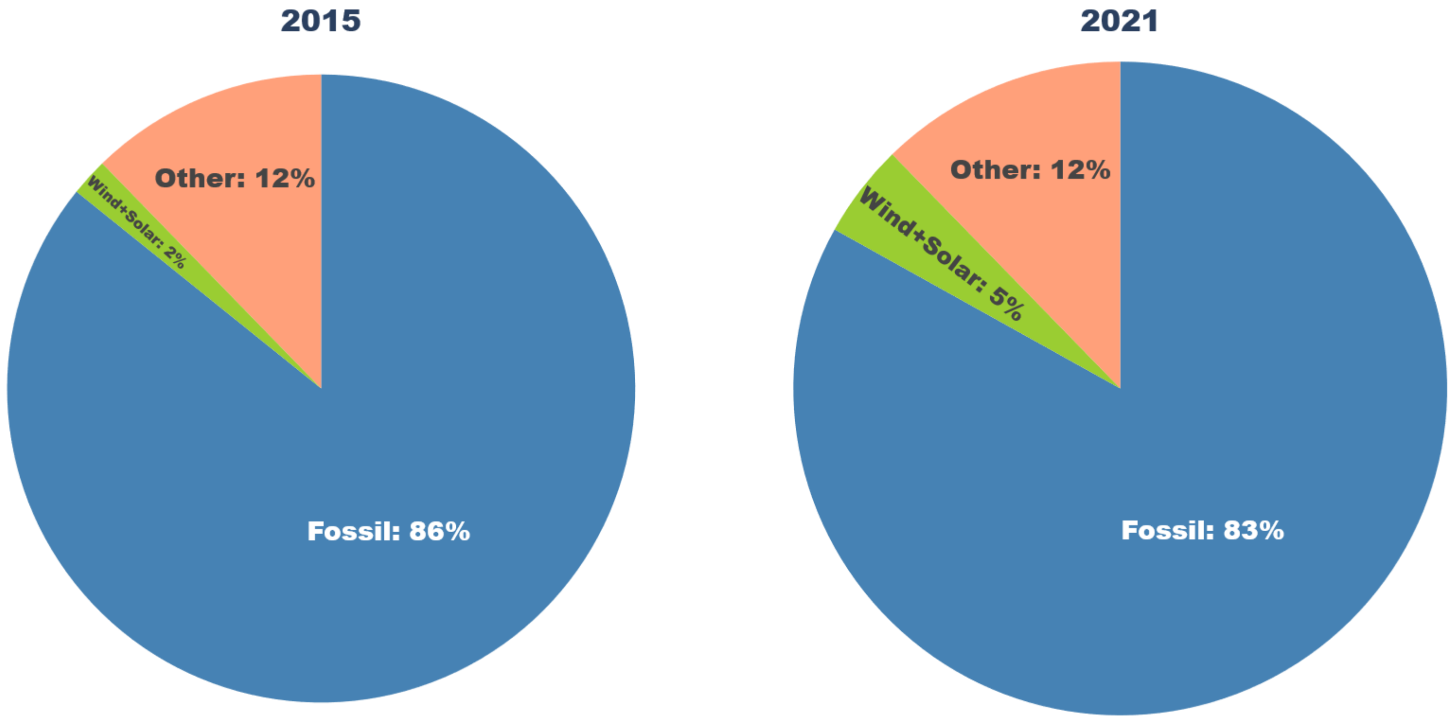
*EU-27 (except Malta and Cyprus) plus Britain, Norway and Switzerland

https://www.economist.com/graphic-detail/2023/05/10/expensive-energy-may-have-killed-more-europeans-than-covid-19-last-winter



Heuberger et al., Energy Environ. Sci., 2016, 9, 2497-2510

Progress since the 2015 Paris Agreement



	2015	2021	Change
Net zero coverage	0	88%	Increase
Global energy use	150,000 TWh	163,000 TWh	~ 9% Increase
% Fossil energy used	86%	83%	~ 3% decrease
Absolute fossil energy used	130,000 TWh	136,000 TWh	~ 5% increase
CO_2 emissions	53.66 Gt	54.59 Gt	~ 2% increase

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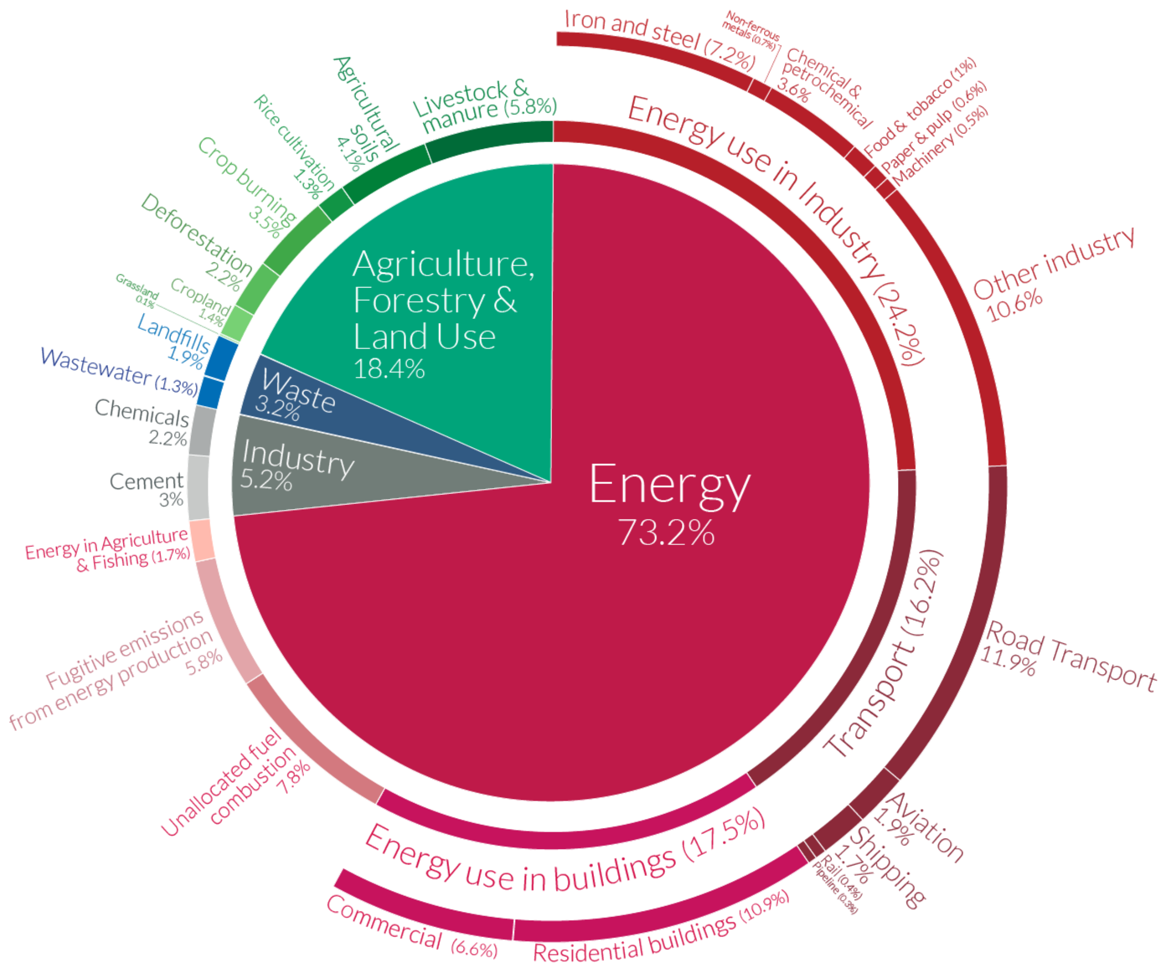
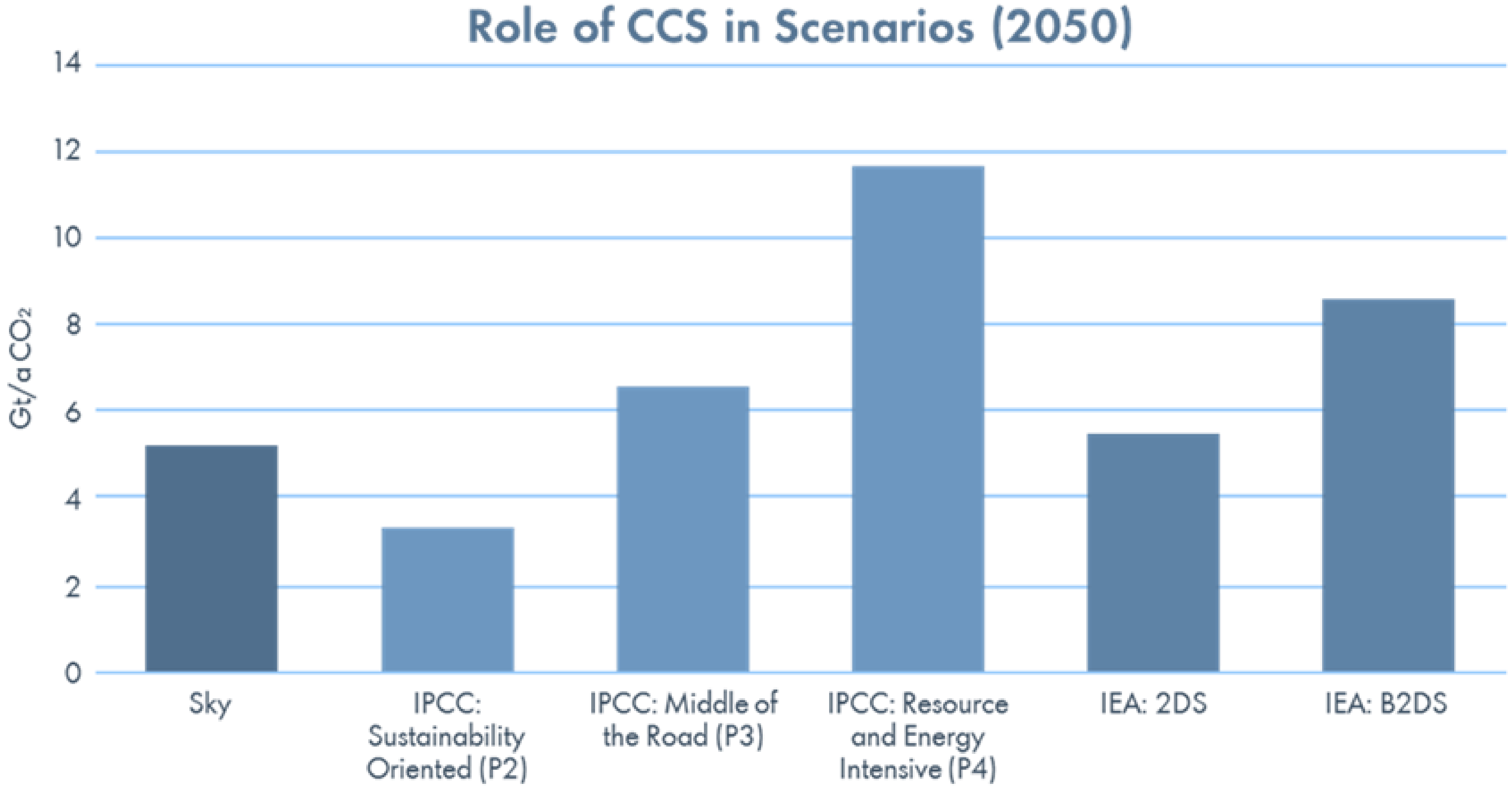
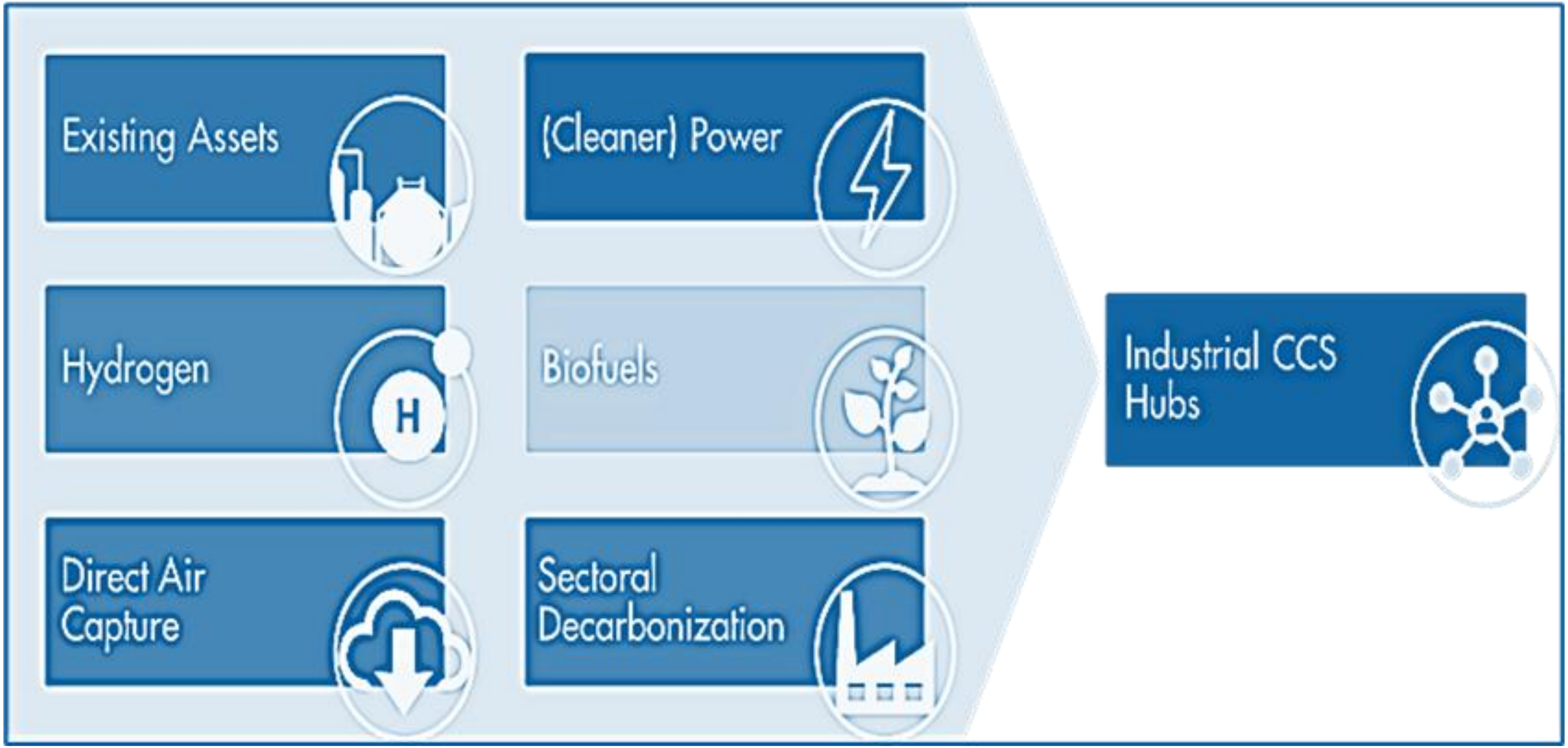
Look again at where GHGs come from



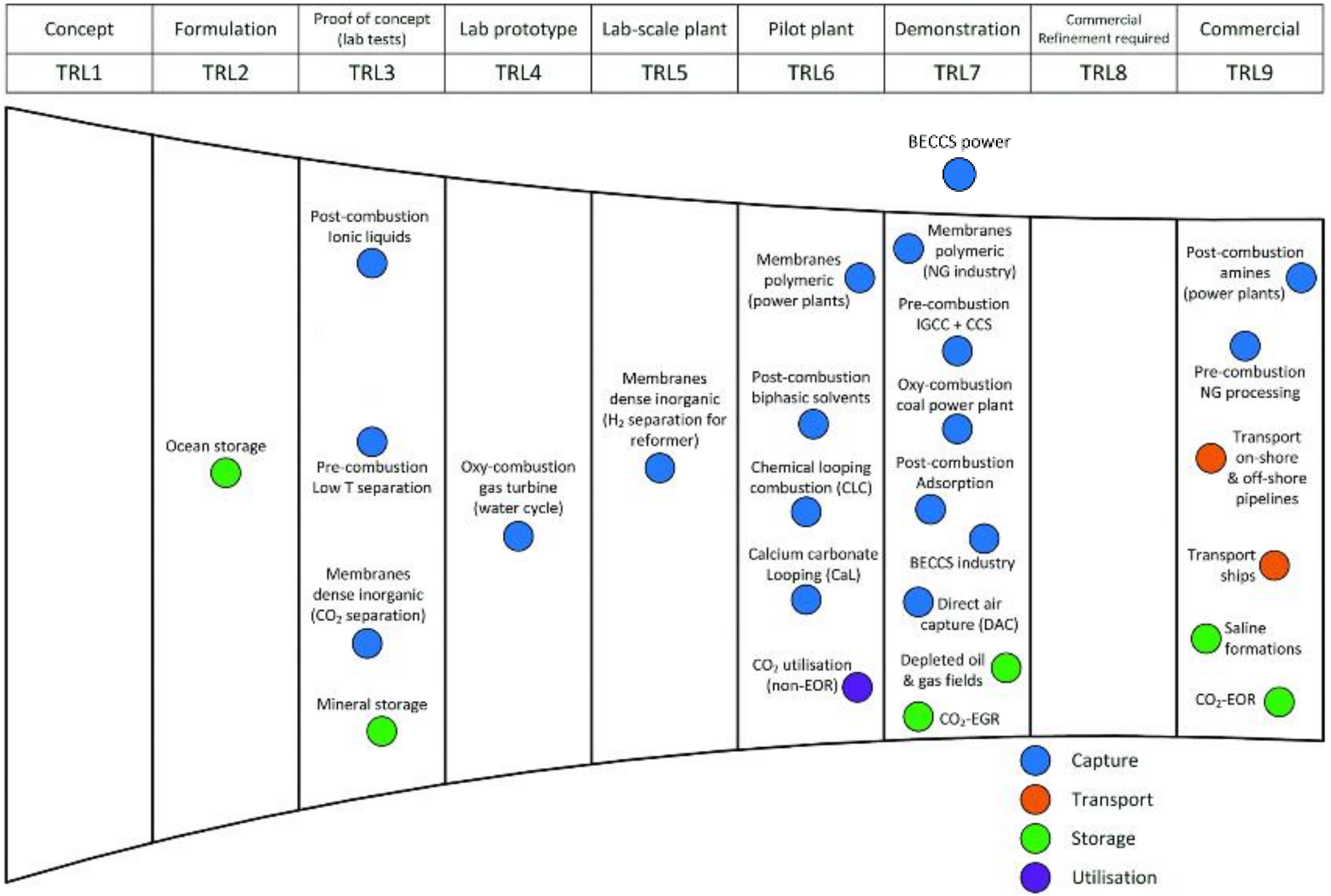
The role of CCS in net zero is unequivocal



CCS provides optionality in the transition

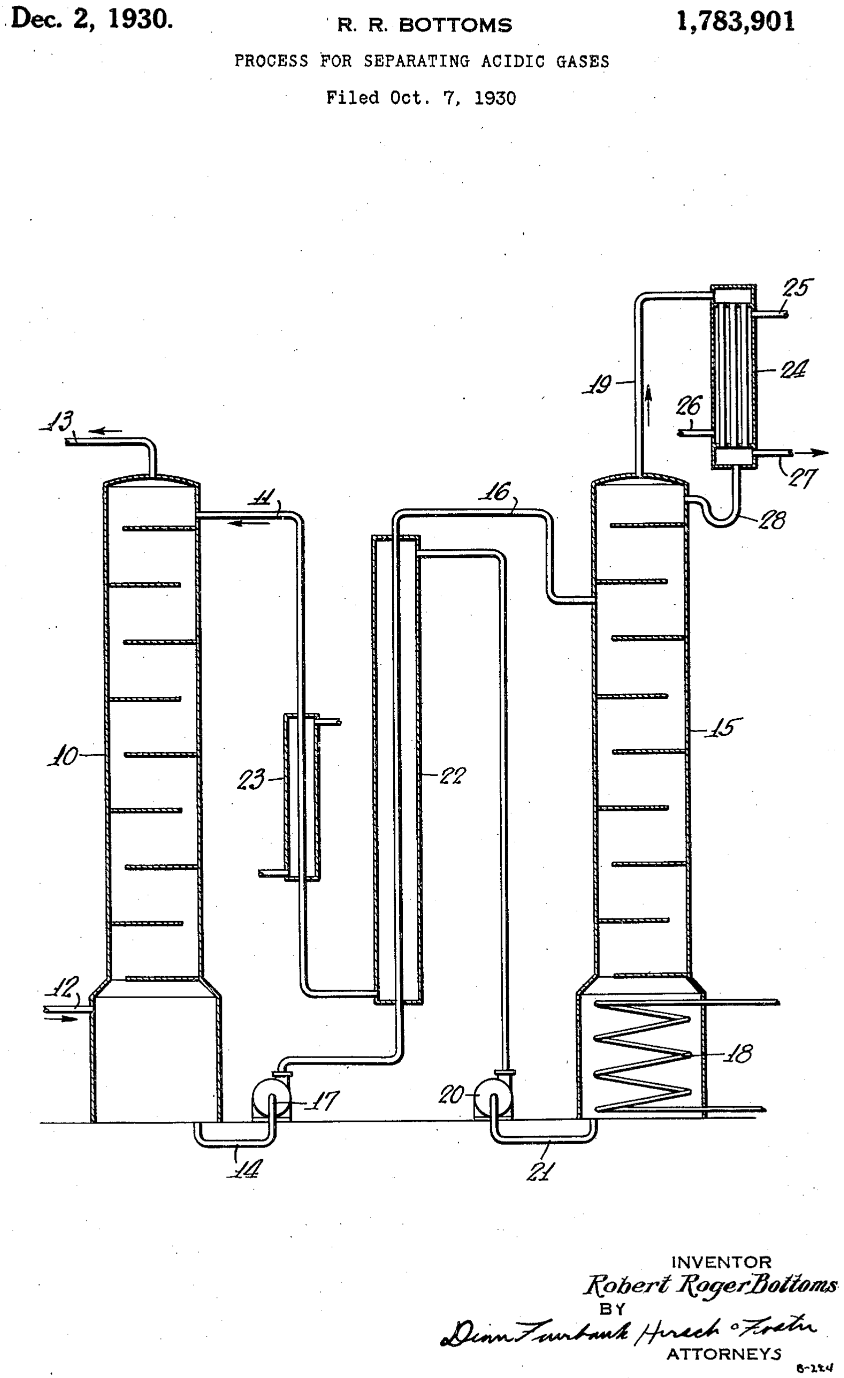


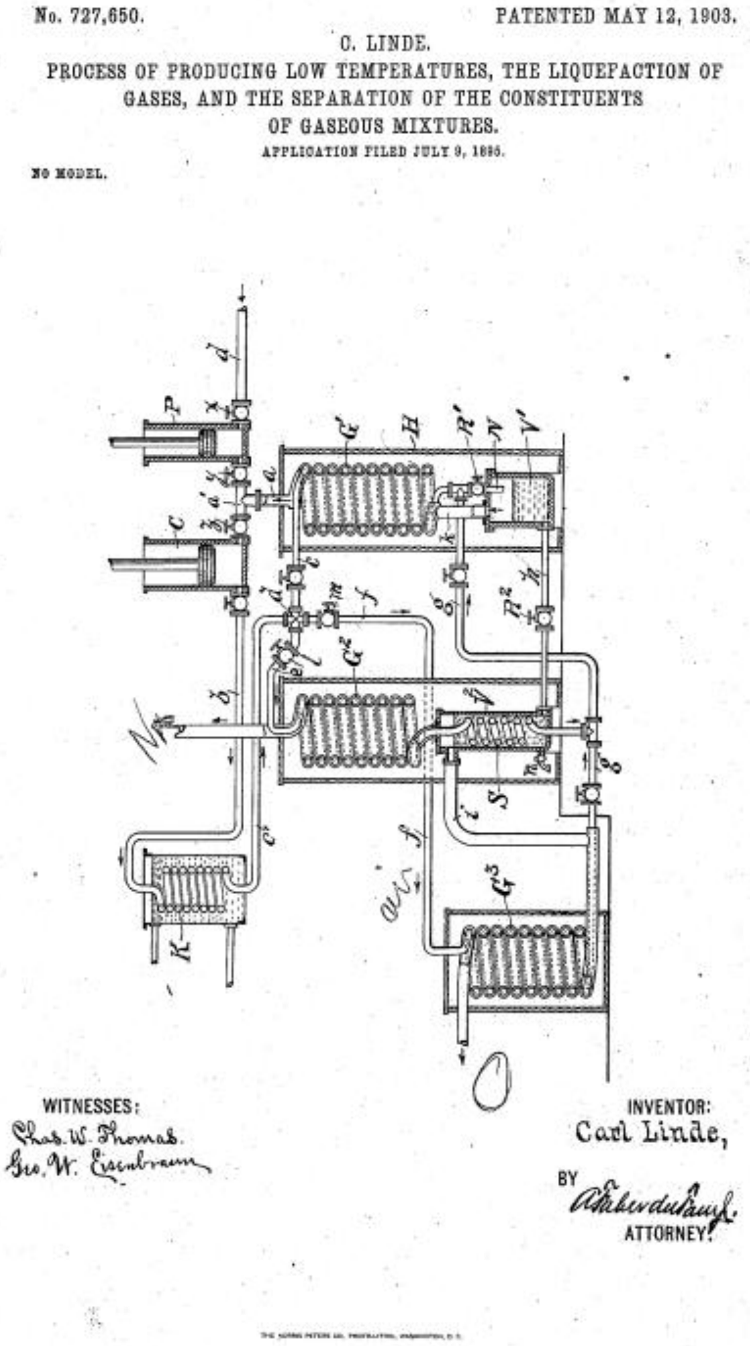
Technology adoption pathway



Not an exhaustive list of technologies

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



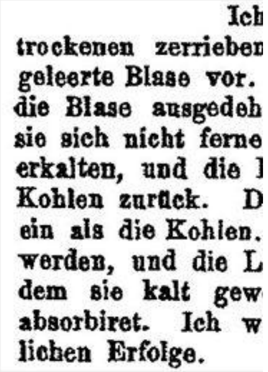


UNIVERSITY OF AMSTERDAM

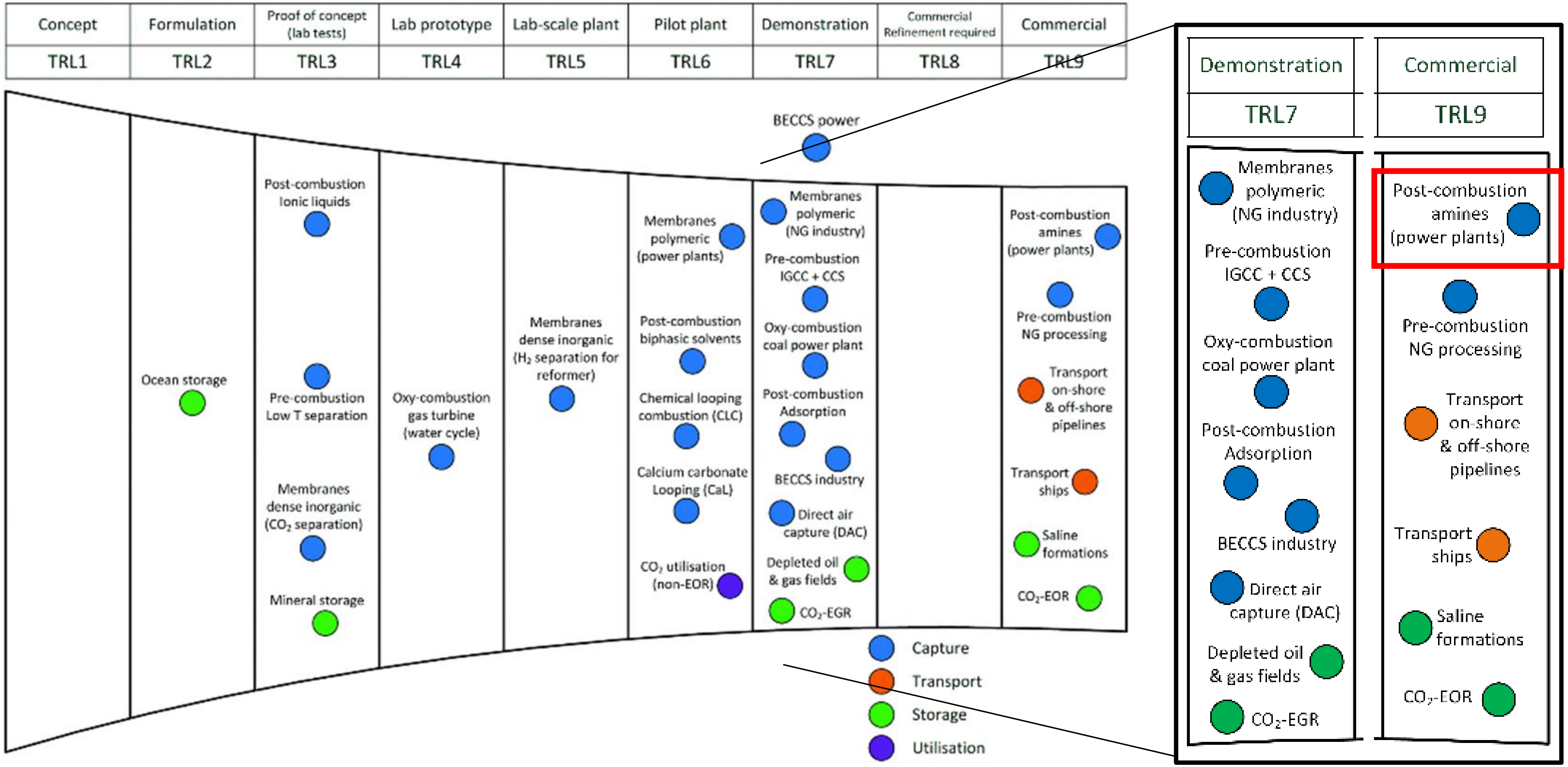
Observations of adsorption

1742 –1786 Carl Wilhelm Scheele

Library of Congress


Ich
trockenen zerrieben
geleerte Blase vor.
die Blase ausgedeh
sie sich nicht ferne
erkalten, und die I
Kohlen zurück. D
ein als die Kohlen.
werden, und die L
dem sie kalt gew
absorbiret. Ich w
lichen Erfolge.

CCS development: technology readiness level (TRL)



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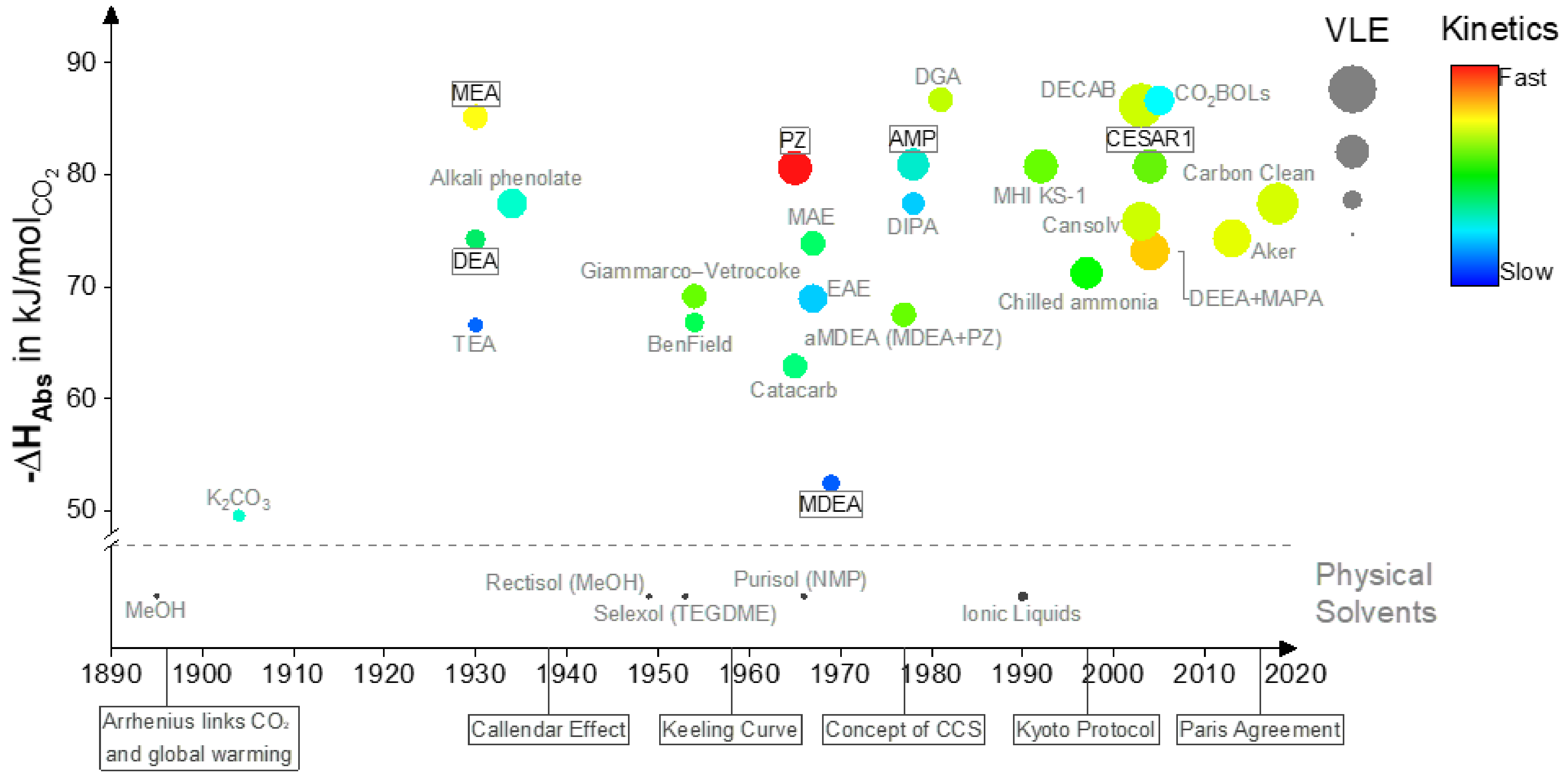
Solvent development has a long history…



Brandl, et al. (2022). Int J GHG Con, 120, 103771

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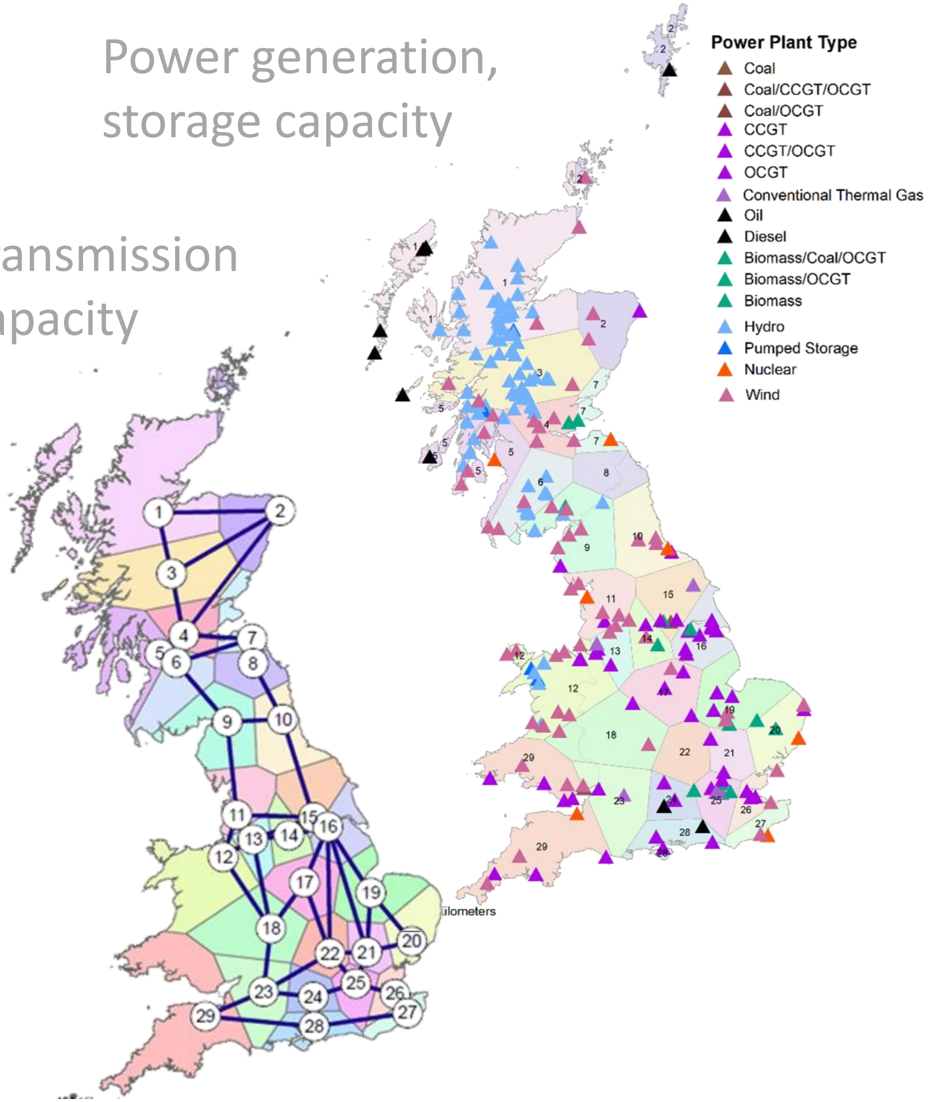
Energy system optimisation (ESO) framework

Power generation, storage capacity

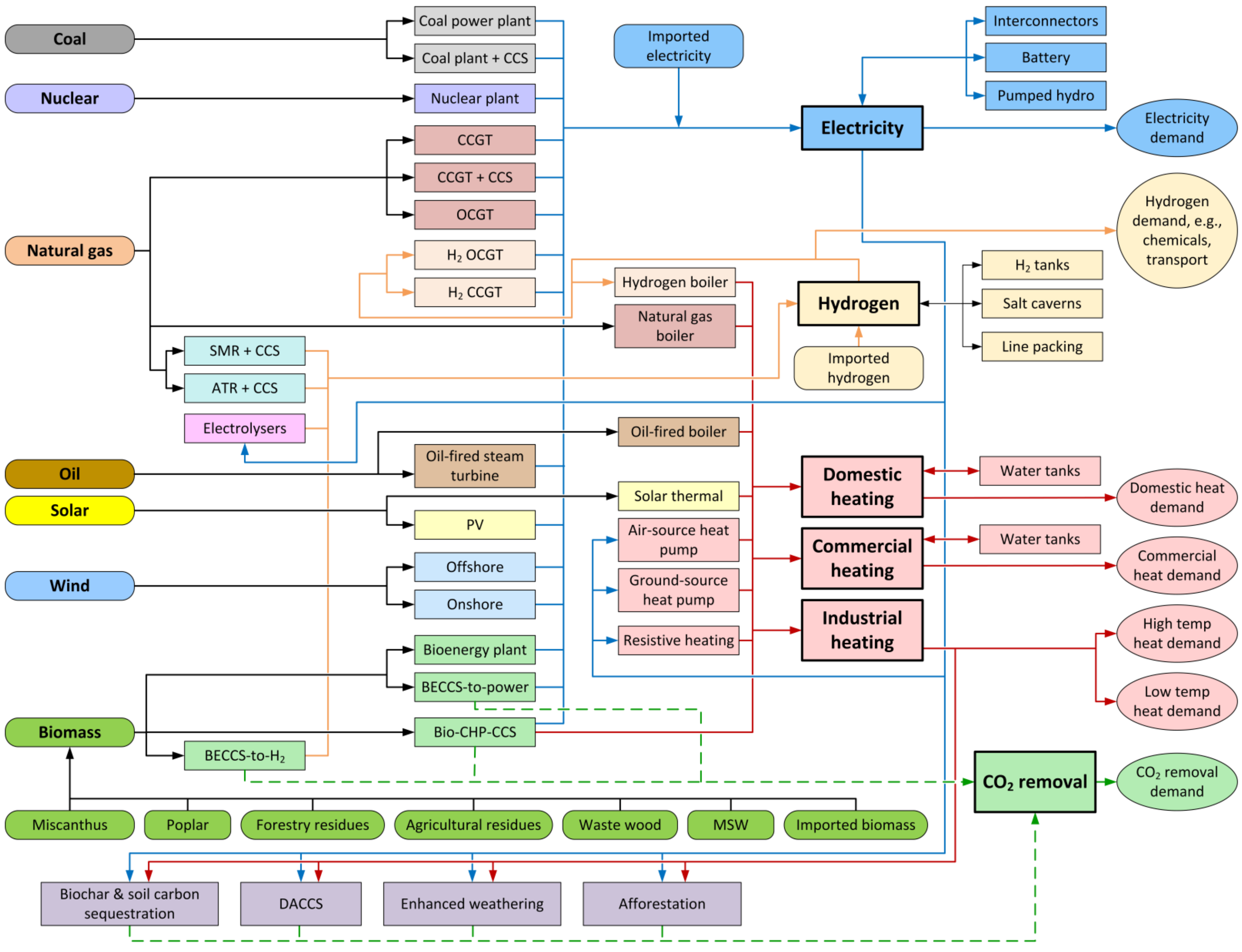
Transmission capacity



$\forall i \in I$ $\forall a \in A$	**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



Mersch, M., Markides, C. N., Mac Dowell, N., “The impact of the energy crisis on the UK’s net zero transition” iScience, 2023, Ganzer, C and Mac Dowell, N, “Pathways to net zero for power and industry in the UK”, Int J GHG Con, 2023

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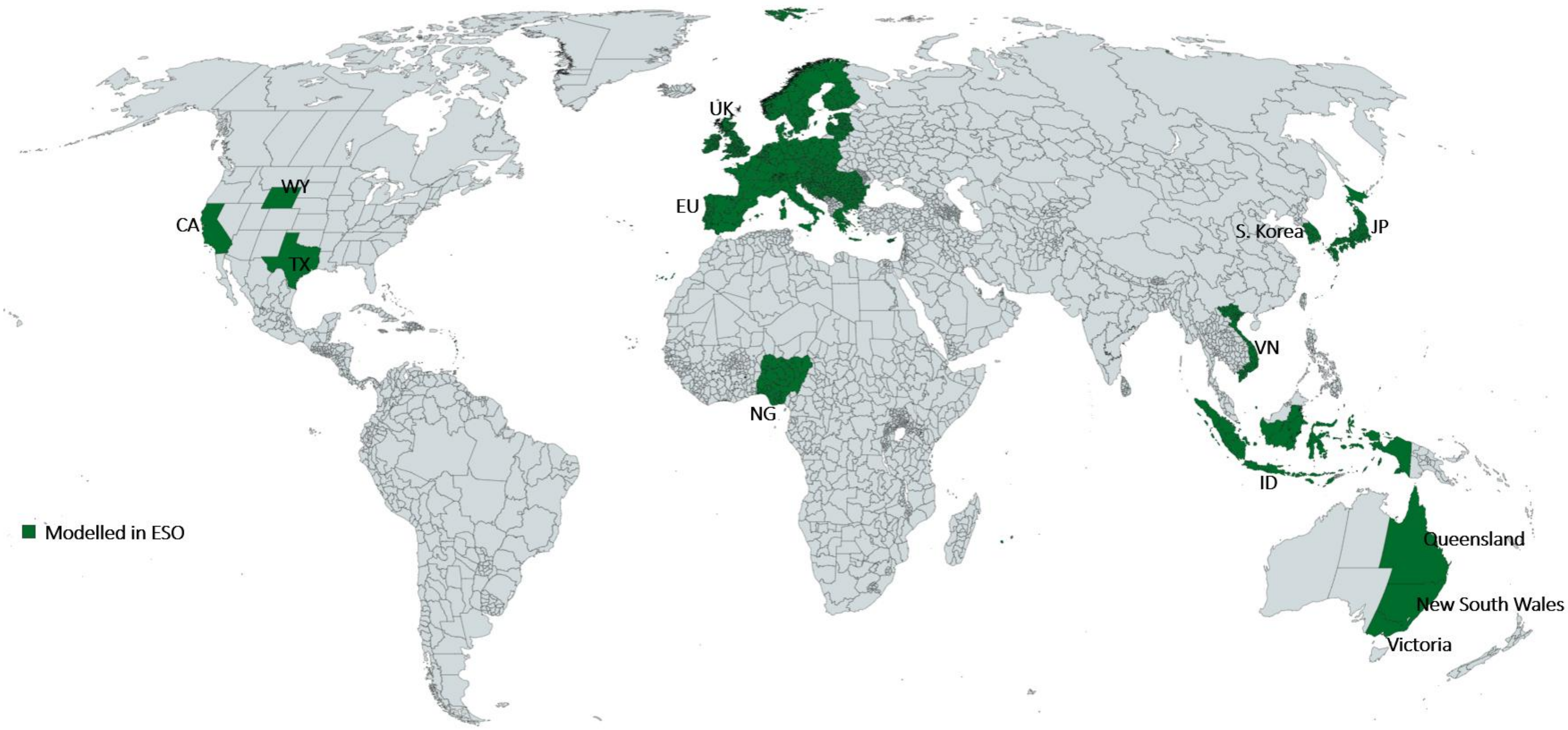
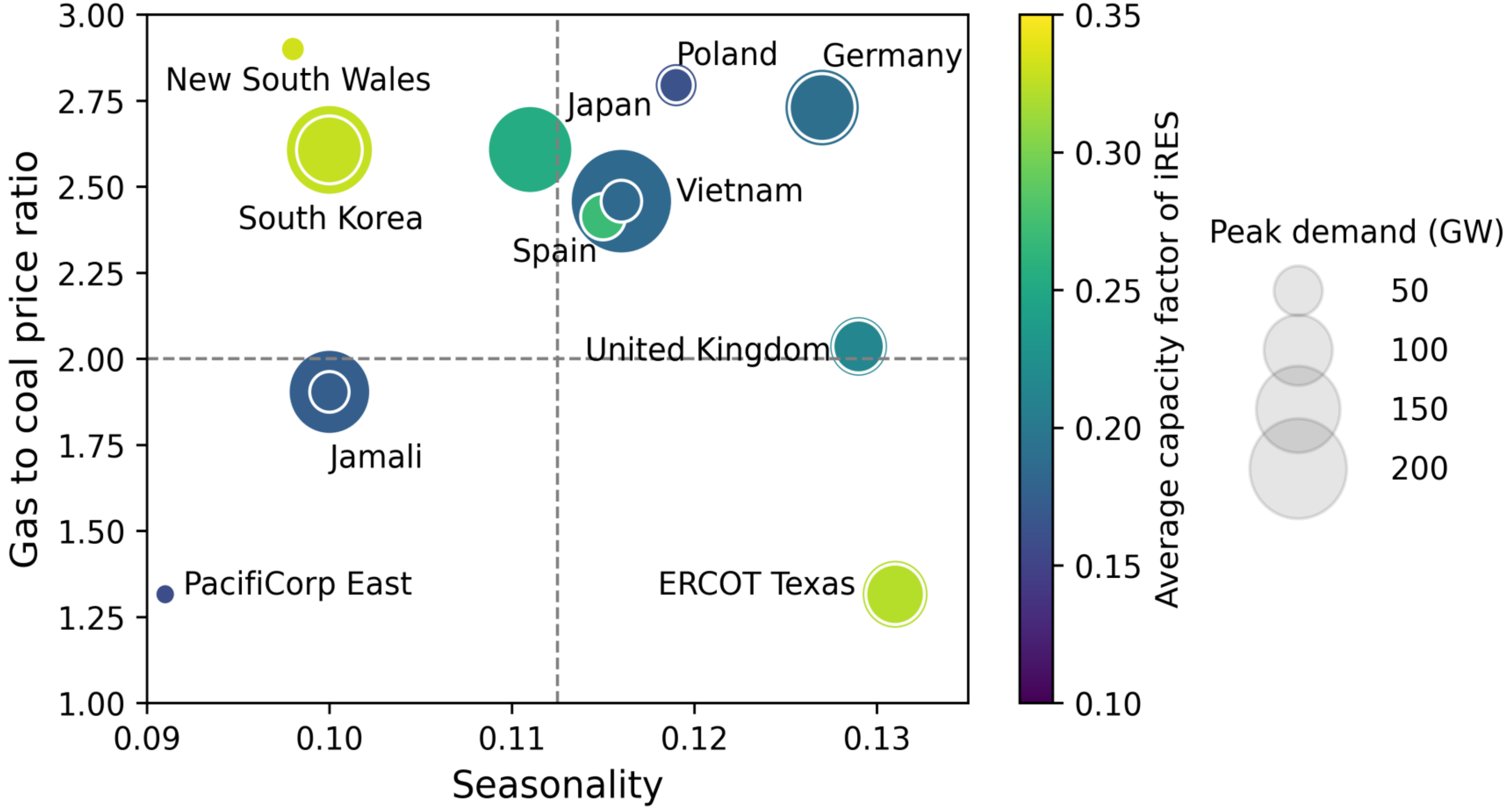


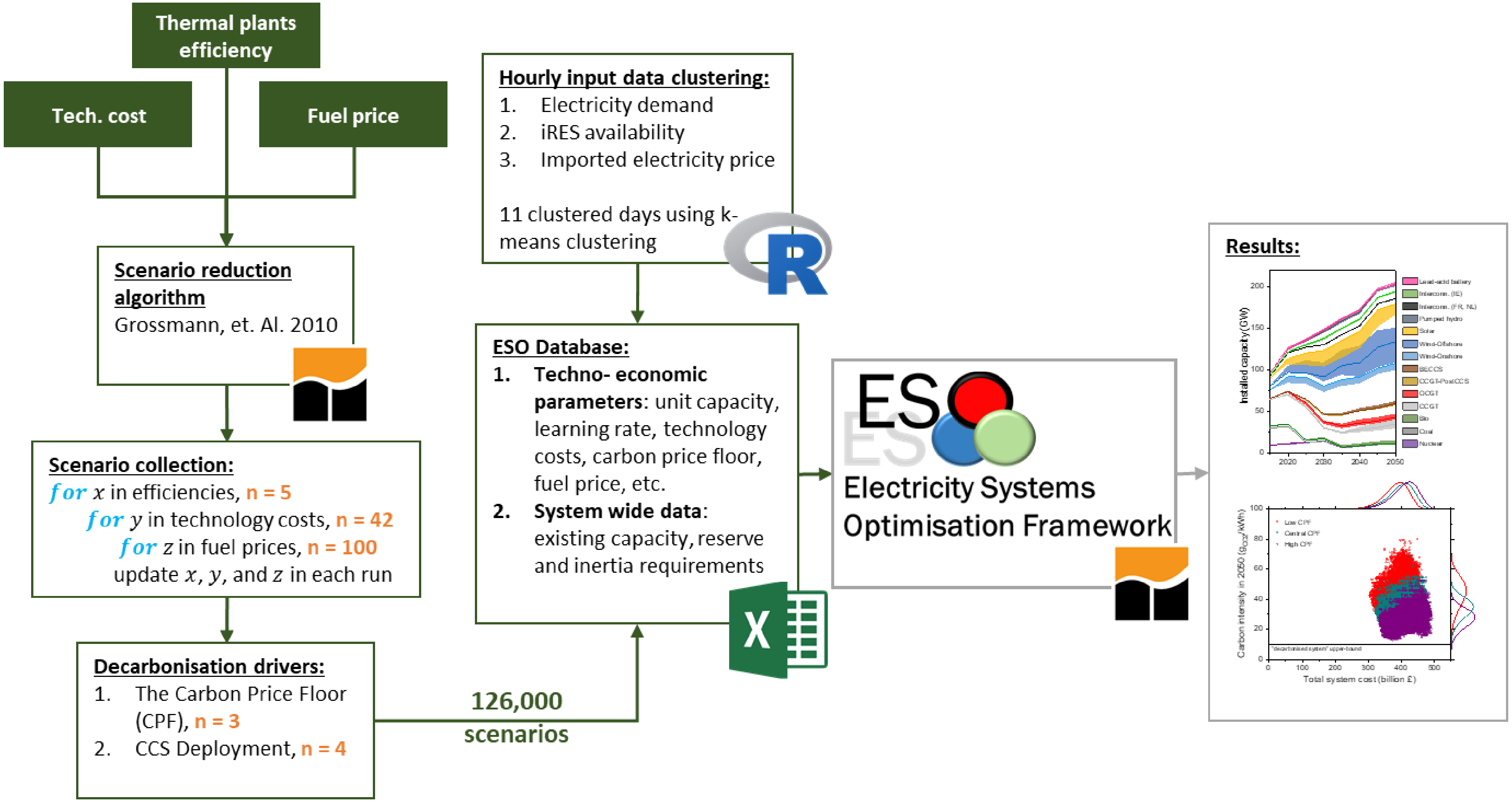
No one size fits all



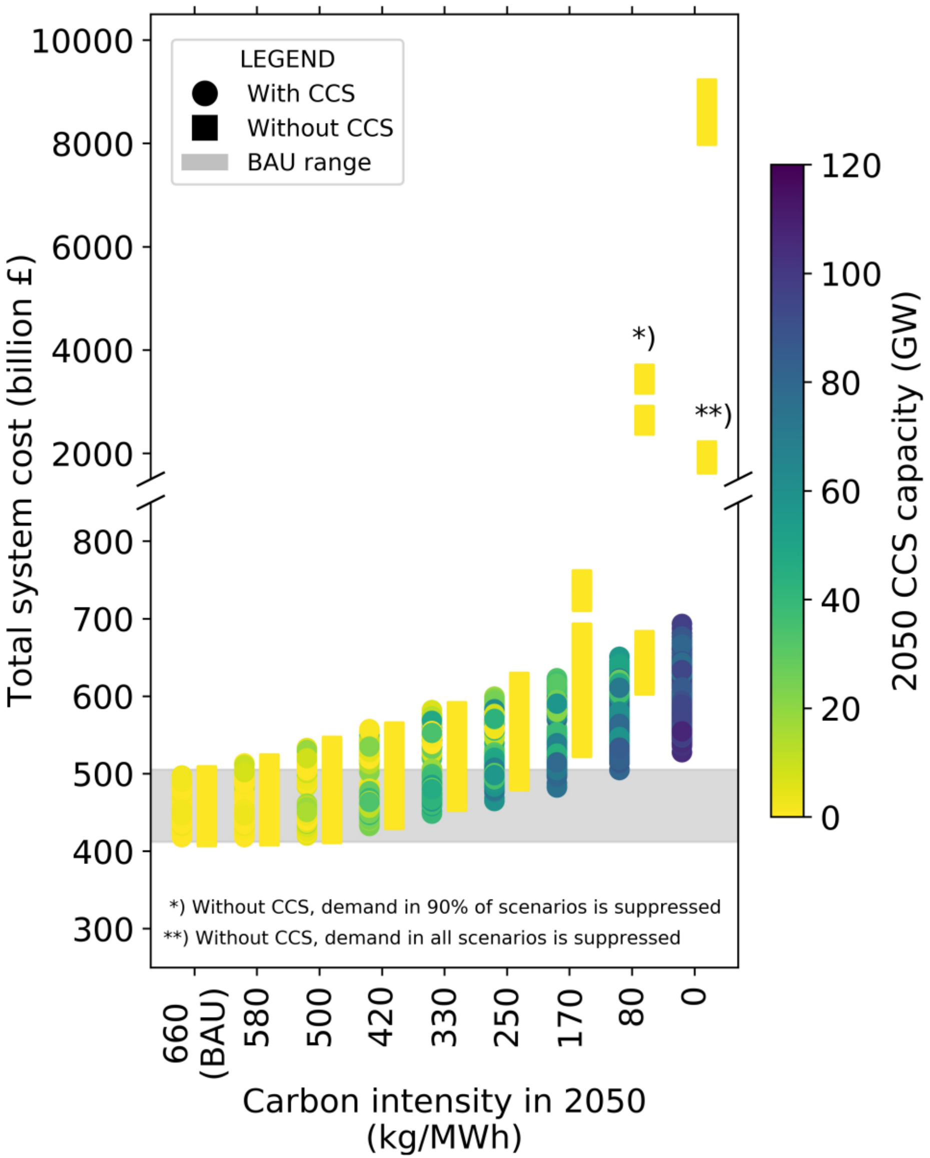
**) Seasonality is defined as the standard deviation of the hourly electricity demand*
Inner and outer circles are 2020 and 2050 peak demand, respectively

Pratama, Patrizio, and Mac Dowell, iScience, 2022

Discerning the probable from the possible..?

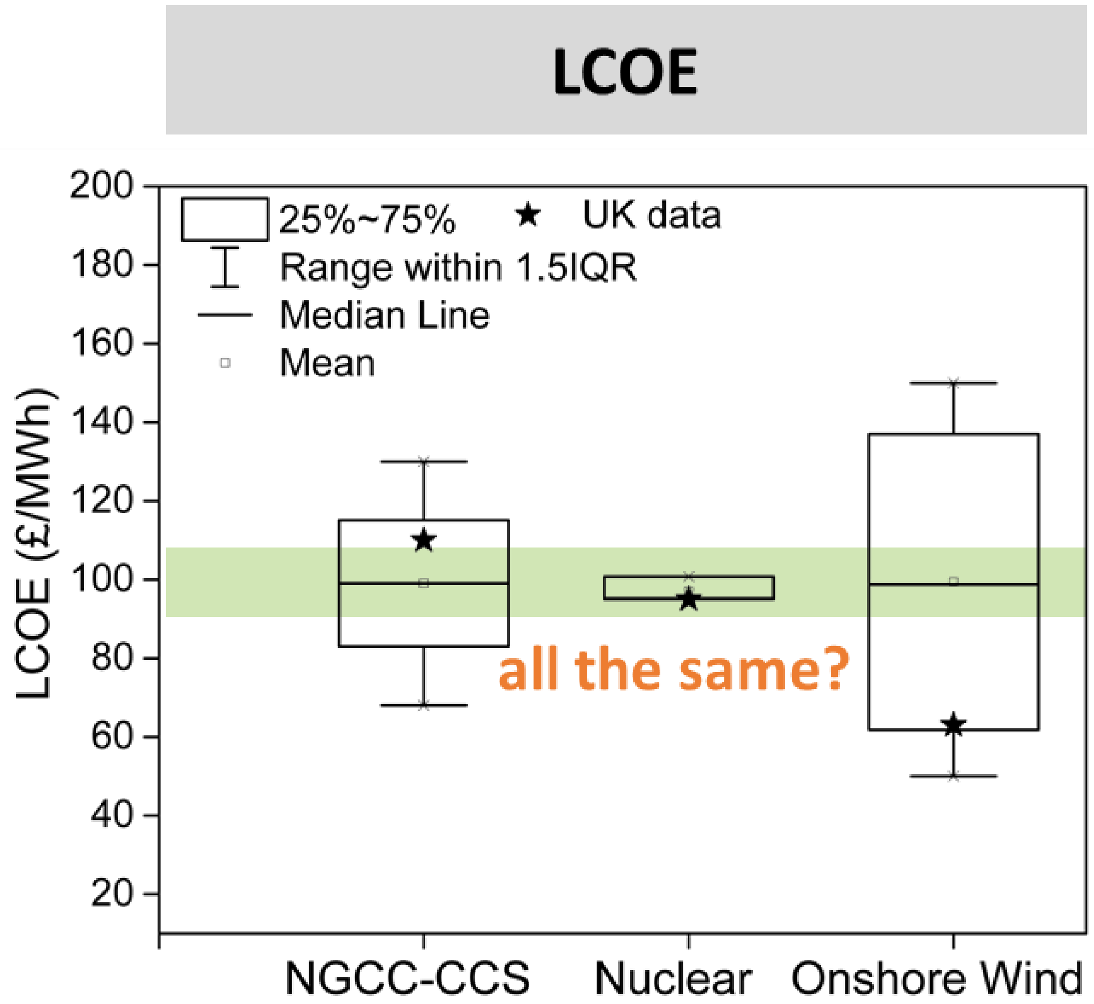


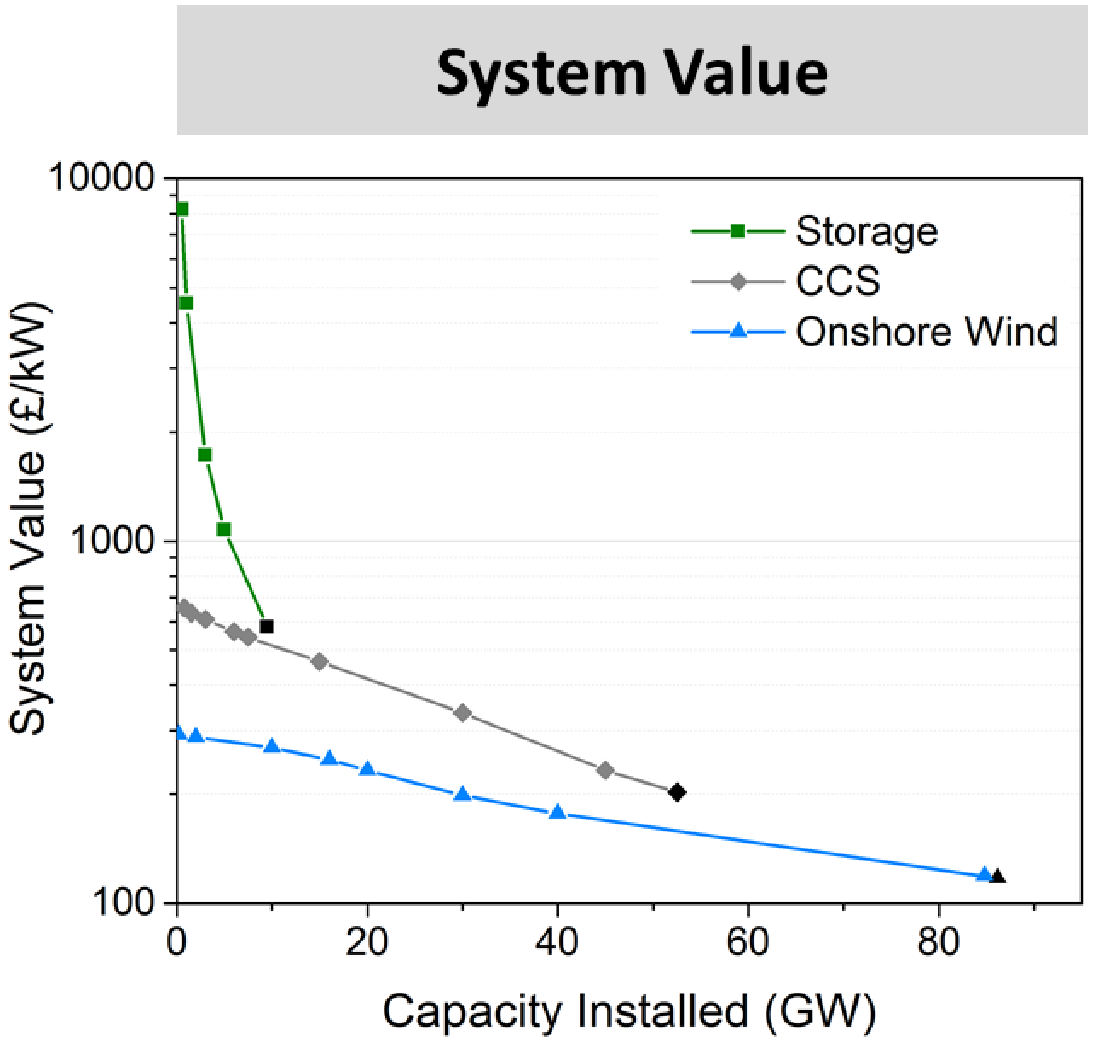
Quantifying the value of CCS (JAMALI)



Pratama and Mac Dowell, IEA CCC, 2021

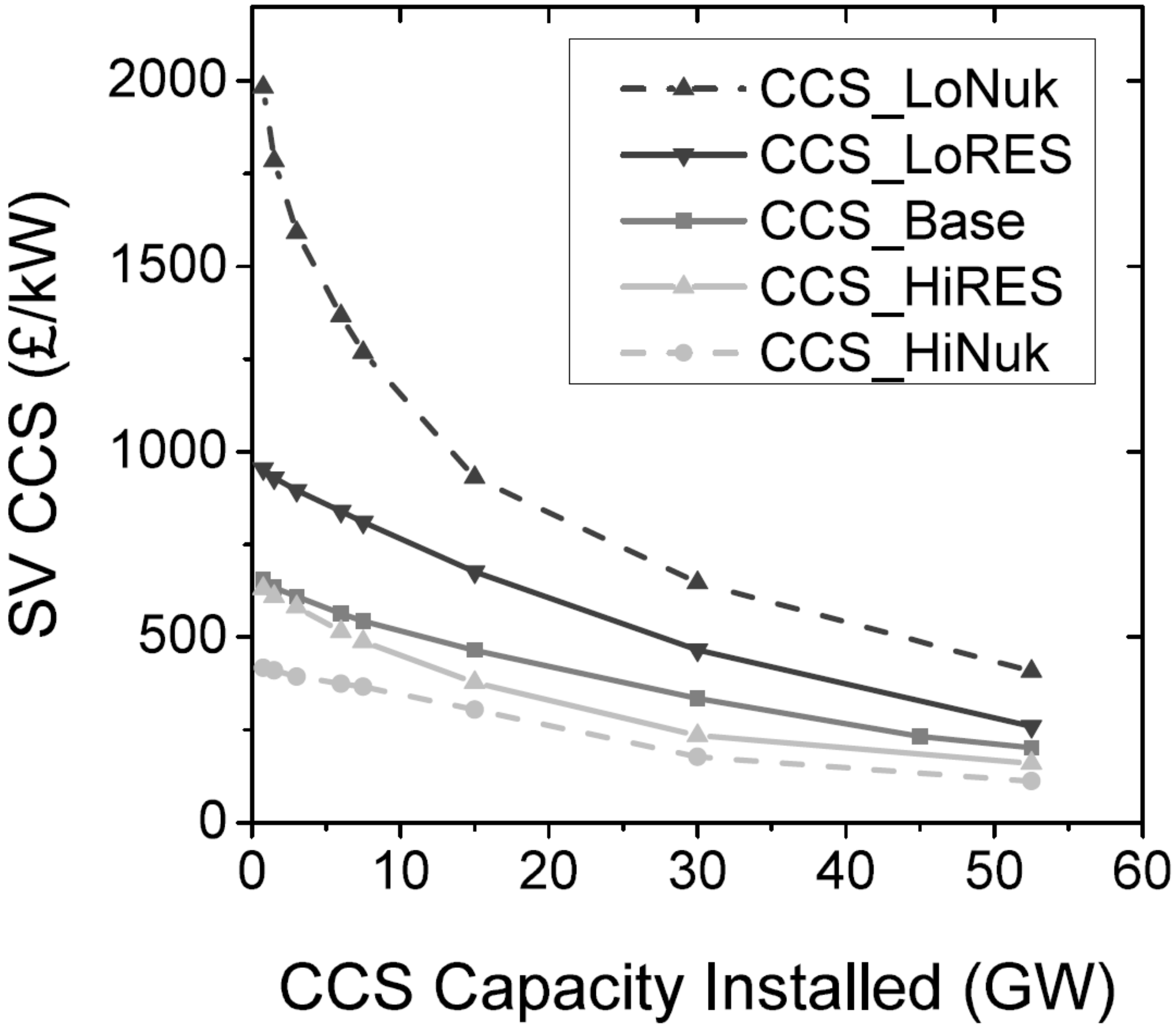
Value ≠ cost





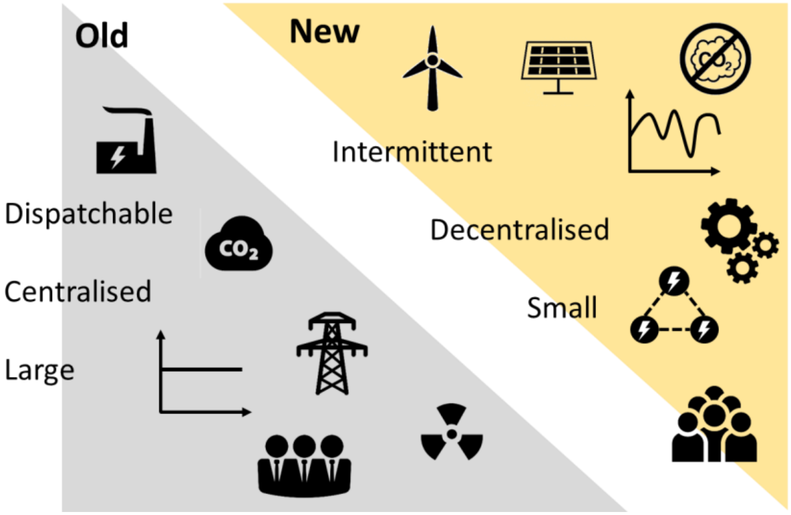
Heuberger, *et al*, Computers and Chemical Engineering, 2017

Value of CCS is context specific



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

What do we need from technology?



The power system is changing…

“+” → “+++” = low → high value

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

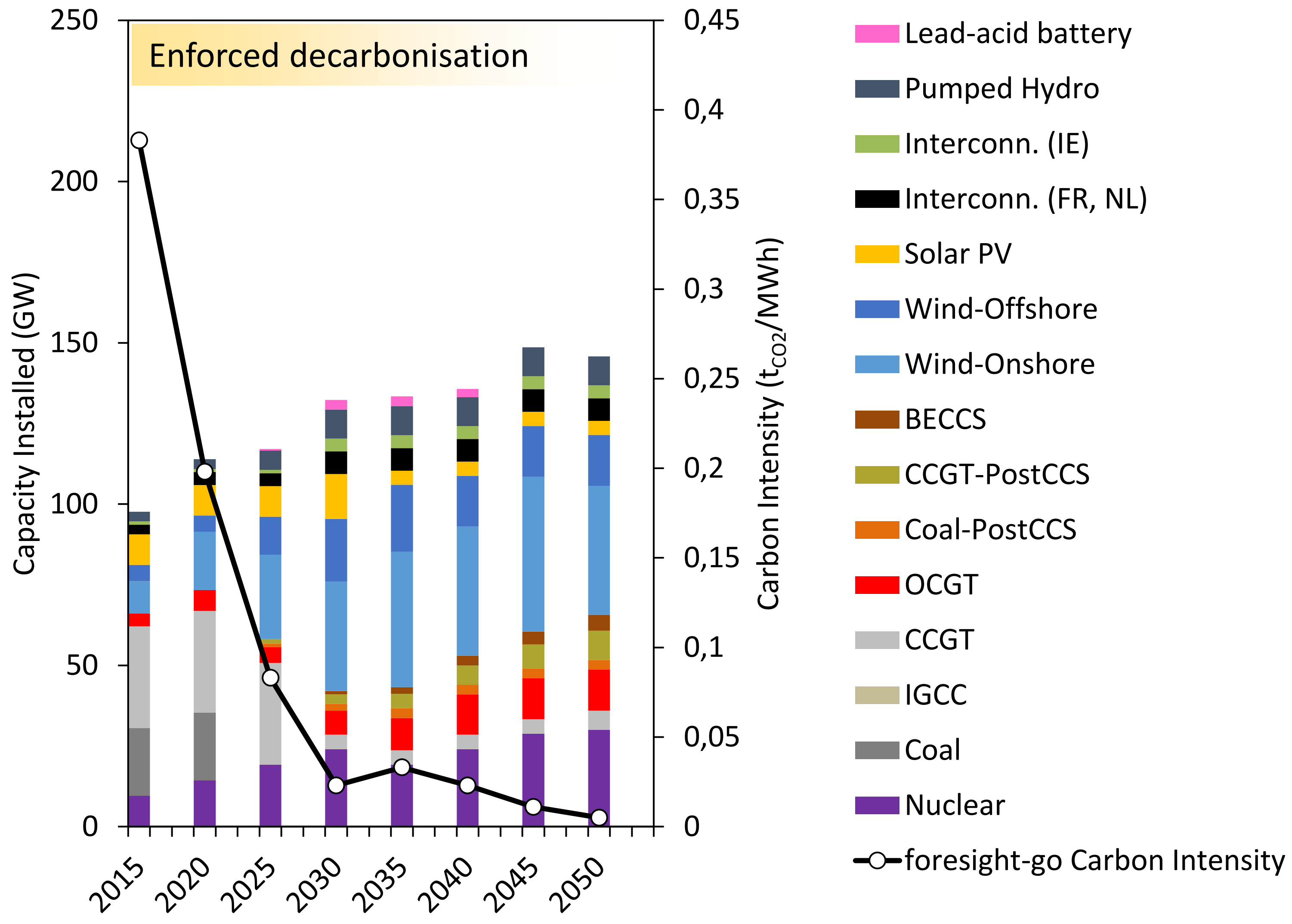
Technology Feature	Value in future power systems
High Efficiency	+
High Flexibility*	++
Low CAPEX	+++
Dispatchability	+++
Firm capacity/ancillary service provision	+++
Low OPEX	+
High Rate of Deployment	++

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

Should we believe in unicorns?

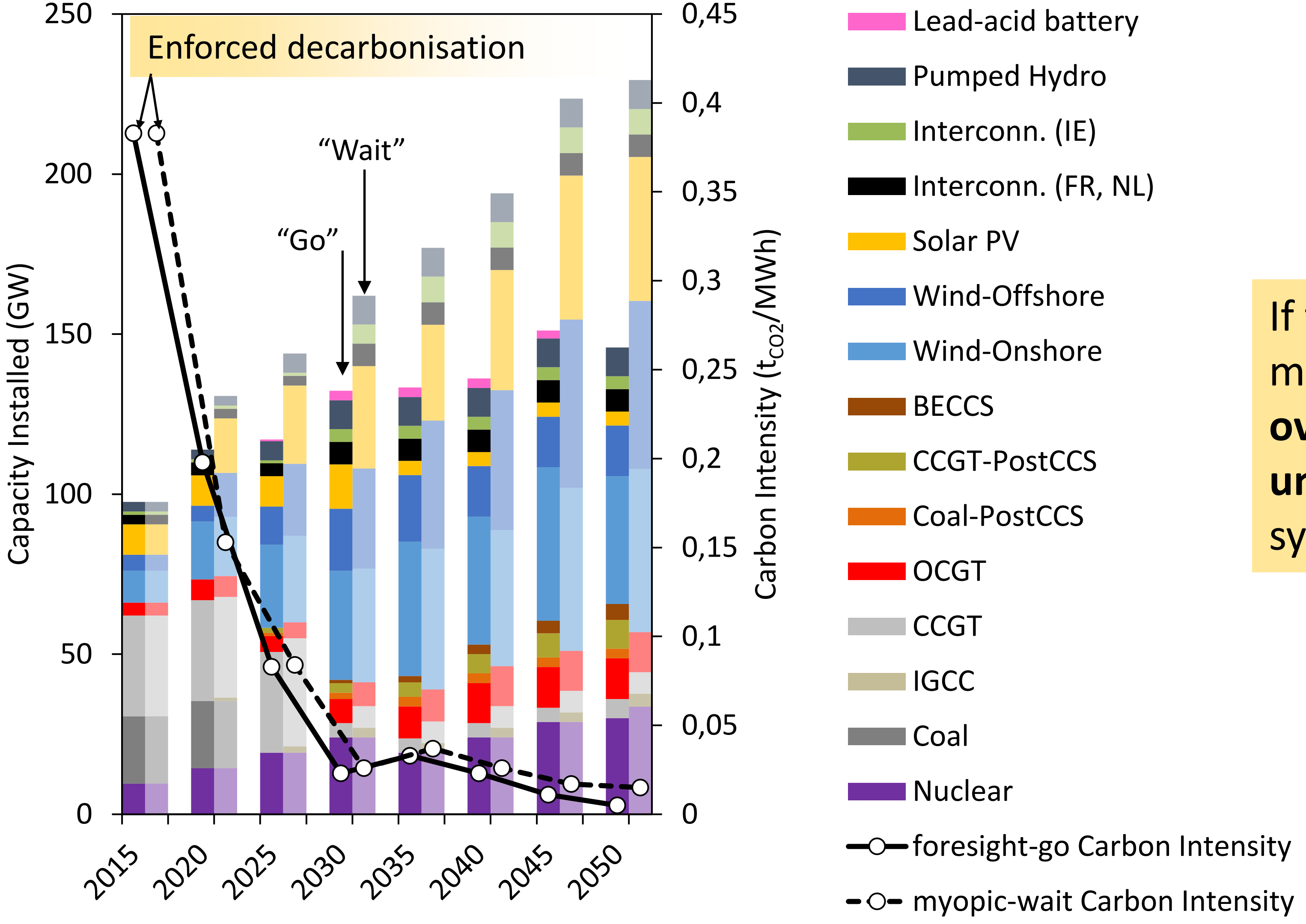
- Modelling often assumes perfect foresight
- This is not the world we live in…
- Can we trust in technological optimism?
- What is the least regrets strategy?

Perfect foresight capacity expansion



Heuberger, *et al.*, Nature Energy, 2018

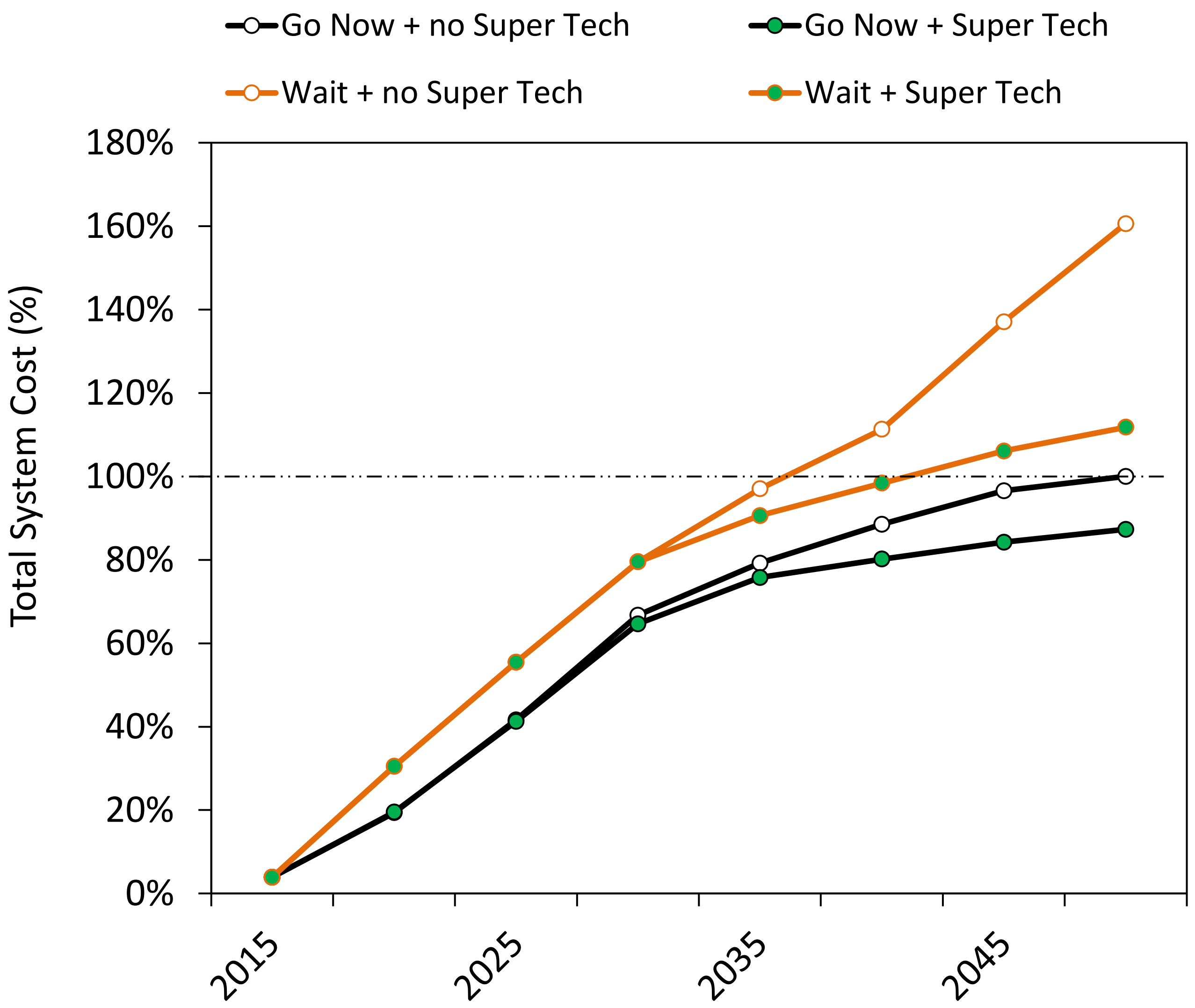
Imperfect foresight capacity expansion



If the "super tech" fails to materialise, we have an **overbuilt and underutilised** power system.

Heuberger, *et al.*, Nature Energy, 2018

Myopia in planning affects operation and cost



CF Heuberger, *et al.*, Nature Energy, 2018

Unicorn hunting

$for\ i_{ccs} \in \{CCS\ coventional + novel\ technologies\}$

Data input:
1. Technology costs
2. Efficiency
3. CCS capture rate
4. CO_2 intensity

Hourly input data clustering:
1. Electricity demand
2. iRES availability
3. Imported electricity price

11 clustered days using K-means clustering

'Unicorn' scenario:

$for\ x$ in efficiencies

$for\ y$ in technology costs

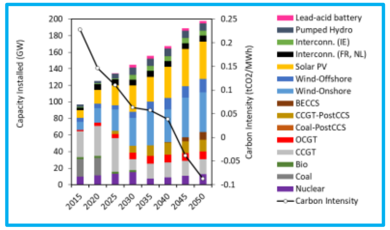
update x and y in Unicorn

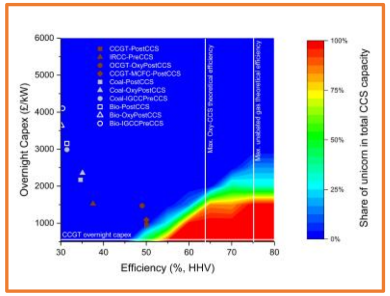
ESO Database:
1. **Techno- economic parameters**: unit capacity, learning rate, technology costs, carbon price floor, fuel price, etc.
2. **System wide data**: existing capacity, reserve and inertia requirements

ESO

Electricity Systems Optimisation Framework

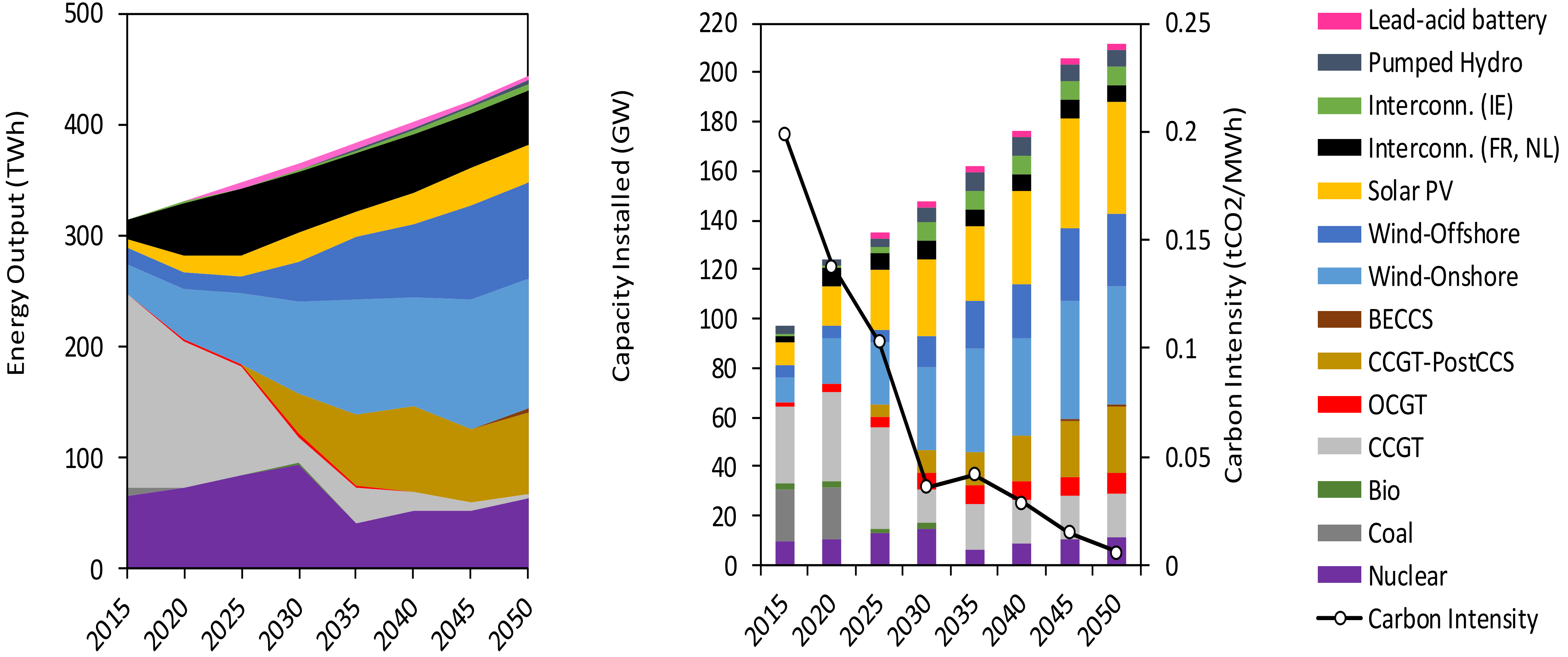
Results:





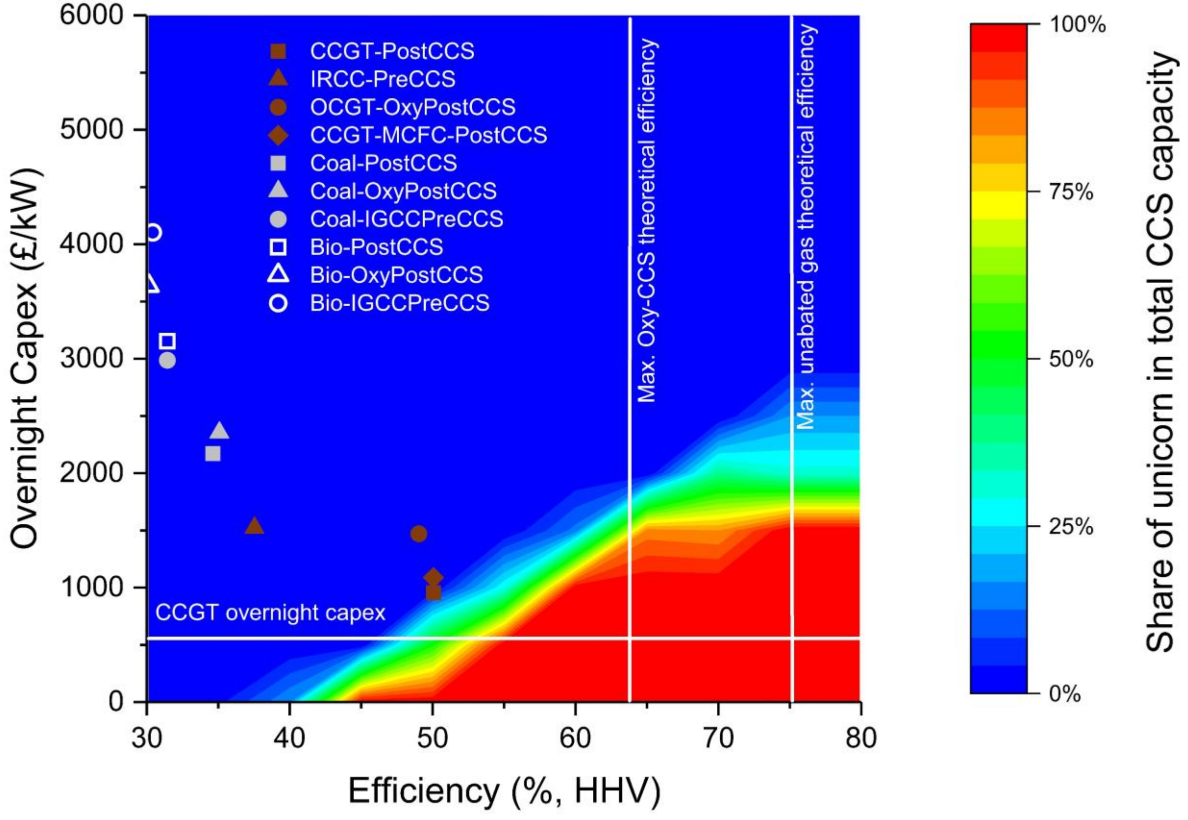
Pratama and Mac Dowell, One Earth, 2022

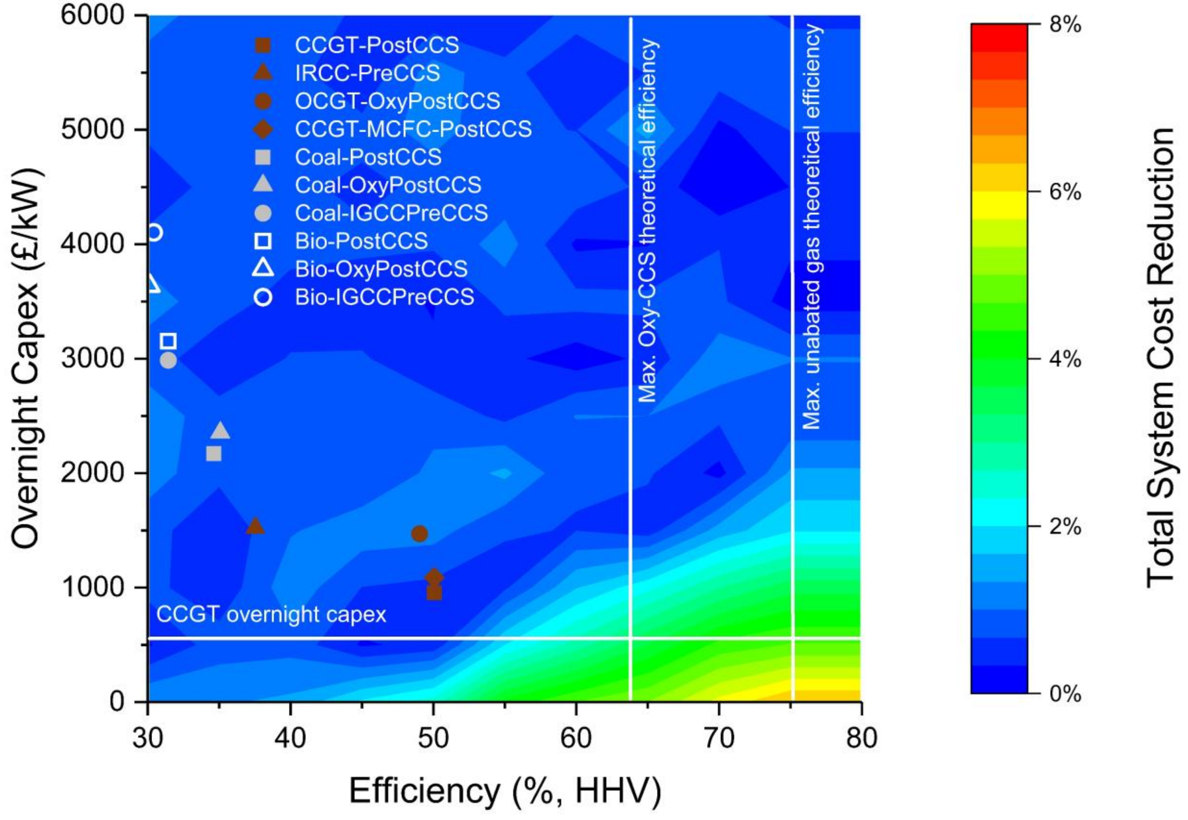
CCGT-CCS still appears to be a dominant technology



Pratama and Mac Dowell, One Earth, 2022

Is there a unicorn worth waiting for?





Pratama and Mac Dowell, One Earth, 2022

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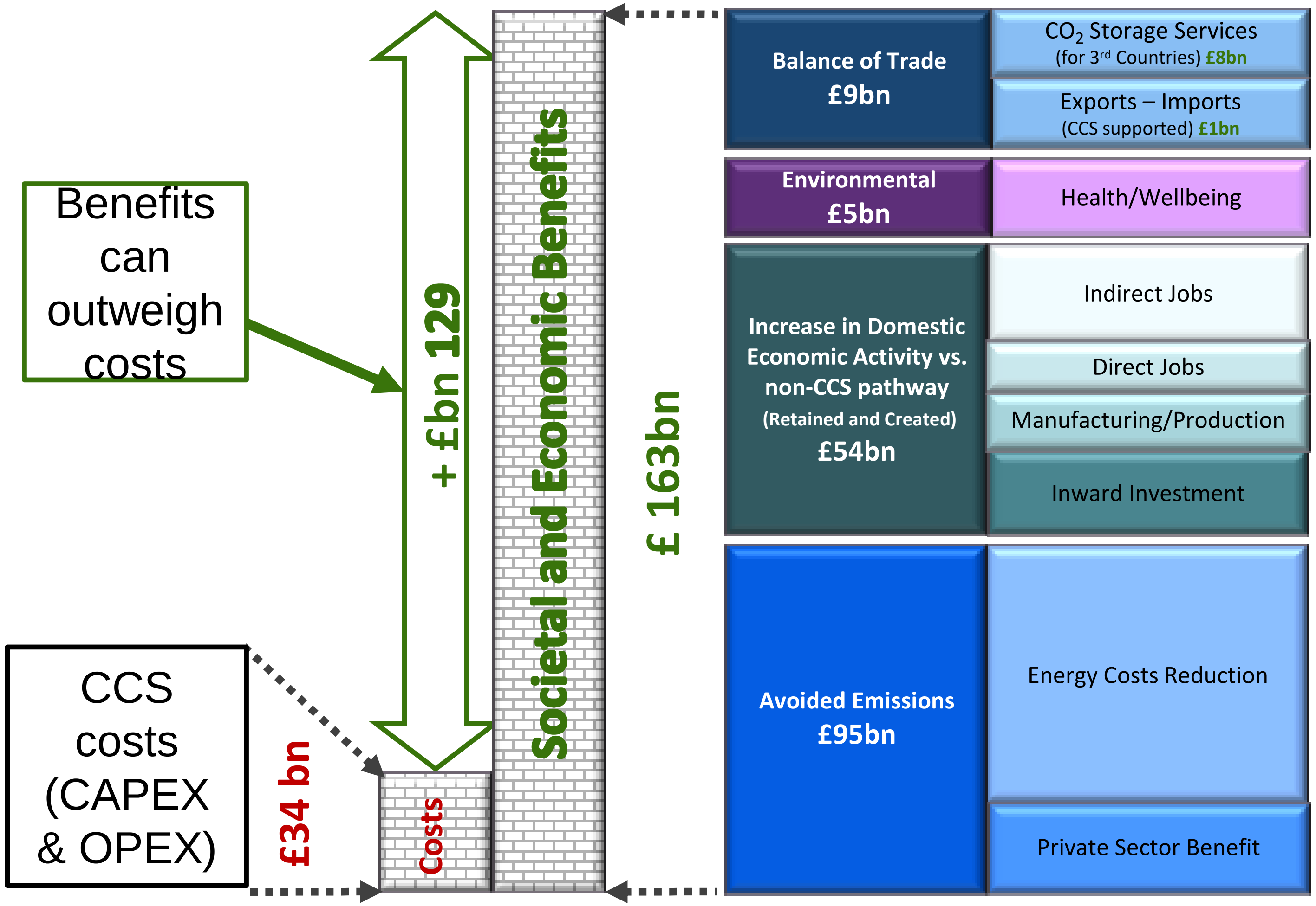
Value of CCS in future energy systems

Policy and decision makers are looking for tangible benefits rather than technical detail, e.g., GDP growth and

Need to demonstrate the societal value of CCS/CCUS.

Every £1 invested for CCS results in £4.8 of societal & economic benefit.

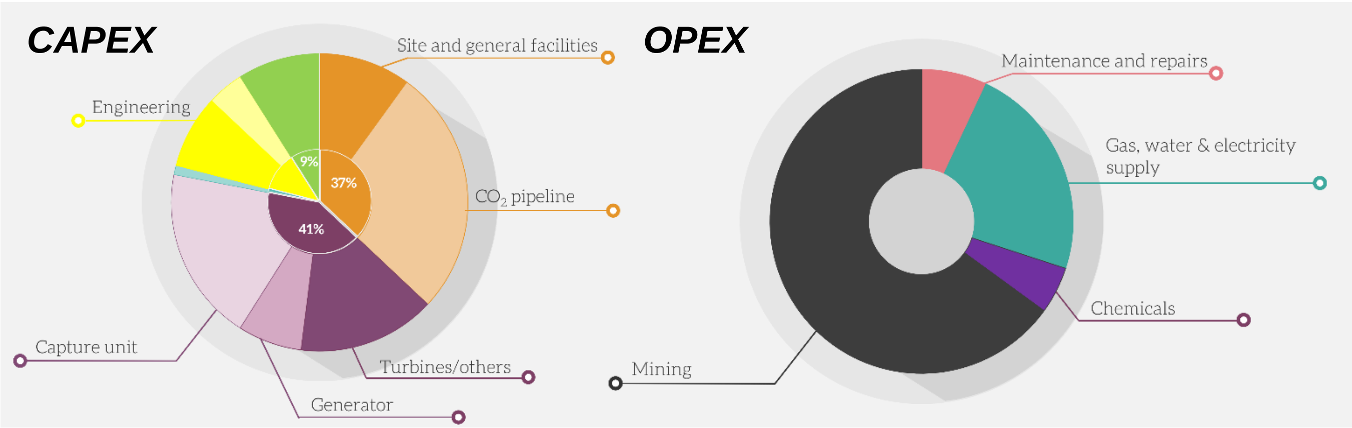


Hackett, Industria Mundum, 2018 http://www.ccsassociation.org/news-and-events/reports-and-publications/clean-air-clean-industry-clean-growth/

Technology cost break-down

Value chain mapping — Socio-economic analysis — Electricity system optimisation — Impact analysis

Example: CCGT-CCS



Global CCS Institute, 2014

CCGT: Combined Cycle Gas Turbine
CCS: Carbon Capture and Storage

Jobs and Economic Development Impacts (JEDI)

Value chain mapping — **Socio-economic analysis** — Electricity system optimisation — Impact analysis

Sector Disaggregation

JEDI model

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Direct Impact

$$VA_{c,i,t} = Output_{i,t} \times \%VA_{c,i}$$

$$Jobs_{c,i} = \sum_{t} \frac{VA_{c,i,t} \times \%HumanCapital_{c,i} \times \%Labor_{i,s}}{Wages_{c,i,s}}$$

$c = country, i = sectors, t = year, s = skill level$

Databases

Socio-economic indicators

- Input output tables
- Gross Value Added
- Employment rate
- Household income
- Labour share of GVA
- Wages
- Labour composition

Requirement matrix

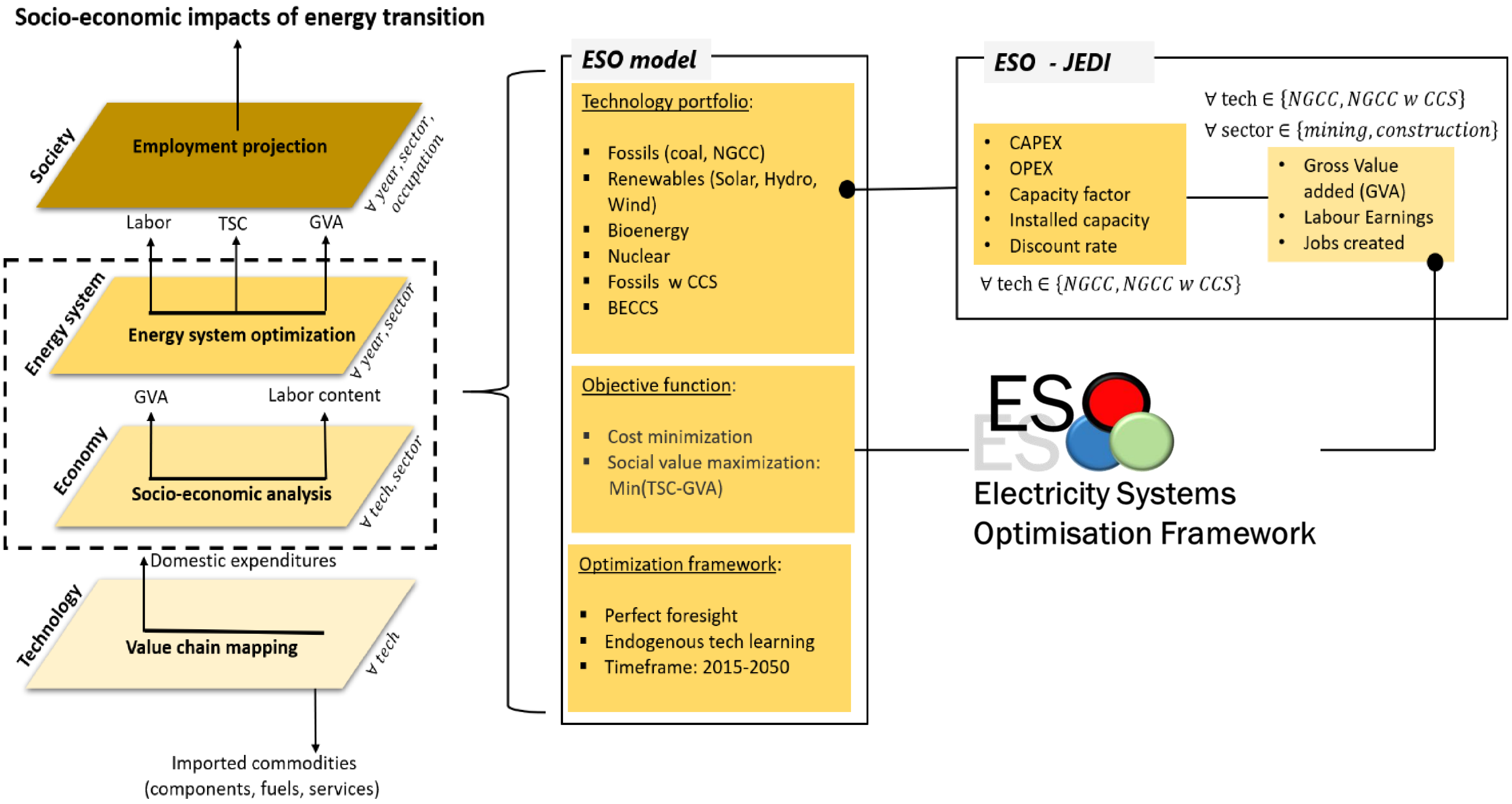
$$A_{i,j} = \begin{bmatrix} A_{i,i} & A_{i,j} \\ A_{j,i} & A_{j,j} \end{bmatrix}$$

$$L_{i,j} = (I - A_{i,j})^{-1}$$

$i, j = sectors$

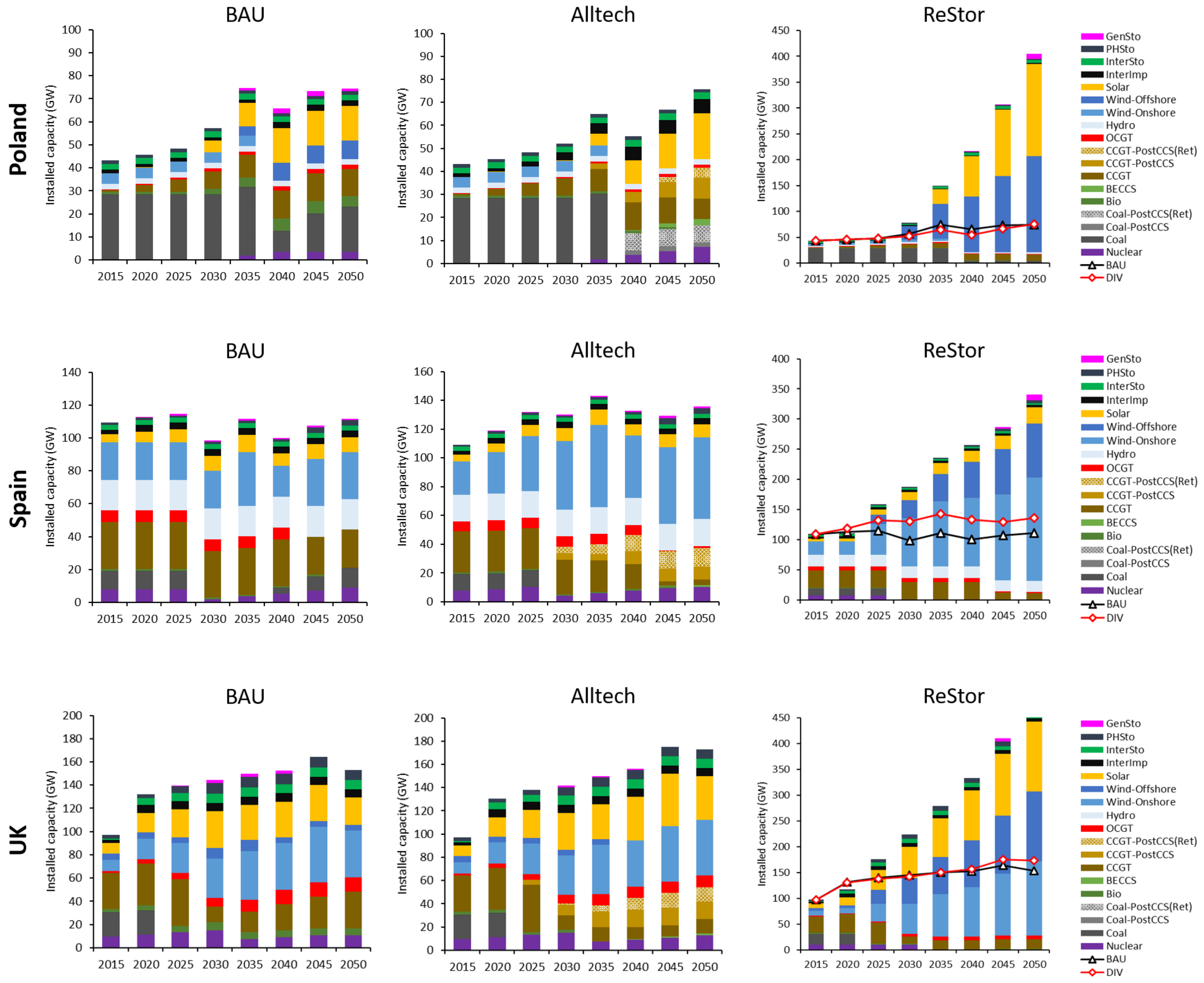
bea Bureau of Economic Analysis U.S. DEPARTMENT OF COMMERCE — BLS — o·net

ESO - JEDI framework



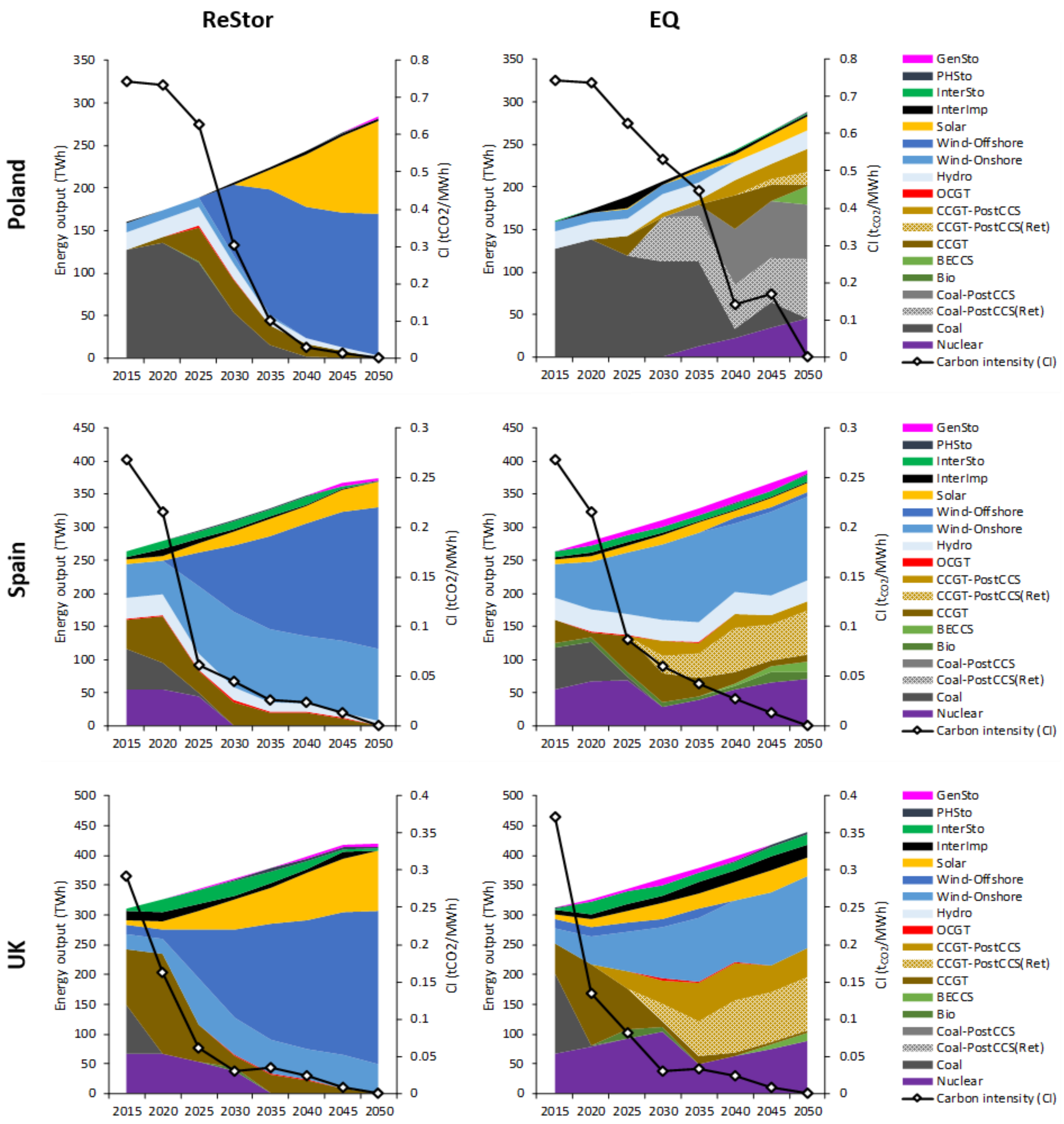
Patrizio, Pratama and Mac Dowell, Joule, 2020

Least cost energy transition pathways

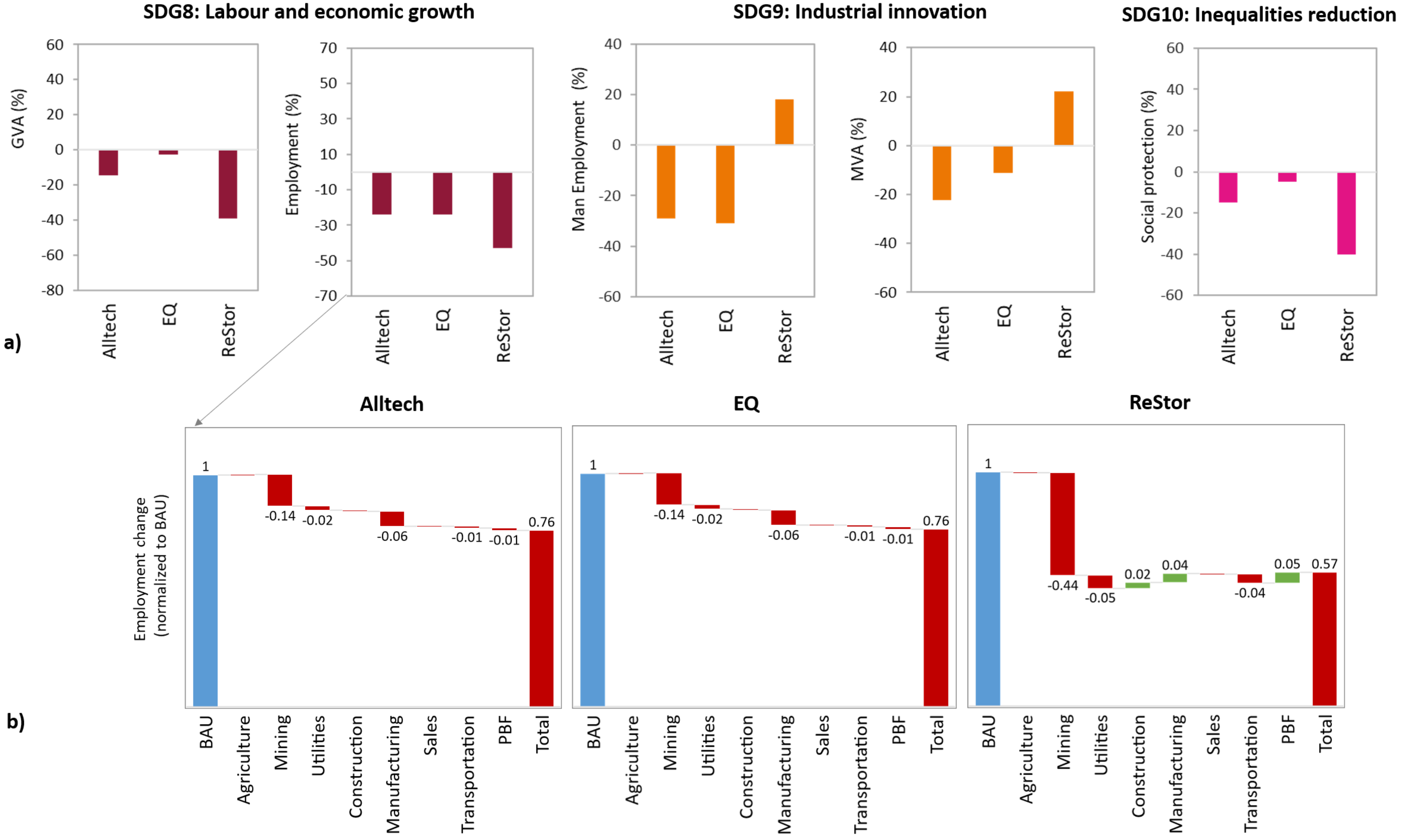


Patrizio, Pratama and Mac Dowell, Joule, 2020

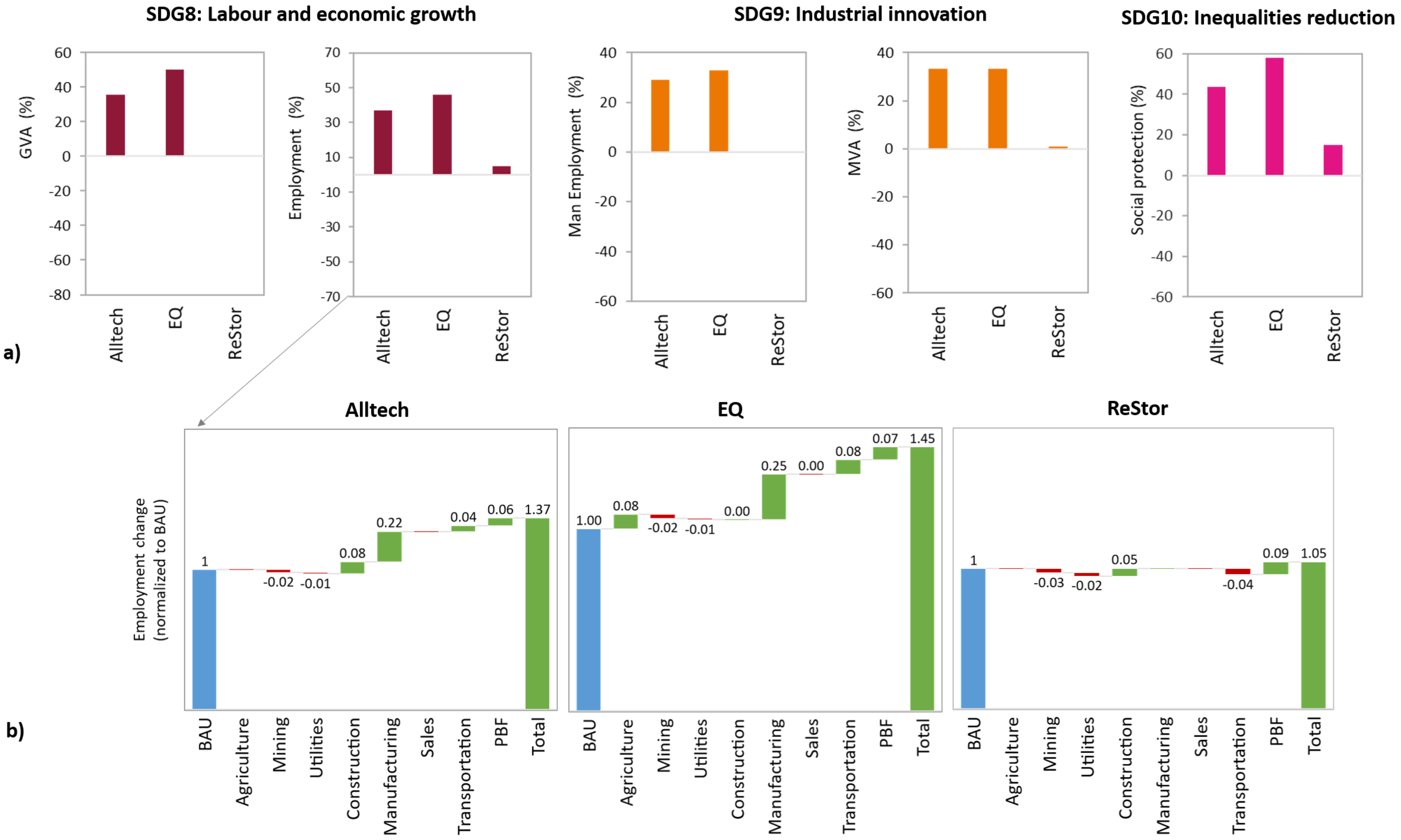
Creating value with the transition



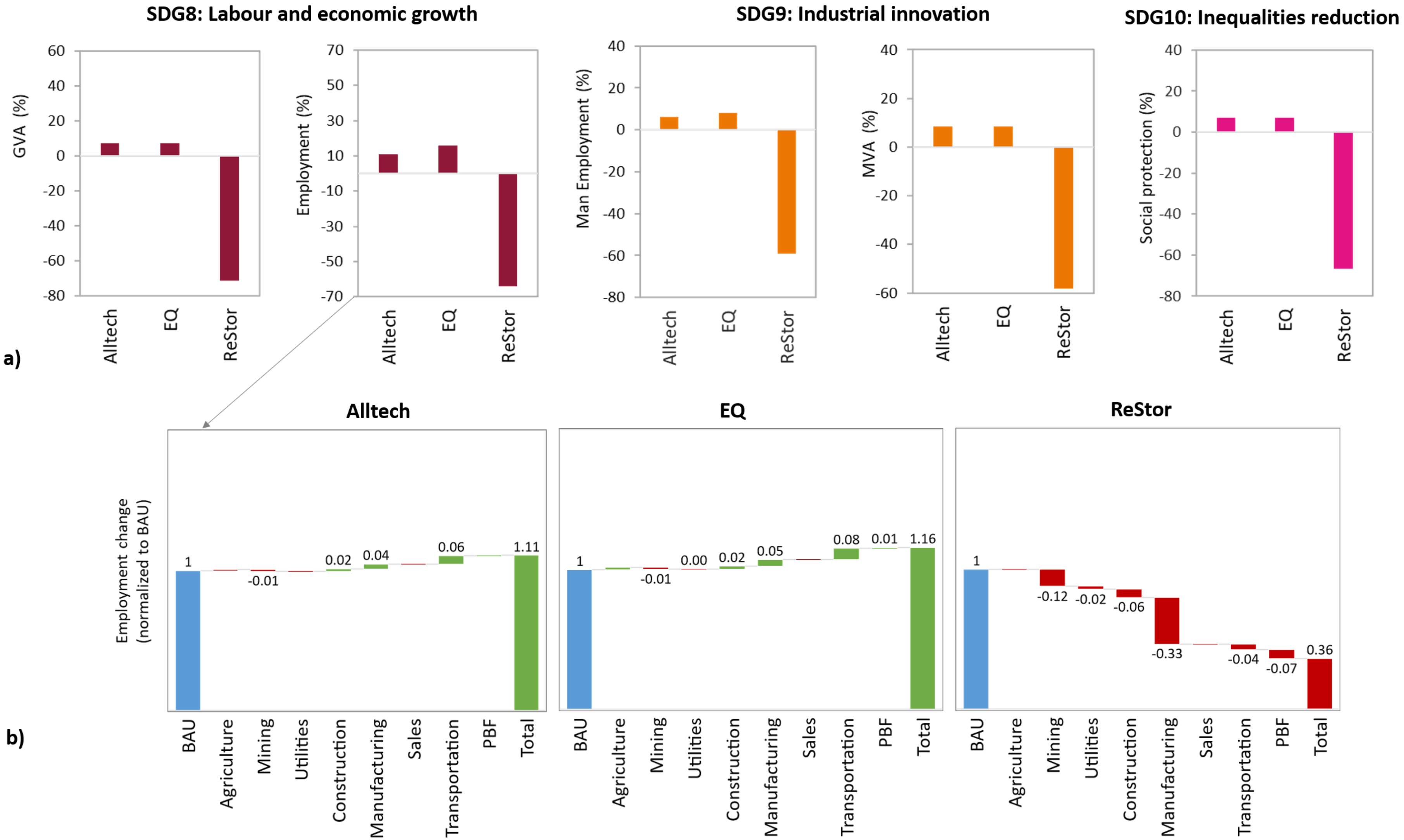
Trade-offs with SDGS goals: Poland



Trade-offs with SDGS goals: Spain



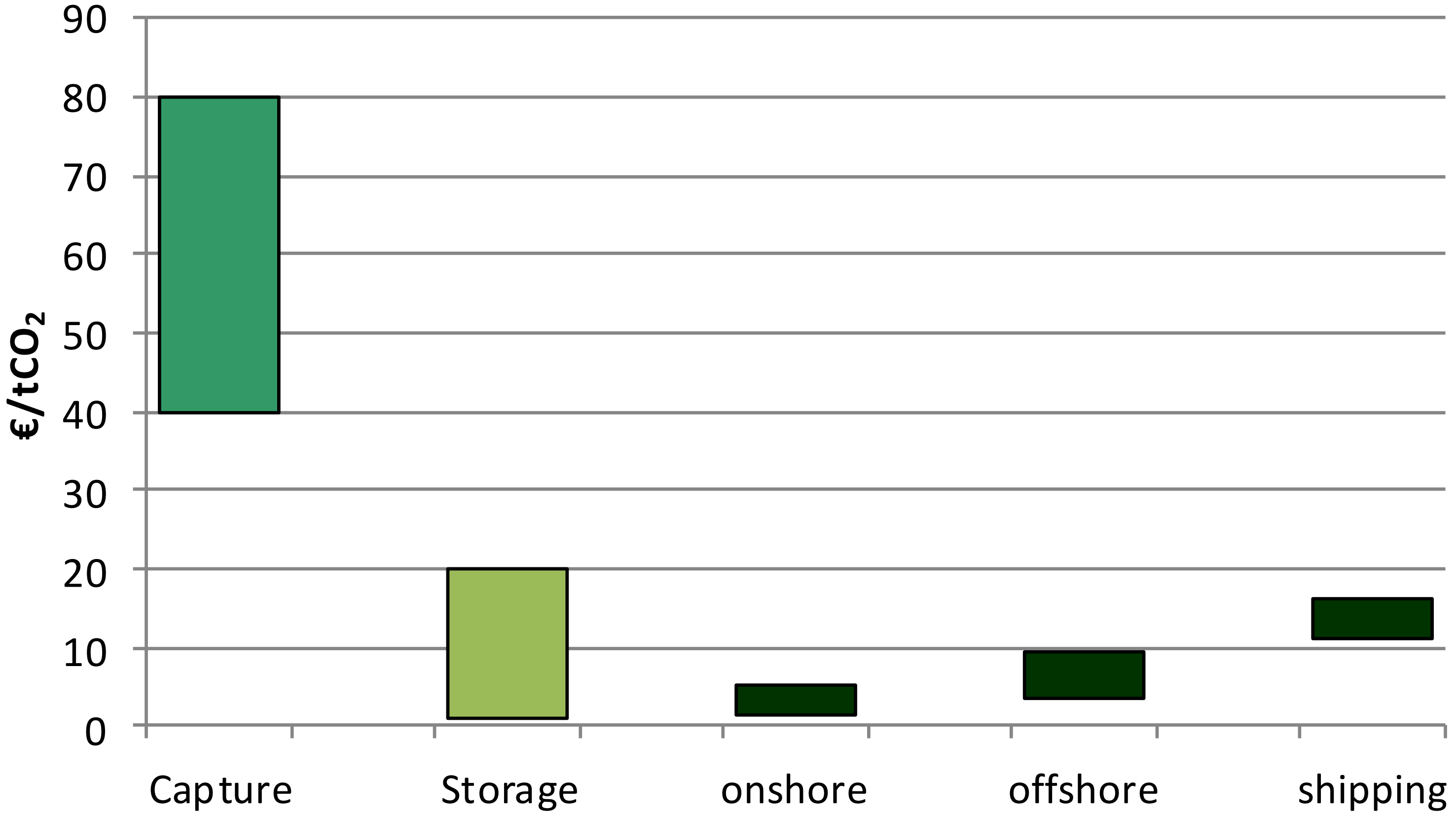
Trade-offs with SDGS goals: the UK



Outline

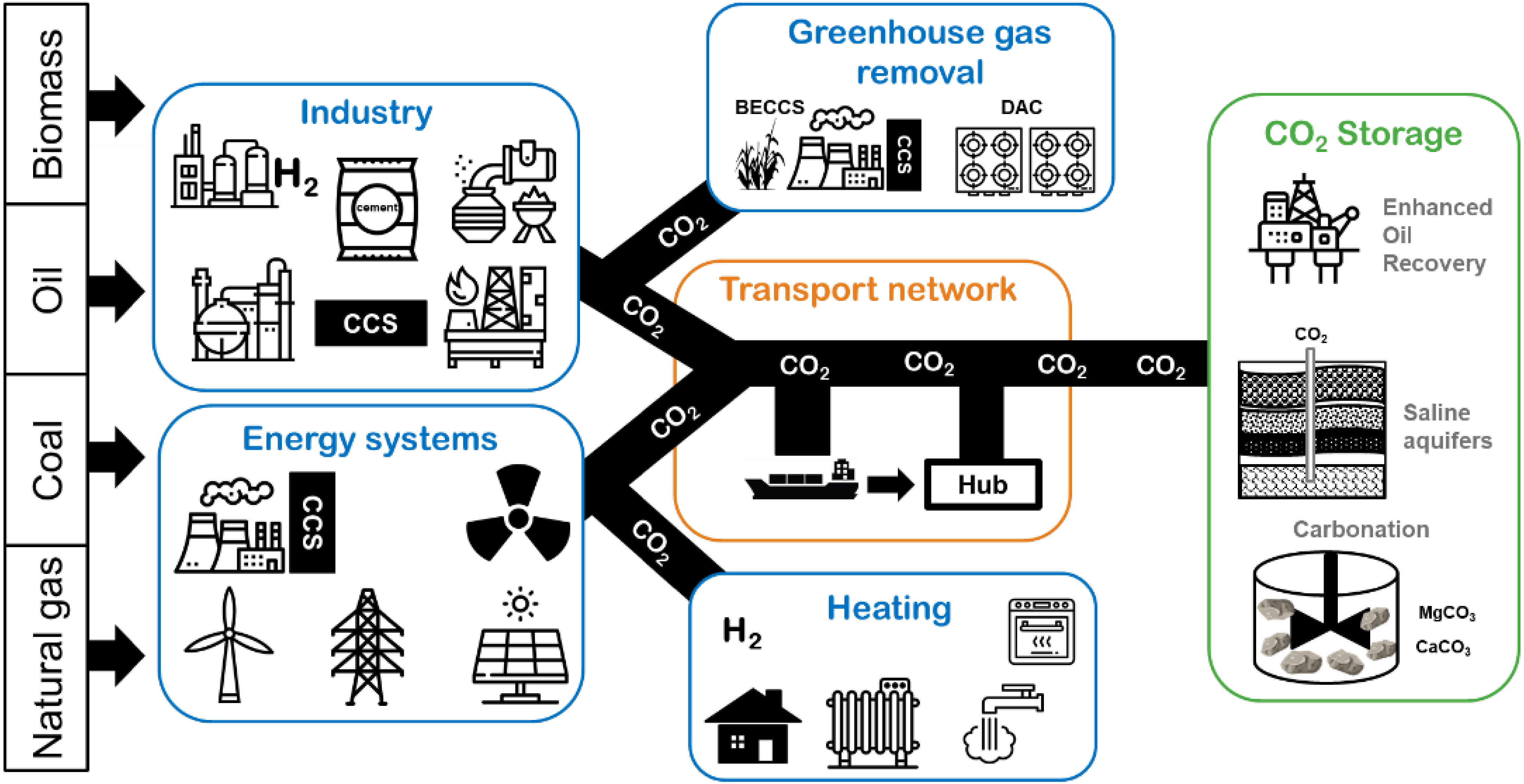
- Scene setting
- CCS – where are we?
- Is CCS an R&D problem?
- The socio-economic dimension
- Thoughts on CCS project development
- Some conclusions

What is the cost of CCS?



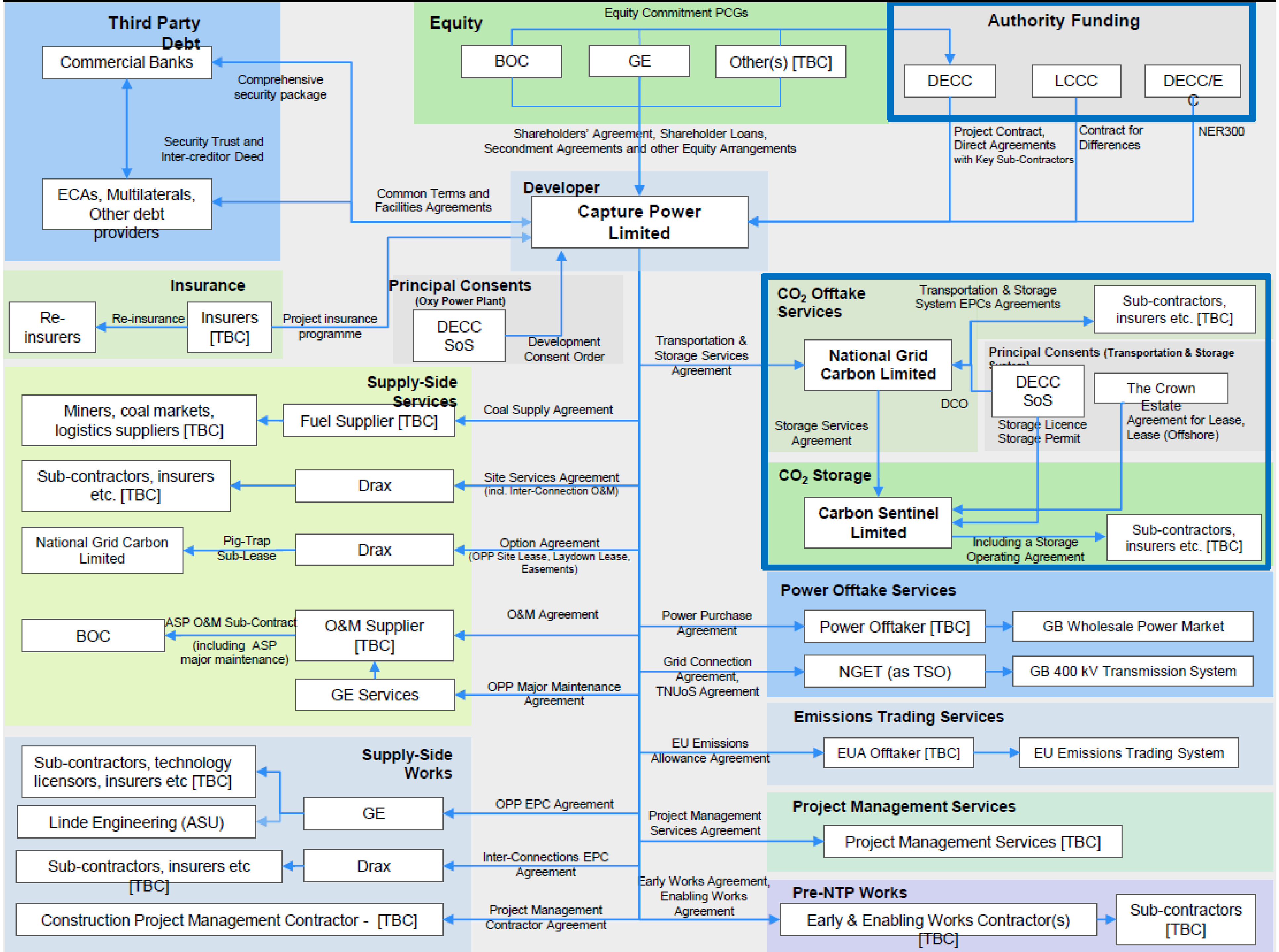
Costs of capture based on IEA (2012b); Cost and Performance of Carbon Dioxide Capture from Power Generation. Paris: IEA.
http://www.iea.org/publications/freepublications/publication/costperf_ccs_powergen.pdf

CO_2 capture is one element of the CCS system



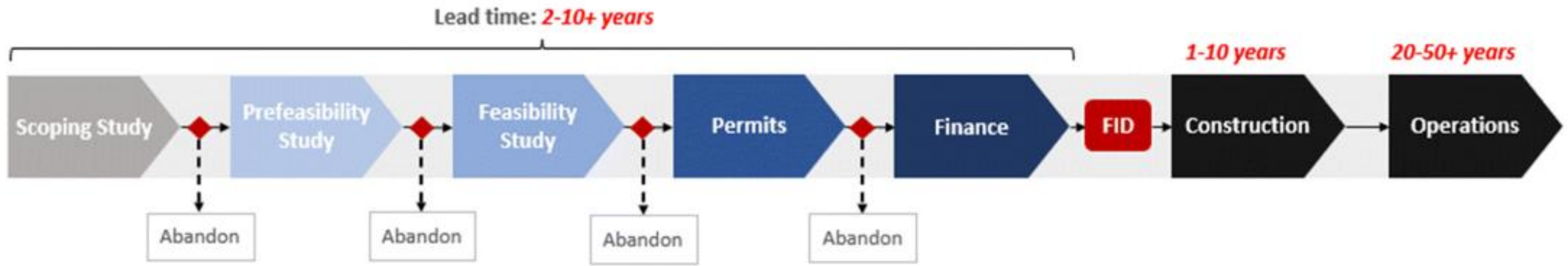
A “few” key questions…

1. Where is the store?
2. What are the permitting requirements to develop the store?
3. Is the store proven?
4. Who owns the store?
5. Who will operate the store?
6. Who will provide whole-life MRV for the store?
7. How do you get to the store?
8. What happens if, during project operation, the store becomes unavailable for a period? Who covers this risk?
9. Are you the only one using the store, or are you part of a hub?
10. Who provides the CO_2 transport service?
11. What are the permitting and regulatory requirements to deliver the transport service?
12. What are the CO_2 purity requirements of the T&S operators?
13. What happens if, during project operation, the transport becomes unavailable for a period? Who covers this risk?
14. How much CO_2 is produced?
15. Is flue gas produced in a steady flow, dynamically, or batch-wise?
16. Including solids and trace elements, what is the composition of the flue gas?
17. Is CO_2 concentration static, or dynamic?
18. **What are the options for CO_2 capture technology?**
19. What is the basis for technology provision, i.e., total asset management, or other? What level of performance guarantee is provided?
20. How much does this cost? How have individual choices impacted cost? How can cost be minimised without increasing technology or engineering risk.
21. What is the business model?
22. How will you pay (balance sheet, grant, debt)?
23. …

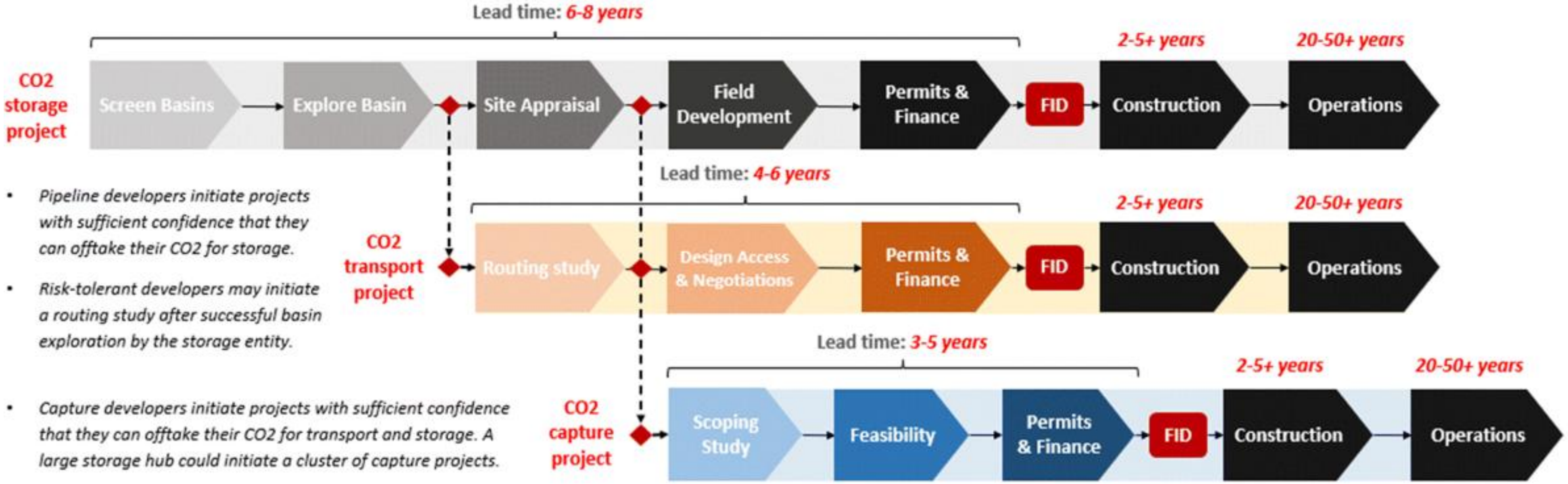


Third Party Debt
Commercial Banks
Comprehensive security package
Security Trust and Inter-creditor Deed
ECAs, Multilaterals, Other debt providers
Common Terms and Facilities Agreements
Equity
Equity Commitment PCGs
BOC
GE
Other(s) [TBC]
Authority Funding
DECC
LCCC
DECC/EC
Shareholders' Agreement, Shareholder Loans, Secondment Agreements and other Equity Arrangements
Project Contract, Direct Agreements with Key Sub-Contractors
Contract for Differences
NER300
Developer
Capture Power Limited
Insurance
Re-insurers
Re-insurance
Insurers [TBC]
Project insurance programme
Principal Consents (Oxy Power Plant)
DECC SoS
Development Consent Order
CO_2 Offtake Services
Transportation & Storage System EPCs Agreements
Sub-contractors, insurers etc. [TBC]
Transportation & Storage Services Agreement
National Grid Carbon Limited
Principal Consents (Transportation & Storage System)
DECC SoS
The Crown Estate
DCO
Storage Services Agreement
Storage Licence
Storage Permit
Agreement for Lease, Lease (Offshore)
CO_2 Storage
Carbon Sentinel Limited
Including a Storage Operating Agreement
Sub-contractors, insurers etc. [TBC]
Supply-Side Services
Miners, coal markets, logistics suppliers [TBC]
Fuel Supplier [TBC]
Coal Supply Agreement
Sub-contractors, insurers etc. [TBC]
Drax
Site Services Agreement (incl. Inter-Connection O&M)
National Grid Carbon Limited
Pig-Trap Sub-Lease
Drax
Option Agreement (OPP Site Lease, Laydown Lease, Easements)
BOC
ASP O&M Sub-Contract (including ASP major maintenance)
O&M Supplier [TBC]
O&M Agreement
GE Services
OPP Major Maintenance Agreement
Power Offtake Services
Power Purchase Agreement
Power Offtaker [TBC]
GB Wholesale Power Market
Grid Connection Agreement, TNUoS Agreement
NGET (as TSO)
GB 400 kV Transmission System
Emissions Trading Services
EU Emissions Allowance Agreement
EUA Offtaker [TBC]
EU Emissions Trading System
Supply-Side Works
Sub-contractors, technology licensors, insurers etc [TBC]
Linde Engineering (ASU)
GE
OPP EPC Agreement
Sub-contractors, insurers etc [TBC]
Drax
Inter-Connections EPC Agreement
Construction Project Management Contractor - [TBC]
Project Management Contractor Agreement
Project Management Services
Project Management Services Agreement
Project Management Services [TBC]
Pre-NTP Works
Early Works Agreement, Enabling Works Agreement
Early & Enabling Works Contractor(s) [TBC]
Sub-contractors [TBC]

a: Generic asset development sequence



b: Counterparty risk and chicken-or-egg interdependency is successfully managed in an integrated carbon capture and storage project *(6)*



Uden, et al, Energy Environ. Sci., 2022, 15, 3114

Barriers to deployment of CCS?

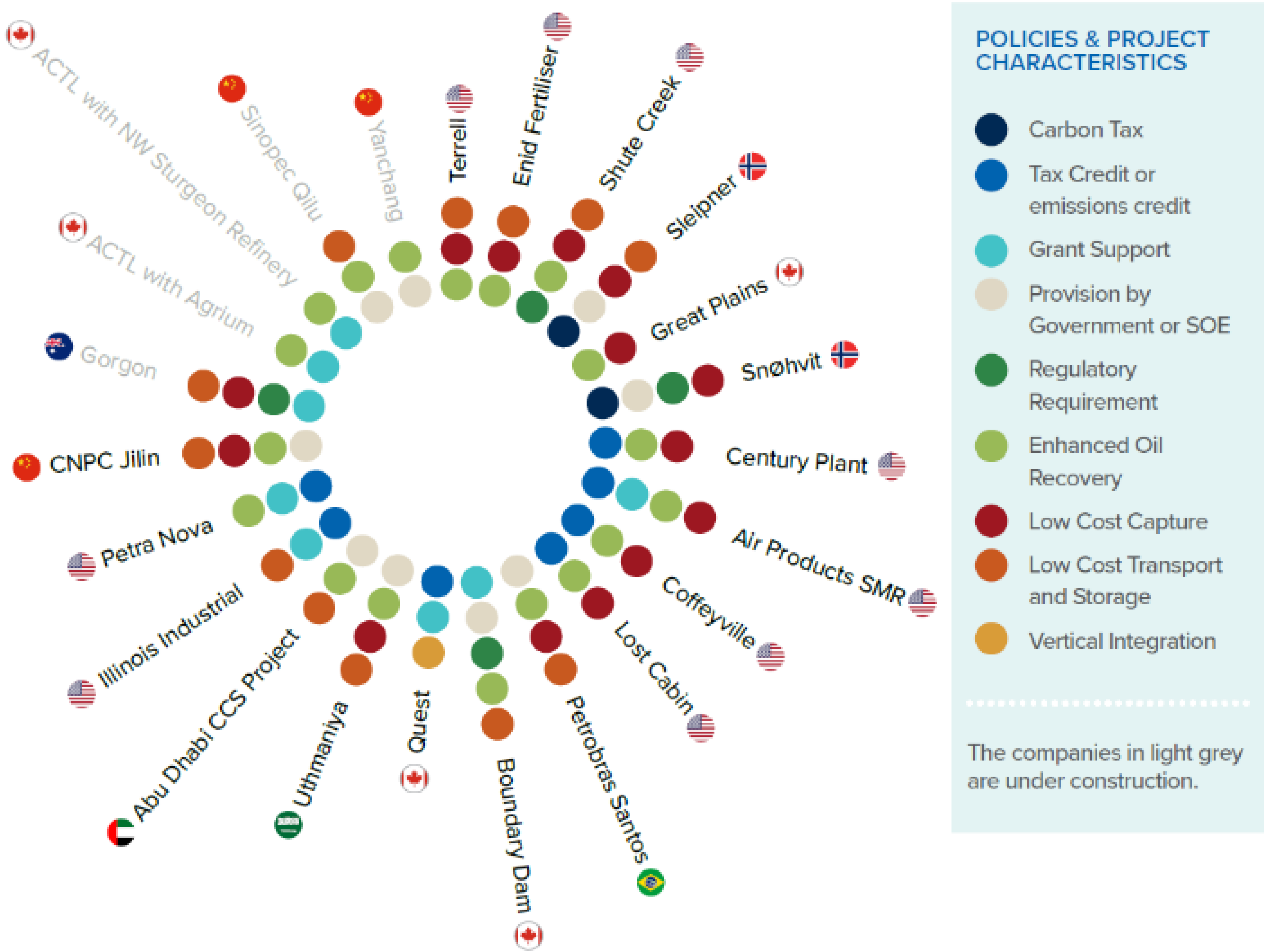
- Consider each element separately:
  - Cryogenic air separation invented in 1895
  - Amine scrubbing was patented in 1932
  - Large scale gas compression is *well understood*
  - Over 8,000 km of CO_2 pipelines in the US, transporting approximately 68 Mtpa
  - Several (Sleipner, In Salah, *etc.*) large scale CO_2 storage projects, operating for extended periods of time (decades) have stored ~ 50 million tonnes of CO_2 to date
- Investors do not share this perspective
  - Policy dependant
  - Heterogeneous
  - Complex value chain

6 key risks to make or break project finance

Risk	
Technology risk	Lack of track record of commercial deployment. Is there construction/delivery risk? Will the technology work as planned in this context?
Revenue risk	Is there a de-risked revenue stream? Are incentives sufficient? Are they volatile? In the case of e.g., tax credits, as in the US, what is the advance rate on these credits?
Regulatory risk	Is the regulatory environment certain? Note this isn't about stringency, its about certainty!
Infrastructure risk	Is both transport and storage infrastructure available? Who owns the cross chain risk? Who is insurer of last resort?
Financial and regulatory risk	Unfavourable tax/financial regulations
Reputational risk	Lack of social licence to operate – key to environmental/climate justice. Does BECCS improve the lives of fence line communities or reduce emission of criteria pollutants? Is it "sustainable"?

Jeff Brown, et al., "Turning CCS Projects into Blue Chip Investments", EFI, 2023

Key project characteristics of successful CCS projects



Reference: GCCSI (2019), Policy priorities to incentivise large scale deployment of CCS. https://www.globalccsinstitute.com/resources/publications-reports-research/policy-priorities-to-incentivise-large-scale-deployment-of-ccs/

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Some conclusions

- Net zero is not a zero sum game
- Technology evangelism and exclusion is unhelpful
- Perfect is absolutely the enemy of the good
- Climate change mitigation will not trump economic growth
- CCS and CDR appear to be necessary
- Existing technologies are more than adequate – the challenge is developing investible business models


EVERYTHING
EVERYWHERE
ALL AT ONCE