Evaluating technology options to mitigate greenhouse gas emissions

Proceedings: CCS Cost Network 2017 Workshop

13 - 14 September 2017

London, UK

IEAGHG Technical Report

2018-03

March 2018

IEA GREENHOUSE GAS R&D PROGRAMME

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ACKNOWLEDGEMENTS AND CITATIONS

The Steering Committee for this workshop were:

- Howard J Herzog, MIT (Chair)
- George Booras, EPRI
- Keith Burnard, IEAGHG
- John Chamberlain, GasNatural Fenosa
- Jon Gibbins, University of Sheffield
- Jeffrey Hoffmann, USDOE NETL
- Wilfried Maas, Shell
- Sean T McCoy, LLNL
- Edward S Rubin, CMU (Editor)

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PROCEEDINGS:
CCS COST NETWORK
2017 WORKSHOP

13–14 SEPTEMBER 2017

LONDON, UK

ORGANISED UNDER THE AEGIS OF THE

CCS COST NETWORK
IEA GREENHOUSE GAS R&D PROGRAMME
CHELTENHAM, UK

BY STEERING COMMITTEE MEMBERS:

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b. Natural Gas Post-combustion, Den Gammer/Andrew Green, ETI

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11:00 Session 2: Cost of Large-scale CCS Projects

Chair: Jeff Hoffmann

a. Petra Nova, David Greeson, NRG
b. Quest, Wilfried Maas, Shell Global

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1:45 Session 3: Cost of Emerging Processes

Chair: George Booras

a. Update on NET Power: Demonstration and Commercial Activities, Mike McGroddy, 8 Rivers Capital
b. Demonstrating CO_2 capture <$40/ton: Experience from Industrial Projects, Prateek Bumb, Carbon Clean Solutions

3:15 Break

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Chair: Keith Burnard

a. A review of CCS techno-economic representation in Integrated Assessment Models James Glynn University College Cork
b. What is the role of CCS in determining costs and climate outcomes of scenario analysis in Integrated Assessment Models?, Richard Millar, Oxford University

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Thursday, September 14, 2017

9:00 Session 5: CCS Flexibility

Chair: Howard Herzog

a. Quantifying and qualifying the role and value of flexible CCS to the decarbonisation of national electricity systems, Clara Heuberger, Imperial College
b. Decarbonising the Australian National Electricity Market - Implications for CCS, Andy Boston, Red Vector

10:30 Three Parallel Breakout Sessions

A. Energy-Economic Models: Is CCS being represented appropriately? (co-chairs: Howard Herzog, Niall MacDowell)
B. Learnings from demonstration projects: what will the next plant cost? (co-chairs: Jeff Hoffmann, George Booras)
C. Beyond demonstrations: CCS projects with multiple repeat units (co-chairs: Jon Gibbins, Den Gammer)

1:30 Lunch

2:30 Breakout Group Reports

3:15 General Discussion

3:45 Next Meeting – Topics, Location, Timing

4:00 Adjourn

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INTRODUCTION

The fifth meeting of the CCS Cost Workshop was held on September 13-14, 2017 at Imperial College London (South Kensington Campus) under the auspices of the IEA Greenhouse Gas R&D Programme.

The meeting was organized by a Steering Committee chaired by Howard Herzog (Massachusetts Institute of Technology), along with representatives from: Carnegie Mellon University (Ed Rubin), Electric Power Research Institute (George Booras), IEA Greenhouse Gas R&D Programme (Keith Burnard), Lawrence Livermore National Laboratory (Sean McCoy), USDOE National Energy Technology Laboratory (Jeff Hoffmann), NaturalGas Fenosa (John Chamberlain), Shell Global (Wilfried Maas) and the University of Sheffield (Jon Gibbins). In addition, the participation of the UK CCS Research Centre and Imperial College London were critical to the planning and success of this meeting.

The purpose of the CCS Cost Workshops is to share and discuss the most currently available information on the cost of carbon capture and storage (CCS) in electric utility and industrial process applications, as well as the outlook for future CCS costs and deployment.

The workshop also seeks to identify other key issues or topics related to CCS costs that merit further discussion and study.

As in past workshops, Day 1 was devoted to a plenary session addressing four general topics. Each session included two invited presentations, followed by a discussion among workshop participants. The second day began with a fifth plenary session topic, followed by three parallel breakout sessions pursuing selected topics in more detail. Reports of the breakout groups were presented in a concluding a plenary session, followed by general discussion and planning for future events.

This document presents brief summaries of the five plenary session topics, together with the full set of presentations by invited speakers. The proceedings of this and all previous CCS Cost Workshop are available at: www.ieaghg.org/networks/costs-network/125-networks/costs-network-members-area/423-costs-network-members-area.

PRESENTATION SUMMARIES

Session 1: Learnings from Recent UK Studies

Rapporteur: J. Gibbins

Two studies on the cost of full-scale CCS deployment in the UK market were presented in this session. Following its previously unsuccessful approach to fund a small-scale demonstration project based on 'competitions', the UK Government is now considering a more holistic approach to CCUS in its Clean Growth Strategy (https://www.gov.uk/government/publications/clean-growth-strategy), which emphasizes the importance of CCUS being cost-competitive with alternative options if it is to achieve widespread deployment.

In this context there is significant UK interest in both the general, longer-term prospects for CCUS costs. A review of expected costs is being undertaken by Amec Foster Wheeler (FW) for the UK Department for Business, Energy & Industrial Strategy (BEIS). Viable projects for initial deployment are also being examined, as in a study by the ETI on natural gas combined cycle plants with post-combustion capture.

UK Costs for a Range of CCS Technologies

Suzanne Ferguson is the Carbon Capture Technical Lead of the Business Solutions Group, Oil, Gas & Chemicals at Amec Foster Wheeler. In her presentation she summarised work done for a forthcoming report, "Benchmarking State-of-the-art and Next Generation Technologies" as part of a BEIS study "Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology". This will eventually be issued into the public domain on the BEIS website. Based on the assumptions used, and within the uncertainty range of the study's cost estimates, this study concluded that the lowest levelised cost of electricity (LCOE) with carbon capture is still natural gas CCGT with a proprietary solvent for CO_2 capture. This result is due to the high efficiency and low capital cost of the base plant, and the fact that natural gas combustion produces CO_2 conditions less challenging than e.g., coal, resulting in less carbon to be captured and compressed per unit of electricity generated.

For capture from natural gas power plants post-combustion routes appear most attractive (with oxy not far behind), but it was noted that this was for baseload operation. The flexibility advantages of pre-combustion routes (e.g., hydrogen production) were not, therefore, quantified. Two of the leading novel technologies, the Allam Cycle and molten carbonate fuel cells, appear well positioned to compete with proprietary solvents for base load power generation if they can reduce their capital costs or improve efficiencies further.

Natural Gas Post-combustion Capture

Den Gammer and Andrew Green reported on work undertaken as part of an Energy Technology Institute (ETI) study performed by SNC-Lavalin, AEOCOM and the University of Sheffield. For a five-train NGCC power plant (each train being an H-class GT, HRSG and steam plant, with a CO_2 capture and compression system) the estimated levelised cost of electricity was in the range of 63 to 93 £/MWh. A conceptual layout for the five train plant, capturing 10 million tonnes/year of CO_2 from a single site, is shown below.

Interestingly, it was noted that even with a "conservative" configuration, the capture energy penalty has dropped by more than two percentage points since their 2010 estimates while the base plant generation efficiency has increased by about two percentage points. Offsetting this improvement, however, the post-Brexit fall in the £/US$ exchange rate has raised the capital cost by 3% to 4%, so overall levelised costs have not changed significantly since earlier ETI estimates.

Session 2: Cost of Large-scale CCS Projects

Rapporteur: J. Hoffmann

Two studies on the cost of full-scale CCS projects were presented in this session.

Petra Nova Carbon Capture

David Greeson from NRG gave an overview of the 240 MW_{eq} carbon capture project operating at NRG's 640 MW coal-fired Petra Nova - WA Parish generating station in Texas. This is a commercial venture between NRG and JX Nippon Oil & Gas Exploration that uses a post-combustion CO_2 capture process developed by Mitsubishi Heavy Industries (MHI) and the Kansai Electric Power Co. It captures 1.6 million tons CO_2 per year which is used for enhanced oil recovery (EOR) at the West Ranch oil field.

Greeson reported that the total project cost was approximately one billion dollars, about half of which was for power plant installations and half for the CO_2 pipeline and oil field development. He expressed the total cost of CCS in units of dollars per thousand cubic feet (mcf) of CO_2. Current cost is about $3.50/mcf, compared to a maximum value for EOR of $2.00/mcf. That gap could be closed in a decade with gradual cost reductions of 4%/year, or much faster with proposed policy incentives.

A unique feature of the Petra Nova project is the commercial structure which includes oil sales. Greeson said that oil revenues pay for the entire project.

Overall, he saw the CCUS industry as progressing and beginning to emerge commercially, but still facing a number of "headwinds" including cost, competition, scale, development, reputation, and time for constructing new projects.

Quest CCS Project Costs

Wilfried Maas from Shell Global summarized Shell's current involvement in CCS projects worldwide, then focused on the Quest CCS project in Alberta, Canada, where CO_2 is being captured at the Scotford Upgrader industrial facility, then stored in a deep saline aquifer (the Basal Cambrian Sands). This project is a joint venture between Shell, Chevron and Marathon Oil. Since startup in August 2015, Quest has captured, transported and safely stored 2 million tonnes of CO_2 as of June 2017.

In terms of cost, the project CAPEX (including the FEED study) was 929.7 million Canadian dollars (CAD), or about 744 million USD. Actual 2016 OPEX was 30.2 million CAD (~24.2 million USD). On a normalized basis the reported costs per tonne of CO_2 avoided were 77.4 CAD/t (62 USD/t) in 2015, increasing to 92.7 CAD/t (74 USD/t) in 2016. The reported costs per tonne captured were 15%—16% lower than the cost per tonne avoided.

Session 3: Cost of Emerging Processes

Rapporteur: G. Booras

This session focused on the cost of new and innovative technologies that include CO_2 capture. Special emphasis was placed on the methodology for estimating capital costs of novel equipment components and systems, and how costs are expected to improve as the technology moves from First-of-a-Kind (FOAK) to *Nth*-of-a-Kind (NOAK) projects. The session included speakers from NET Power and Carbon Clean Solutions.

Update on NET Power: Demonstration and Commercial Activities

Mike McGroddy from 8 Rivers Capital gave an overview of the NET Power supercritical CO_2 power cycle (Allam Cycle) technology and its development and commercialization timeline. The NET Power partners include 8 Rivers, Excelon, and CB&I. The power cycle is very efficient and captures CO_2 as an inherent part of the process. 8 Rivers believes the process will be economically competitive with NGCC plants that do not include CCS. The novel components are the combustor and turbine, which are being developed by Toshiba. McGroddy noted that the turbine, which has an inlet pressure of 300 bar, looks like a gas turbine in a steam turbine shell. He gave a status update on their 50 MWt demonstration plant in La Porte, Texas. They are also developing a design and cost estimate for a commercial-scale plant.

Learnings from the design and construction of the demo plant are being incorporated in the FOAK commercial plant design. McGroddy noted that cost-efficiency trade-offs are helping reduce the capital cost with only minimal efficiency loss. He concluded by describing some of the future cost reductions that may apply to the Nth-of-a-kind plant. The inventor of this supercritical CO_2 power cycle, Rodney Allam, was also present for this session and helped respond to some of the questions.

Demonstrating CO_2 Capture at <$40/ton: Experience from Industrial Projects

Aniruddha Sharma, CEO of Clean Carbon Solutions Limited, talked about their process for capture of CO_2 from industrial sources. Their process, known as CDRMax, uses advanced amine chemistry to remove CO_2 from a variety of gas streams. Sharma reviewed their process flow diagram, which looks like a conventional amine-based absorber-stripper configuration. Some of the advantages of their advanced amine are that it has very low solvent-aerosol emissions and can be used in a carbon steel absorber. The process has been tested at the Technology Centre Mongstad (TCM) in Norway. They have a commercial-scale (174 tpd) CO2 capture-to-chemicals plant that was commissioned in India in late 2016. It captures CO2 from a 10 MW coal boiler flue gas stream. The capture cost is claimed to be less than $40/ metric tonne, including capex and opex.

Clean Carbon Solutions' plan for cost reductions in future plants is based on a "standardize and replicate" philosophy. They are also investigating stacking of equipment to reduce the overall footprint. Sharma foresees many CO_2 capture plants being built at smaller industrial scale facilities, referred to as iCCUS. They plan to deliver three industrial-scale CO_2 capture projects in 2017, and are conducting two conceptual studies in Norway for 1500 tons/day (75MW) CO_2 capture plants.

Session 4: CCS in Energy-Economic Models

Rapporteur: K. Burnard

This session focused on the treatment of CCS in energy-economic models. In the Paris Agreement developed at COP21 in December 2015, governments signed up to a stringent "well below 2°C" target and a more ambitious pursuit to limit the global average temperature increase to 1.5°C above pre-industrial levels.

Energy-economic models are a key methodological tool for investigating long-term trade-offs among the energy system, the climate system and the broader economic system. Such models play an important role in underpinning the scientific debate on climate change mitigation and adaptation. They are developed and operated by a wide range of international, national, academic and industrial organisations. Outputs from these models are important because their results inform assessments by bodies such as the IPCC, and directly or indirectly influence the advice and decisions of national and international policy makers and regulators. Two presentations informed the workshop on recent modeling developments related to CCS.

A Review of CCS Techno-Economic Representation in Integrated Assessment Models

James Glynn, a Postdoctoral Researcher and member of the Energy Policy and Modelling Research Group at University College Cork, discussed the findings of a new IEAGHG-sponsored study on the representation of CCS in techno-economic models. CCS is represented in most of these models and plays a role in many climate scenarios consistent with a 2°C temperature limit.

While the models often align on high-level messaging about the value and need for CCS, the actual role, impact and applications of CCS vary considerably.For example, there are differences in terms of CCS applications in the power sector versus the industry sector, the extent to which it is applied to coal or gas, and the degree of biomass energy with CCS (BECCS).

Glynn's presentation provided some transparency on the input data, calibration and cost assumptions for a range of approaches used to represent CCS in energy-economic models for climate scenario analysis. The work represented a broad collaborative review of the technical and economic calibration of CCS technology options in influential models, and outlined a best-practice calibration of CCS costs in energy-economic models.

The Role of CCS in Determining Costs and Climate Outcomes of Scenario Analysis in Integrated Assessment Models

This presentation was given by Richard Millar, a Postdoctoral Research Assistant in the Environmental Change Institute at the University of Oxford. As recognised in the previous presentation, energy-economic models have regularly shown CCS to be a key technology in scenarios that meet the long-term goals of the Paris Agreement to limit global warming to "well below 2°C. However, the reasons underlying its importance in determining the total costs of mitigation are often not well understood.

Millar investigated the impact of assumptions regarding CCS calibration by technology type, model type and the level of granularity on cost curves for capture, transport and storage, as well as the time evolution of mitigation technology portfolios deployed to meet climate goals. Using a review of intermodal comparison projects databases, he explored the key determinants of CCS cost learning curves as well as their implications on cost-effective mitigation frames. Finally, Millar discussed his results on the effectiveness of supporting near-term deployment of CCS as a way to bring down the overall cost of meeting climate goals.

Session 5: CCS Flexibility

Rapporteur: H.J. Herzog

The levelized cost of electricity (LCOE) is often used to characterize and compare the cost of differing electricity generating technologies. However, there is a growing realization that LCOE alone is inadequate for this task, especially as more intermittent energy supply technologies get deployed. Characteristics such as flexibility can add value to a generating technology. The two presentations in this session explore this question. Using models, they quantify the value of flexibility and other services required to provide grid stability. Both presentations show that the value of CCS as a low-carbon supply technology is significantly greater when these system characteristics are taken into account compared to simply using LCOE.

Quantifying and Qualifying the Role and Value of Flexible CCS to the Decarbonisation of National Electricity Systems

This presentation by Clara Heuberger of Imperial College used the concept of "system value metric" to help quantify the value of flexibility in electricity supply technologies. This is defined as the difference in total system cost resulting from the deployment of a power generation or storage technology. Models based on this Electricity System Optimization (ESO) framework were developed. Key features are described as including bottom-up engineering model of a wide range of technologies, features, and learning (technology-agnostic); cost-optimal capacity planning considering adequacy, security, and carbon (transition planning); and granular representation of time and space with long-term foresight (operational detail).

Model results show significantly greater value for CCS than simple modeling using only LCOE. Conclusions of the presentation, based on modeling results for the UK, were that "the value of a power technology changes as a function of the penetration level and is dependent on the incumbent system conditions; flexible CCS technologies provide an additional value in being able to accommodate higher levels of intermittent renewable capacity and power generation; and total system cost by mid-century can be reduced when investments into low-carbon technologies are made now."

Keeping the Lights on Whilst Decarbonising Electricity

This presentation by Andy Boston of Red Vector was based on a study looking at decarbonization in Australia. The project used a model called MEGS (Modelling Energy & Grid Services). This is medium resolution model validated using historical data . It allows for simulating 100s of scenarios and includes interconnect capabilities, economics, and system stability.

Boston's overall messages are that, (1) it is important to consider the whole system across all time scales to 2050 and beyond; (2) a secure grid requires a range of essential services; (3) the solution will be diverse; and (4) providing reliable low emissions electricity comes at a cost. Regarding the technology options, the study concludes: "The effectiveness of a technology depends on how much exists already (costs increase in a non-linear fashion as they are added and simple metric like LCOE can't explain or represent that behavior); renewables appears to be cheapest for initial steps, but not for deeper decarbonisation (diminishing returns); building gas is cheaper for mid-levels of decarbonization, around 50%; only CCS can get to deep (>60%) decarbonisation levels; and the cost of gas CCS and coal CCS are similar at $12/GJ".

BREAKOUT SESSIONS

Day 2 of the workshop included three parallel breakout sessions to discuss selected topics in greater detail. Issues and discussion points arising in these sessions are outlined below.

Energy-Economic Models: Is CCS being represented appropriately?

Rapporteur: H. Herzog

This session was a far-ranging discussion and commentary on topics raised in Session 4 of the first day plenary, centered around the findings of a recent workshop on the representation of CCS in large-scale energy-economic models. The results and findings of that workshop are summarized in an IEAGHG report entitled: *Proceedings of USDOE Workshop: Energy-Economic Modeling Review*, IEAGHG Technical Report 2017-06, June 2017, 20p.

Learnings from demonstration projects: what will the next plant cost?

Rapporteur: G. Booras

Topics and comments discussed in this session included the following:

- Learnings from failures
- Learnings from DOE demos
- Execution risk
- Demo vs. commercial
- Procurement

- Commercial guides demo scale, then feeds back to commercial
- Up front cost? 5-8%, 20% including detailed engineering
- Danger of moving too quickly from design to construction
- Don Valley project moved too fast

- Modularization, engineering, contingency
- New vs retrofit? (Petra Nova less risk – no cutting into steam system)
- N^{th} is 5 to 10 plants (no technology changes to get to *N*)
- 1st plant reduces technical risk

- 2nd plant reduces execution risk

- Close in design and close in time to get to 2nd plant
- How do we learn?
- Power companies do not understand technology risk
- Risk allocation is key
- Knowledge transfer from proprietary processes?
- Execution learning
- Next plant = 1st commercial plant following demo
- Need to add cost of commercial wrap

- TRL 8 = full scale. Can you go from TRL 7 to 9?
- Is LSTK the right way to go? Pay extra for risk vs. cost reimbursable or EPCM approach
- Loan guarantee better for plant 2
- Open book structure for plant 1
- 1st to 2nd cost reductions are outside of kit cost

- IP inhibits learning and tech transfer
- Location of 2nd plant is important
- Licensor has to see market potential
- Commercial plant – full guarantees (plant 1)
- Plant 1 to plant 2: cost2 = (scale2/scale1)^0.5, then less 30%
- IEA reports: Lessons learned from BD3 and other projects

Beyond demonstrations: CCS projects with multiple repeat units

Rapporteur: J. Gibbins

Notes and comments from this session are summarised in the following outline.

1. RISKS AND WHO CONTROLS THEM OR HAS TO TAKE THEM

1.1 Industry controls:

• Construction risk – industry can handle this, but not just turnkey contracts

• Get a specialist in chemical plant, electricity generator supply land, steam, electricity

1.2 Government controls/takes:

Long term storage risk:

• The province of Alberta dealt with it, abandon the well according to the regulations

• EOR – storage has to be done properly

CCS as a waste disposal business:

• Regulated return on investment

• Fees for CO_2 T&S regulated – could be passed through to first project and they pass on to market (e.g. 20 year CFD), no system yet for industrial CCS

Market risk:

• Power station goes bust or CCS not built because government supported renewables

2. REWARDS

• Oil companies supply the gas and store the resulting CO_2

• Regulated asset model (new regulator probably for transport & storage)

• Assets privately owned with regulated return

• Operator – fee for operating

3. BREAKING UP THE CCS CHAIN

(different from BD3, PetraNova, Peterhead)

Hard to find a company that could take on the whole chain, especially at the large scale for offshore storage.

3.1 Generator

• Capture (could be over the fence for post-com, over the fence oxygen)

• Separate control room?

• Over the fence - pass through risk for power, gas etc.

3.2 Transport: • Open access

3.3 Storage

• Must have somewhere for the CO_2 to go

• CCS systems with EOR different from systems with storage, no value to drive the project, also with offshore storage the system is much larger (BUT need to be able to accommodate EOR)

• Limited value in existing infrastructure (pipelines/wells, not in the right place, right conditions)

4. RECIPE FOR A CLUSTER WITH A POWER ANCHOR PROJECT IN THE UK

4.1 PART 1

• Anchor project needed for CCS cluster

• Multiple units required to get >5Mt CO_2/yr

• Only power can be an anchor project – it cannot move away

Ingredient #1: T&S is available as regulated utility

Ingredient #2:'CFD' to guarantee the investment is recovered, alternatively 'base facility charge' separate from operating costs, incentives for efficiency etc. in industrial gases, analogue in power market is capacity payment

4.2 PART 2

• Anchor is 3+ units (for gas, less for biomass)

• Not too few as average costs too high

• Not too many as reduces future options – technology will improve

• Benefits of scale reduce after about 3 units, zero by 5, difficult to find sites for larger numbers of units

• Characteristics of sites set by legacy infrastructure, enough brownfield sites available in the UK.

• Bigger than 24 inch CO_2 pipeline a bit difficult – around 15Mt CO_2/yr

• Design first pipeline, compressor stations etc. to add a second

• Maybe a third where large storage available, need strategy for storage capacity development

• Storage hub required, first store or two stores or backup wells. Would depend on what is there, the geology. Appraisal requirements different for old hydrocarbon reservoirs vs aquifers. Full derisking of storage will be required at this scale but complete assessment not feasible until injection has progressed (due to injectivity, salt buildup, compartmentalization).

• EOR may come in once CO_2 is available; leave it as a future option if possible.

• Key is getting Treasury on board – jobs, growth prospects better than alternatives.

• Oil companies getting more motivated, power needs confidence rebuilt.

5. ADDITIONAL NOTES ON BUILDING SITES WITH MULTIPLE UNITS

E.g., 3-10 units, power

• Can construction be staged to get learning?

• Pipe sized for maximum flow 10 years ahead, pressure drop increases over time

• Storage sites can be developed in stages provided necessary lead time is noted

• How long to operate to get learning – 2 years?

• Get some learning once construction is finished (i.e. before running)?

• Test facilities may be able to get info in parallel, 3000 hrs plus operation required to verify satisfactory solvent management approach for amines

CLOSING PLENARY

Participants affirmed the continuing value of this workshop series. The next meeting will be planned by the Steering Committee, with a tentative date of March 2019 at a location to be determined.

Photo credits: J. Gibbins/ETI

PRESENTATIONS

Session 1: Learnings from Recent UK Studies

1a. UK costs for a range of CCS technologies

Suzanne Ferguson, Amec Foster Wheeler

UK Costs for a Range of CCS Technologies

13th September 2017

Imperial College London

By Suzie Ferguson, Amec Foster Wheeler, Business Solutions Group

Agenda

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

Introduction

- Amec Foster Wheeler has performed over 50 CCS studies since the mid-1990s.
  - Comparing state of the art technologies (benchmarking)
  - Assessing new technologies

- Performed several CCS FEEDs
  - DF-1 Peterhead
  - Hydrogen Power Abu Dhabi
  - E.ON Kingsnorth
  - Don Valley Power Project

- Various pre-FEEDs including:
  - Statoil Snovhit Train II
  - Cameroon LNG

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Introduction

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

4

BEIS 2017 CCS Study Overview

- Key aims of the study included:
  - Technology performance & cost update of state of the art CCS technologies
  - Assessment of selected novel technologies, biomass & hydrogen schemes with CCS
- State of the Art CCS Technologies included:
  - Natural gas CCGT with proprietary amine-based post combustion capture
  - Natural gas reforming combined cycle with pre-combustion capture
  - Supercritical pulverised coal with proprietary amine-based post combustion capture
  - Supercritical pulverised coal with oxy-combustion capture
  - Coal gasification combined cycle with pre-combustion capture
- 2017 study aims to incorporate latest cost & technical performance:
  - improvements in the base power plants
  - further development & operational experience from CCS schemes in operation.

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BEIS 2017 CCS Study Overview

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

  *Results not included in this presentation

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

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Methodology

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

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Key Assumptions

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

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

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

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State of the Art Technology Results

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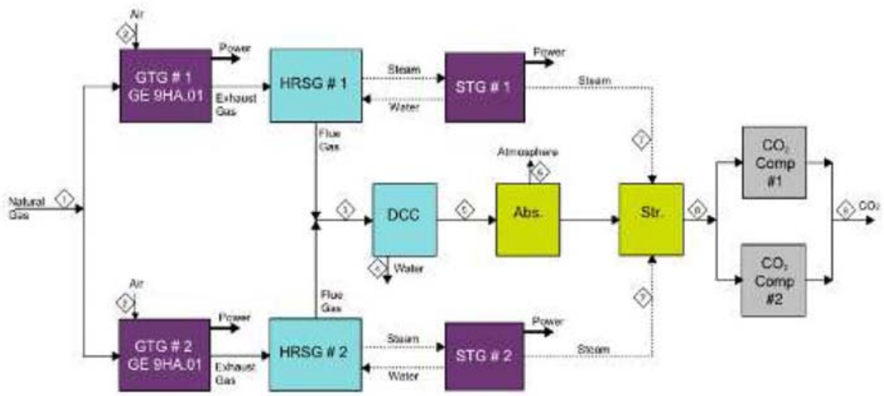
- Natural Gas CCGT with Cansolv CO_2 Capture
  - 2 x GE 9HA.01 gas turbines in combined cycle, scale 1,200 MWe nominal
  - Single train of CO_2 capture using combined concrete structure for direct contact cooler & absorber



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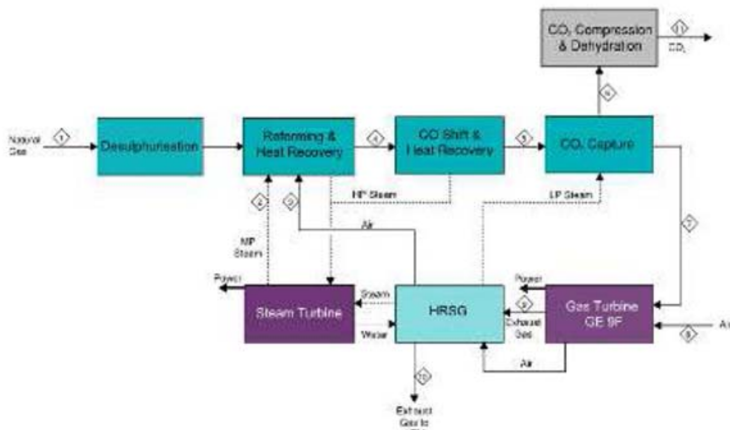
State of the Art Technology Results

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



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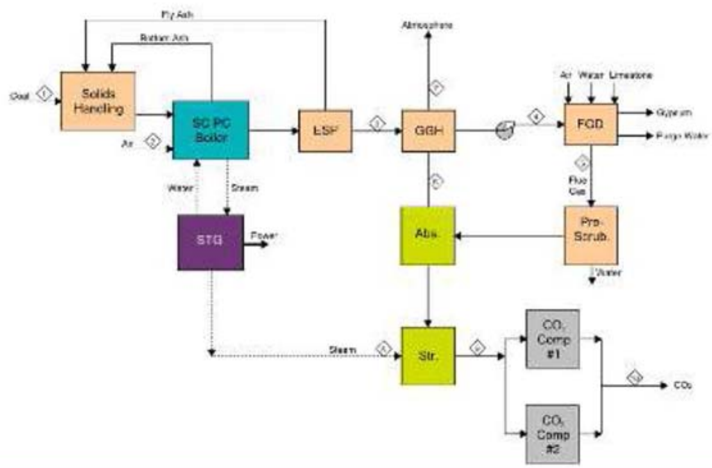
State of the Art Technology Results

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



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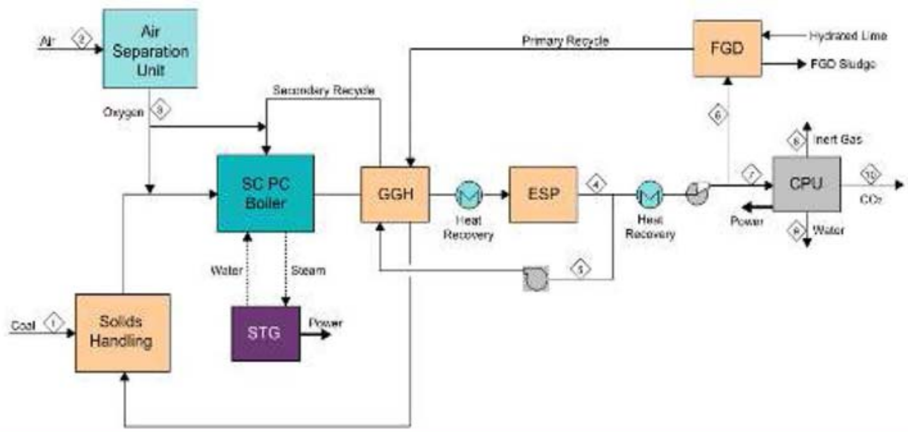
State of the Art Technology Results

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



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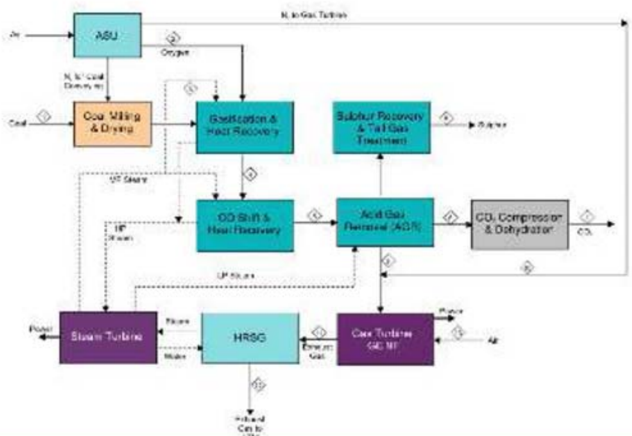
State of the Art Technology Results

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



State of the Art Technology Results

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Please refer to the final report "Benchmarking State-of-the-art and Next Generation Technologies" from the BEIS study "Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology", expected to be issued into the public domain in November 2017.

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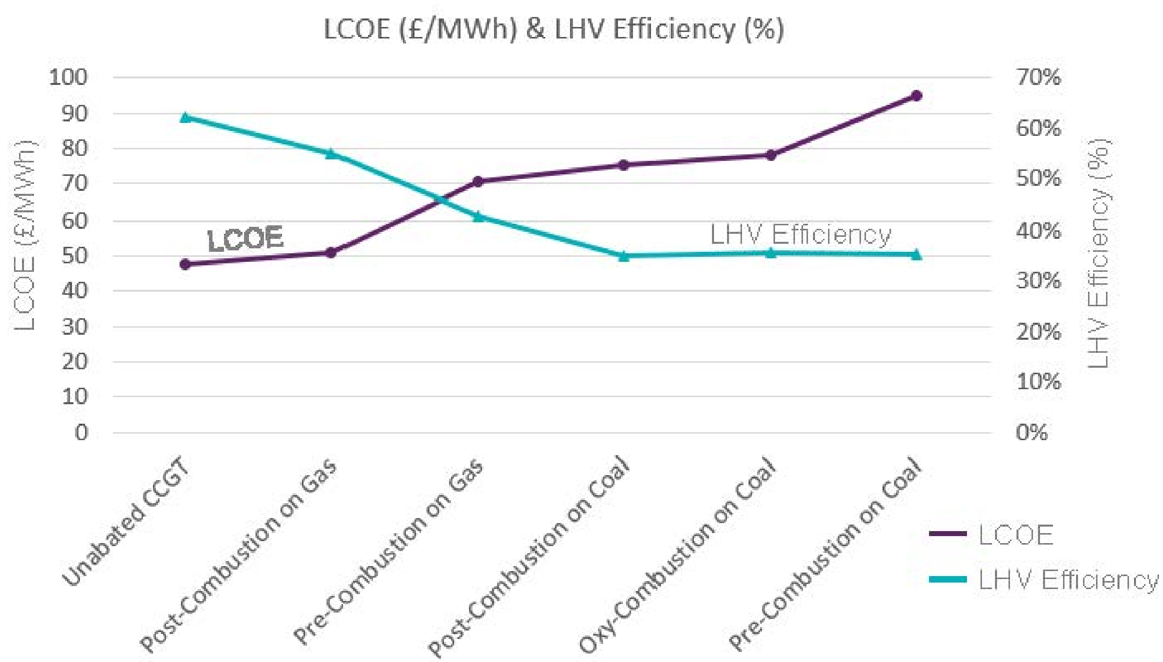
State of the Art Technology Results



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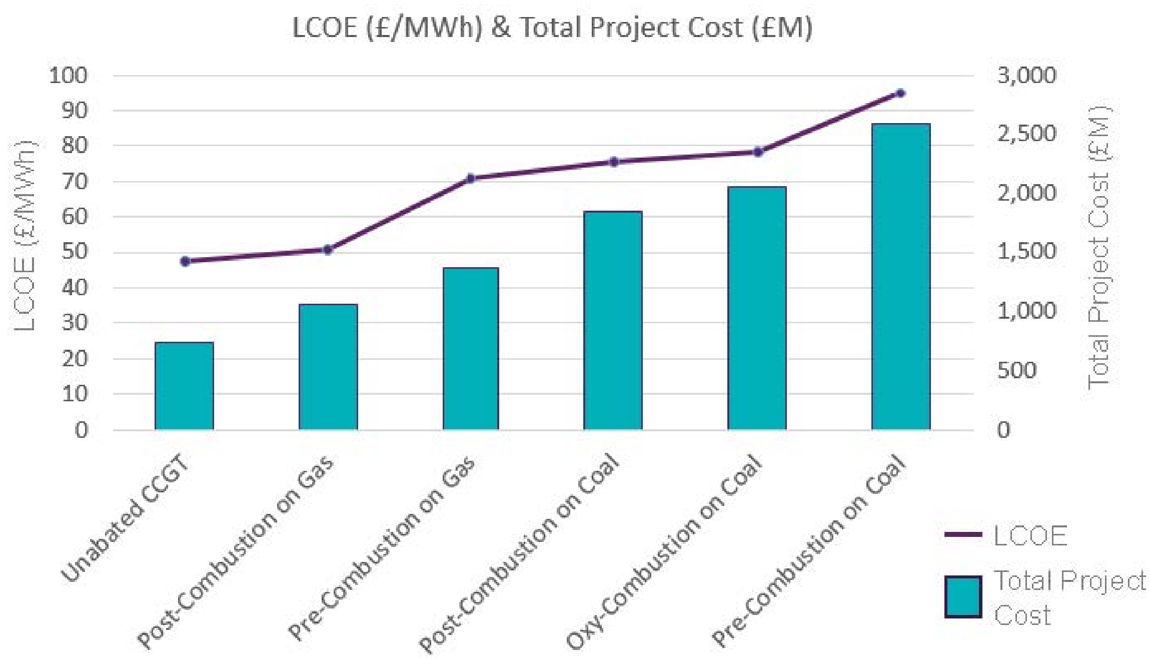
State of the Art Technology Results



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Novel Technology Potential – 2 Examples

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

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Novel Technology Results

Please refer to the final report "Benchmarking State-of-the-art and Next Generation Technologies" from the BEIS study "Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology", expected to be issued into the public domain in November 2017.

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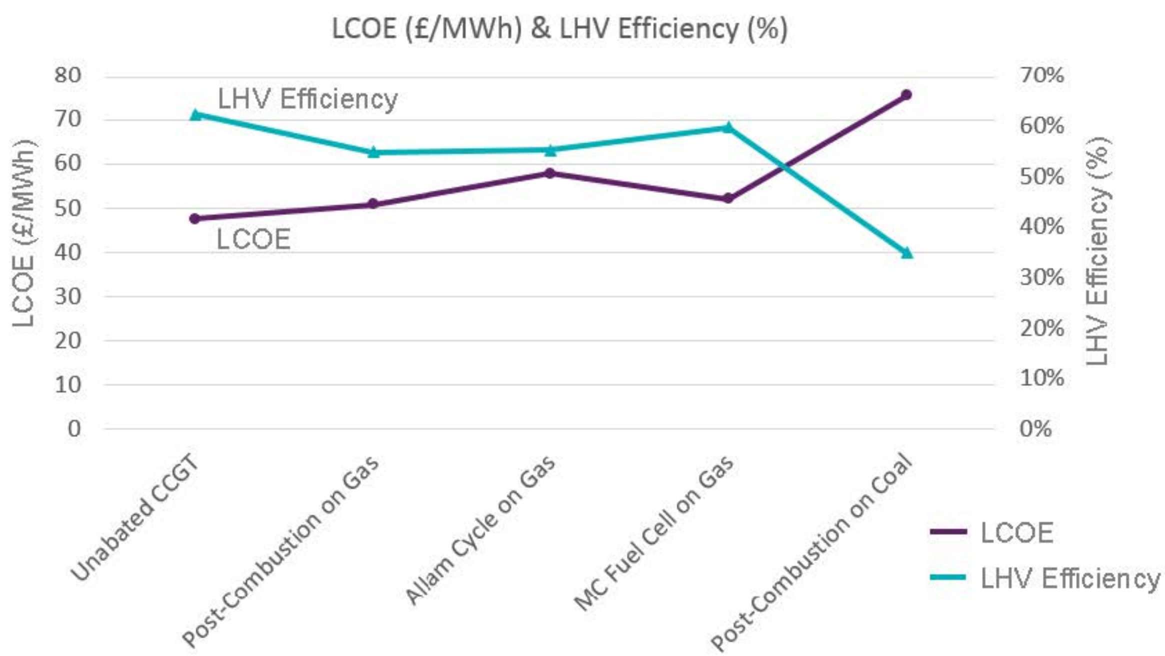
Novel Technology Results



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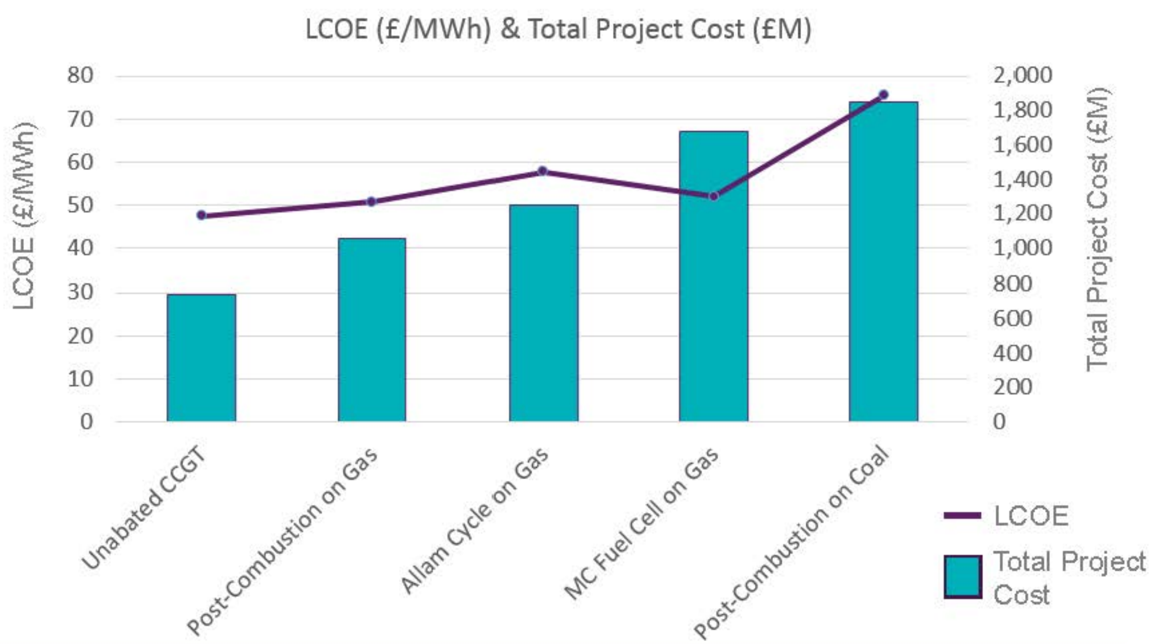
Novel Technology Results



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Conclusions

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

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Thank you!

Questions?

Suzie Ferguson
Suzanne.Ferguson@amecfw.com

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1b. Natural Gas Post-combustion

Den Gammer and Andrew Green, ETI

energy technologies institute

www.eti.co.uk

IEAGHG CCS Cost Workshop, 13th Sept 2017

Session 1 : Learnings from Recent Studies

Den Gammer

ETI10 TEN YEARS OF INNOVATION 2007—2017

ETI Generic Business Case

energy technologies institute

Purpose

- Obtain the most credible costs possible for CCGT with CCS in UK
  Lower risk technology selection – "where we are".

  - full scale plant (not demonstration/competition scale) , advantageous locations
  - use latest costs and performance (BEIS KKD, DECC Strategic UK Appraisal Project)
  - use latest GTs (size, efficiency)

- Capital Estimate Class

  - AACE Class IV (-15% to – 30% and +20% to +50%)

- Scope

  - from 1 to 5 trains of GTs (ie to 3GWe), in 5 different regions
  - locational work includes bespoke connection costs, feasibility study level pipeline routes
  - include all contingencies, risk allowances, profits

SNC·LAVALIN AECOM The University Of Sheffield.

Scope in Pictures

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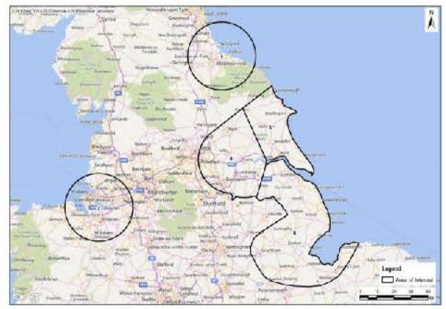
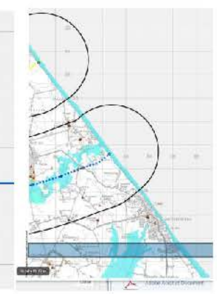
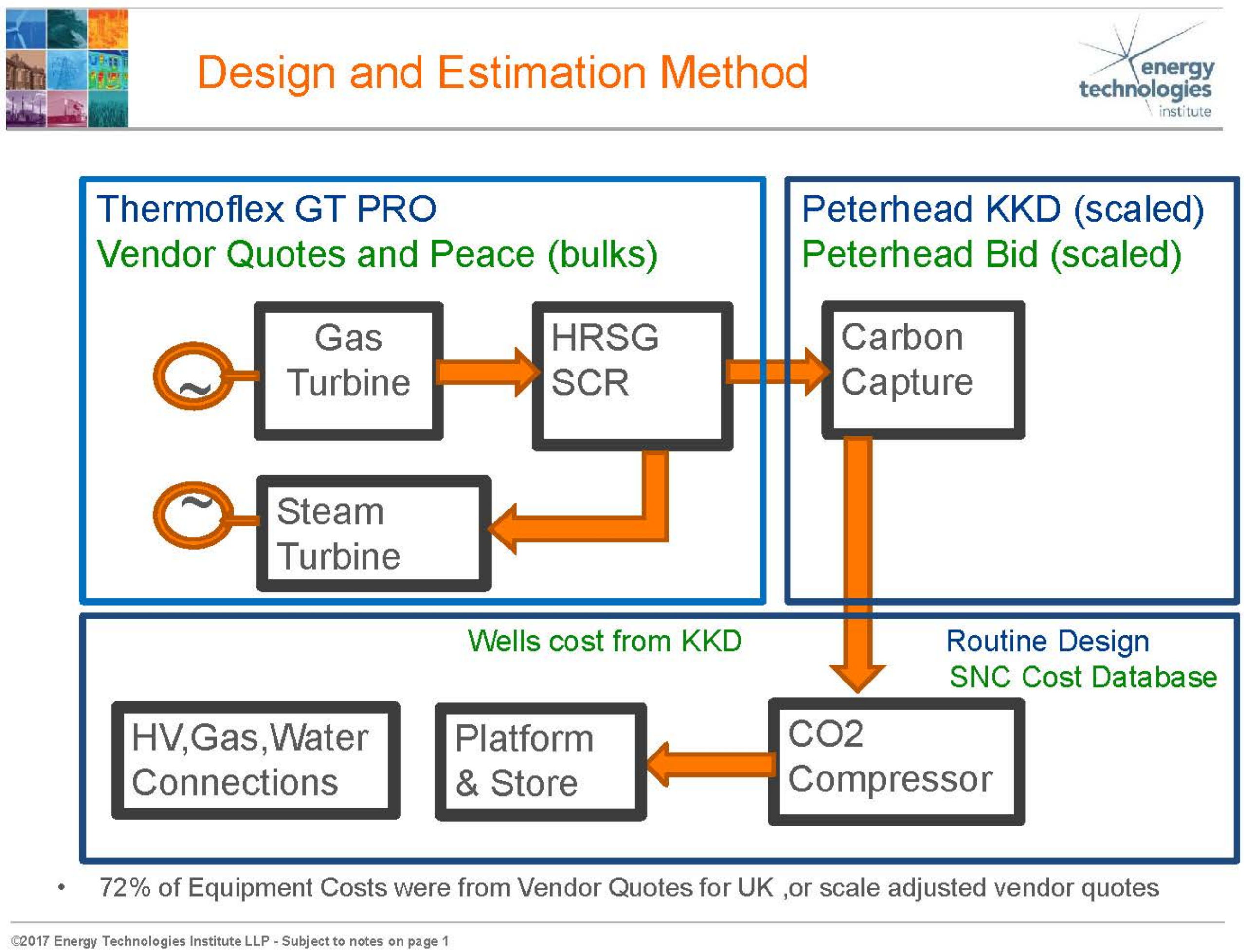


	Store	Trains 1	Trains 2	Trains 3	Trains 4	Trains 5
Power, GWe		0.6	1.2	1.9	2.5	3.2
CO2, MTe/a		2	4	6	8	10
Scotland	Gold/Capt. X	£xxx	xxx	xxx	xxx	xxx
Teesside	Endurance	xxx	xxx	xxx	xxx	xxx
North Humber	Endurance	xxx	xxx	xxx	xxx	xxx
South Humber	Endurance	xxx	xxx	xxx	xxx	xxx
North West	Hamilton	xxx	xxx	xxx	xxx	£xxx




Design and Estimation Method
energy technologies institute
Thermoflex GT PRO
Vendor Quotes and Peace (bulks)
Gas Turbine
HRSG SCR
Steam Turbine
Peterhead KKD (scaled)
Peterhead Bid (scaled)
Carbon Capture
Wells cost from KKD
Routine Design
SNC Cost Database
HV,Gas,Water Connections
Platform & Store
CO2 Compressor
• 72% of Equipment Costs were from Vendor Quotes for UK ,or scale adjusted vendor quotes
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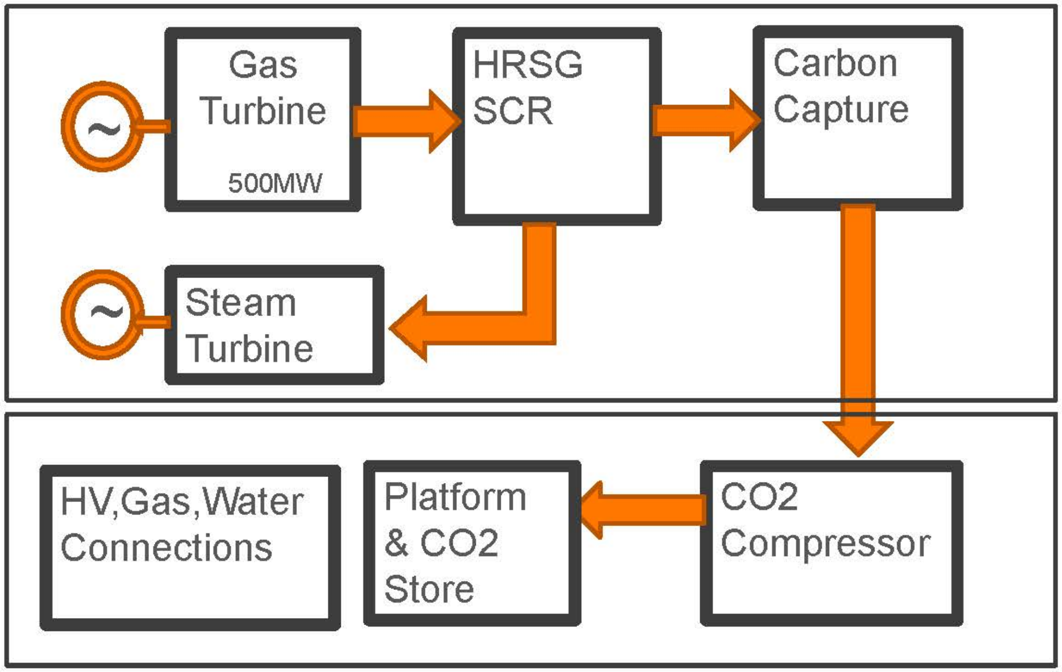
Build up of Estimates for Different Sizes and Locations



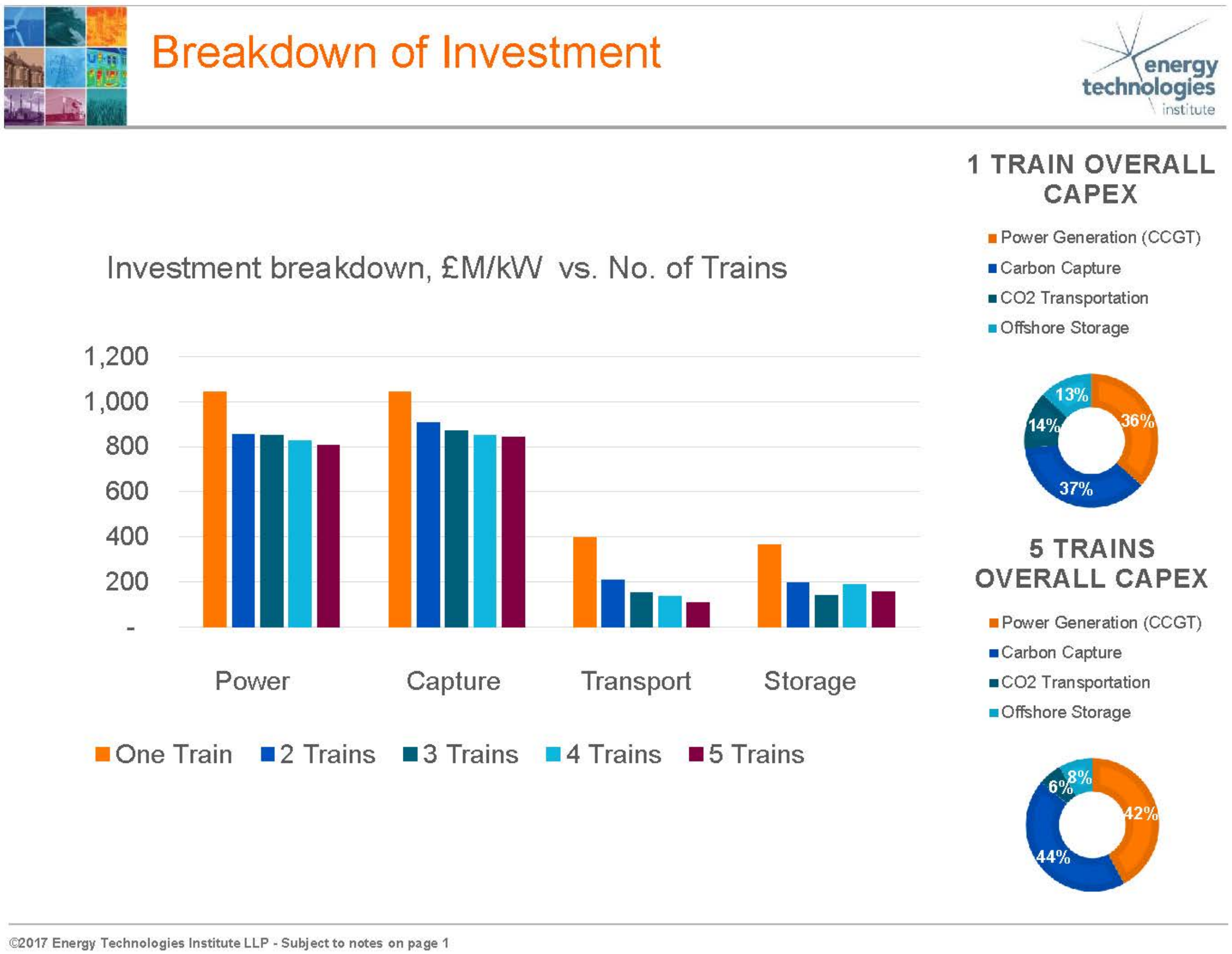
Multiple Identical Trains

- Regional Adjustment

Customised for :

- Location
- Size

- KKDS can be found on the BEIS website : (https://www.gov.uk/guidance/uk-carbon-capture-and-storage-governmentfunding-and-support).


Breakdown of Investment
energy technologies institute
Investment breakdown, £M/kW vs. No. of Trains
1,200
1,000
800
600
400
200
-
Power
Capture
Transport
Storage
One Train
2 Trains
3 Trains
4 Trains
5 Trains
1 TRAIN OVERALL CAPEX
Power Generation (CCGT)
Carbon Capture
CO2 Transportation
Offshore Storage
13%
14%
36%
37%
5 TRAINS OVERALL CAPEX
Power Generation (CCGT)
Carbon Capture
CO2 Transportation
Offshore Storage
6%
8%
42%
44%
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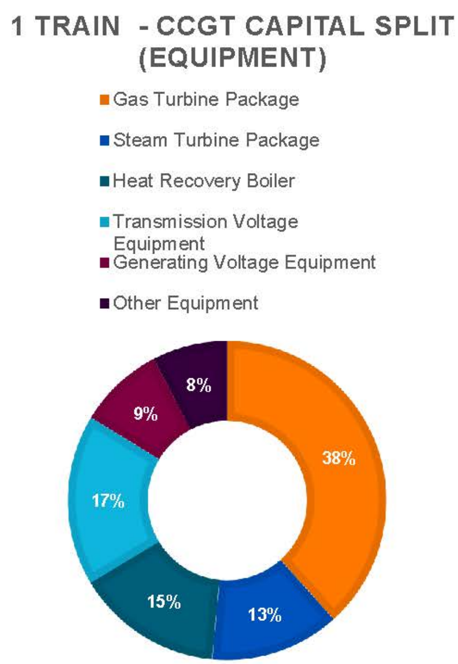
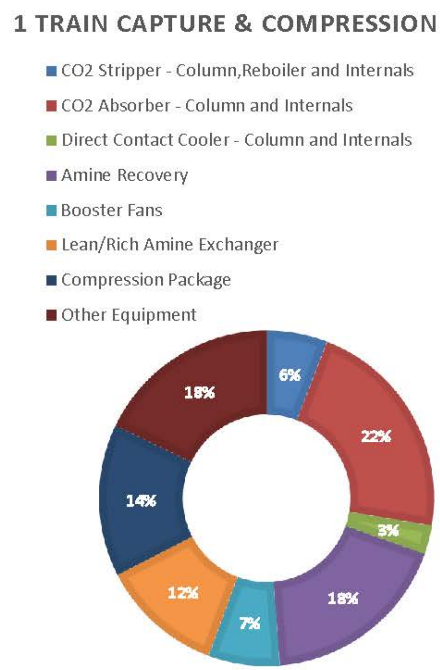
Generation and Capture cost Breakdown





Multiple trains - cost curve example

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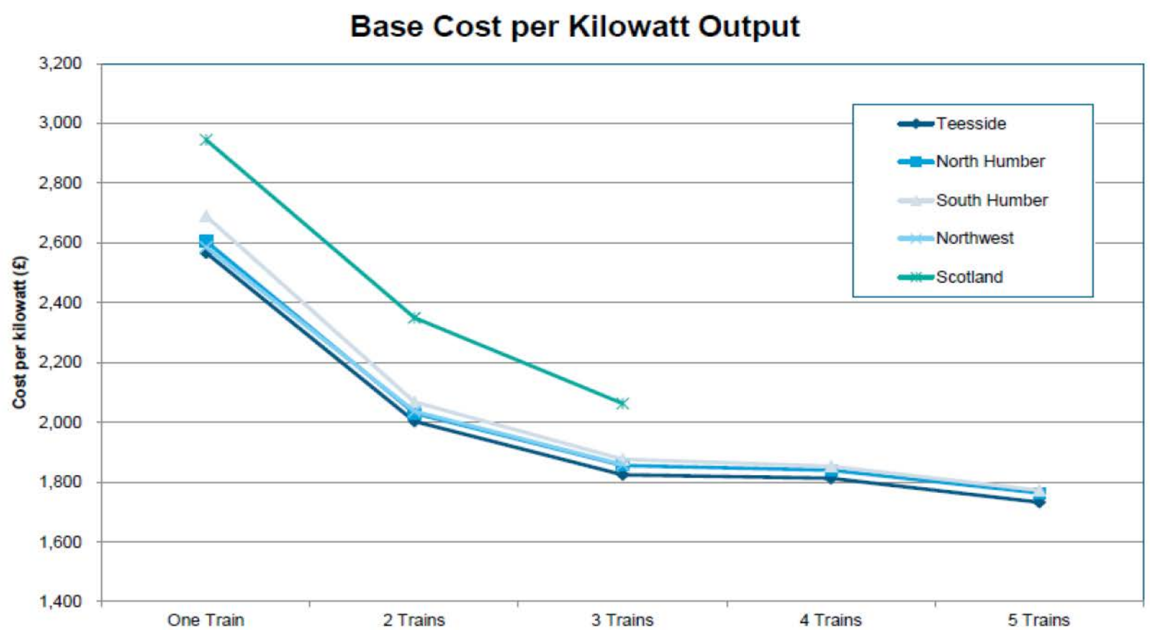

Overall Power Costs – CCGT with CCS

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- The post Brexit fall in the £/US$ caused an escalation of 3% - 4% alone
- Even with a "conservative" configuration, the capture energy penalty has dropped by more than ~ 2% points since 2010 estimates. Generation efficiency has gained 2% points.
- Overall, levelised costs have not changed significantly since earlier ETI estimates and are in the range :

LEVELISED COST of ELECTRICITY

Range : £/MWh 63 to £/MWh 93

SIMPLIFIED ASSUMPTIONS

- Discount Factor - 10%
- Gas Prices, p/therm : Lo- 30 Med- 50 Hi- 70
- 5 Train capex
- 25 year life
- Costs, Q1 2016
- Load Factor 90%
- LHV Efficiency 52.7% (by calculation)
- 100% equity

"Conservative": No 2+1 for Steam Turbines, Absorbers, ARU's etc , 316 SS in capture unit , multishaft, HRSG/ST etc sized for full GT flow, energy penalty 7.9% (2.99GJ/te reboiler)

Next Steps

- Engage any interested third parties (under confidentiality if requested)
- Build in refreshed power station opex
- Sensitivity on train configurations (“2+1”s)
- Publish formatted estimate and summary to community end Q4

- Conclusion
  - Most realistic cost estimate yet in UK at full scale
  - CCGT/CCS a highly competitive option

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For the latest ETI news and announcements email info@eti.co.uk

For more information about the ETI visit www.eti.co.uk

The ETI can also be followed on Twitter @the_ETI

TEN YEARS OF INNOVATION 2007 – 2017

Session 2: Cost of Large-scale CCS Projects

2a. Petra Nova **Carbon Capture**

David Greeson, NRG

PETRA NOVA Carbon Capture

Carbon capture at commercial scale

- 240MW equivalent CO_2 scrubber on a 640MW coal-fired power plant
- Captures approximately 1.6 million tons per year of CO_2
  - To date, over 800,000 tons have been captured
- CO_2 is used to enhance oil production at the West Ranch Oilfield
  - To date, over 500,000 barrels of oil have been produced
- Sequestering 5,200 tons of CO_2 per day

PETRA NOVA Carbon Capture

Carbon capture at commercial scale

- 240MW equivalent CO_2 scrubber on a 640MW coal-fired power plant
- Captures approximately 1.6 million tons per year of CO_2
  - To date, over 800,000 tons have been captured
- Sequestering 5,200 tons of CO_2 per day

No impact on power plant or its costs

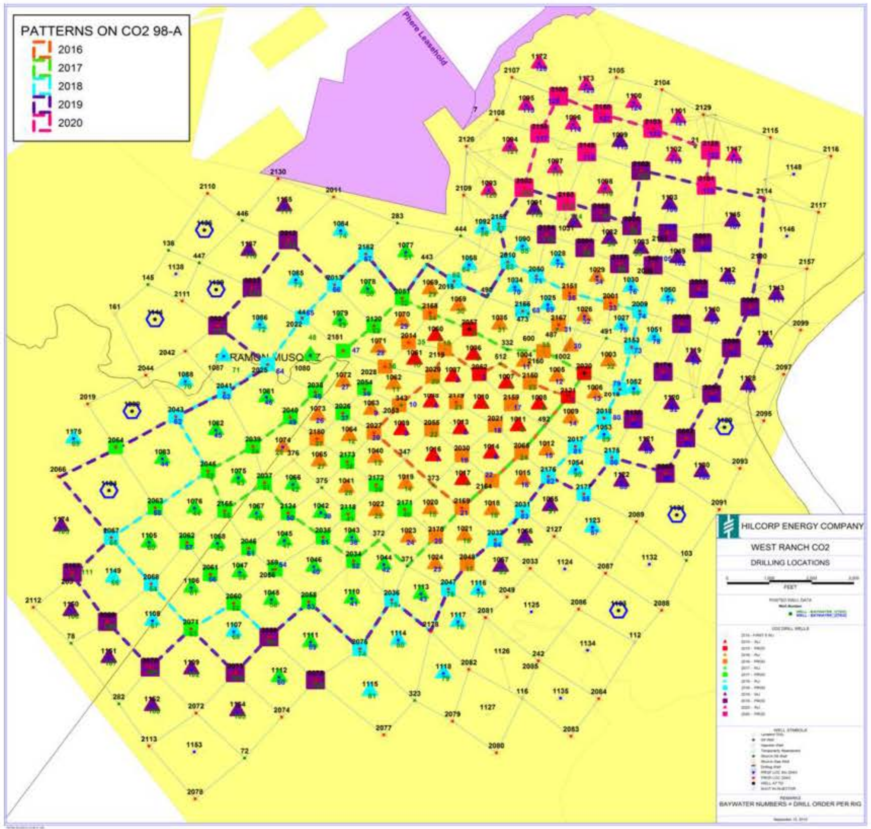
PETRA NOVA Carbon Capture

Carbon Capture System Site Layout

Petra Nova
Carbon Capture
Site

PETRA NOVA Carbon Capture

Enhanced Oil Recovery Project



West Ranch Field Development

- Field is being flooded using a “5-spot” pattern (each injector surrounded by 4 producers)
- A comprehensive monitoring, verification, and accounting plan is in place to track the flow of CO2 and to insure that it is sequestered in the reservoir.
- University of Texas Bureau of Economic Geology developed the plan to sync with oilfield operations.

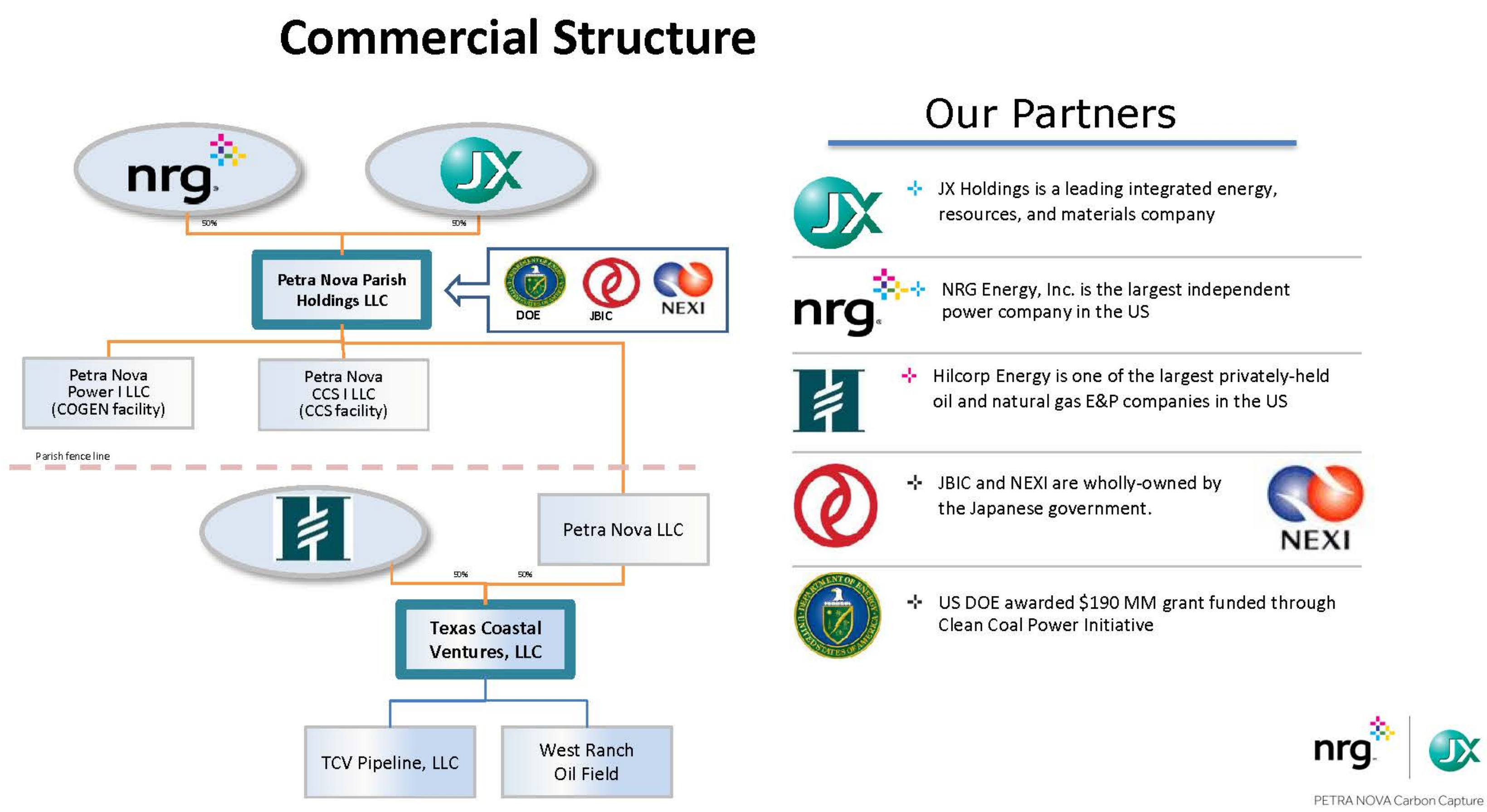
PETRA NOVA Carbon Capture

Oilfield Facilities Recapture and Inject CO_2

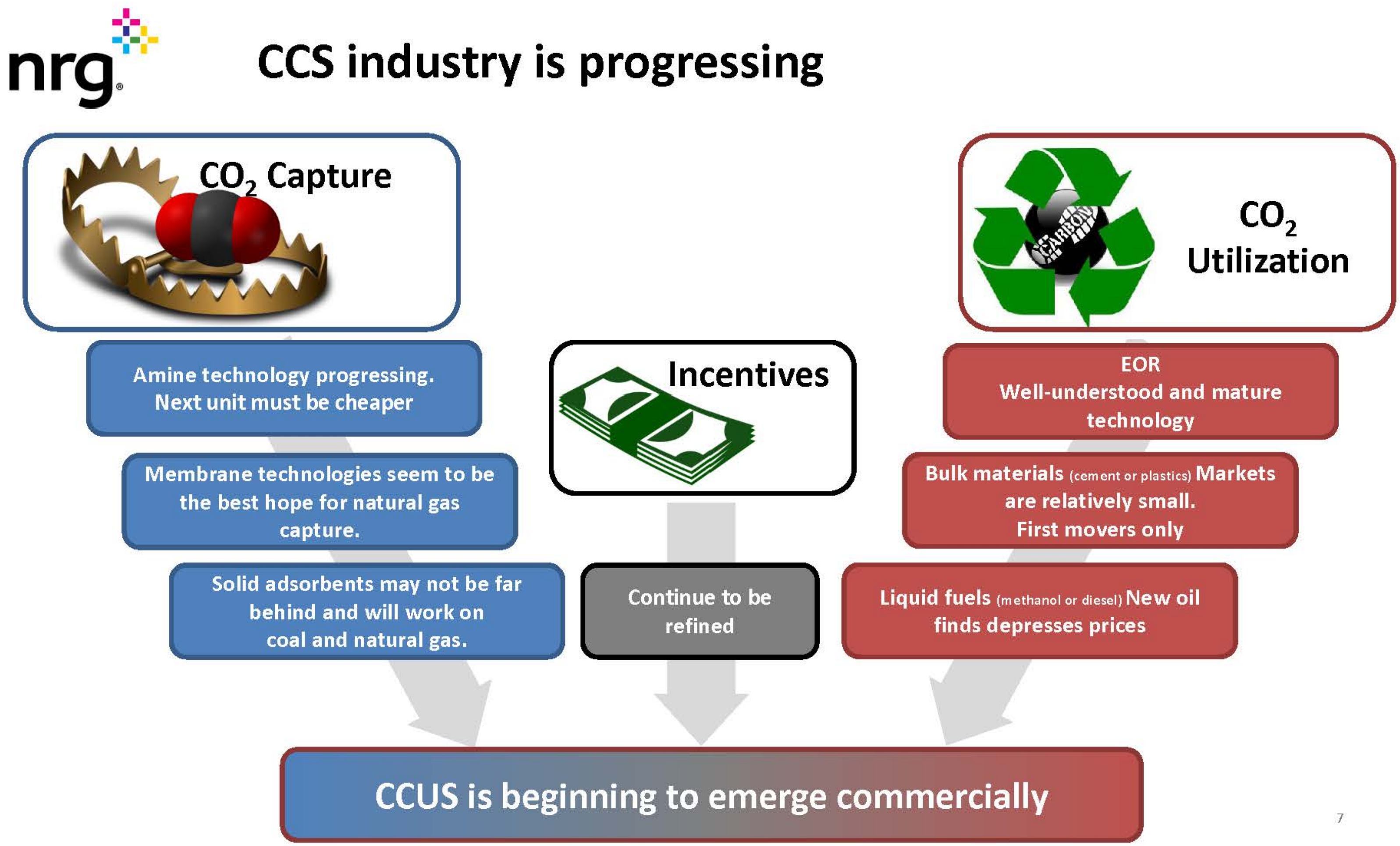
West Ranch Field Central Facilities

- Over 300 new wells to be drilled
- 2 central processing facilities to separate oil-CO_2-water
- All produced CO_2 and water is re-injected into the formation

PETRA NOVA Carbon Capture



Commercial Structure
nrg
JX
50%
50%
Petra Nova Parish Holdings LLC
DOE
JBIC
NEXI
Petra Nova Power I LLC (COGEN facility)
Petra Nova CCS I LLC (CCS facility)
Parish fence line
Petra Nova LLC
50%
50%
Texas Coastal Ventures, LLC
TCV Pipeline, LLC
West Ranch Oil Field
Our Partners
JX Holdings is a leading integrated energy, resources, and materials company
NRG Energy, Inc. is the largest independent power company in the US
Hilcorp Energy is one of the largest privately-held oil and natural gas E&P companies in the US
JBIC and NEXI are wholly-owned by the Japanese government.
US DOE awarded $190 MM grant funded through Clean Coal Power Initiative
PETRA NOVA Carbon Capture


nrg
CCS industry is progressing
CO2 Capture
Amine technology progressing. Next unit must be cheaper
Membrane technologies seem to be the best hope for natural gas capture.
Solid adsorbents may not be far behind and will work on coal and natural gas.
Incentives
Continue to be refined
CO2 Utilization
EOR Well-understood and mature technology
Bulk materials (cement or plastics) Markets are relatively small. First movers only
Liquid fuels (methanol or diesel) New oil finds depresses prices
CCUS is beginning to emerge commercially
7

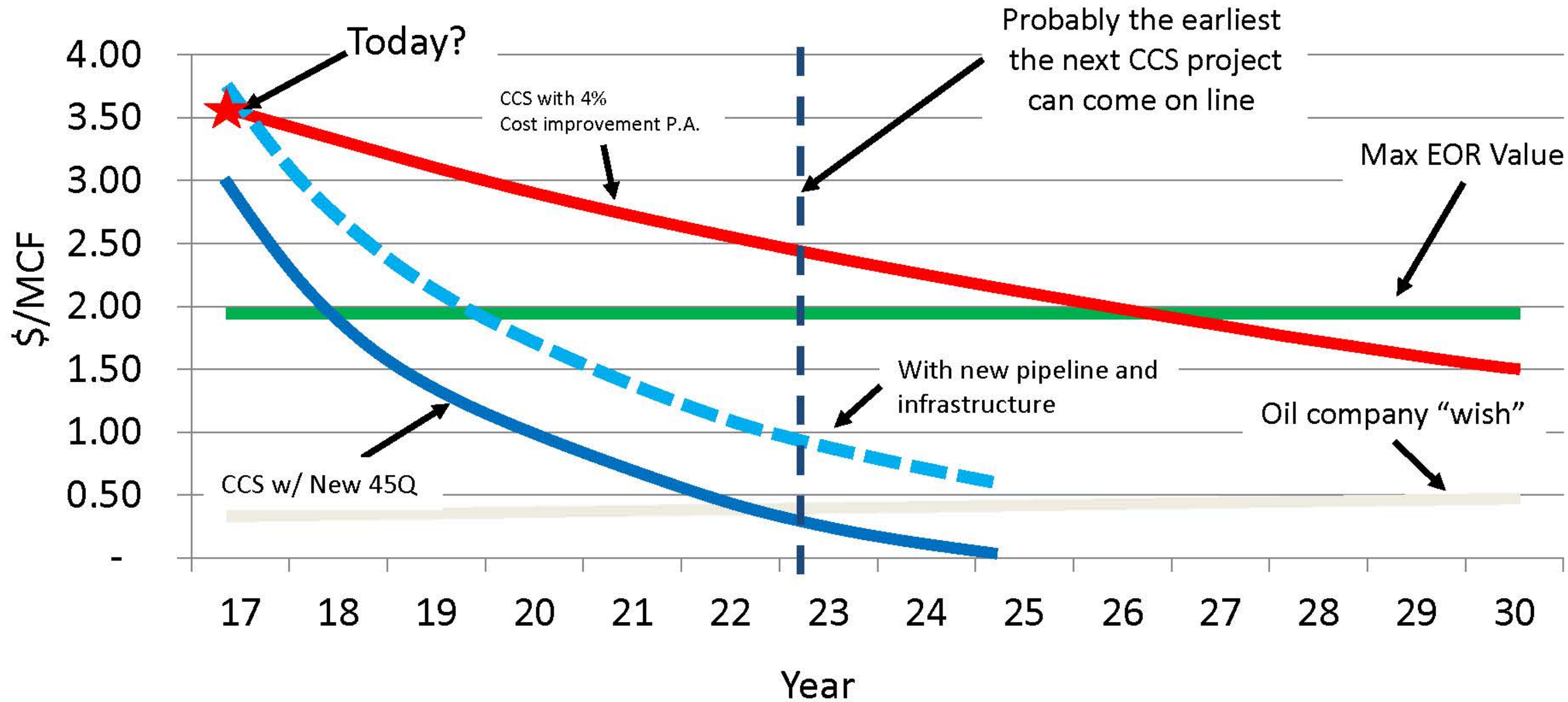
nrg

Some headwinds moving forward

1. Cost	Commercially available technologies are capital intensive
2. Competition	More options and technologies are needed
3. Scale	Technologies need to be proven at a sufficient scale
4. Development	Approaches and incentives need to be re-evaluated
5. Reputation	Confidence in this space has eroded
6. Time	Need to start now. Projects can take years to develop and build

8

Path to success – improving economics



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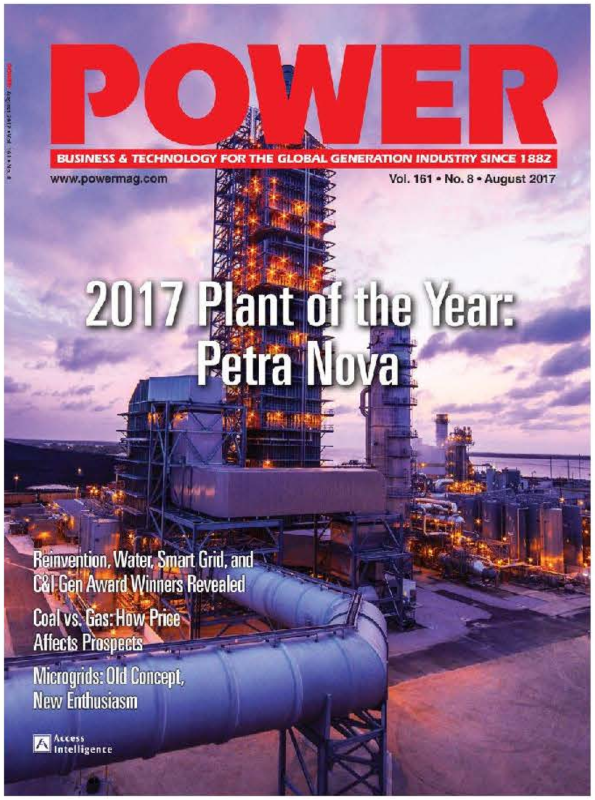
PETRA NOVA Carbon Capture

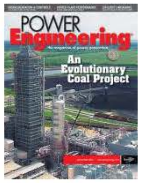
Interest is high right now



2017

Numerous tours

Several speaking engagements



30+ articles written

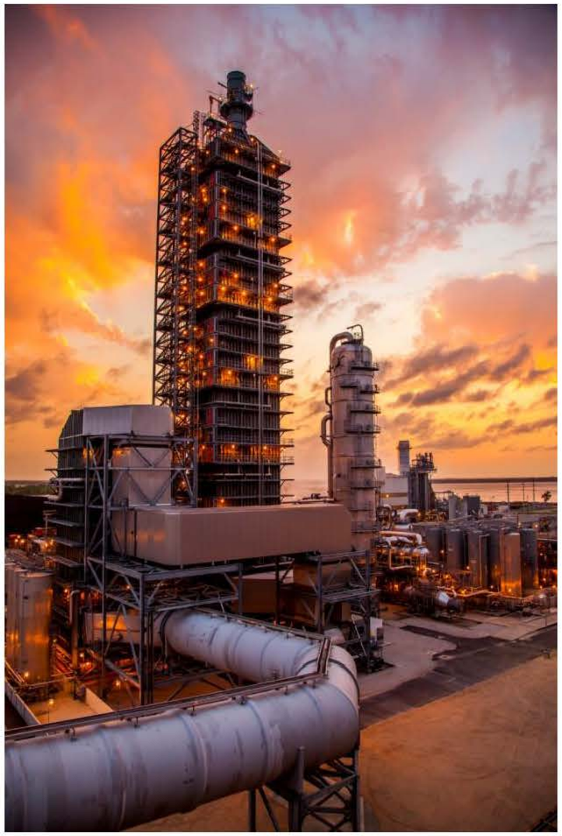
When Petra Nova is operating, Parish Unit 8 has the same carbon intensity as a combined cycle.

10

nrg | JX

PETRA NOVA Carbon Capture

Thank You!



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2b. Quest CCS Project Costs

Wilfried Maas, Shell Global


UP HERE, TOO MUCH CO_2 IS A PROBLEM
Quest CCS Project Costs
IEAGHG CCS Cost Network Workshop
13-14 September 2017, London
Wilfried Maas
General Manager CCS & CO_2

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The companies in which Royal Dutch Shell plc directly and indirectly owns investments are separate legal entities. In this presentation "Shell", "Shell group" and "Royal Dutch Shell" are sometimes used for convenience where references are made to Royal Dutch Shell plc and its subsidiaries in general. Likewise, the words "we", "us" and "our" are also used to refer to subsidiaries in general or to those who work for them. These expressions are also used where no useful purpose is served by identifying the particular company or companies. ''Subsidiaries'', "Shell subsidiaries" and "Shell companies" as used in this presentation refer to companies over which Royal Dutch Shell plc either directly or indirectly has control. Entities and unincorporated arrangements over which Shell has joint control are generally referred to as "joint ventures" and "joint operations" respectively. Entities over which Shell has significant influence but neither control nor joint control are referred to as "associates". The term "Shell interest" is used for convenience to indicate the direct and/or indirect ownership interest held by Shell in a venture, partnership or company, after exclusion of all third-party interest.

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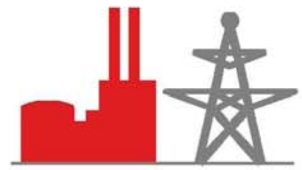
 August 2017 2

The energy challenge

There is more demand for energy globally as the world's population and living standards increase



Growing population

Global population is expected to increase from around 7 billion today to nearly 10 billion by 2050, with 67% living in cities.

Rising demand

Global energy demand will likely be almost 60% higher in 2060 than today, with 2 billion vehicles on the road (800 million today).

Ongoing supply

Renewable energy could triple by 2050, but we will still need large amounts of oil and gas to provide the full range of energy products that the world needs.

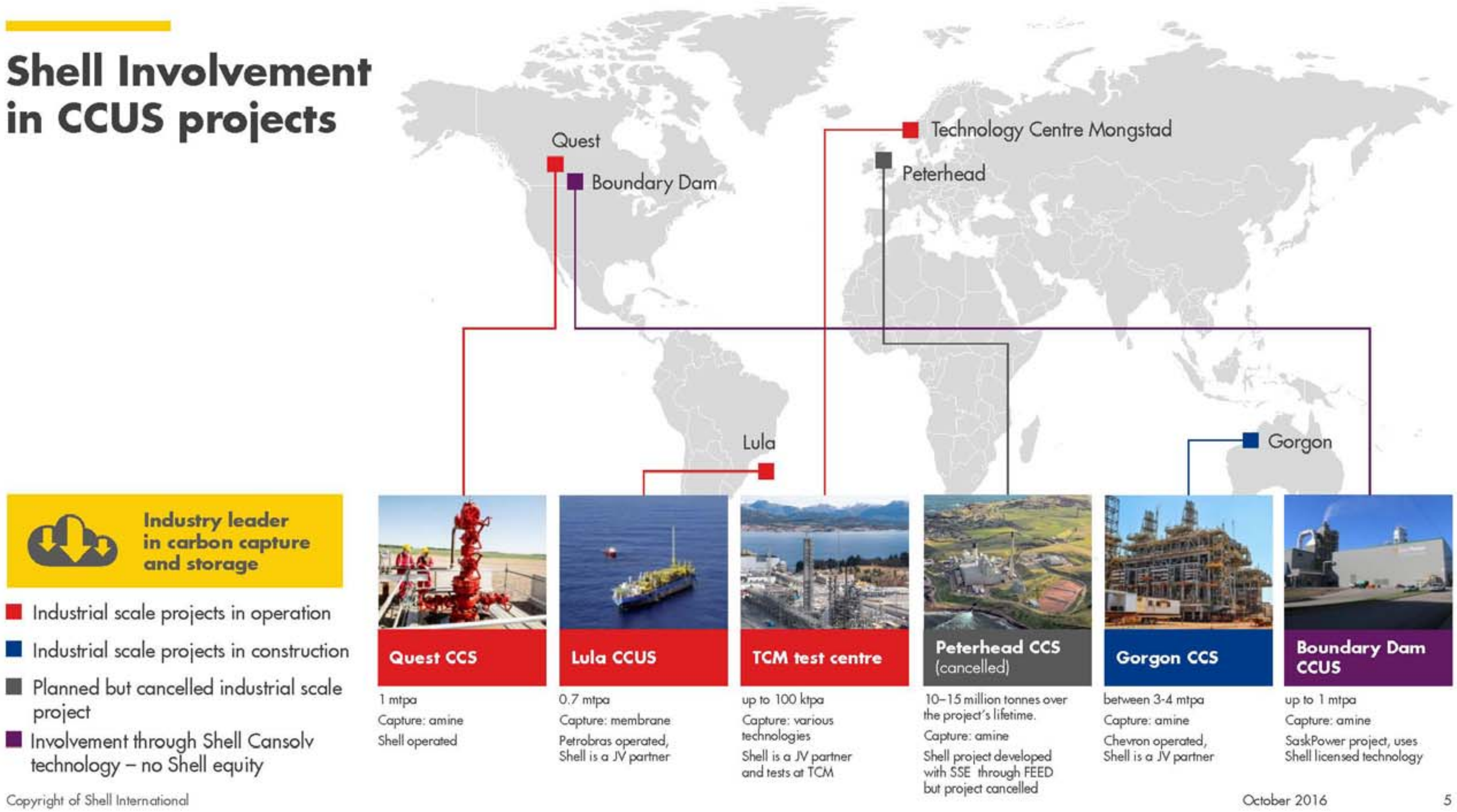
Mitigating climate change

Net-zero emissions is a potentially achievable societal ambition.

Towards a lower-carbon future

Shell is working to meet the energy challenge in many different ways.

- Bringing lower-carbon natural gas to a wider market
- Industry leader in carbon capture and storage
- A biofuels business
- Investment in lower-carbon technologies, such as hydrogen and wind power
- Continued investment in oil and gas to meet growing demand
- Advocating government-led carbon-pricing mechanisms


Shell Involvement in CCUS projects
Quest
Boundary Dam
Technology Centre Mongstad
Peterhead
Lula
Gorgon
Industry leader in carbon capture and storage
Industrial scale projects in operation
Industrial scale projects in construction
Planned but cancelled industrial scale project
Involvement through Shell Cansolv technology – no Shell equity
Quest CCS
1 mtpa
Capture: amine
Shell operated
Lula CCUS
0.7 mtpa
Capture: membrane
Petrobras operated, Shell is a JV partner
TCM test centre
up to 100 ktpa
Capture: various technologies
Shell is a JV partner and tests at TCM
Peterhead CCS (cancelled)
10–15 million tonnes over the project's lifetime.
Capture: amine
Shell project developed with SSE through FEED but project cancelled
Gorgon CCS
between 3-4 mtpa
Capture: amine
Chevron operated, Shell is a JV partner
Boundary Dam CCUS
up to 1 mtpa
Capture: amine
SaskPower project, uses Shell licensed technology
Copyright of Shell International
October 2016
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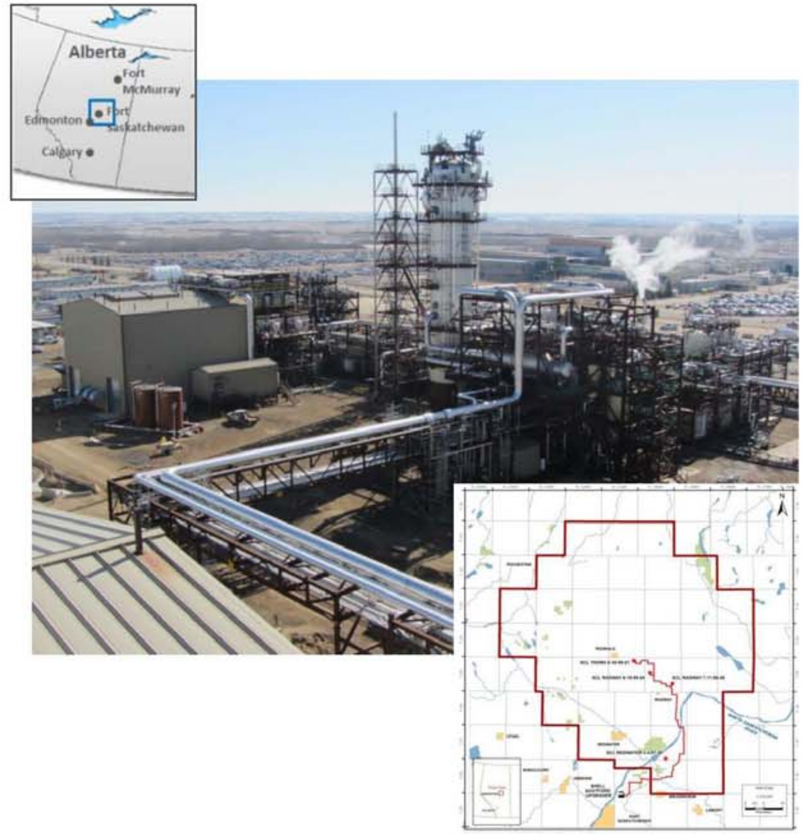
Quest Project at a Glance

- **What** – fully integrated, commercial scale CCS project at an industrial facility
- **Where** – capture at Scotford Upgrader; storage in a deep saline aquifer: the Basal Cambrian Sands (at a depth of 2000m)
- **Who** – joint venture between Shell, Chevron and Marathon
- **Impact** – potentially 25 million tonnes of CO_2 captured over a 25 year period (1/3 of CO_2 from the Upgrader) – equivalent to the emissions of about 250,000 cars each year
- **Technology** – syngas capture using amines



August 2017 6

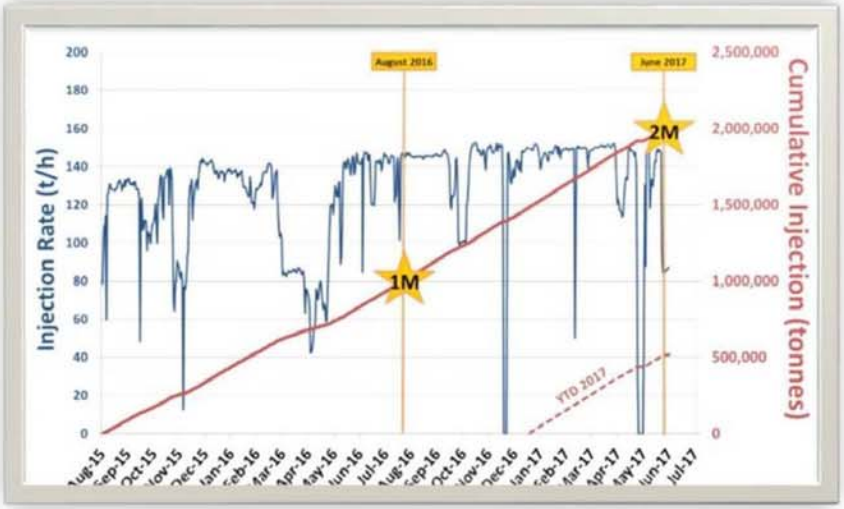
Performance up to now

Capture:

- As of June 2017, Quest has captured, transported, and safely stored **2 million tonnes of CO_2**.
- Quest has the global CCS record for total injection volumes in a one-year period – **1.2 Mtpa CO_2**.
- Operating costs lower than expected due to operating efficiencies

MMV:

- MMV systems working well – no triggers
- Multiple technologies indicate that the CO_2 is where it is expected to be



Wells:

- Only 2 wells active – contributing to significant wells and MMV savings

Reservoir:

- Excellent injectivity – comparable to high case scenarios
- After 25 years, we only expect to use 5-7% of the available pore space

Knowledge Sharing

http://www.energy.alberta.ca/CCS/3848.asp

- Carbon Capture and Storage
  - About CCS
  - CCS Projects in Alberta
  - Alberta's CCS Knowledge Sharing Program
  - Legislation and Policy
  - CCS Contacts
- Coal
- Electricity
- Minerals
- Natural Gas
- Oil
- Oil Sands
- Renewable and Alternative Energy
- Tenure
- Unconventional Resources

Knowledge Sharing Reports

These reports require agreement of the Terms and Conditions prior to access.

The following reports are being saved in web versions and posted on this website, some of the documents are large and may require a little extra time to load. All documents are posted as they have been provided by the companies. Contact us if you have any questions about these documents.

2015

Alberta Carbon Trunk Line Project

Enhance Energy Inc. and North West Redwater Partnership

Summary Report - 2015 Detailed Reports

Quest Project

Shell Canada Energy, Chevron Canada Limited, Marathon Oil Canada Corporation

Summary Report - 2015 Detailed Reports

Project Costs (Mln CAD)

	Mln CAD	Mln USD, Assuming rate of ~0.8
FEED	139.4	~112
CAPEX		
Labor and commissioning	147.9	~118
Tie-ins	37.1	~30
Capture	437.5	~350
Transport	127.4	~102
Storage	40.4	~32
Total CAPEX	790.3	~632
Total for CAPEX + FEED	929.7	~744
Annual OPEX		
2016 Actual	30.2	~24.2
2017 Estimate	35	~28

Sources: 2015 report for CAPEX (available at http://www.energy.alberta.ca/CCS/CCSQuestReport2015.pdf), 2016 report for OPEX (to be published online soon).

Project revenues (in Mln CAD)

- Funding and Grant

	2009 - 2014	2015	2016+ Estimate
Alberta Innovates Grant	6.6		
NRCan Funding	108	12	
GoA Funding	298	149	298
Total funding	412.6	161	298
Cumulative on Total Project Spend (%)	30.2%	42.0%	63.9%

- CO_2 Reduction Credits
  - 2016 – 3.3 MCAD

Sources: 2015 report (available at http://www.energy.alberta.ca/CCS/CCSQuestReport2015.pdf).

Cost per Tonne CO_2

Estimate of the Cost per Tonne of CO_2 for the Alberta's CCS Funding Program

			2015 **	2016
Capture	Annualized CAPEX	$ million	41.20	41.20
	Annual OPEX	$ million	8.12	26.22
	Total	$ million	49.32	67.42
Transport	Annualized CAPEX	$ million	8.97	8.97
	Annual OPEX	$ million	0.01	0.35
	Total	$ million	8.98	9.32
Storage	Annualized CAPEX	$ million	7.42	7.42
	Annual OPEX	$ million	1.78	3.62
	Total	$ million	9.21	11.04
	Total CAPEX + OPEX	$ million	67.51	87.79
	Annual CO_2 Captured	million tonnes	1.03	1.11
	Annual CO_2 Avoided	million tonnes	0.87	0.95
	Reported Cost/Tonne Captured	$/tonne	**65.31**	**79.24**
	Reported Cost/Tonne Avoided	$/tonne	**77.35**	**92.70**

Note: The costs in this table are in Canadian currency.

- Here: Annuity CAPEX / Non-discounted tonnes CO_2

74 USD/t CO_2 avoided
(at 0.8 USD/CAD)

- Reported $/t cost is lower than forecasted $/t cost due to lower actual OPEX.
- The calculation is performed using methodology specific for the projects under the Funding Agreement (funding by Canadian government).
- The discount rate is weighted 75% towards the Alberta's 10 year term bond rate and 25% towards the industry standard discount rate.
- Use of a different methodology including discounting of CO_2 (PV/RT, PV/PV, ...) and value of discount rate may result in a different $/t outcome.

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Metrics count

- Calculation is performed using methodology specific for the projects under the Funding Agreement (funding by Canadian government).

Reported Cost per Tonne - Formulas

$$(Cost\ per\ tonne\ Capture)_t = \frac{CAPEX \times FCF + (OPEX)_t}{(m_{CO_2\_Captured})_t}$$

$$(Cost\ per\ tonne\ Avoided)_t = \frac{CAPEX \times FCF + (OPEX)_t}{(m_{CO_2\_Avoided})_t}$$

$(Cost\ per\ tonne)_t$	\$/tonne	Cost per tonne reported and calculated for year t
$Annualized\ CAPEX$	\$	Uses the value calculated from worksheet Forecast. Based on actual numbers, the ***Annualized CAPEX*** can be slightly different than the Calculated Annualized Capex
$(OPEX)_t$	\$	Reported ***OPEX*** in year t
$(m_{CO2\_Captured})_t$	tonnes	Mass of CO_2 Captured reported in year t
$(m_{CO2\_Avoided})_t$	tonnes	Mass of CO_2 Avoided reported in year t

$$FCF = \frac{r\,(1+r)^T}{(1+r)^T - 1}$$

r	fraction	The nominal annual rate used to discount values, usually taken to be a pre-defined rate of return required to cover equity and debt costs
T	year	Economic life of the plant relative to the base year of the analysis (star of injection)

Acknowledgements

- Government of Alberta, Department of Energy (DOE)
- Government of Canada, Natural Resources Canada (NRCan)
- Shell staff (Calgary, Scotford , Houston, EU and in the field)
- 3rd Party Contractors: Fluor, Golder Assoc., ESG, Boreal, Air Liquide, U. of C., U.B.C., U. Vic., et al.
- Partners: Chevron Canada Ltd & Marathon Oil Canada


Q&A
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Session 3: Cost of Emerging Processes

3a. Update on NET Power: Demonstration and Commercial Activities,

Mike McGroddy, 8 Rivers Capital

NET Power

Truly Clean, Cheaper Energy

5th CCS Cost Network Workshop
Imperial College, London

September 2017


"NET Power does not make natural gas a bridge—or a pier.
It makes it a destination."
-Senior DOE official

NETPOWER

World Class Partners

CBI

Exelon

8 RIVERS

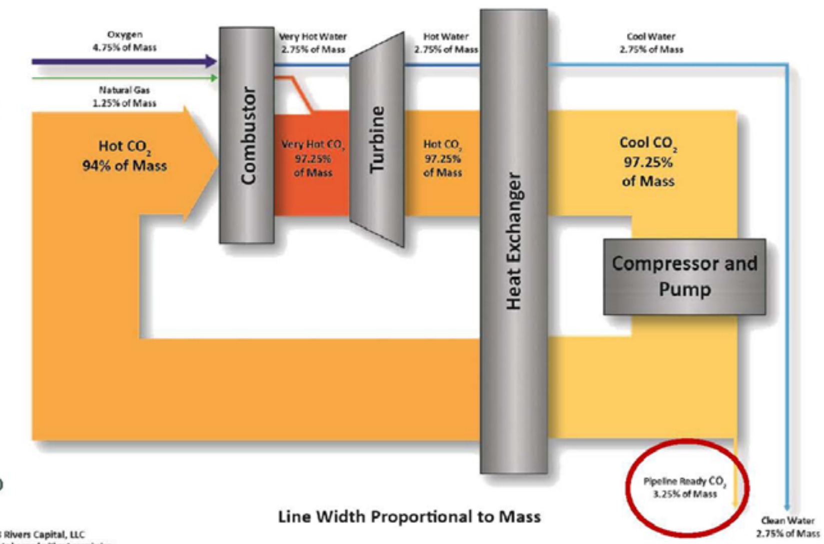
In the press

Gas Turbine World · Forbes · Science AAAS · Bloomberg Business · The New York Times · Vox · Energy Procedia ELSEVIER

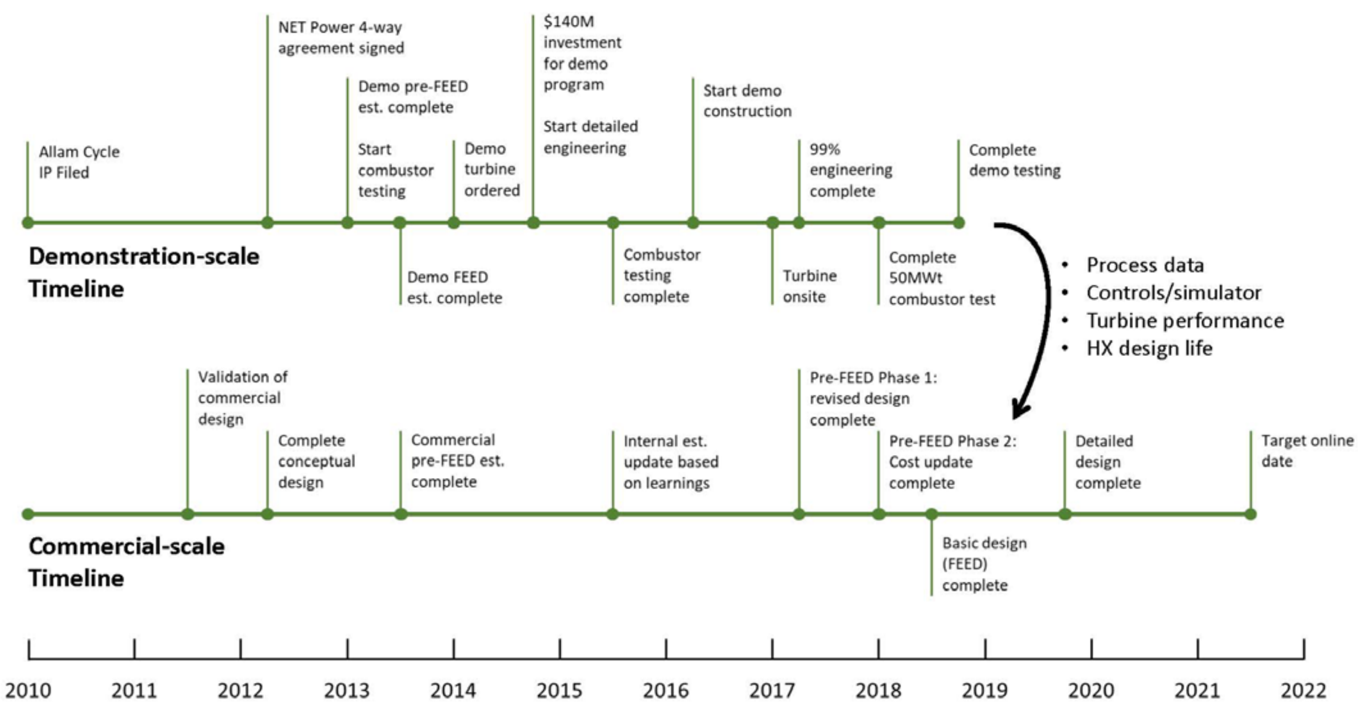
NETPOWER

The supercritical CO_2 Allam Cycle is simple

- **Historically, CO_2 capture has been expensive, whether using air to combust or oxy-combustion**
  - Air combustion
    - $\underbrace{8N_2 + 2O_2}_{air} + CH_4 \rightarrow \underbrace{8N_2 + CO_2}_{\substack{expensive\ to \\ separate}} + 2H_2O$
  - Oxy-combustion
    - $\underbrace{2O_2}_{\substack{expensive \\ to\ produce}} + CH_4 \rightarrow CO_2 + 2H_2O$
- **The Allam Cycle makes oxy-combustion economic by:**
  - Relying on a more efficient core power cycle
  - Recycling heat within the system to reduce O_2 and CH_4 consumption, and associated costs of the ASU



Overview of NET Power Commercialization Schedule



September 2017

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NETPOWER

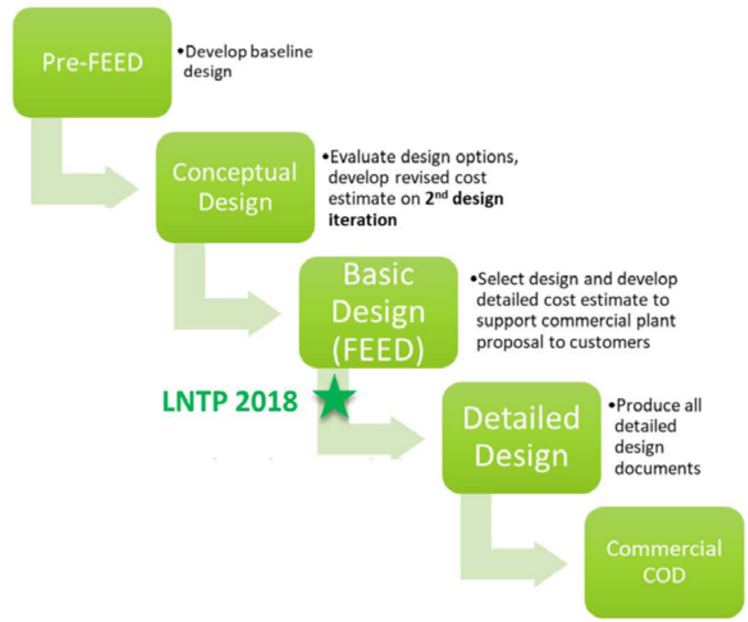
Status Update on Demonstration

La Porte Demonstration Facility – April 2017

NETPOWER

Status Update on Commercial

- Engaging several first potential customers
- Site down-selection for first project underway
- Revised costing effort underway to support first commercial online by 2021



NETPOWER

NET Power Estimating History

FOAK Estimate History

2013 Pre-FEED → Interim Updates → 2017 Pre-FEED

2013 Pre-FEED

- Class 4 estimate
- Gulf Coast basis
- HX/turbine estimate scaled from demo
- ROM bids from single suppliers for primary equip
- No design optimization
- Use of internal scaling factors

Interim Updates

- Updated process design, efficiency improvement
- Updated equipment specs
- Updated layout for reduced piping/labor
- Revised cooler designs

2017 Pre-FEED

- Class 3/4* estimate
- Updated process design
- Revised, modularized layout
- Competitive bidding for equip
- MTOs for bulk quantities
- Initial ISOs for HE pipe
- Detailed review of EPC rates
- Minimized use of parameterized estimating

In Progress…

September 2017

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NETPOWER

Overview of Revised Design Effort

- **Design philosophy**
  - Minimize pipe runs and maximize spool lengths
  - Optimize use of upgraded alloys (HE or corrosion-resistant piping)
  - Consolidate heat exchanger arrays into common header solutions
  - Adopt O&M equipment access favoring “petro-chem” facility layout
  - Embrace modularization in order to minimize field labor
  - Minimize non-critical redundancy for target availability
- **Updates from small-scale demonstration design**
  - Employ proven refractory lined pipe solutions in place of large-diameter 740H for plant #1
  - Evaluate high temperature S&T HX technology for temperatures above 550 C
  - Simplify low-grade heat integration by performing preheating outside the main recuperative heat exchanger train
- **Biggest cost drivers in current design**
  - Contingency and first of a kind home office engineering
  - Bulk quantities
  - Turnkey ASU pricing

NETPOWER

Cost Optimization on FOAK Design

- At the limit, small changes in efficiency have large impact on plant CAPEX.
- Previous designs were on the wrong side of a "cost asymptote" regarding main recuperator design.
- Current design efforts will optimize for cost/efficiency trade-offs.

NETPOWER

Cost Reductions to Nth

- Significant reduction in EPC, contingency and labor hours expected with experience from FOAK to NOAK
- Preferred vendor pricing expected with near-term contractual commitments and multiple orders (estimated 10% reduction in equipment bids)
- HX/Turbine package maturation
  - All HX technology alternatives being evaluated. S&T design presents CAPEX savings due to available size.
  - Working with vendors to optimize block size and modularization of headers.
  - Future HX cost reductions could mirror that of HRSG designs with optimized factory production.
  - Turbine cost reductions vs. one-off FOAK turbine supply.
- Work with vendors on modularized ASU design
  - Significantly drops costs vs. "stick build"
  - Foreign equipment suppliers and in-house construction will also be explored
  - ITM a possible future development, pending successful R&D efforts
- "Next-gen" to compete directly with advanced class GTs
  - NET Power is more akin to "simple cycle" design. Adding a second expansion turbine achieves additional ~30% reduction in $/kW.

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NETPOWER

Q&A

August 2017

3b. Demonstrating CO_2 capture <$40/ton: Experience from Industrial Projects

Prateek Bumb, Carbon Clean Solution

Carbon Clean Solutions

Demonstrating CO_2 capture <$40/ton: Experience from Industrial Project

Presentation at IEAGHG 5th CCS Cost Network Workshop | London | 13/09/17

Aniruddha Sharma
CEO
Carbon Clean Solutions Limited

Agenda

CCSL Company

- Carbon Clean Solutions
- Industrial CO_2 capture
- Cost Reduction Potential
- Next Steps

Company

CCSL Company

- Global leader in CO_2 capture from flue gas & natural gas
- CO_2 capture at <$40/ton (capex & opex included)
- Headquartered in the UK, with offices in USA, Germany and India
- Offer: design license, patented solvent & services
- Delivering 3+ industrial CO_2 capture projects in 2017
- 2 concept studies in Norway for 1500 tons/day (75MW) CO_2 capture plant: KEA & Yara

VEOLIA APPLY SØRCO ThyssenKrupp Industrial Solutions Mabel WORLD ECONOMIC FORUM Technology Pioneer

CO_2 Capture for Industrial Sites

CCSL Company

- Price is defined by customer's alternative i.e. commodity
- $$ savings the only incentive to switch (there are no grants!)
- Space is a big constraint …. and so is water!
- Understanding steam cycle / integration is a challenge!
- Utilities are expensive
- However, process engineers and HSE are well trained on issues like COMAH / chemical waste

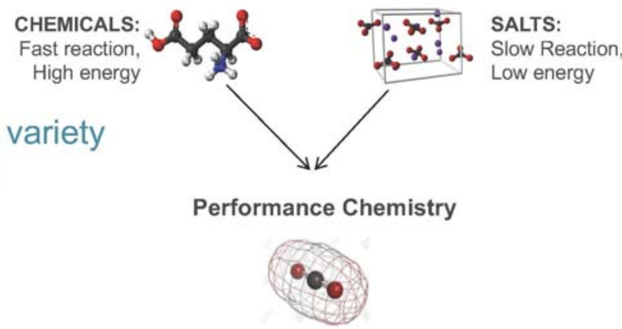
Factors Driving Cost

CCSL Company

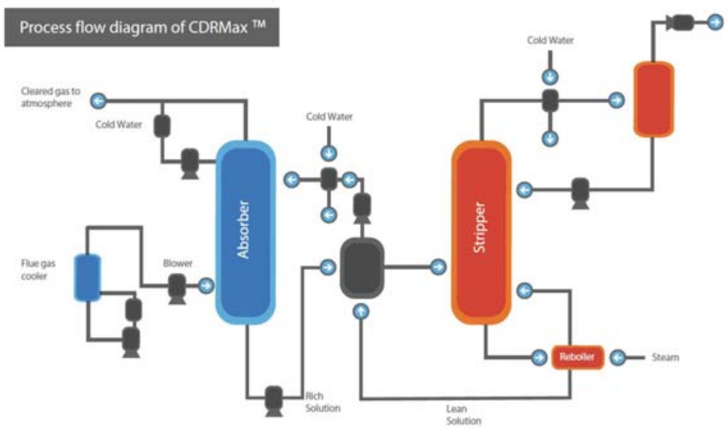
- Environmental permits / emissions norms
  - Solvent / Aerosols emissions
- Capital Costs
  - Type of steel used
- Operating Costs
  - Utilities
- Solvent Make-up / Disposal
  - No special disposal procedures

CDRMax Technology

CCSL Company



Our advanced chemistry remove CO_2 from a variety of gas streams – for use in new and existing industrial facilities.

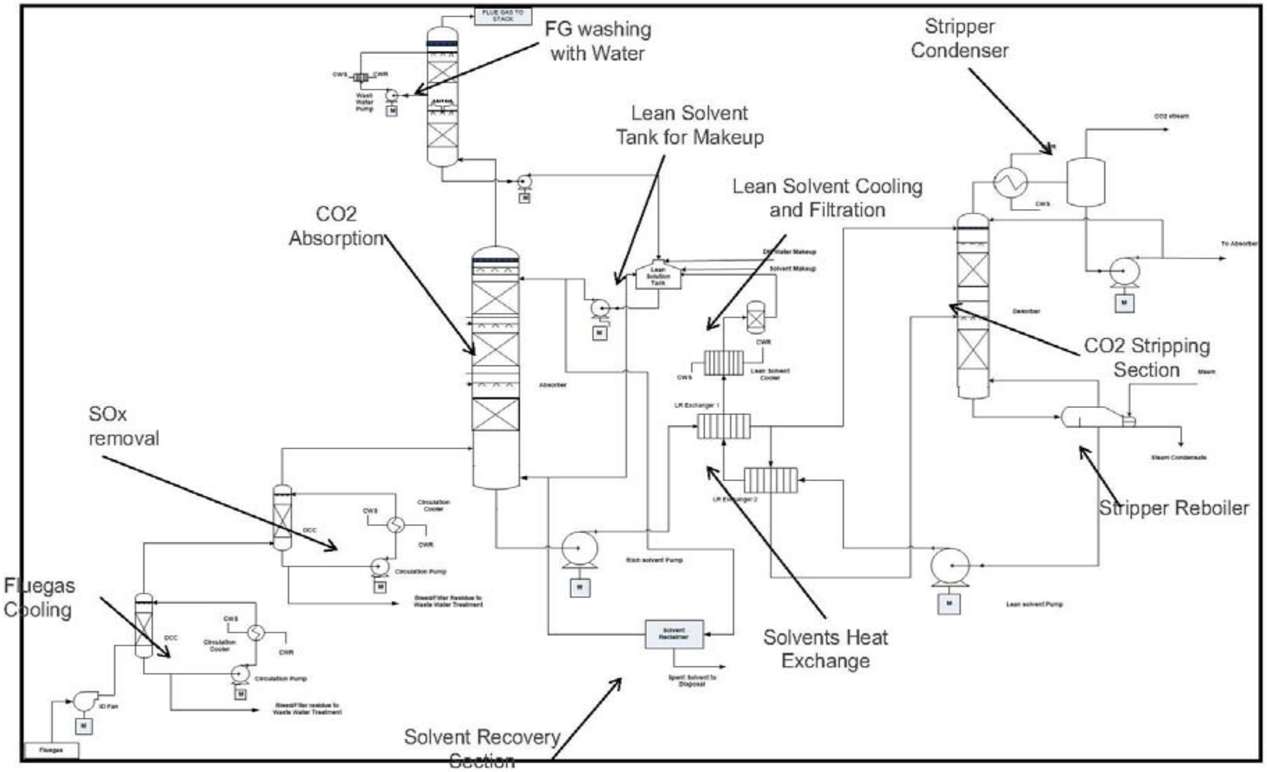


Our CDRMax® process technology generates transformational results for the capture and recovery of CO_2.

Presentation at IEAGHG CCS Cost Network Workshop | 13/09/17

Plant PFD

CCSL Company



Presentation at IEAGHG CCS Cost Network Workshop | 13/09/17

Our Industrial Experience

CCSL Company

Greenfield 174 TPD CO_2 Use Facility	Brownfield: TCM Demonstration, 240TPD

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Commercial CO_2 Capture to Chemicals Project

CCSL Company

- 174TPD CO_2 capture from 10MW coal boiler flue gas
- Commissioning October, 2016
- FEED completed 2015
- Absorber: H= 27m , D= 3.8m (carbon steel)

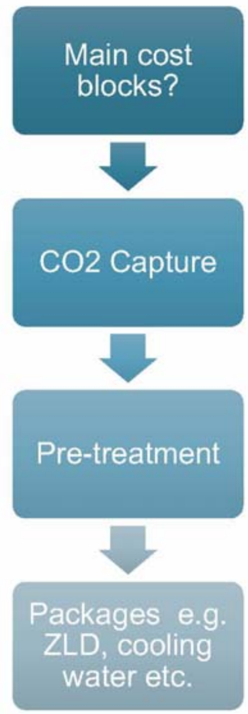
Outcome:

- <$40/metric tonne CO2 capture cost
- "PPB" solvent emissions; Ion exchange re-claimer

Flue Gas Composition & Major Costs for FOAK

CCSL Company

Composition (Wet Basis, mole%)	At blower inlet
CO_2	8
N_2	76.6
O_2	12.4
SO_X	350 (mg/Nm^3)
NOx (Nitrogen Oxides)	>100 (mg/Nm^3)
Water	3.4
Particulate matter (mg/Nm^3)	<10 (mg/Nm^3)
Quantity taken (Nm^3/hr)	60000
Temperature, Deg C	190
Pressure, bar(g)	0



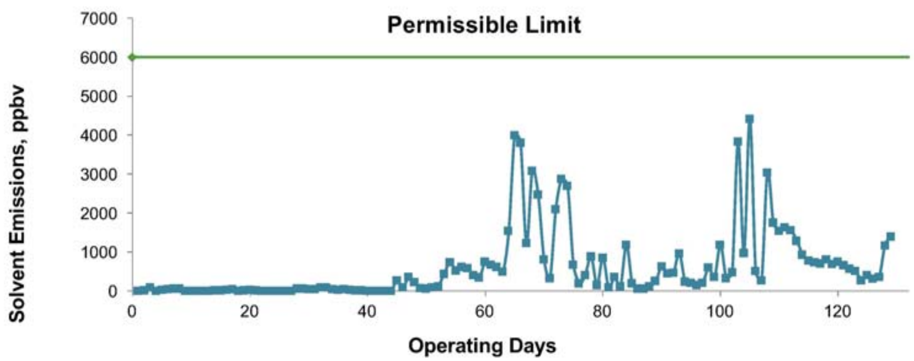
Cost Reduction due to MoC change

CSL Company

Conclusion from demo:

1. Absorber on Carbon Steel
2. Desorber on 304L
3. Piping?
4. Packages?

Cost Reduction due to Negligible Emissions



MEA aerosols emissions
1587 mg/Nm^3

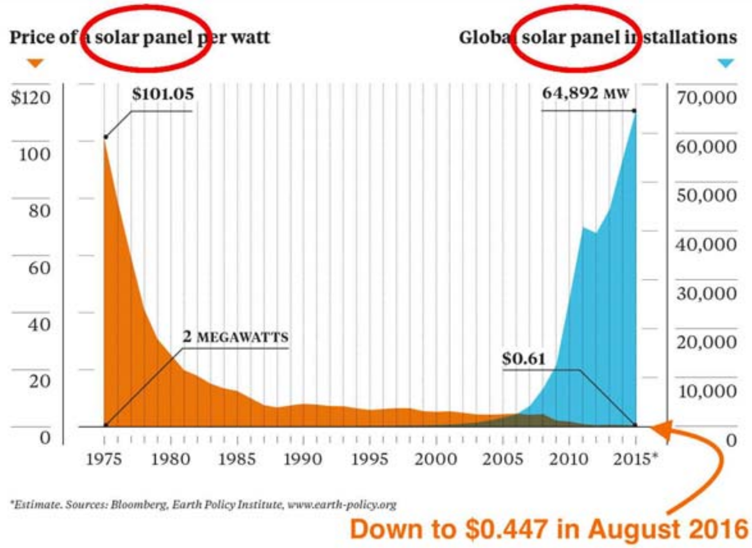
Conclusion from demo:

1. Feedstock change will impact emission
2. No acid wash or multiple stage wash will dramatically reduce costs
3. Water is expensive on industrial sites…use as little as possible!

CDRMax aerosols emissions
28 mg/Nm^3

Where do we go next?

CCSL Company



1. **Standardise & replicate**
2. **Standardise & replicate**
3. **Standardise & replicate**

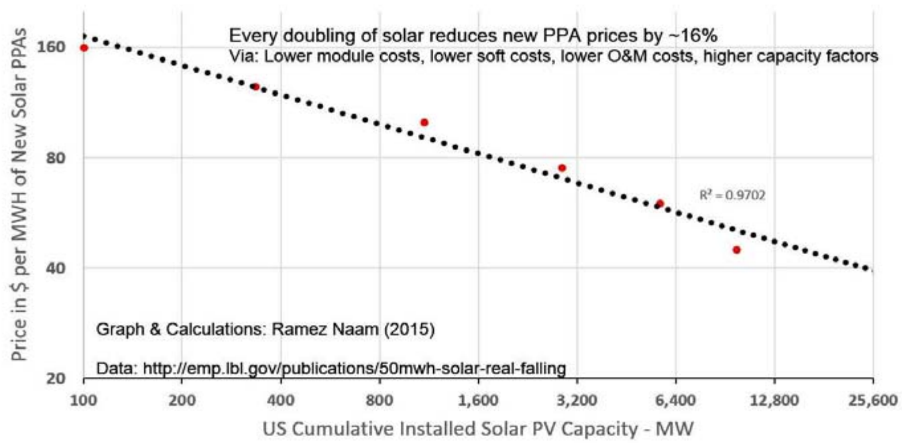
Can we replicate same for iCCUS?

CCSL Company

Carbon Clean's SOAK (2nd Of A Kind):

1. 40% area reduction due to equipment stacking / better design
2. 15% cost reduction due to equipment standardisation
3. 5% - 10% reduction in water footprint
4. More MoC change? Choose a geography with govt. grants?

But is there an evidence of cost reduction from other industry?



iCCUS : Costs are coming down but policy support is required

CCSL Company

- Industrial CCUS is very new but fast developing space, support in the form of match funding /others desired to move first projects
- Policy support via appropriate mechanisms required to develop the FOAK / SOAK
- “Standardize & Replicate” probably better way to approach industrial decarbonisation approach rather than $1bn project
- iCCUS could also be supported by policy incentives for CarbonClean industrial production

Presentation at IEAGHG CCS Cost Network Workshop | 13/09/17

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Questions?

CCSL Company

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Tel: +44 20 3865 0639

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Berkshire, United Kingdom

Session 4: CCS in Energy-Economic Models

4a. CCS techno-economic representation in Integrated Assessment Models

James Glynn University College Cork


MaREI
Centre for Marine and
Renewable Energy
A World Leading SFI Research Centre
Science
Foundation
Ireland
sfi
For what's next

A review of CCS techno-economic representation in Integrated Assessment Models

James Glynn,
Richard Millar, Paul Deane, Niall MacDowell, Myles Allen, Brian Ó Gallachóir

5th CCS in Costs Network Workshop
Roderic Hill Building, Imperial College London

Session 4 – CCS in Energy-Economic Models

EPMG
ENERGY POLICY & MODELLING GROUP

MaREI
Centre for Marine and Renewable Energy

ERI
Environmental Research Institute
University College Cork

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

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EPMG

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Dr James Glynn
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Project contact point

Dr Paul Deane

Prof Brian Ó Gallachóir
(Apologies, cannot attend)

Environmental Change Institute,
University of Oxford, UK

Prof Myles Allen

Dr Richard Millar

Imperial College London, UK

Dr Niall Mac Dowell

Outline

- IEAGHG CCS in IAMs project introduction
- A review of the US DoE workshop, Washington DC, April 2017.
    - Workshop outcomes and lessons
- A review of the techno-economic input into influential Integrated Assessment Models (IAMs)
    - Metrics to decide which IAMS are the most influential.
    - Data gathering on CCS parameterisation in IAMs.
- CCS techno-economic representation in influential Integrated Assessment Models (IAMs)
    - Overview of the IPCC AR5 scenario results and emissions trajectories
    - Focus on 27th Energy Modelling Forum (EMF27) sensitivity analysis to CCS
    - Update on more recent CCS in IAMs Literature

High level aims of the study

- Provide transparency on the data inputs and calibration of CCS in IAMS
- Document the range of outcomes for CCS in the most influential IAMS
- Provide insights into the important drivers of the range of outcomes in these IAMs
- Provide an assessment of best practice and review up-to-date data for configuring CCS by technology type and region in IAMs.

US DoE Workshop on CCS in techno-economic models

EPMG

- The US Department of Energy's Office of Fossil Energy hosted an energy-economy modelling review workshop on 3-4 April, in Washington DC. The aim of the workshop was to review the representation of carbon capture and storage (CCS) and advanced fossil technologies in integrated assessment models (IAMs).
- IAMs are computer models and can range in the mathematical methods that underpin them, but largely they incorporate representations of the energy system, the economy and earth systems into one integrated assessment model.
- These computational models are then used at global, national and city scales to gain insights into energy and economic system dynamics under various constraints, e.g. from government policy, from socio-economics and from the environment. IAMs are widely used in climate change mitigation scenario analysis to develop technology roadmaps and inform policy pathways.
- The workshop brought CCS technology experts, CCS data providers, CCS process engineers and relevant stakeholders, together with IAM modellers from policy, industry and academia

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Coláiste na hOllscoile Corcaigh

IAM modelling Teams Present at Workshop

Model	Institution	Speaker
GCAM	PNNL	Leon Clarke
IPM	EPA	Misha Adamantiades
CTUS-NEMS	NETL	Chuck Zelek
NEMS	EIA	David Daniels
EPPA	MIT	Sergey Paltsev
ESIM	ANL	Don Hanson
Phoenix/ADAGE	EPA	Jim McFarland
ReEDS	NREL	Stuart Cohen
MARKAL/EPAUS9r	EPA	Dan Loughlin
MARKAL	NETL	Chris Nichols
REGEN	EPRI	John Bistline
MERGE	EPRI	Steven Rose
IEA-TIMES	IEA-ETP	Uwe Remme
ESO	ICL	Clara Heuberger
Irish-TIMES/ETSAP	UCC/IEA-ETSAP	Brian Ó Gallachóir

- Note the US focus – from Global IAMs to National Power system models

EPMG

Science Foundation Ireland sfi For what's next

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Break out discussion session conclusions

- Regional differences are important at local and national level models, but at the global level CCS cost modelling becomes represented by an aggregated portfolio of CCS options across a region with a distribution of costs. The range of uncertainty within this distribution of costs should be explored and understood to reduce any biases.
- IAMs should have at least 3 factor CCS cost curves including 1)capture, 2)transport, 3)storage & 4)learning.
  - Transportation costs vary significantly by region/country
- There is insufficient good quality data on geological storage sites, their injection rates and dynamics over time.
- Modellers need a cost curve on how capture rates (30%-90%+) impact on capture investment costs.
- IAMs need to ensure consistent/smart CO_2 market representation and not simply link CO_2 sources directly to sinks.
- IAMs focus on broad systemic interactions, and as such CCS has not historically been a priority research area in IAMs.
  - More single model sensitivity analyses are required.
  - IAM modellers need more information on first of a kind (FOAK) and N^{th} of a kind (NOAK) cost curves and learning rates from industry and demonstration projections.

Workshop & Report Outcomes

- Many IAMs employed a simplistic representation of CCS transport and storage costs, with a variation in capture costs depending on the CCS technologies represented. Where data is available, IAMs should aim to have cost curves (and, potentially, learning rates) for capture, transport and storage.
- US National Energy Technology Laboratory (NETL) have gathered and estimated baseline CCS datasets critical to developing detailed state-of-the-art cost curves for capture, storage and transport that could be used for CCS calibration in IAMs. The data has not yet been widely distributed among IAM teams.
- Communication between CCS technology experts and IAM modellers needs to be enhanced. Such communication should include a regular meeting, with accessible, open and transparent data-sharing essential.

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Science Foundation Ireland For what's next

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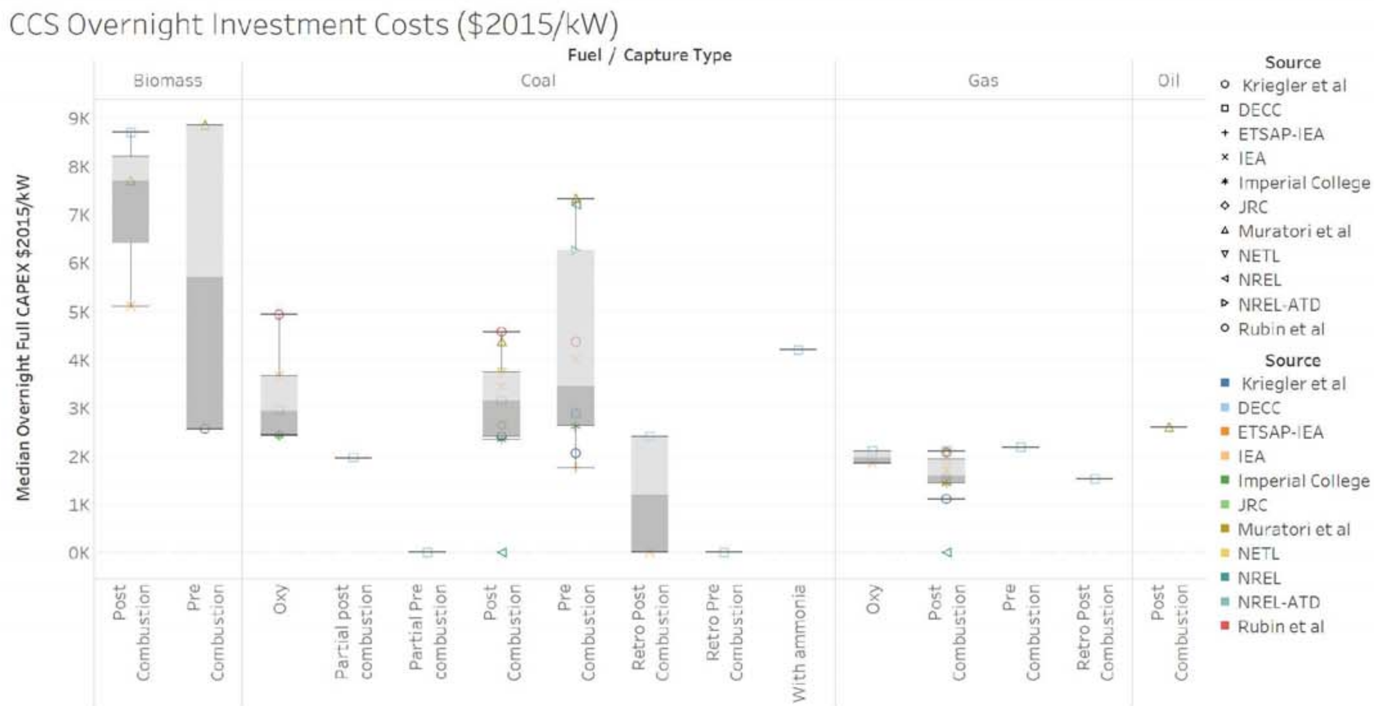
Review CCS data input and assumptions

EPMG

Source	Fuel	Capture Type	Plant type	HHV Efficiency (%)	Overnight Full CAPEX \$2015/kW	Range Min	Range Max	FOM (\$/kW/year)	Range FOM MAX (\$/kW/year)	Range FOM MIN (\$/kW/year)	VOM \$/MWh	Range MIN VOM \$/MWh	Range MAX VOM \$/MWh	Build date of Plant	Capture rate	CO2 Transport Cost (\$/Tonne CO2)	Range CO2 Transport Cost (\$/Tonne CO2)	CO2 Storage Costs (\$/Tonne CO2)	Range MIN CO2 Storage Costs (\$/Tonne CO2)
NETL	Coal	Post Combustion	Subcritical	31.2	4,523										90%	2.3744	-	9.2114	9.42
NETL	Coal	Post Combustion	Supercritical	32.5	4,593	1,802	2,862								90%	2.3744	-	9.2114	9.42
NETL	Gas	Post Combustion	Combined Cycle	45.7	1,912	1,166	1,908								90%	2.3744	-	9.2114	9.42
DECC	Gas	Post Combustion	Combined Cycle	44	1,540	1,246	1,980	23	18	26	2.46	2.13	2.93	2025	90%		-		5.89
DECC	Gas	Retro Post Combustion	Combined Cycle	44	1,027	1,246	1,980	23	18	26	2.46	2.13	3.01	2025	90%		-		5.89
DECC	Gas	Pre Combustion	Combined Cycle	38	1,466	2,126	3,153	22	18	26	2.79	2.42	3.30	2025	93%		-		5.89
DECC	Gas	Oxy	Combined Cycle	42	1,540	2,420	3,666	61	52	71	2.65	2.27	3.15	2025	100%		-		5.89
DECC	Coal	Oxy	Supercritical	32	2,493	2,493	4,033	50	43	57	4.18	3.59	4.77	2025	89%		-		5.89
DECC	Coal	Pre Combustion	IGCC	30	2,860	1,540	2,493	48	40	55	0.00	3.67	-	2025	90%		-		5.89
DECC	Coal	Post Combustion	Supercritical	32	3,061	2,493	4,033	58	49	66	2.23	1.91	2.57	2025	89%		-		5.89
DECC	Coal	Partial post combustion	Supercritical	38	1,906	1,393	2,200	41	35	48	2.22	1.91	2.57	2025	33%		-		5.89
DECC	Coal	With ammonia	Supercritical	32	3,080	2,126	3,226	58	50	67	2.23	1.91	2.57	2025	89%		-		5.89
DECC	Coal	Retro Post Combustion	Supercritical	32	1,760	1,833	2,640	59	51	68	2.24	1.91	2.57	2025	89%		-		5.89
DECC	Coal	Oxy	Supercritical	32	2,493	2,640	3,959	50	43	57	4.18	3.59	4.77	2025	91%		-		5.89
DECC	Coal	Partial Pre combustion	IGCC	35	2,053	5,279	8,359	38	32	44	3.67	3.15	4.18	2025	30%		-		5.89
DECC	Coal	Retro Pre Combustion	IGCC	27	3,080	1,540	1,980	60	51	70	4.71	4.03	5.50	2025	89%		-		5.89
DECC	Biomass	Post Combustion	Conventional Boiler	15	6,379	1,246	1,613	102	87	117	5.76	4.91	6.60	2025	89%		-		5.89

Investment Cost input assumptions review



Scenario Data Sources

- IPCC AR5 WG3 Scenario Database
  - Compile database of scenario projected sequestration rates, volumes, by technology, scenario, and IAM type
    - LIMITS
    - AMPERE
    - AR5
    - MILES
  - Enable Identification of key outlier scenarios and models and projections
  - Focus on EMF27 – CCS scenarios to isolate the CCS influence on IAM scenarios
  - Published before 2015
- Add recent SSP Marker Model Scenario Database
  - 5 Shared Socioeconomic Pathways
  - Published Early 2017
- Literature Review of Academic and Industry Sources
  - NETL, IEA, MIPs

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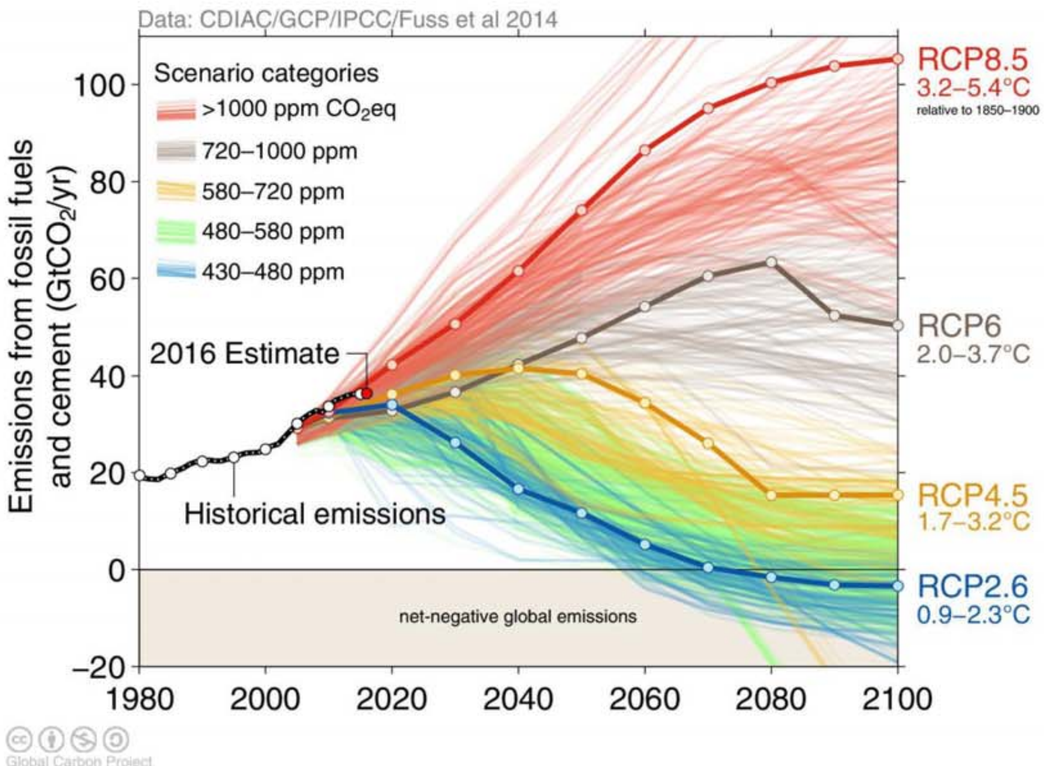
IPCC AR5 WGIII - Energy System Scenarios



Identify Influential IAMS

Model	GCAM	IMAGE	MESSAGE	REMIND	WITCH	AIM
MIPs	9	6	6	6	6	5
AR5 Scenarios	139	79	140	158	132	41

- Most influential models currently and into the future for IPCC 6th Assessment Report (AR6) are likely to be the SSP marker models.
  - SSP1 - Sustainability- **IMAGE (PBL)** – Hybrid systems dynamics and GE
  - SSP2 - Middle of the Road - **MESSAGE-GLOBIOM (IIASA)** – Hybrid
  - SSP3 – Regional Rivalry - **AIM/CGE (NIES)** – General Equilibrium (GE)
  - SSP4 – Inequality - **GCAM4 (PNNL)** – Partial Equilibrium (PE)
  - SSP5 - Fossil fuelled Development - **REMIND-MAGPIE (PIK)** – GE

- Others
  - WITCH-GLOBIOM (FEEM) – General Equilibrium

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EMF 27 – Low Temperature CO2 Pathways

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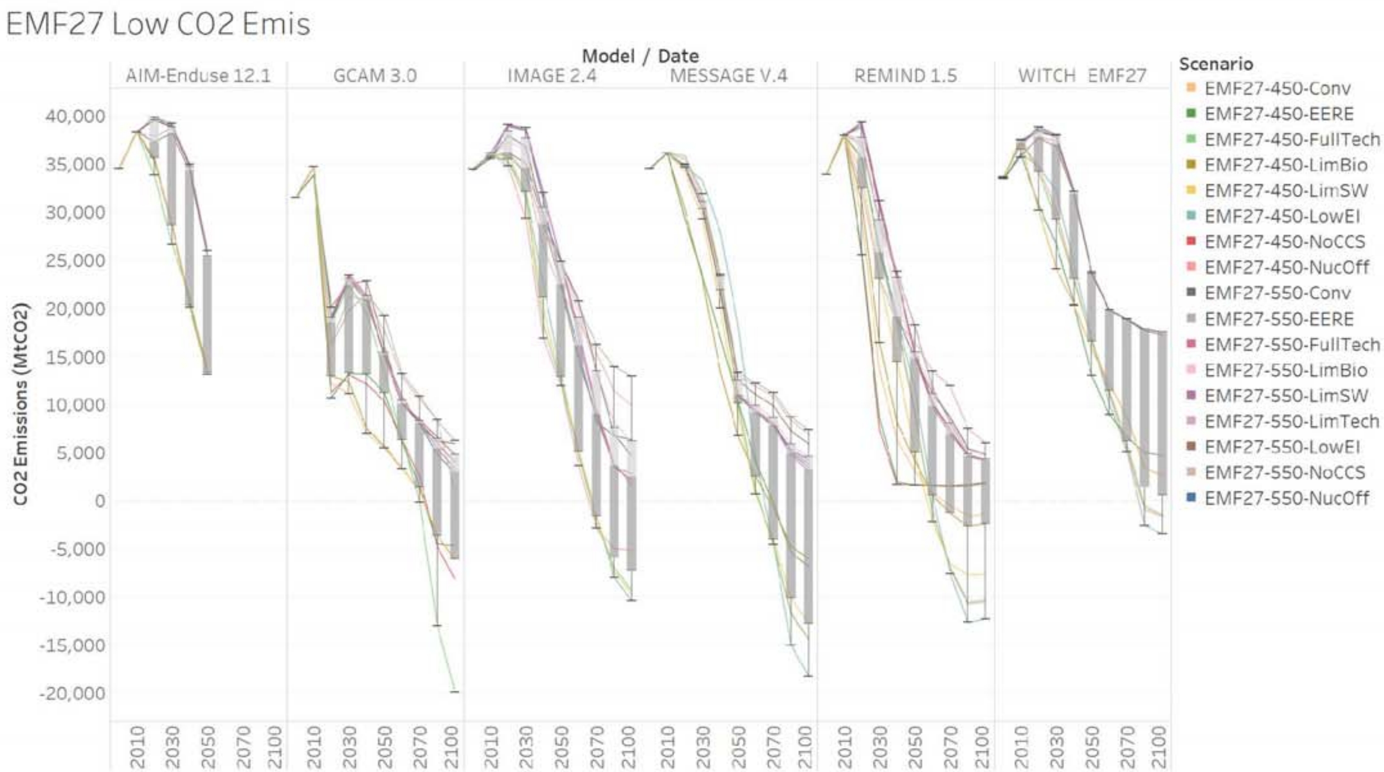

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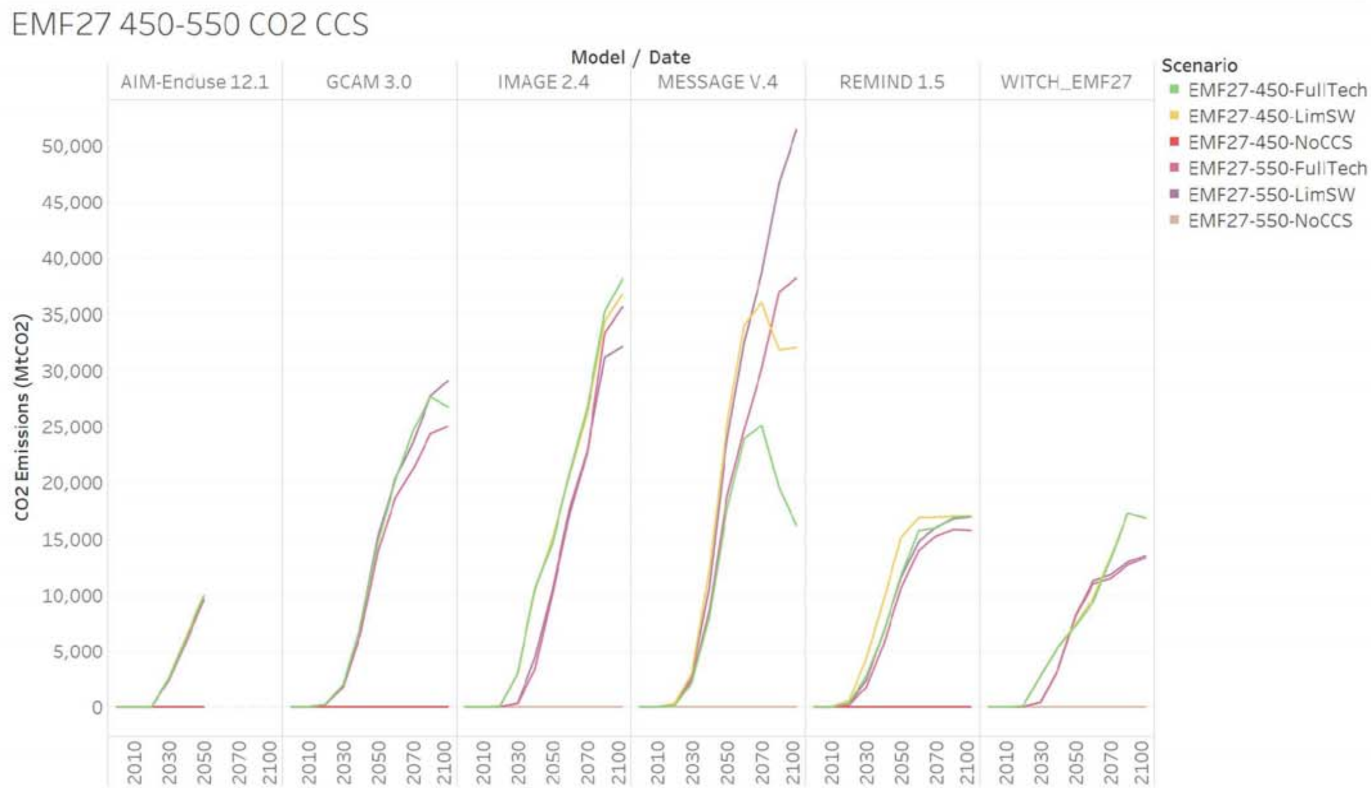
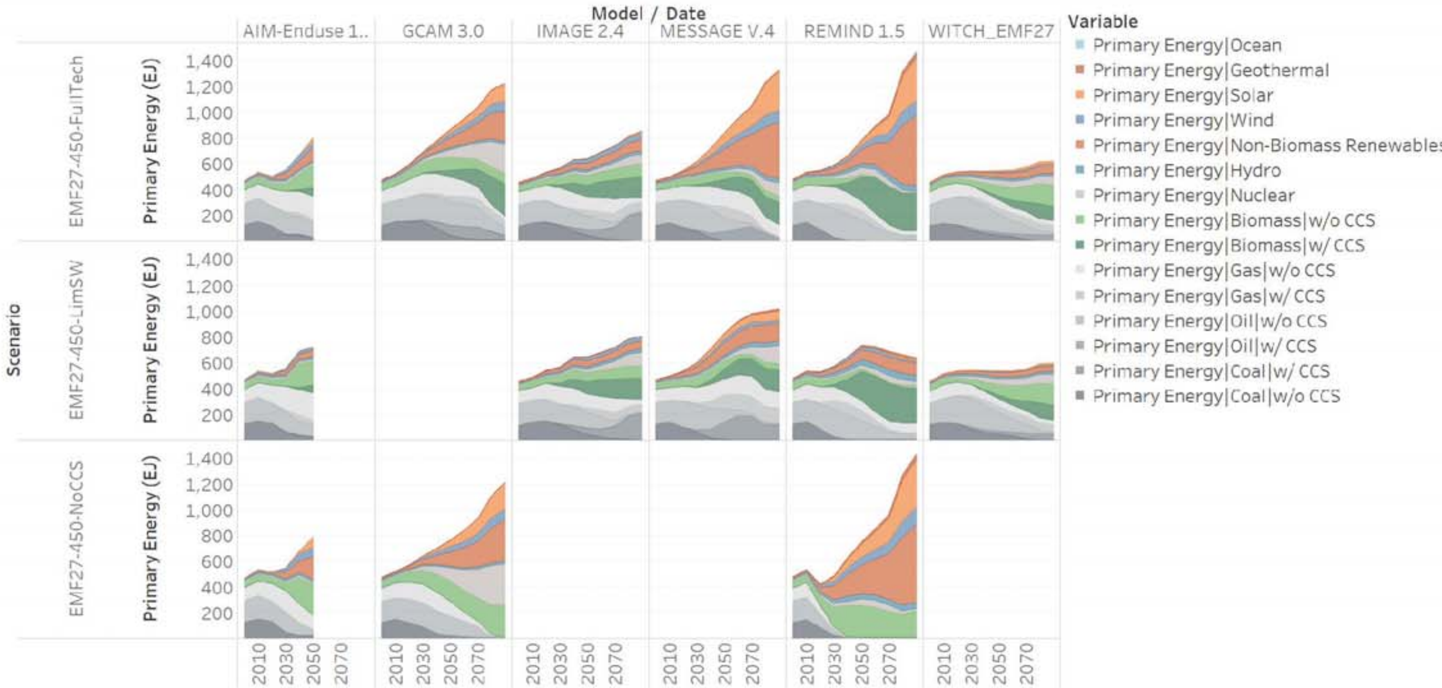
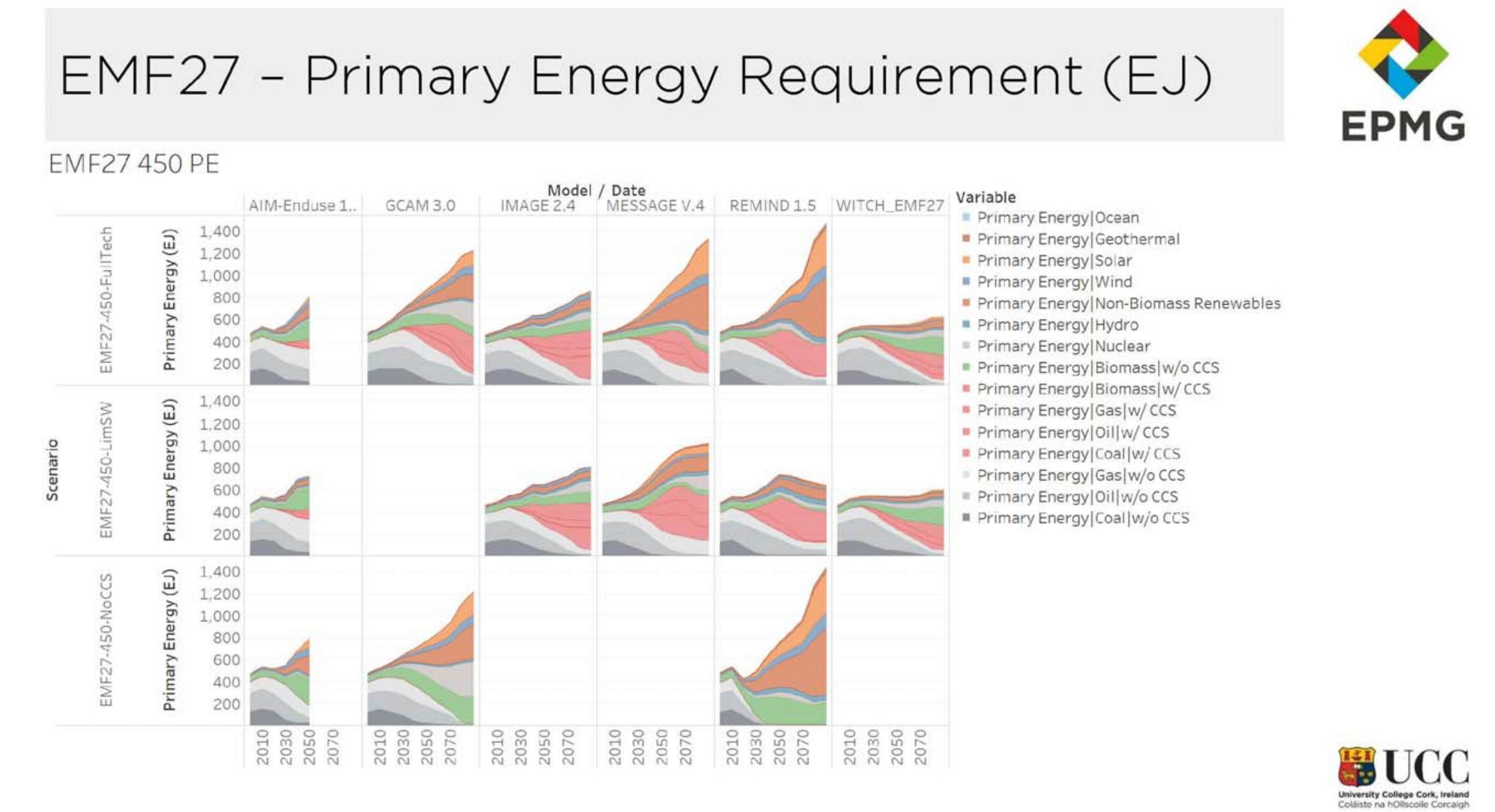
CO2 Capture in EMF27 550-450ppm cases



EMF27 – Primary Energy Requirement (EJ)

EMF27 450 PE




EMF27 – Primary Energy Requirement (EJ)
EPMG
EMF27 450 PE
Model / Date
AIM-Enduse 1..
GCAM 3.0
IMAGE 2.4
MESSAGE V.4
REMIND 1.5
WITCH_EMF27
Scenario
EMF27-450-FullTech
EMF27-450-LimSW
EMF27-450-NoCCS
Primary Energy (EJ)
1,400
1,200
1,000
800
600
400
200
2010
2030
2050
2070
Variable
Primary Energy|Ocean
Primary Energy|Geothermal
Primary Energy|Solar
Primary Energy|Wind
Primary Energy|Non-Biomass Renewables
Primary Energy|Hydro
Primary Energy|Nuclear
Primary Energy|Biomass|w/o CCS
Primary Energy|Biomass|w/ CCS
Primary Energy|Gas|w/ CCS
Primary Energy|Oil|w/ CCS
Primary Energy|Coal|w/ CCS
Primary Energy|Gas|w/o CCS
Primary Energy|Oil|w/o CCS
Primary Energy|Coal|w/o CCS
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Uncertainty in CCS deployment Projections

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- Exploring the EMF 27 model database for the chosen influential core models.

Table 2 Model assumptions about CO_2 storage and transport

Model name	(1) Is there a maximum storage rate	(2) Regional differentiation of storage capacity	(3) Possibility of international trade of CO_2 storage space	(4) Regional differentiation of transport and/or storage cos	(5) Storage and transport cost[a] in $\$US_{2005}/tCO_2$	(6) Number of storage types	(7) Storage cost differ per reservoir type	(8) Storage capacity in $GtCO_2$
BET	No	Yes	No	No	$ 8	No differentiation	No	3538
FARM	No	Yes[b]	No	Yes[b]	$ 13.8[b] - ∞	No differentiation	No	Unlimited[b]
GCAM	No	Yes	Yes[c]	Yes	$ 0.1–$96	2[d]	Yes	7178
GRAPE	No	Yes	No	Yes	$ 12.6–262	4[e]	Yes	~20000
IMACLIM	No	No	Yes[f]	Yes		No differentiation	No	Unlimited[g]
IMAGE	No	Yes	No	Yes	$ -6–50	11[h]	Yes	5856
MERGE	No	No[i]		No	$10	No differentiation	No	Unlimited[j]
MESSAGE	No	No	Yes[k]	No	$ 7–9[l]	No differentiation	No	Unlimited[m]
POLES	No	Yes	No	Yes	$ 10–300	2[n]	Yes	Unlimited
REMIND	Yes	Yes	No	No	$~6	No differentiation	No	3959
TIAM-WORLD	No	Yes	No	Yes[o]	$ 8–57	8[p]	Yes	11600[q]
WITCH	No	Yes[r]	No	Yes[s]	$ 5–10[t] (initial cost) -~ <100	No differentiation	No	Unlimited[u]

Personal communication with Bertram, C.; Bibas, R.; Blanford, G.; Calvin, K.; Carrara, S.;Yamamoto, H.; Kanudia, A.; Kitous A.G.; Krey, V.; Kurosawa, A.; Labriet, M.; Russ, P.; Sands, R.; Sugiyama, M

Climatic Change (2014) 123:461–476

Source: Koelbl, B. S., Broek, M. A. van den, Faaij, A. P. C. & Vuuren, D. P. van. Uncertainty in Carbon Capture and Storage (CCS) deployment projections: a cross-model comparison exercise. Climatic Change 123, 461–476 (2014).

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The Shared Socio Economic Pathways of the Energy Sector – Bauer et al http://dx.doi.org/10.1016/j.gloenvcha.2016.07.006

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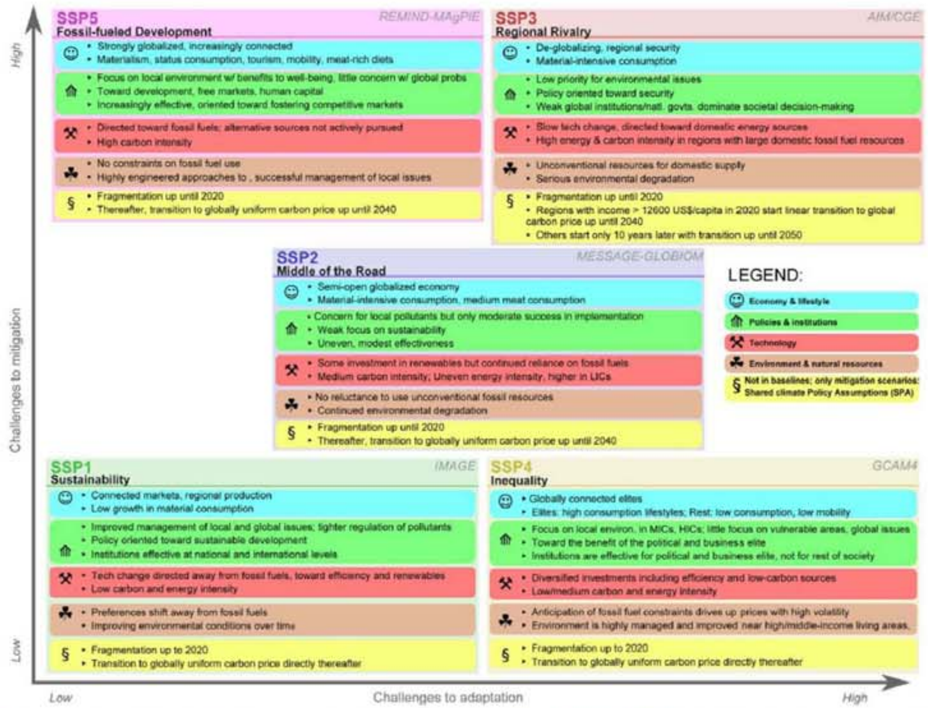

Fig. 1. Overview of *basic* SSPs, the energy sector elements of the narratives and the SPA specifications (O'Neill et al., 2016). HIC and MIC abbreviations for High and Medium Income Countries, respectively. The Shared Climate Policy Assumptions (SPAs), colored in yellow, are not used in the baseline scenarios, but only in the mitigation scenarios introduced in Sec. 2.2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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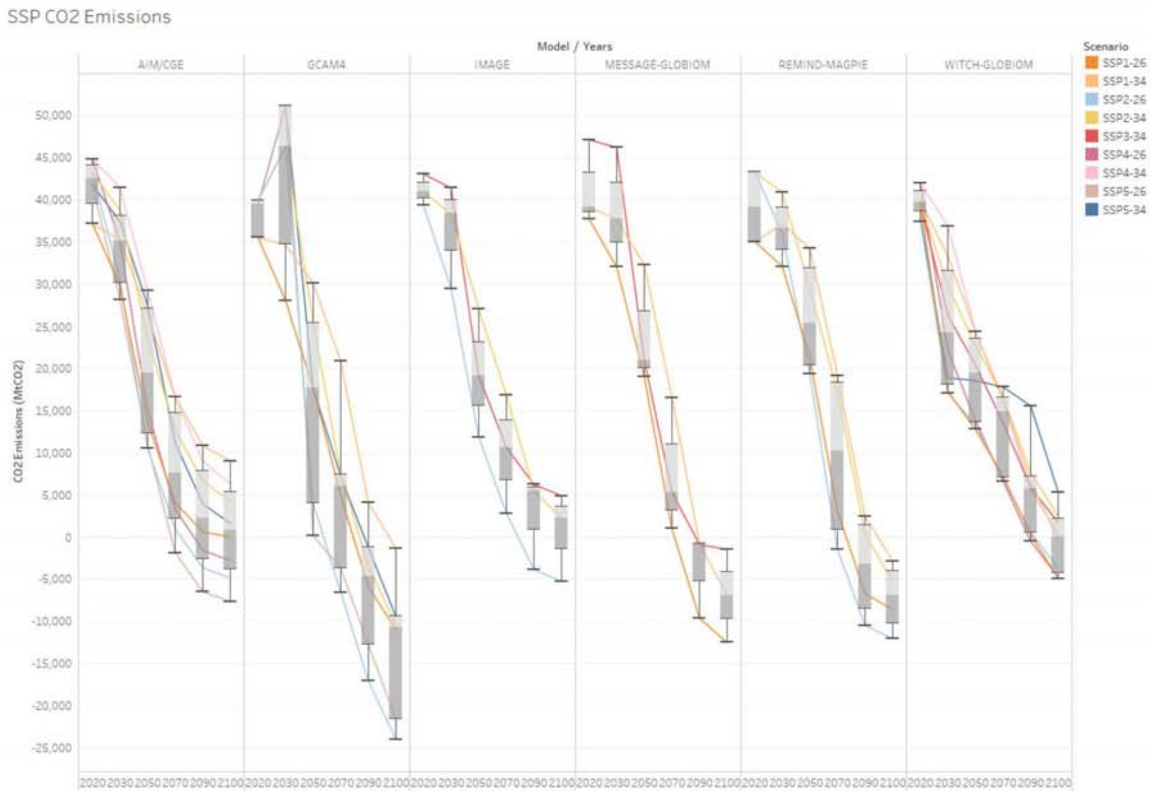
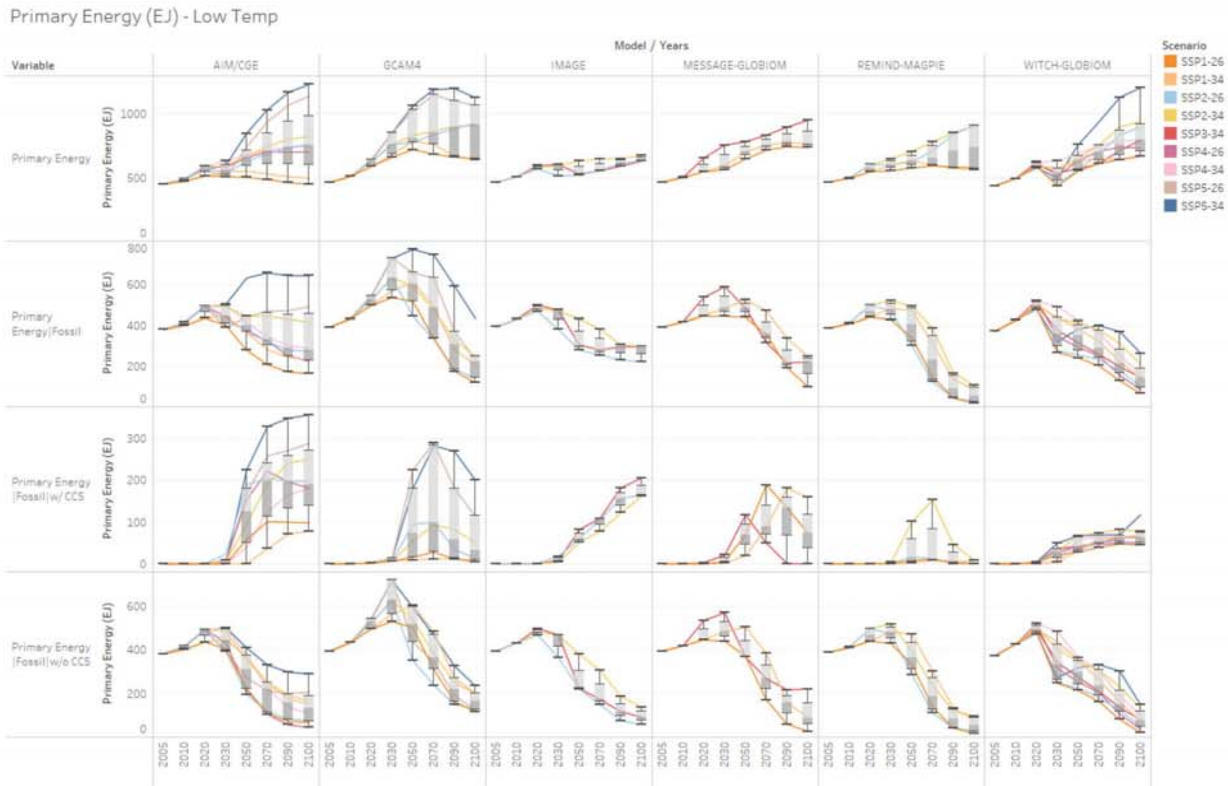
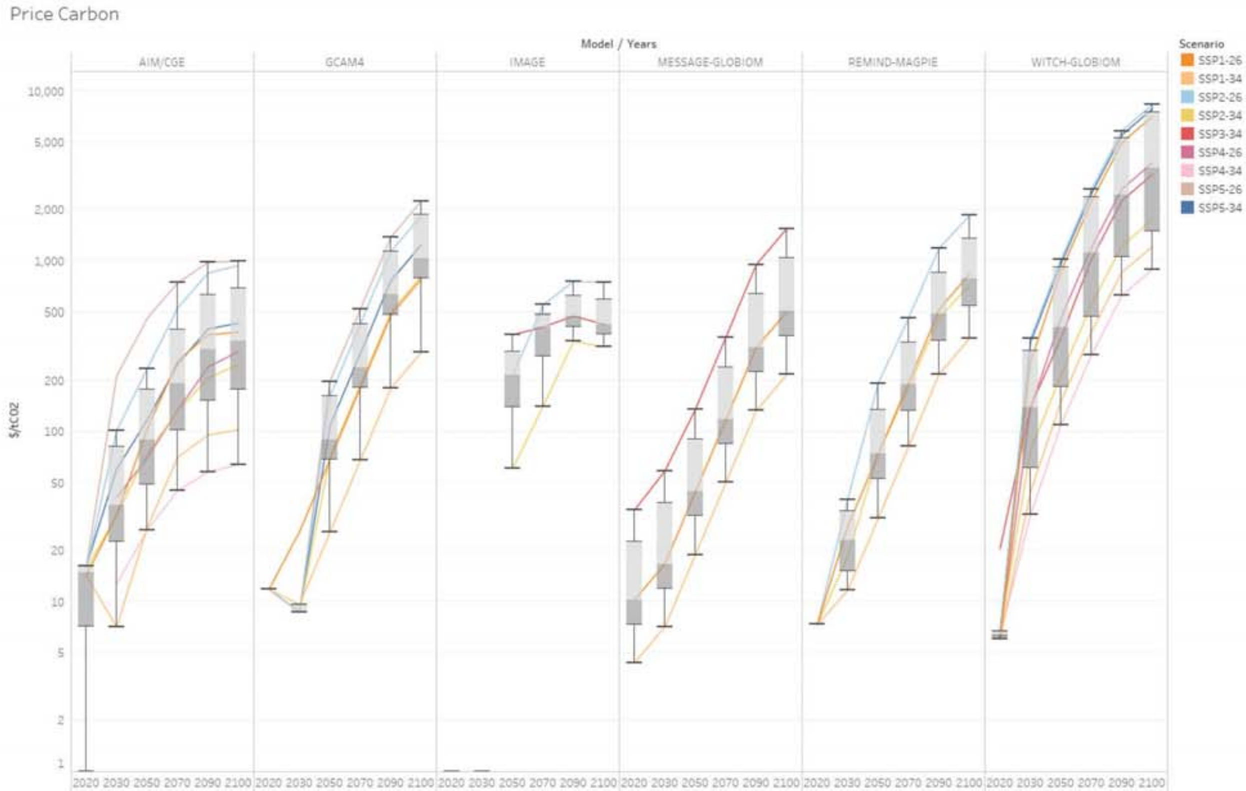
SSP – Low Temperature CO2 Pathways



Primary Energy–Low Temperature Scenarios



Carbon Price in Low Temperature Scenario SSPs



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Conclusion & Discussion points

- There appears to be an reliance upon the IPCC (2005) SR on CCS for calibration of CCS in IAMs, in the absence of other data sources.
- There is not a general awareness of the NETL baseline data sets within the IAM community.

- When considering the EMF27 study, the strong variation of CCS deployment projection rates could not be related to the reported differences in the assumptions of the models by means of a cross model comparison.
  - Source: Koelbl, B. S., Broek, M. A. van den, Faaij, A. P. C. & Vuuren, D. P. van. Uncertainty in Carbon Capture and Storage (CCS) deployment projections: a cross-model comparison exercise. Climatic Change 123, 461–476 (2014).
  - Investment costs were not included in the analysis that underpins this statement.
  - Investment costs, and CCS technology specification input assumptions need to be published as standard with CCS sensitivity analysis within IAM runs for cross model comparison.
- Model specific sensitivity runs on CCS calibration are required for further insights to go beyond the general statements from the EMF27 MIP type studies.
  - Muratori, M. et al. Carbon capture and storage across fuels and sectors in energy system transformation pathways. International Journal of Greenhouse Gas Control 57, 34–41 (2017).


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Environmental Research Institute
Instiúd Taighde Comshaoil

Energy Policy and Modelling Group
www.ucc.ie/energypolicy

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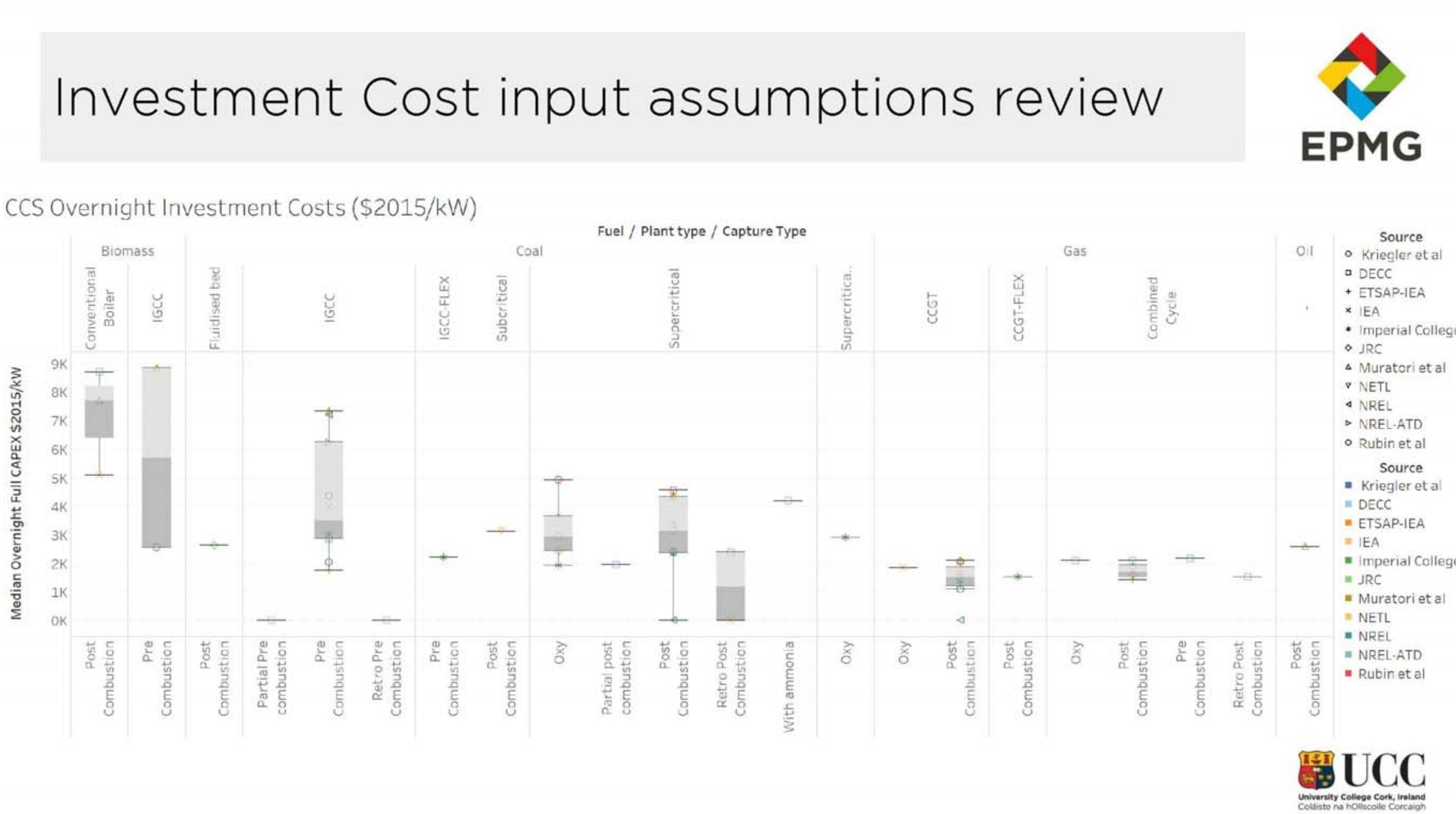
Investment Cost input assumptions review
EPMG
CCS Overnight Investment Costs ($2015/kW)
Fuel / Plant type / Capture Type
Biomass
Coal
Gas
Oil
Conventional Boiler
IGCC
Fluidised bed
IGCC
IGCC-FLEX
Subcritical
Supercritical
Supercritica..
CCGT
CCGT-FLEX
Combined Cycle
Median Overnight Full CAPEX $2015/kW
9K
8K
7K
6K
5K
4K
3K
2K
1K
0K
Post Combustion
Pre Combustion
Post Combustion
Partial Pre combustion
Pre Combustion
Retro Pre Combustion
Pre Combustion
Post Combustion
Oxy
Partial post combustion
Post Combustion
Retro Post Combustion
With ammonia
Oxy
Oxy
Post Combustion
Post Combustion
Oxy
Post Combustion
Pre Combustion
Retro Post Combustion
Post Combustion
Source
Kriegler et al
DECC
ETSAP-IEA
IEA
Imperial College
JRC
Muratori et al
NETL
NREL
NREL-ATD
Rubin et al
Source
Kriegler et al
DECC
ETSAP-IEA
IEA
Imperial College
JRC
Muratori et al
NETL
NREL
NREL-ATD
Rubin et al
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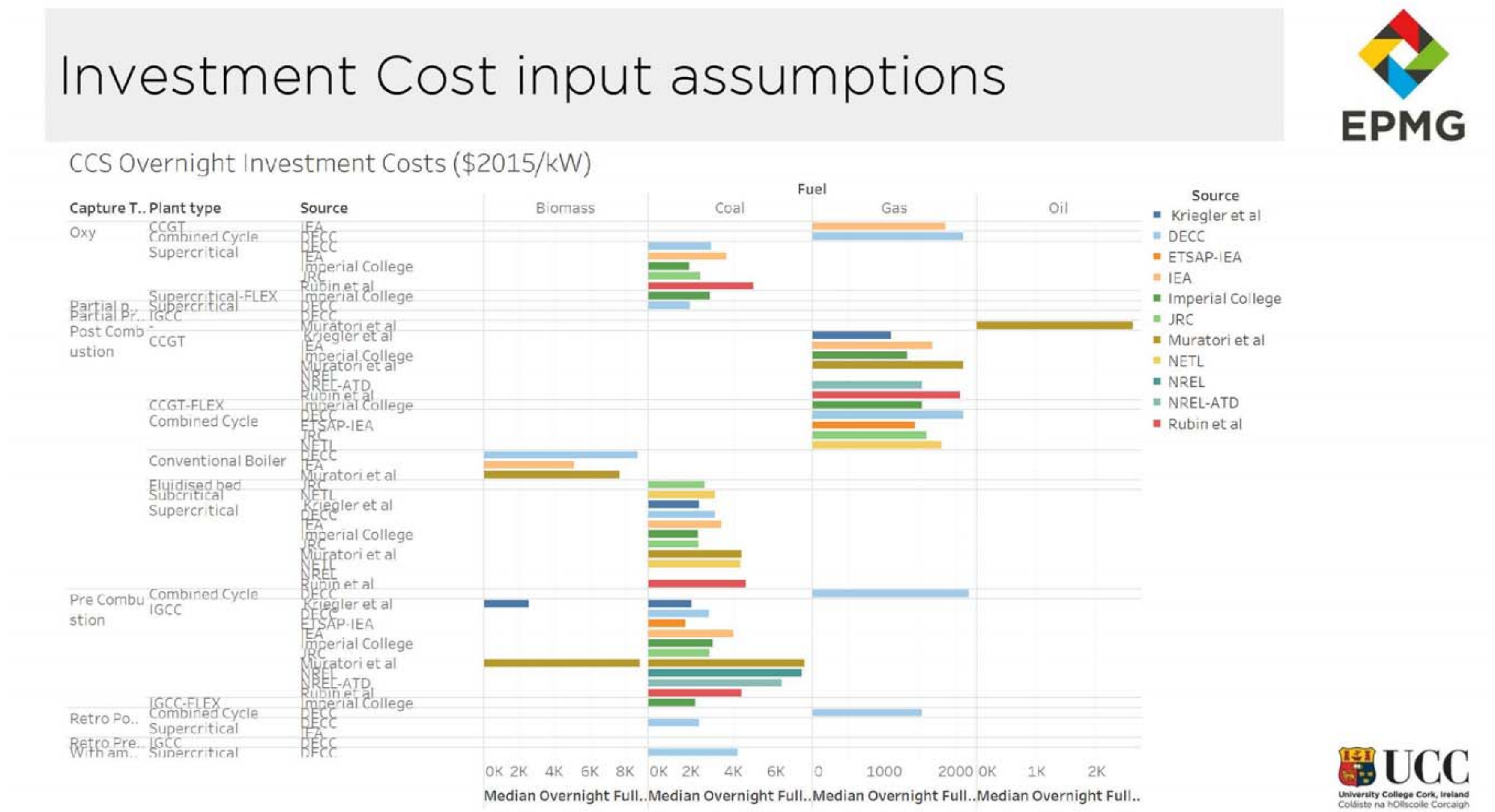
Investment Cost input assumptions
EPMG
CCS Overnight Investment Costs ($2015/kW)
Fuel
Capture T..
Plant type
Source
Biomass
Coal
Gas
Oil
Oxy
Post Comb ustion
Pre Combu stion
Retro Po..
CCGT
Combined Cycle
Supercritical
Supercritical-FLEX
IGCC
CCGT-FLEX
Conventional Boiler
Subcritical
IGCC-FLEX
Kriegler et al
DECC
ETSAP-IEA
IEA
Imperial College
JRC
Muratori et al
NETL
NREL
NREL-ATD
Rubin et al
0K 2K 4K 6K 8K
0K 2K 4K 6K
0 1000 2000
0K 1K 2K
Median Overnight Full..
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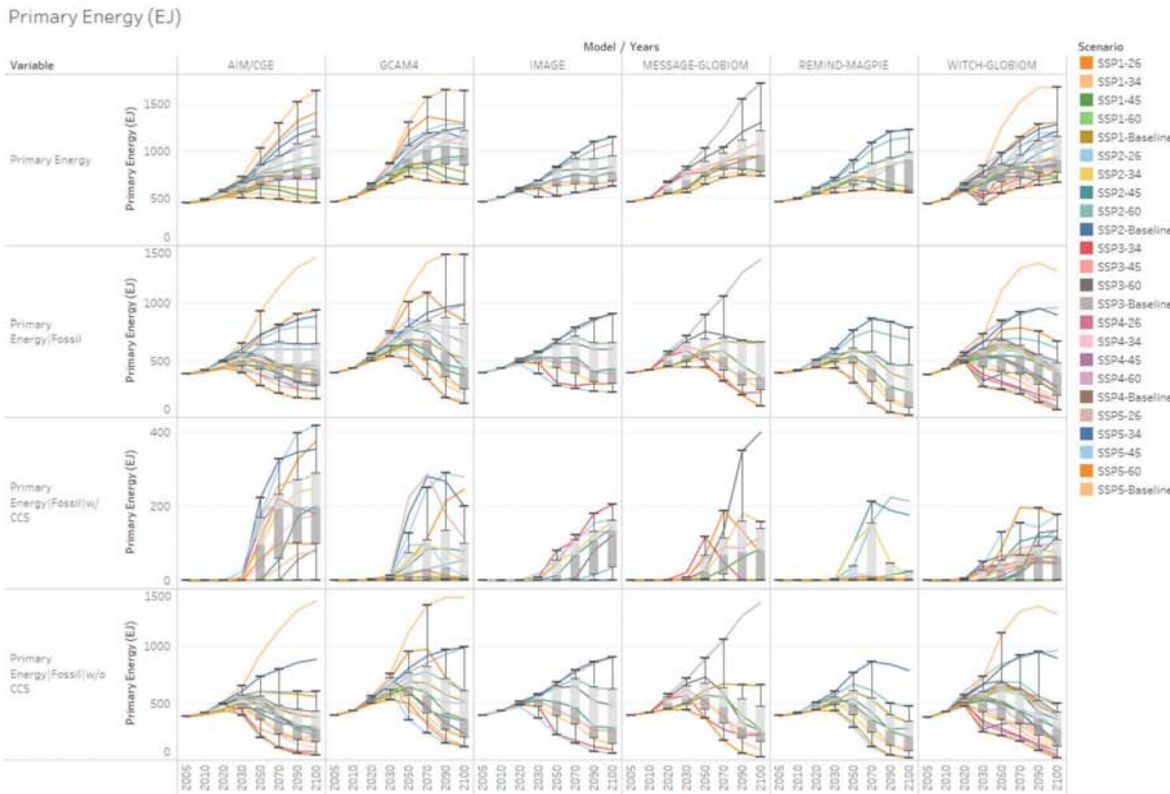
Primary Energy Across All SSPs



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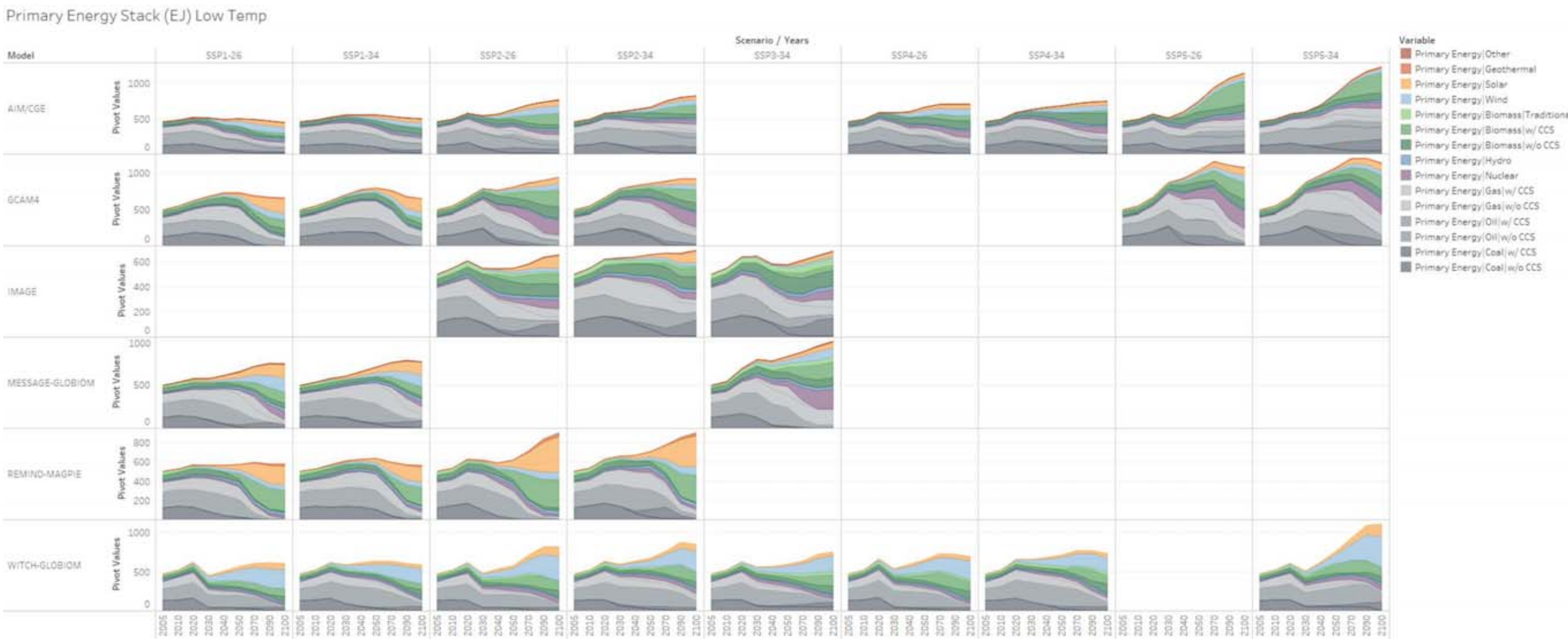
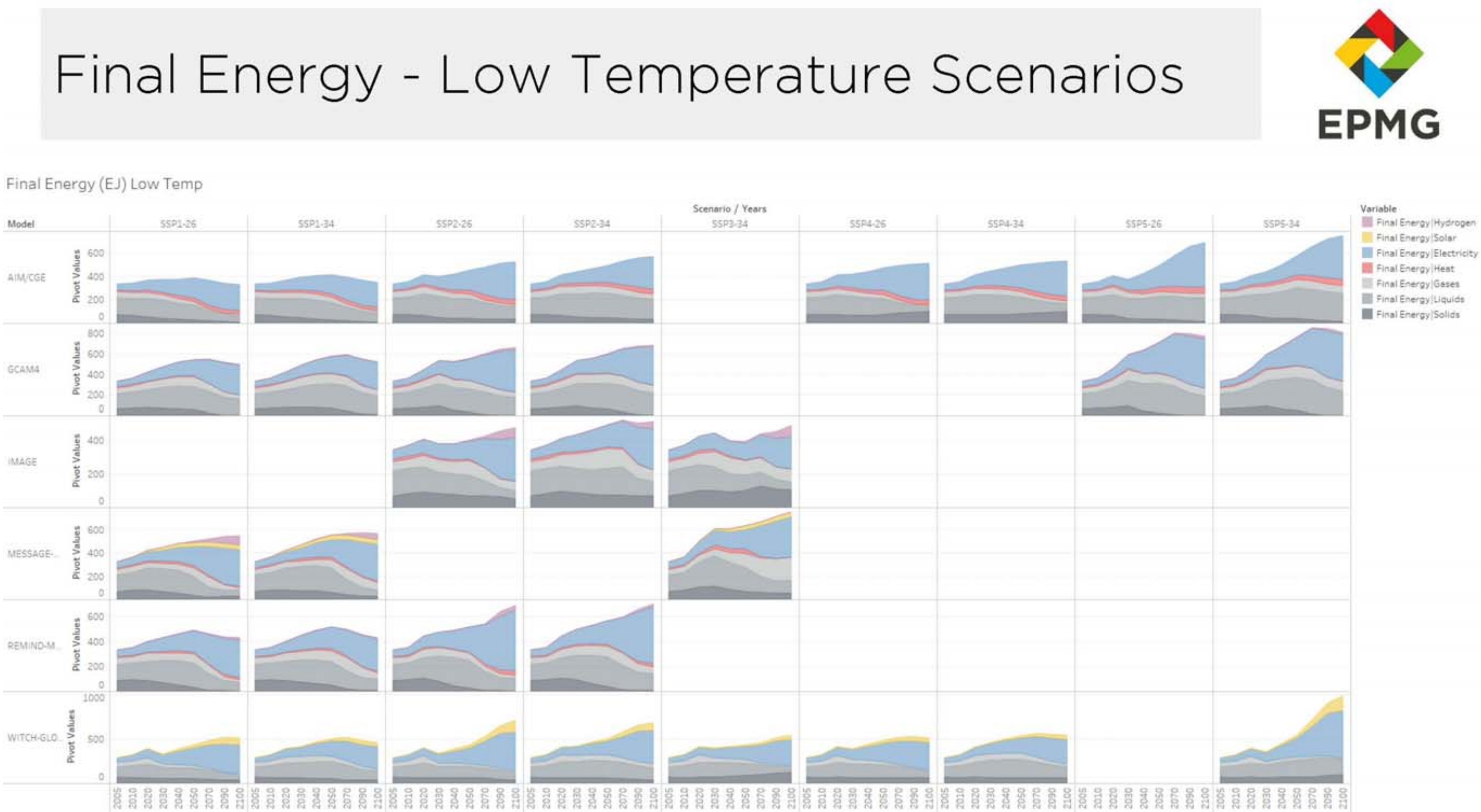
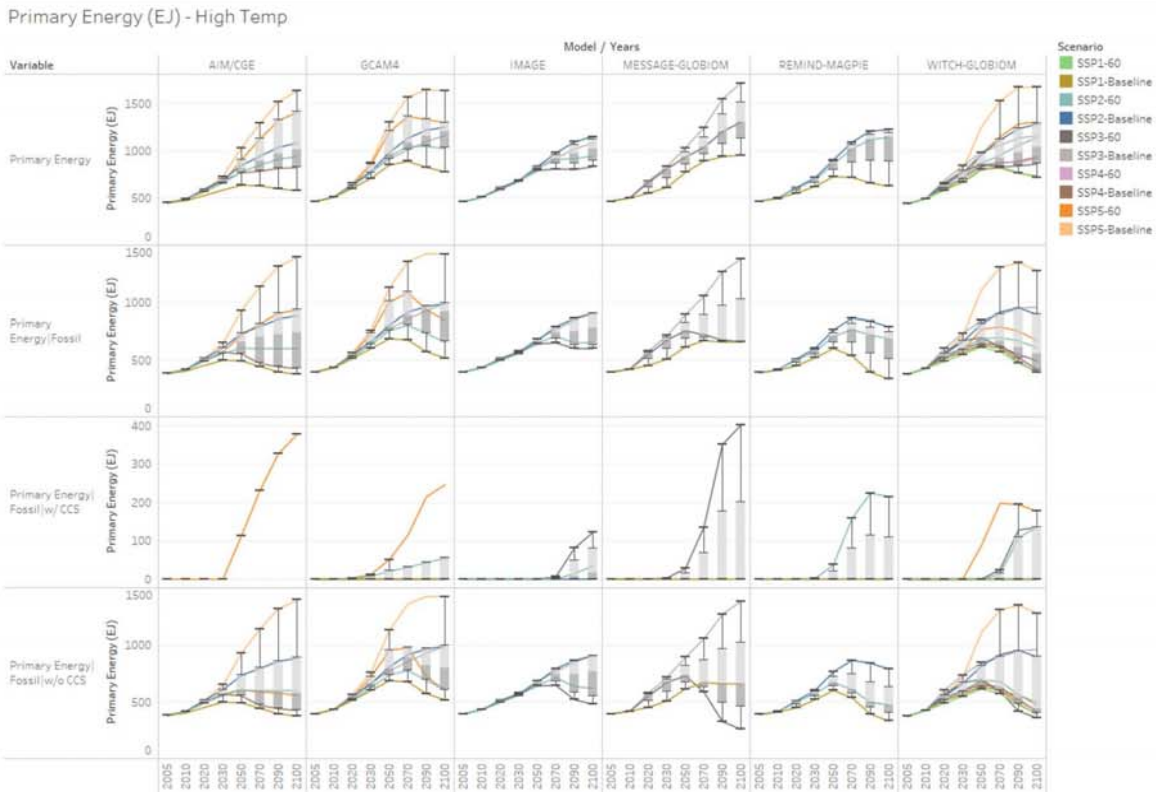
Primary Energy by Fuel by Model

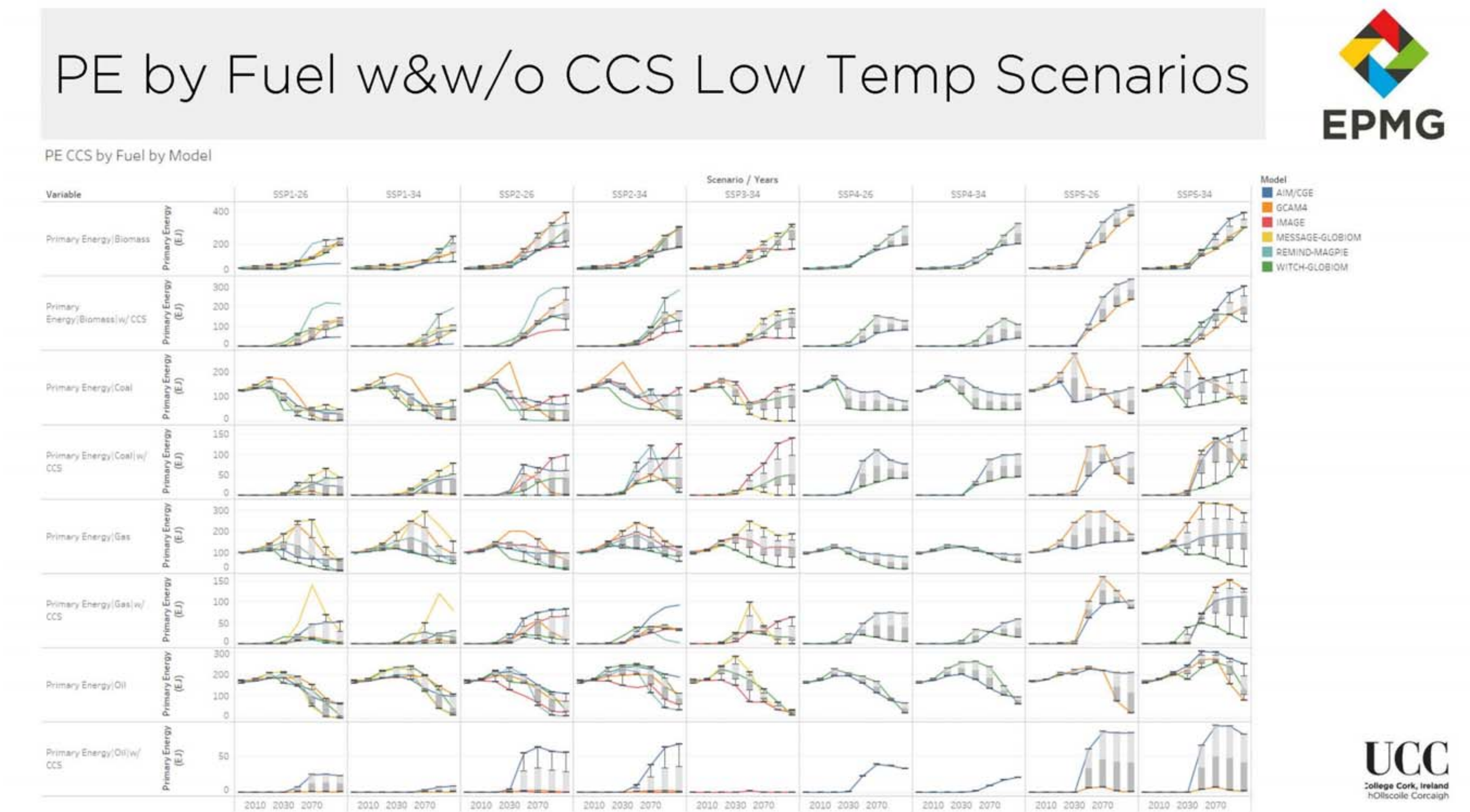


Final Energy - Low Temperature Scenarios



Primary Energy–High Temperature Scenarios




PE by Fuel w&w/o CCS Low Temp Scenarios
EPMG
PE CCS by Fuel by Model
Scenario / Years
Variable
SSP1-26
SSP1-34
SSP2-26
SSP2-34
SSP3-34
SSP4-26
SSP4-34
SSP5-26
SSP5-34
Primary Energy|Biomass
Primary Energy|Biomass|w/ CCS
Primary Energy|Coal
Primary Energy|Coal|w/ CCS
Primary Energy|Gas
Primary Energy|Gas|w/ CCS
Primary Energy|Oil
Primary Energy|Oil|w/ CCS
Primary Energy (EJ)
2010 2030 2070
Model
AIM/CGE
GCAM4
IMAGE
MESSAGE-GLOBIOM
REMIND-MAGPIE
WITCH-GLOBIOM
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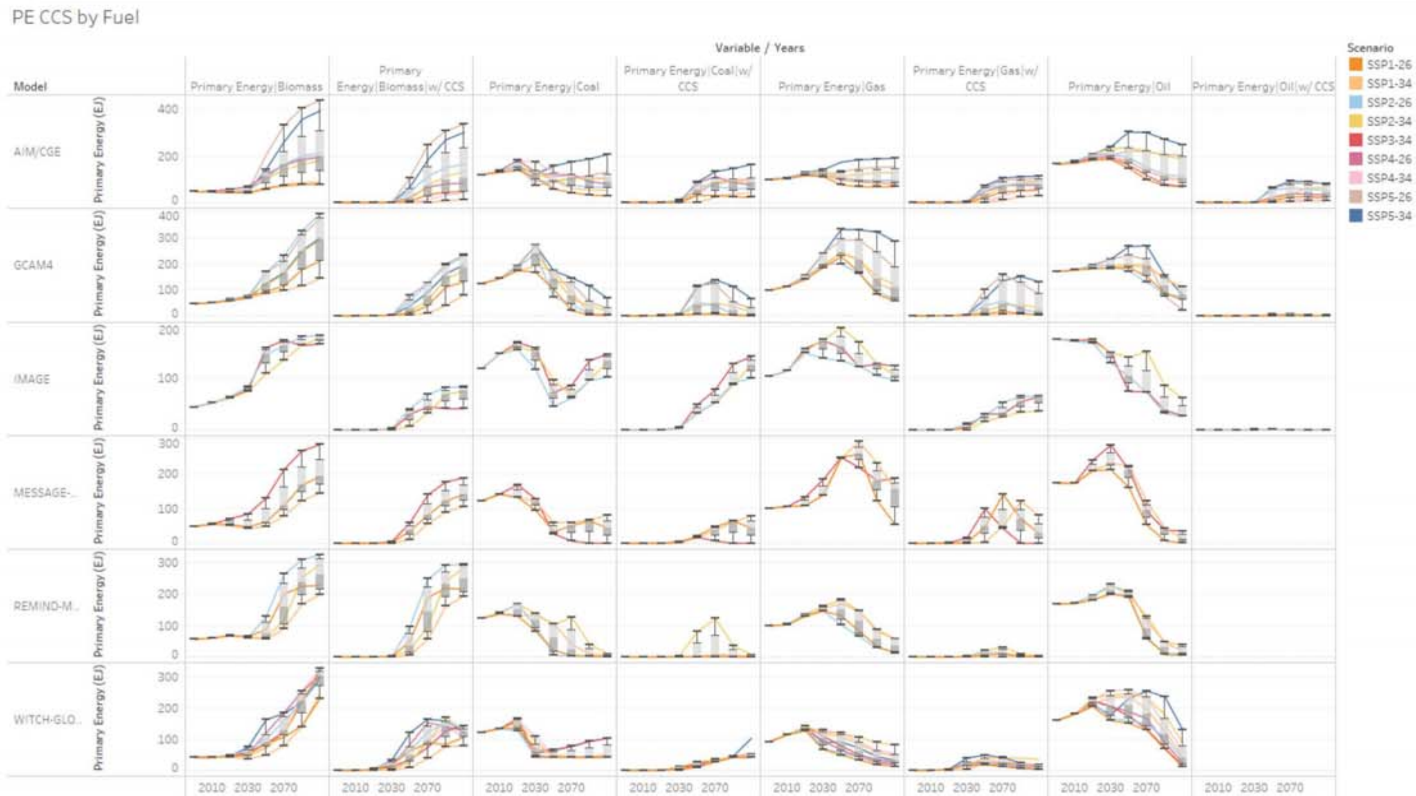
PE by Fuel w&w/o CCS Low Temp Scenarios

EPMG



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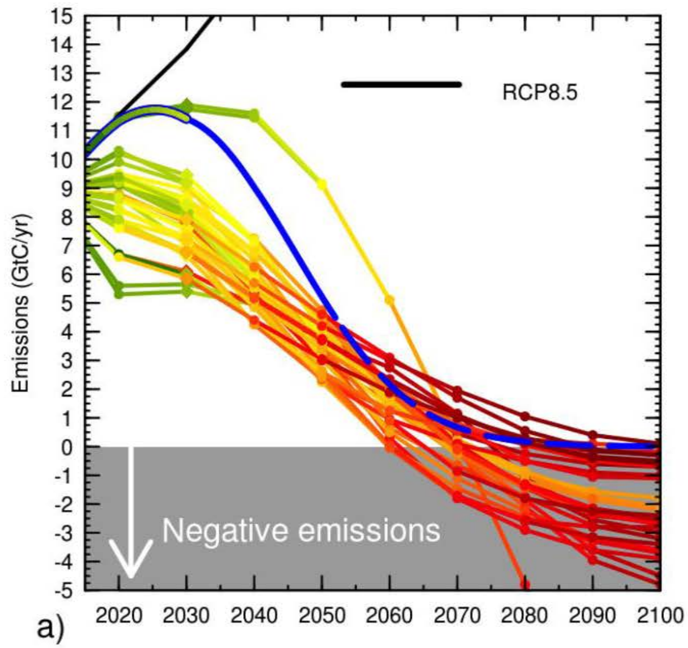
Are these scenarios achievable?

Total emissions in scenarios in IPCC WGIII "430-480ppm" (lowest) scenario category



Colours show total policy cost in US$$_{2005}$

eci

Figures courtesy of Richard Millar based on IPCC AR5 WBIII database hosted by IIASA
From Millar et al, 2016?

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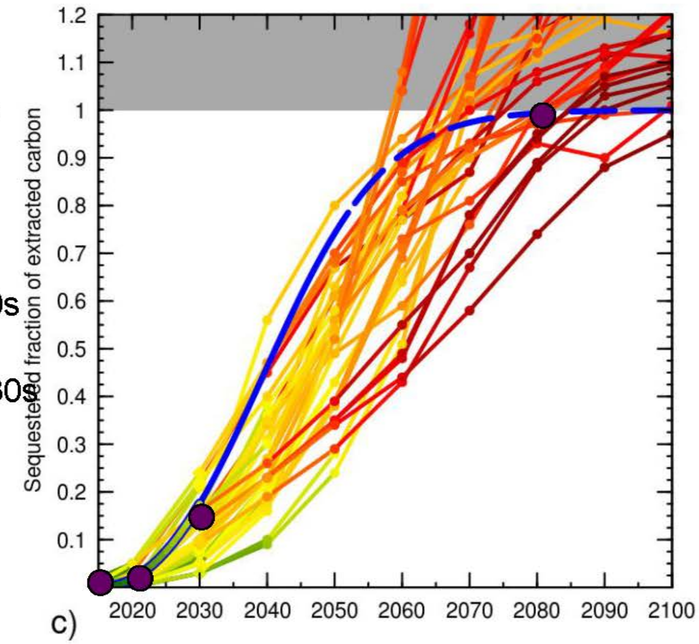
How to avoid mitigation costs >60 T$/year

A scenario for progressive deployment of CO_2 disposal

1% by mid-2020s

15% by mid-2030s

100% before temperatures reach 2°C



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Figures courtesy of Richard Millar based on IIASA database
From Millar et al, 2016?

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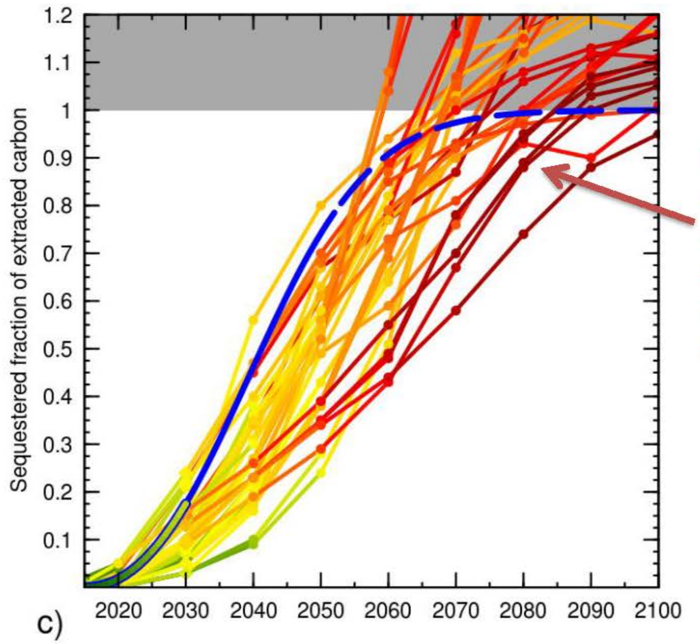
Another way of looking at IPCC WG3 "well below 2°C" scenarios

Net fraction of extracted carbon that is re-injected through CCS, BECCS or DAC



Delayed deployment of CO_2 disposal is associated with mitigation costs >$60 T$_{2005}$/year

Figures courtesy of Richard Millar based on IIASA database
From Millar et al, 2016?

4b. What is the role of CCS in determining costs and climate outcomes of scenario analysis in Integrated Assessment Models?

Richard Millar, Oxford University

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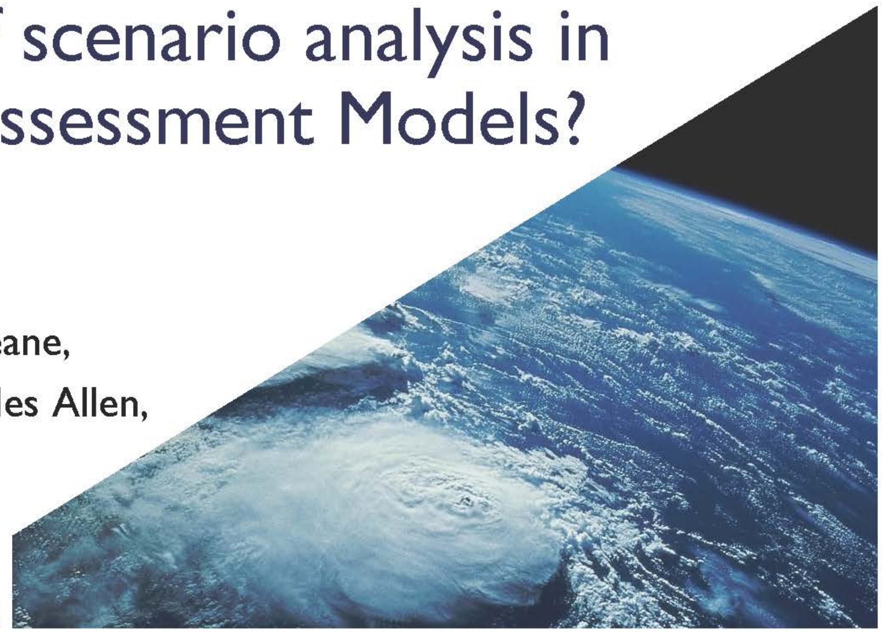
What is the role of CCS in determining costs and climate outcomes of scenario analysis in Integrated Assessment Models?



Richard Millar

James Glynn, Paul Deane,
Niall MacDowell, Myles Allen,
Brian Ó Gallachóir

richard.millar@ouce.ox.ac.uk

1

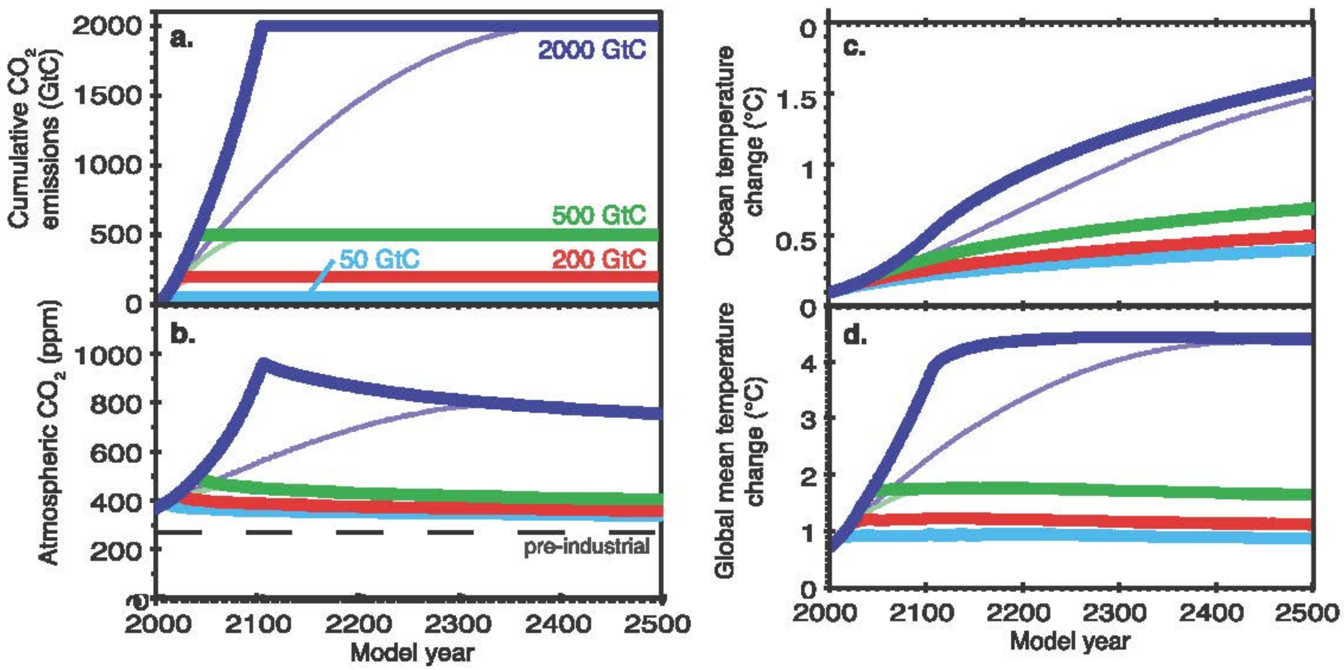
Overview

1. The climate context
2. High-level insights into the role of CCS in climate scenarios
3. CCS deployment as a driver of cost in climate scenarios

Overview

1. The climate context
2. High-level insights into the role of CCS in climate scenarios
3. CCS deployment as a driver of cost in climate scenarios

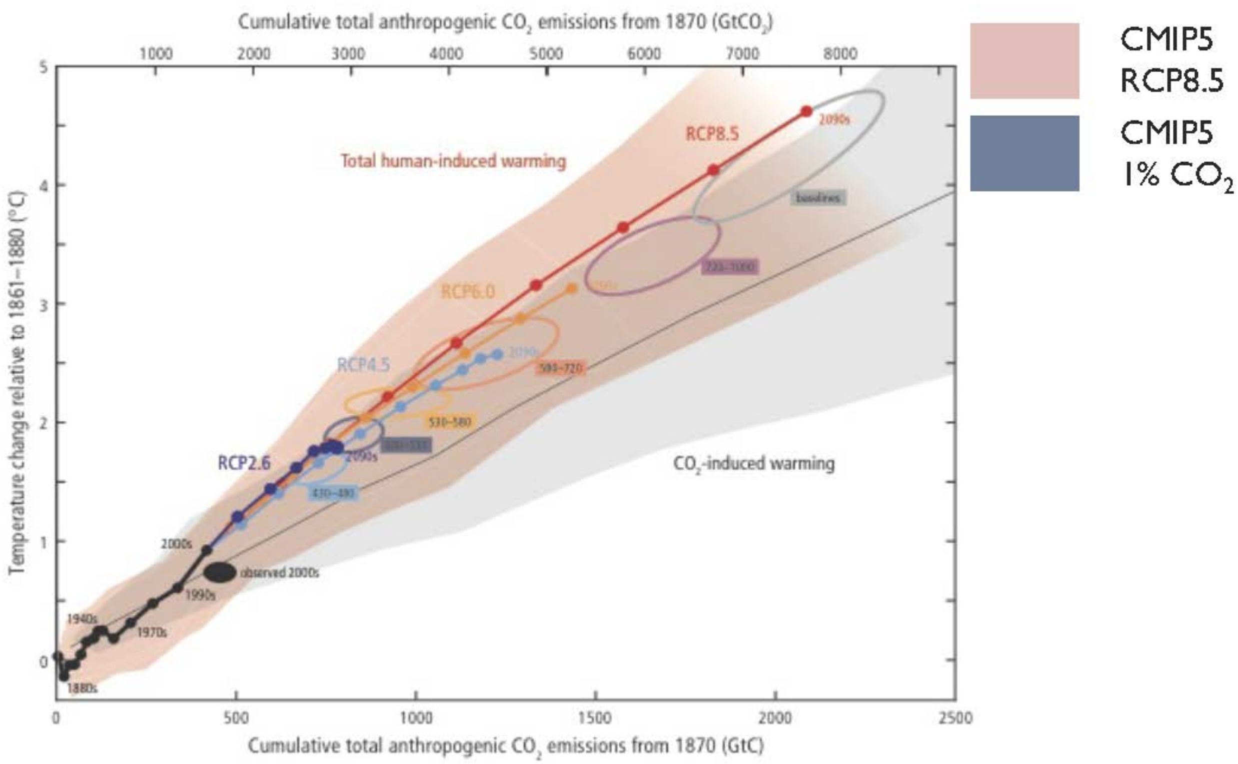
Limiting warming to Paris goals is still possible but requires net-zero CO_2 emissions



Source: Matthews & Caldeira *GRL* (2008)

4

Peak warming depends on **cumulative** carbon emissions, but budgets are uncertain



Source: IPCC AR5 Synthesis Report (2014)

5

Peak warming depends on **cumulative** carbon emissions, but budgets are uncertain

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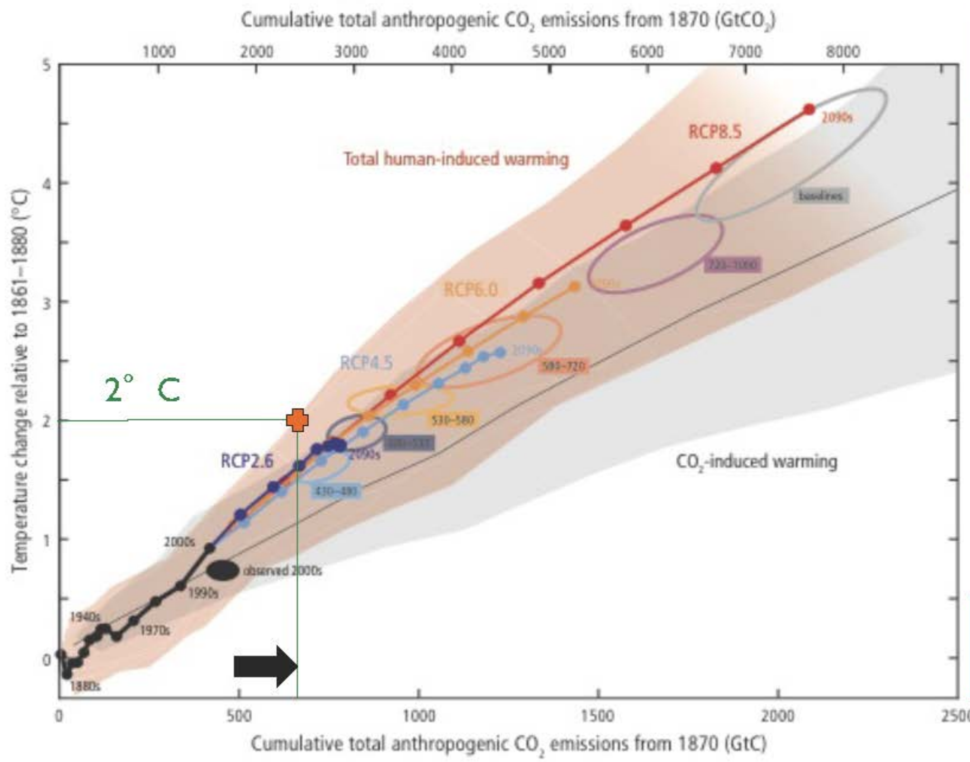

CMIP5 RCP8.5

CMIP5 1% CO_2

Remaining carbon budget : ~ 100 GtC

Source: IPCC AR5 Synthesis Report (2014)

6

Peak warming depends on **cumulative** carbon emissions, but budgets are uncertain

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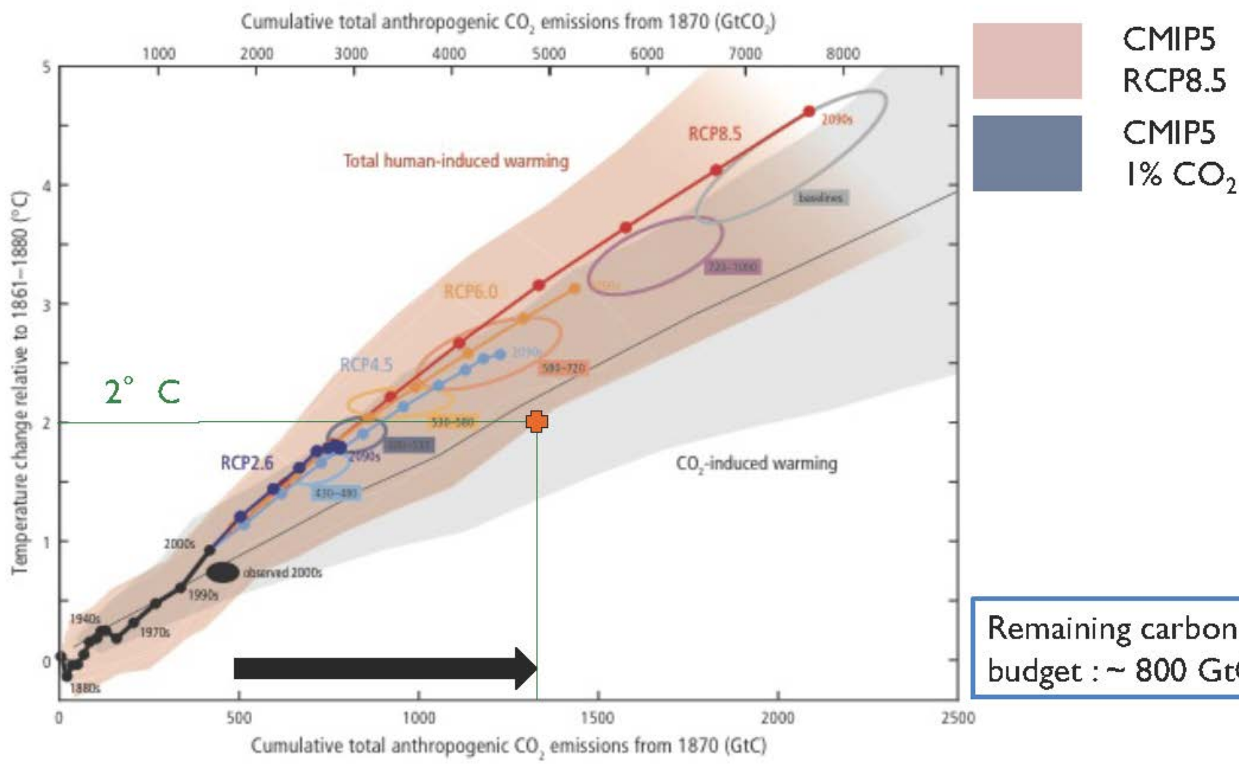
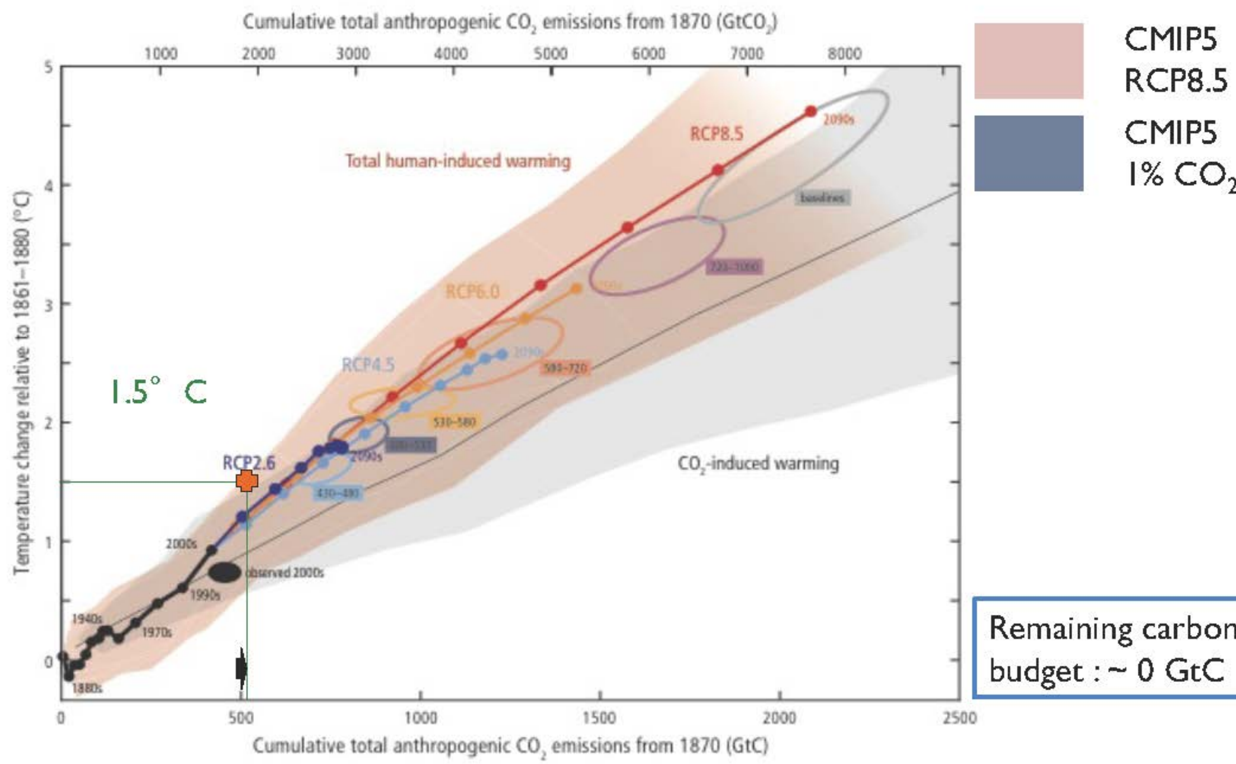


Remaining carbon budget : ~ 800 GtC

Source: IPCC AR5 Synthesis Report (2014)

7

Peak warming depends on **cumulative** carbon emissions, but budgets are uncertain



Remaining carbon budget : ~ 0 GtC

Source: IPCC AR5 Synthesis Report (2014)

8

Peak warming depends on **cumulative** carbon emissions, but budgets are uncertain

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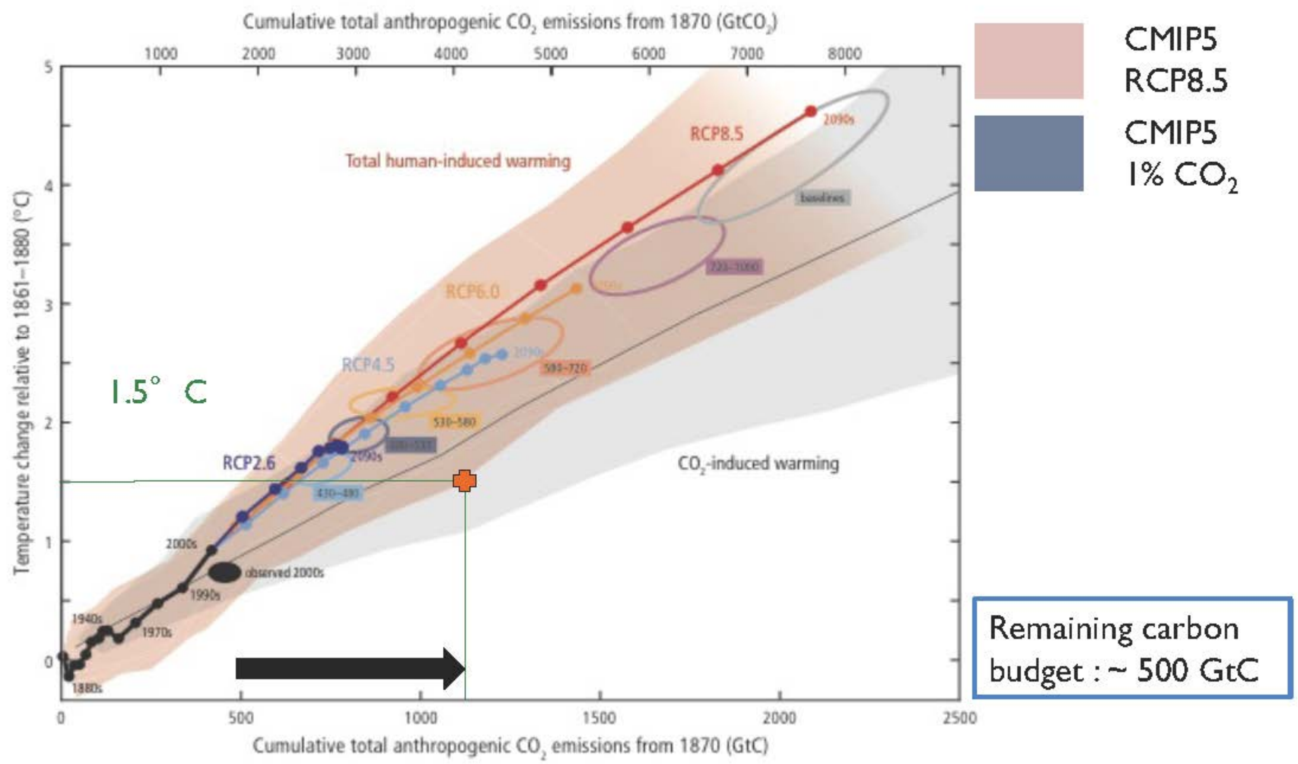

Source: IPCC AR5 Synthesis Report (2014)

9

Peak warming depends on **cumulative** carbon emissions, but budgets are uncertain

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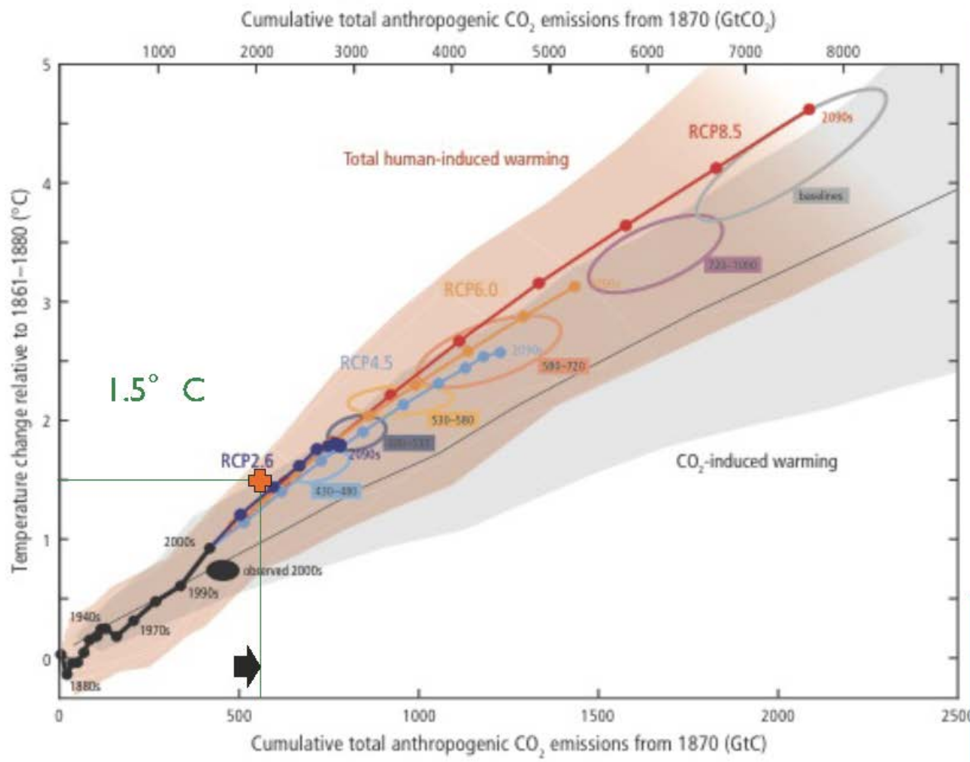

CMIP5 RCP8.5

CMIP5 1% CO_2

Remaining carbon budget : ~56 GtC from 2015 (>66% probability)

Source: IPCC AR5 Synthesis Report (2014)

10

Overview

1. The climate context
2. High-level insights into the role of CCS in climate scenarios
3. CCS deployment as a driver of cost in climate scenarios

In scenarios with large emissions reductions demand for carbon remains high

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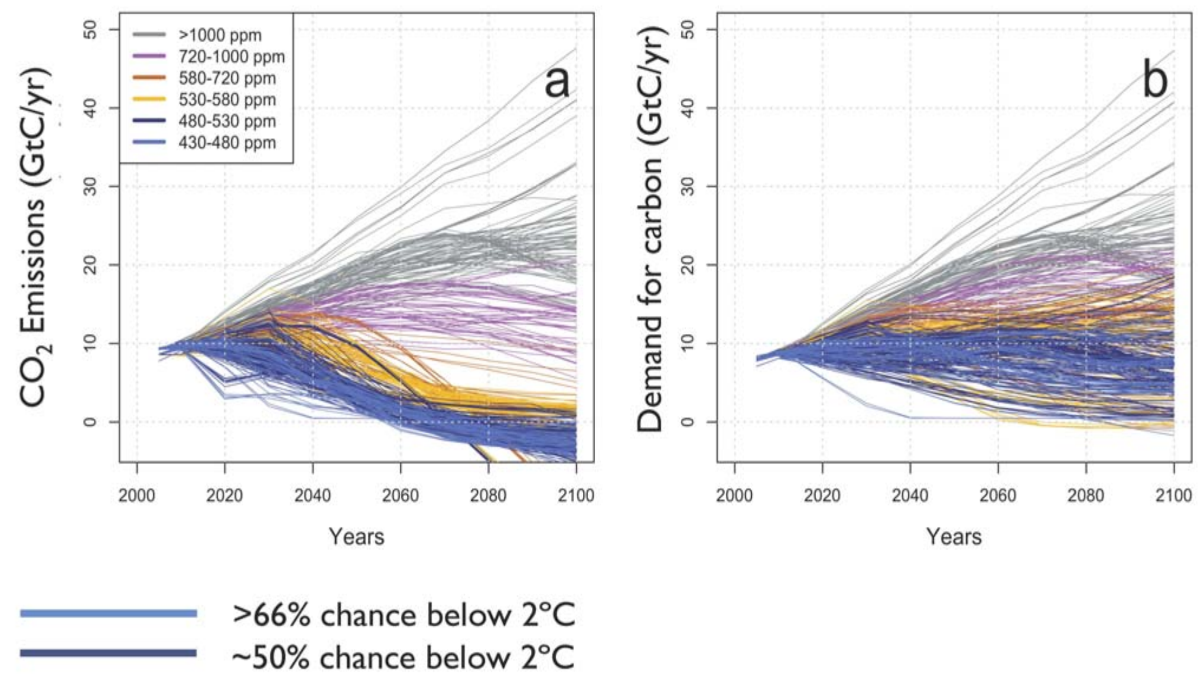

Source: Millar et al *Global Sustainability* (in review)

12

The fraction of extracted carbon that is sequestered via CCS rises steadily over time

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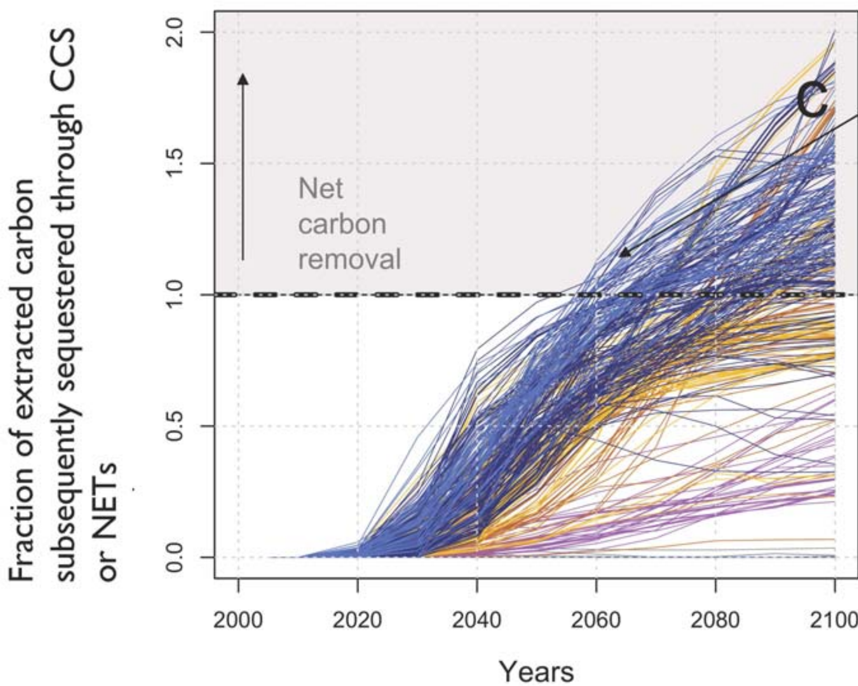


Sequestered fraction rises gradually and must reach 1.0 at some point in all scenarios that limit warming

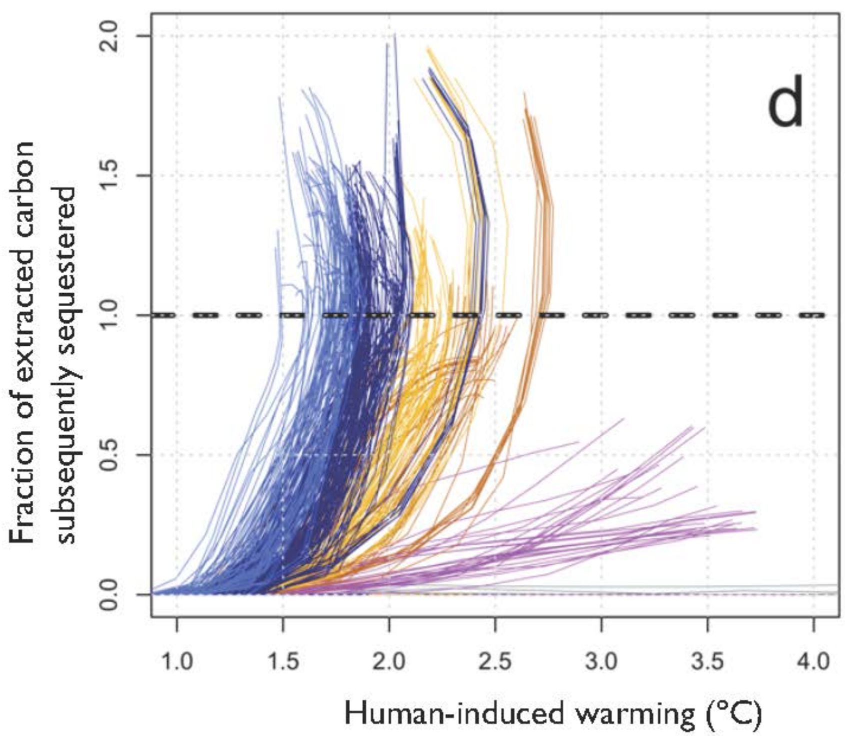
>66% chance below 2°C

~50% chance below 2°C

Source: Millar et al *Global Sustainability* (in review)

13

CCS deployment is a well-constrained function of future warming in scenarios



Scenarios show a steady upward curvature with warming beyond today, with peak warming occurring when the sequestered fraction reaches 1.

Source: Millar et al *Global Sustainability* (in review)

Overview

1. The climate context
2. High-level insights into the role of CCS in climate scenarios
3. CCS deployment as a driver of cost in climate scenarios

Cost of staying "well below 2°C" tend to go up with delayed deployment of CCS

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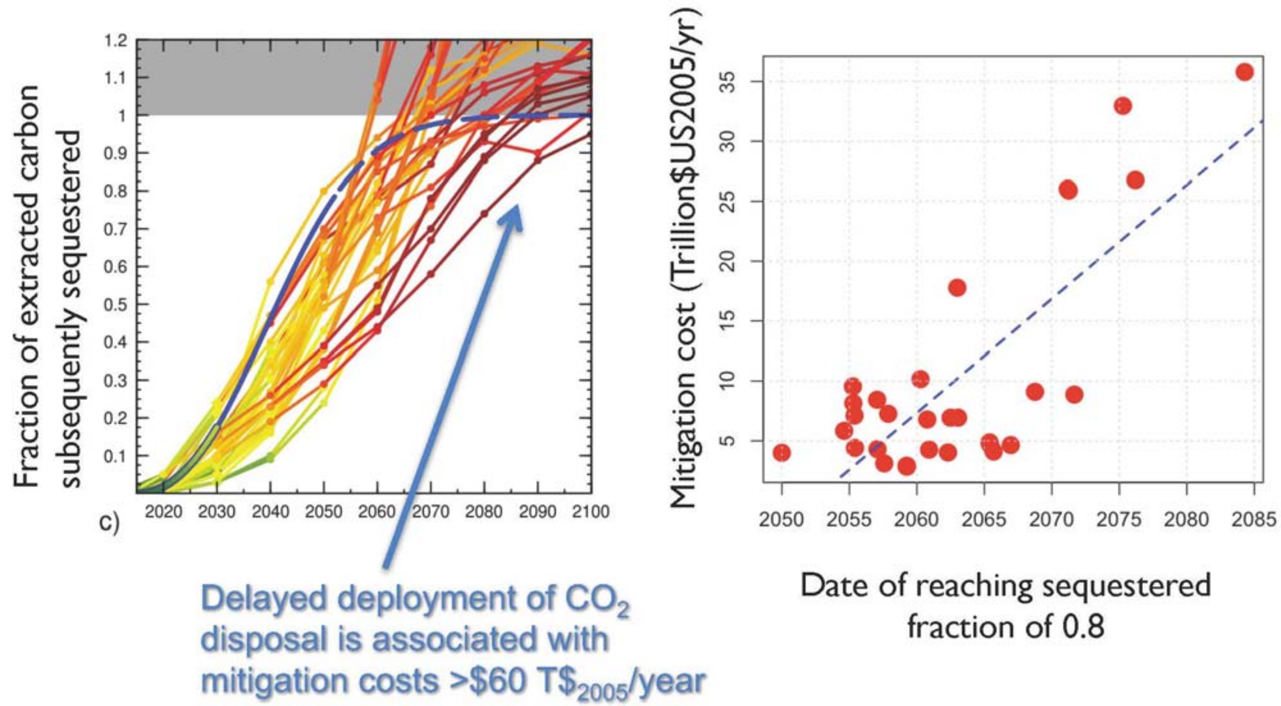

16

Representations of learning effects can drive deployment profiles of CCS

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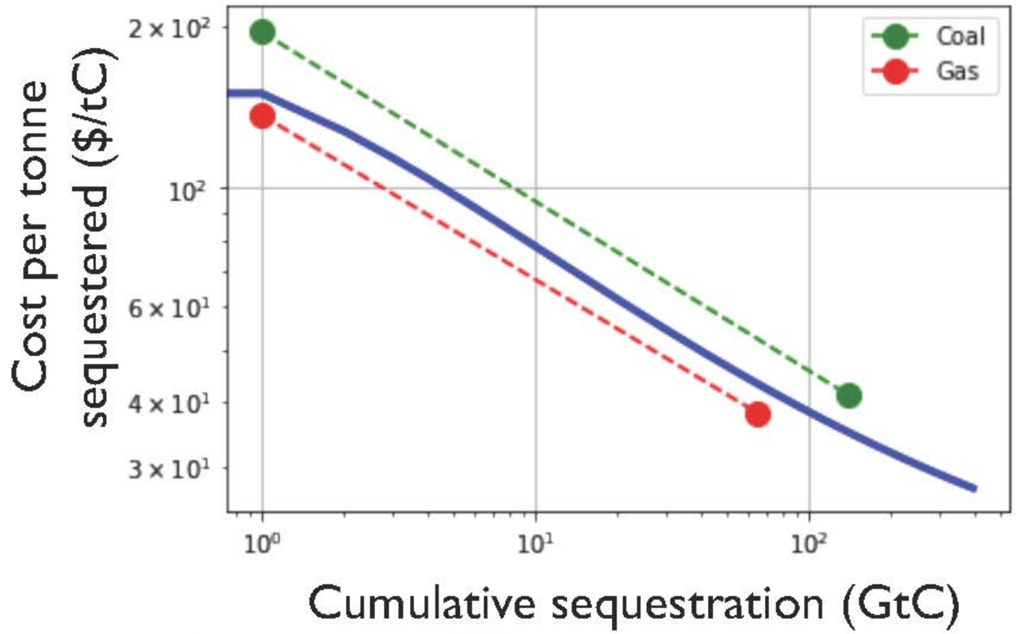
Riahi et al show that endogenous learning in MESSAGE reduces abatement costs to ¼ of initial values

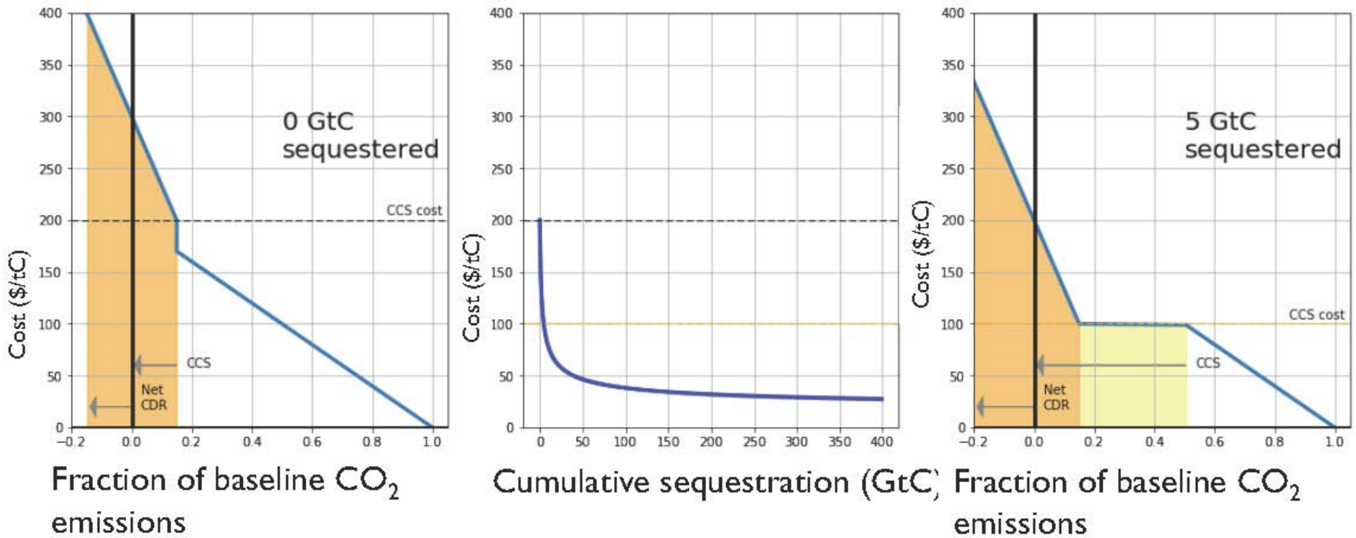


CCS deployment magnitude can vary by 100% or more depending on whether endogenous learning is allowed

Source: Riahi et al, *Energy Economics* (2004)

17

Representations of learning effects can drive deployment profiles of CCS



Using toy cost curves, with a very basic CCS/CDR learning effect model inbuilt, early deployment of CCS can be cost-optimal solution to meet a given carbon budget for relatively weak discounting of the future…

BECCS cost-curves can also be an important driver of carbon price and mitigation costs

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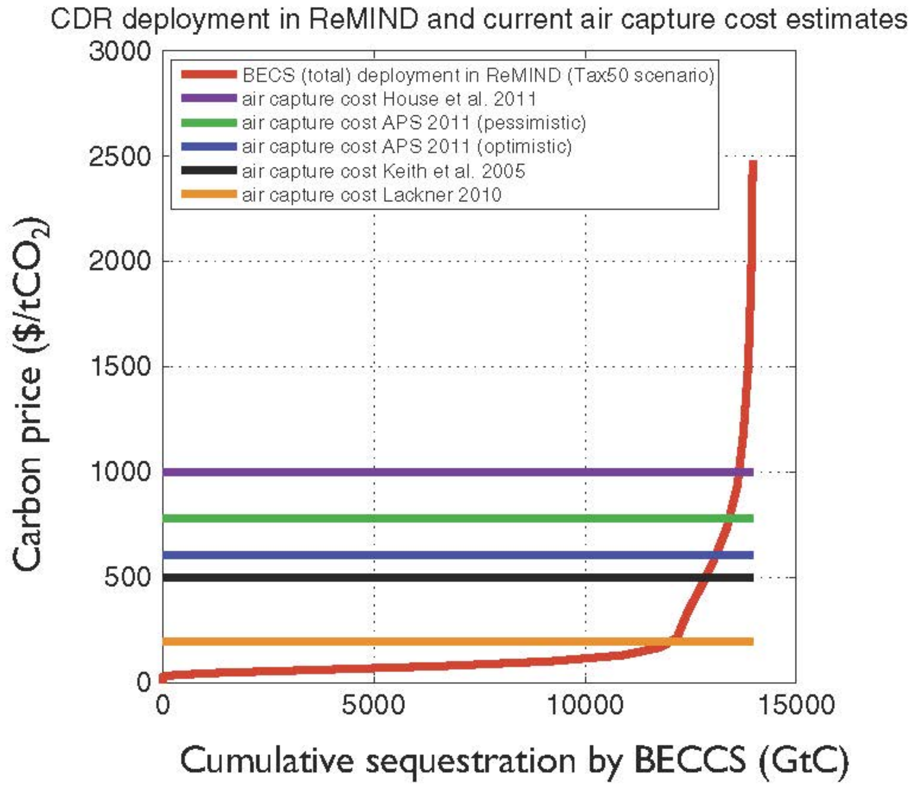


Source: Kriegler et al, *Climatic Change* (2013)

19

Session 5: CCS Flexibility

5a. Quantifying and qualifying the role and value of flexible CCS to the decarbonisation of national electricity systems

Clara Heuberger, Imperial College

Quantifying and qualifying the role and value of flexible CCS to the decarbonisation of national electricity systems

Contribution to the 5th IEAGHG CCS Cost Network Workshop

Clara F. Heuberger[a,b]

and Iain Staffell[a], Nilay Shah[b,c], Niall Mac Dowell[a,b]

[a] Centre for Environmental Policy (CEP)

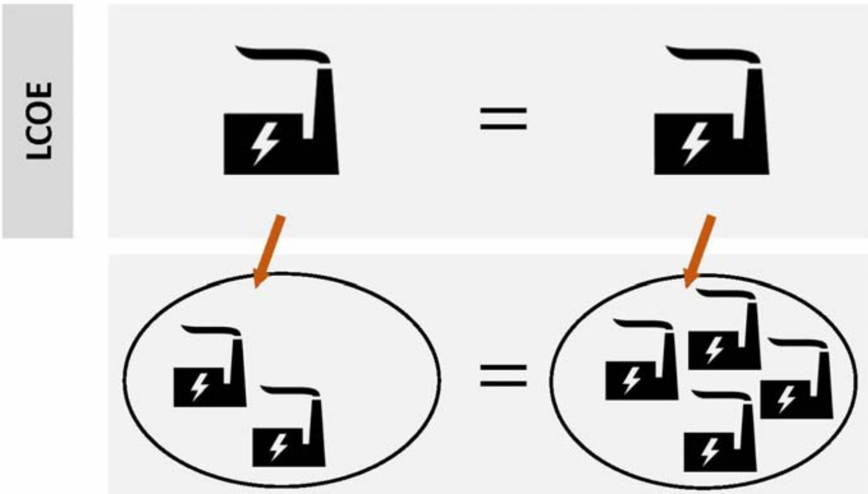
[b] Centre for Process Systems Engineering (CPSE)

[c] Department of Chemical Engineering, Imperial College London

London, 14st September 2017

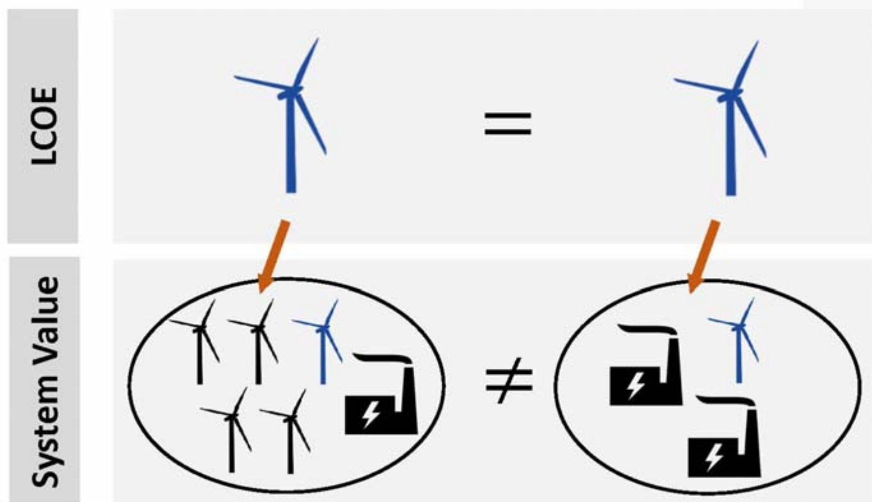
Valuation metrics of power technologies

In a 20th century power system…



Valuation metrics of power technologies

Today…



+ Widely used
+ Easily calculated
- No account of system integration effects

+ Explicitly accounts for system integration
- Requires full/sectoral energy systems model

CF Heuberger, I Staffell, N Shah, N Mac Dowell, Grantham Briefing Note 7, 2017

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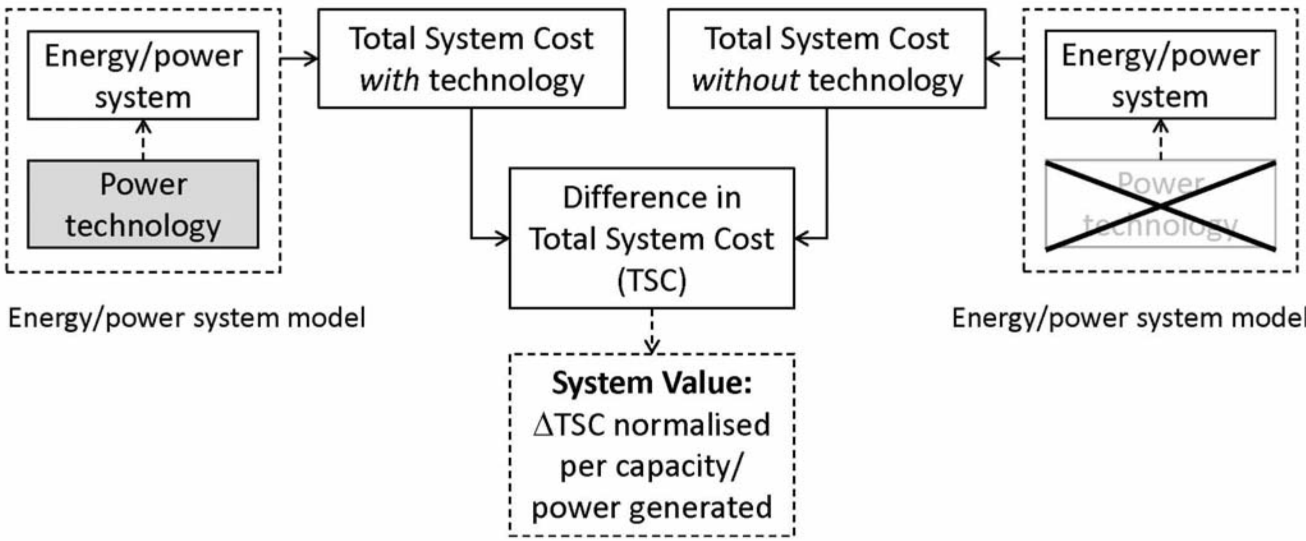
The system value metric

The system value can be quantified as the difference in total system cost caused upon the deployment of a power generation or storage technology.



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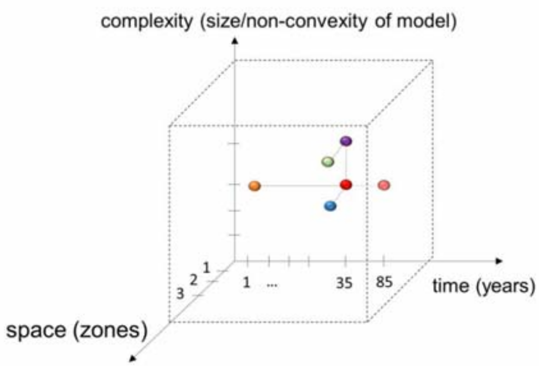
The Electricity Systems Optimisation framework



Characteristic		Model Name
single node, clustered time and full hourly, one year		ESO
single node, full hourly, 35 years		ESO-X
single node, 35 years, tech. LR		ESO-XEL
multi-zone, clustered time		ESONE-X, ESONE-XEL
single node, 35+ years, market competition		ESO-XEQ

completed

planned

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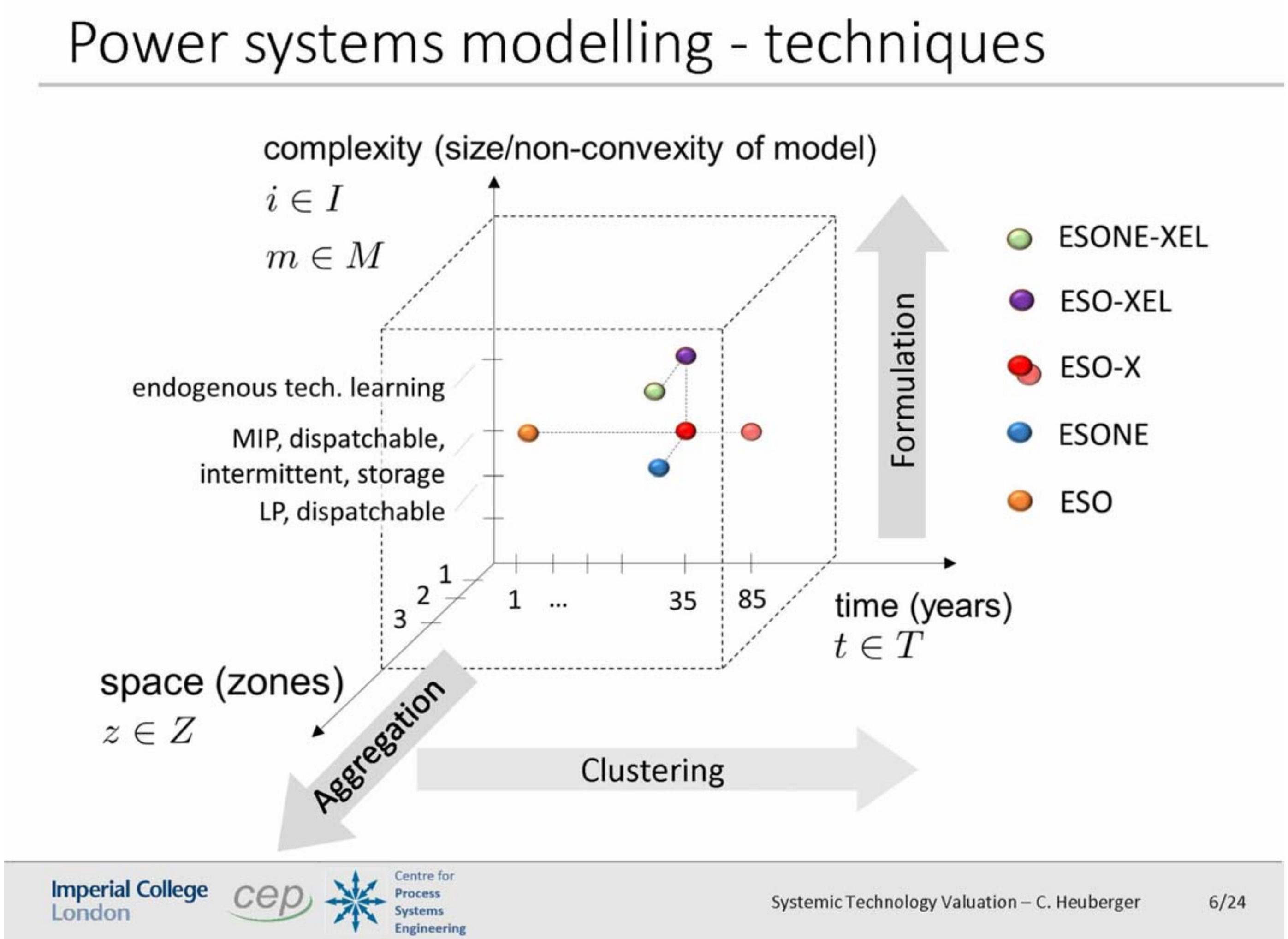
Power systems modelling - techniques
complexity (size/non-convexity of model)
$i \in I$
$m \in M$
endogenous tech. learning
MIP, dispatchable,
intermittent, storage
LP, dispatchable
1
2
3
1 ... 35 85
time (years)
$t \in T$
space (zones)
$z \in Z$
Formulation
Aggregation
Clustering
ESONE-XEL
ESO-XEL
ESO-X
ESONE
ESO
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6/24

Mathematical model formulation

$\forall i \in I$ $\forall a \in A$ $\forall z \in Z$	**Capacity expansion**	• Initial installed capacity • Build rate constraints • Life time constraints • Maximum resource constraints
$\forall c \in C$ $\forall z \in Z$	**System-wide constraints**	• Electricity demand • Reserve, inertia requirements • Emission target • Transmission between zones
$\forall t \in T$ $\forall z \in Z$	**Tech.-wise constraints** **Integer scheduling**	• Power, reserve, inertia provision • Flexibility of generation/storage units • Carbon emissions by technology • Uptime and downtime
$\forall l \in L$	**Endogenous Cost Learning**	• Line segment on cumulative cost curve • Cumulative CAPEX at cumulative capacity
sum	**Objective**	min { CAPEX + mode-specific OPEX }

CF Heuberger, E Rubin, I Staffell, N Shah, N Mac Dowell, Applied Energy, 2017, 204: 831–845

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Mathematical model formulation

$\forall i \in I$ $\forall a \in A$ $\forall z \in Z$	Capacity expansion	$d_{i,a} = DIni_i \quad \forall i, a = 1$ $b_{i,a} \leq BR_i \, \Delta_a \quad \forall i, a > 1$ $d_{i,a} = d_{i,a-1} - b_{i,a-LTIni_i/\Delta_a} + b_{i,a} \ \forall i, a \leq ..; \ d_{i,a} = ..$ $d_{i,a} \leq DMax_i \quad \forall i, a$
$\forall c \in C$ $\forall z \in Z$	System-wide constraints	$\sum_{ig} p2d_{ig,a,c,t} + \sum_{is} s2d_{is,a,c,t} = SD_{c,t,a} \, (1 + TL) - slak_{a,c,t} \, \forall ...$ $\sum_{ig} r_{ig,a,c,t} \, RP_{ig} + \sum_{is} s2r... \geq SD_{c,t,a} \, RM + \sum_{ir} p2d_{ir,a,c,t} \, WR \forall ..$ $\sum_{ig} n_{ig,a,c,t} \, Des_{ig} \, IP_{ig} \geq SI \quad \forall a, c, t$ $\sum_{ig,c,t} e_{ig,a,c,t} \, WF_c \leq SE_a \quad \forall a,$ ...cap const., VoLL constr.
$\forall t \in T$ $\forall z \in Z$	Tech.-wise constraints	$n_{ig,a,c,t} \leq d_{ig,a} \quad \forall ig, a, c, t$ $u_{ig,a,c,t} \geq n_{ig,a,c,t} - n_{ig,a,c,t-1} \quad \forall ig, a, c, t$
	Integer scheduling	switch, min/max, reserve, storage charging/discharging.. ...
$\forall l \in L$	Endogenous Cost Learning	$\sum_l \rho_{il,a,l} = 1 \quad \forall il, a$ $xs_{il,a,l} \geq Xlo_{il,l} \, \rho_{il,a,l} \quad \forall il, a, l,$ ..lin. interpol. constr.
sum	Objective	$min\{tsc\}; tsc = \sum_{i \in I \setminus il,a} CAPEX_i \, b_{i,a}.. + OPEX_i \, n_{i,a,c,t} + ..$

CF Heuberger, E Rubin, I Staffell, N Shah, N Mac Dowell, Applied Energy, 2017, 204: 831–845

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The ESO framework – key features

1

Bottom-up engineering model of a wide range of technologies, features, learning	➢ Technology agnostic

2

Cost-optimal capacity planning considering adequacy, security, carbon	➢ Transition planning

3

Granular representation of time and space with long-term foresight	➢ Operational detail

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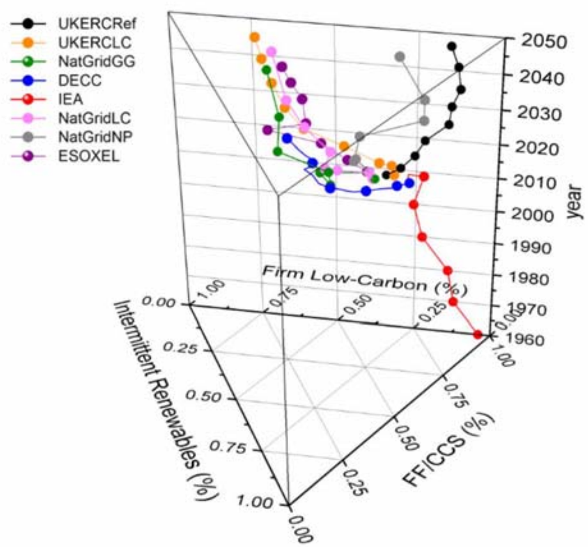
The ESO framework – key applications



Model validation: The ESO-XEL trajectories fall well within the branch of other UK power system models.

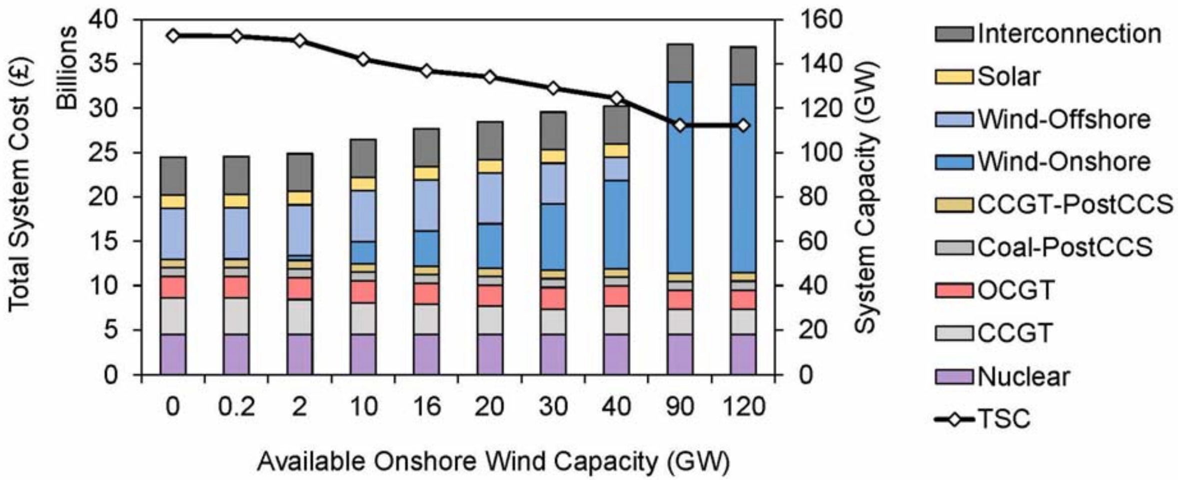
1

➢ Systemic technology valuation

2

➢ Optimal generation expansion planning

System impact of onshore wind in 2035



The value of onshore wind changes as a function of the available amount of capacity.

CF Heuberger, I Staffell, N Shah, N Mac Dowell, Computers and Chemical Engineering, 2017, ISSN: 0098-1354

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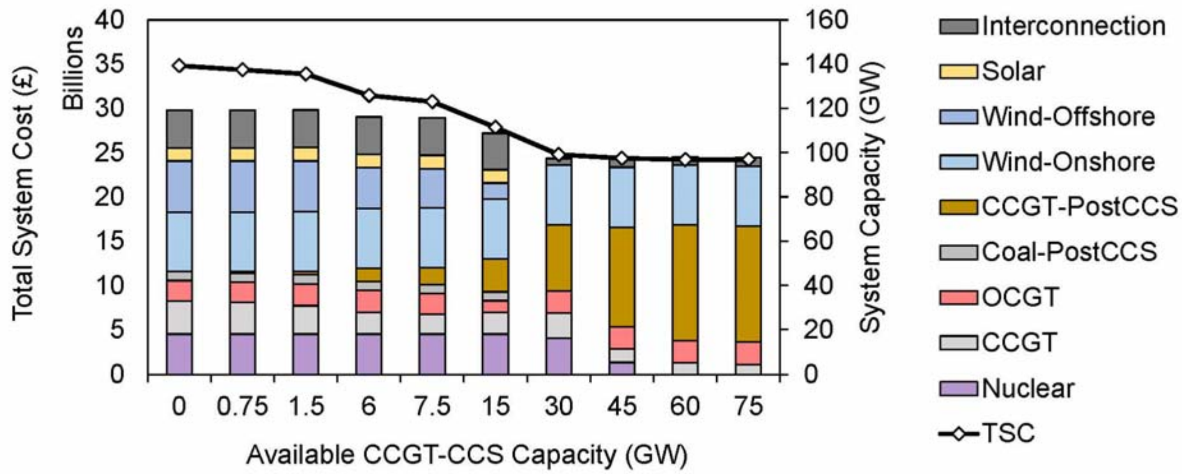
System impact of CCGT post-combustion CCS



- The deployment of CCS capacity can reduce total capacity requirements and TSC.
- CCS utilisation increases as unabated and intermittent capacity is replaced.

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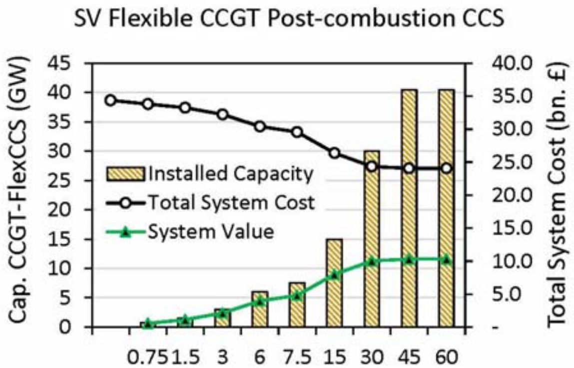
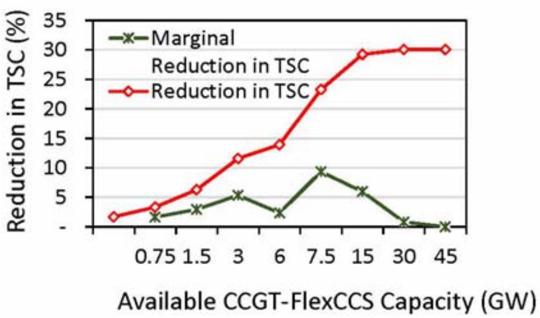
Flexible CCGT post-combustion CCS





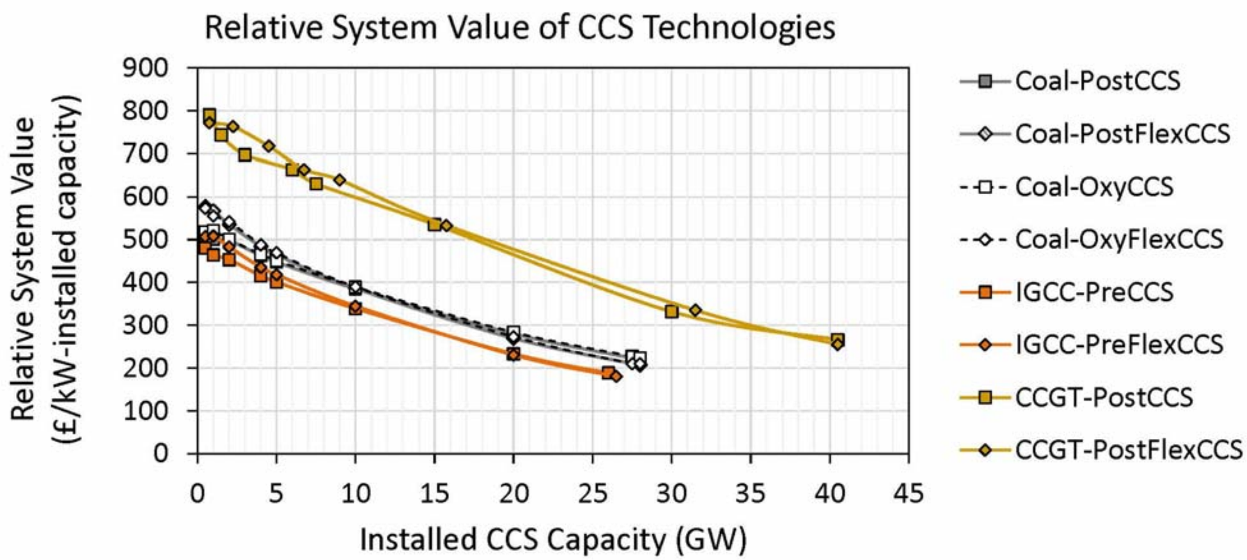
Base case: without CCS	TSC Reduction	Avg. Asset Utilisation
CCS cases: + 5 GW total	↓	↑
coal-post, coal-oxy, IGCC-pre, CCGT-post CCS	-6.2 %	+12%
flexible coal-post, coal-oxy, IGCC-pre, CCGT-post CCS	-6.3 %	+11 %

Start-up cost -2 % (CCGT)
No Load/fuel -0.4% (CCS, OCGT)
CAPEX + 0.2% (CCS)

CF Heuberger, I Staffell, N Shah, N Mac Dowell, Valuing Flexibility in CCS Power Plants – FlexEVAL project for the IEAGHG, 2016

System Value – Summary for CCS options

CCGT-CCS technologies provide the highest relative system value in the UK power system.



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System Value – Summary for CCS options

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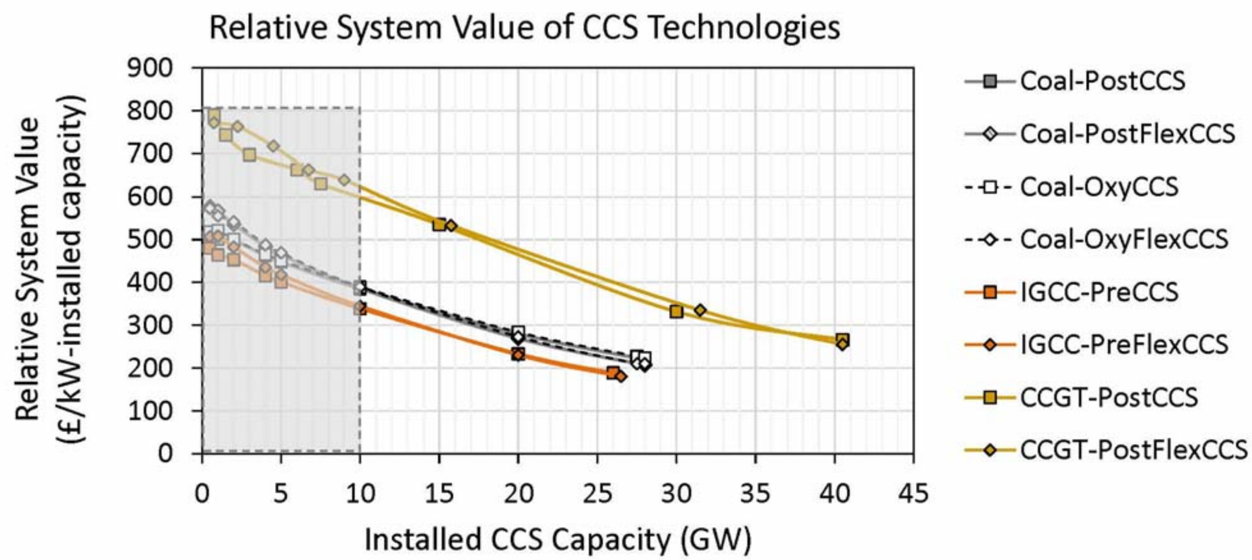
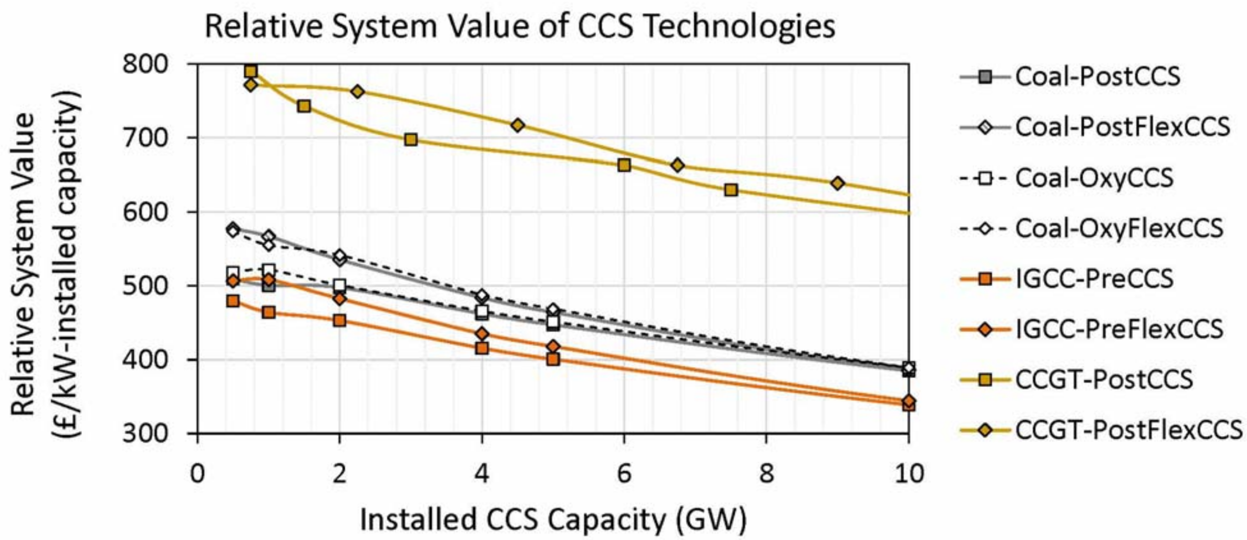


Value of flexible CCS options

Flexible CCS technologies provide an additional value by accommodating higher levels of intermittent renewable capacity and power generation.



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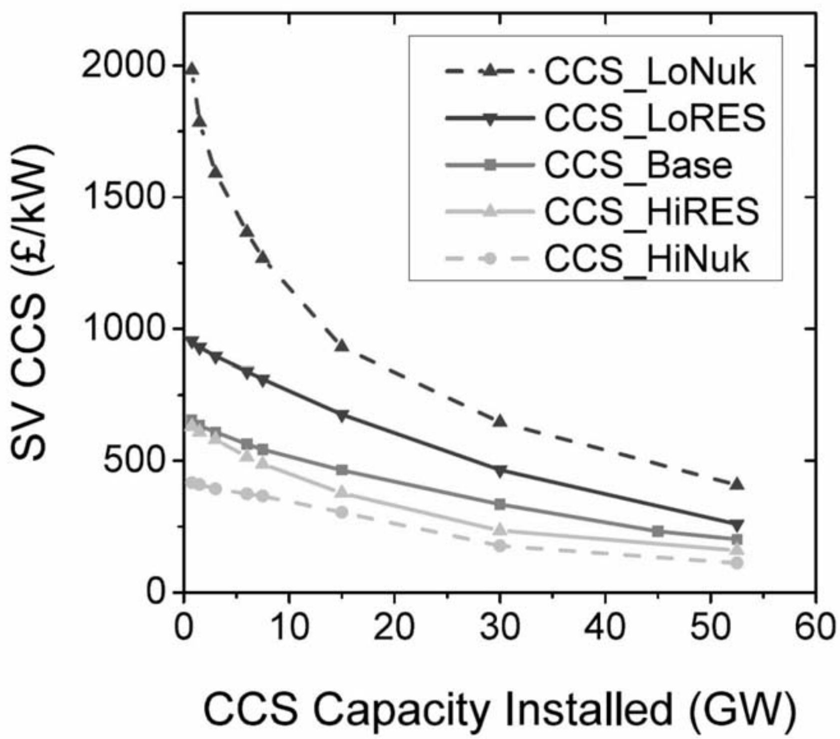
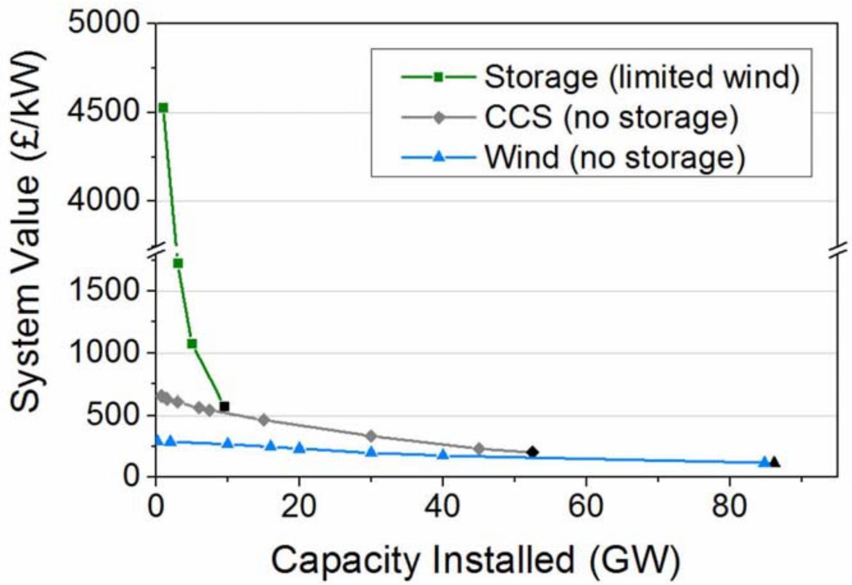
SV is sensitive to the system conditions



The availability of low-carbon power generators, firm or intermittent, influences the SV.

System value – CCS, wind, energy storage



Initially energy storage capacity reduce total system cost most. CCS and Wind capacity are valuable to the system.

CF Heuberger, I Staffell, N Shah, N Mac Dowell, Computers and Chemical Engineering, 2017, ISSN: 0098-1354

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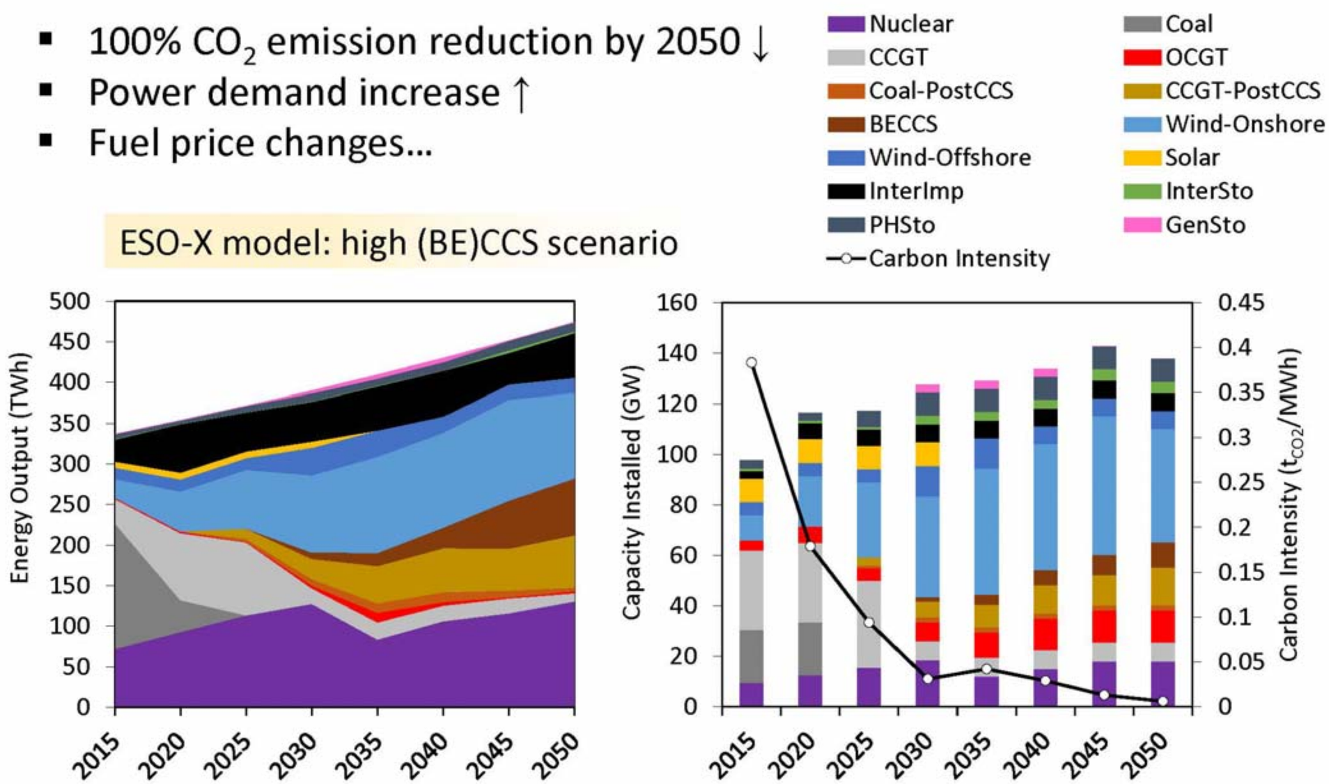
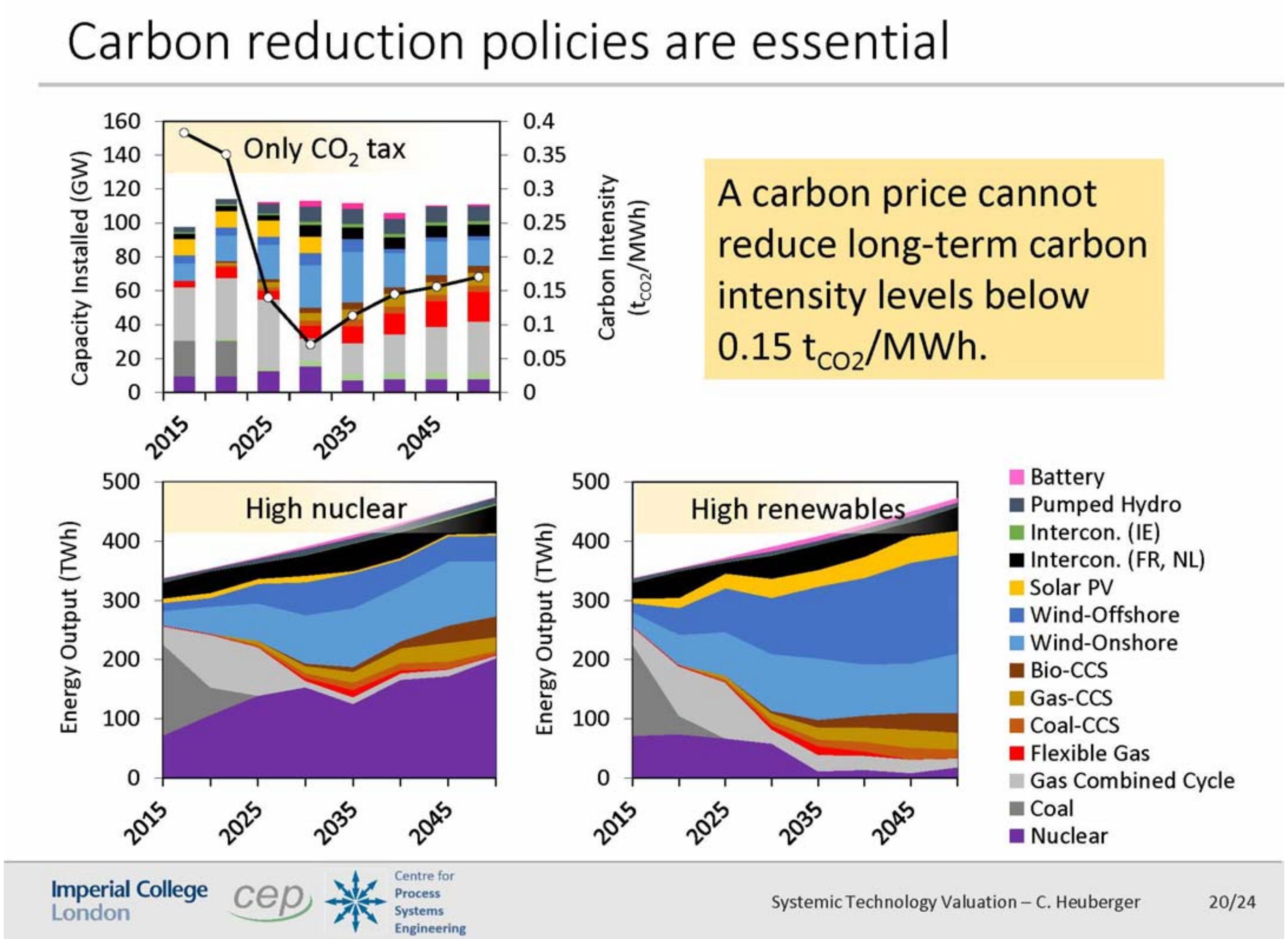
Optimal generation expansion for the UK

- 100% CO_2 emission reduction by 2050 ↓
- Power demand increase ↑
- Fuel price changes...




Carbon reduction policies are essential
Only CO2 tax
Capacity Installed (GW)
Carbon Intensity (tCO2/MWh)
160
140
120
100
80
60
40
20
0
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2015
2025
2035
2045
A carbon price cannot reduce long-term carbon intensity levels below 0.15 tCO2/MWh.
High nuclear
High renewables
Energy Output (TWh)
500
400
300
200
100
0
Battery
Pumped Hydro
Intercon. (IE)
Intercon. (FR, NL)
Solar PV
Wind-Offshore
Wind-Onshore
Bio-CCS
Gas-CCS
Coal-CCS
Flexible Gas
Gas Combined Cycle
Coal
Nuclear
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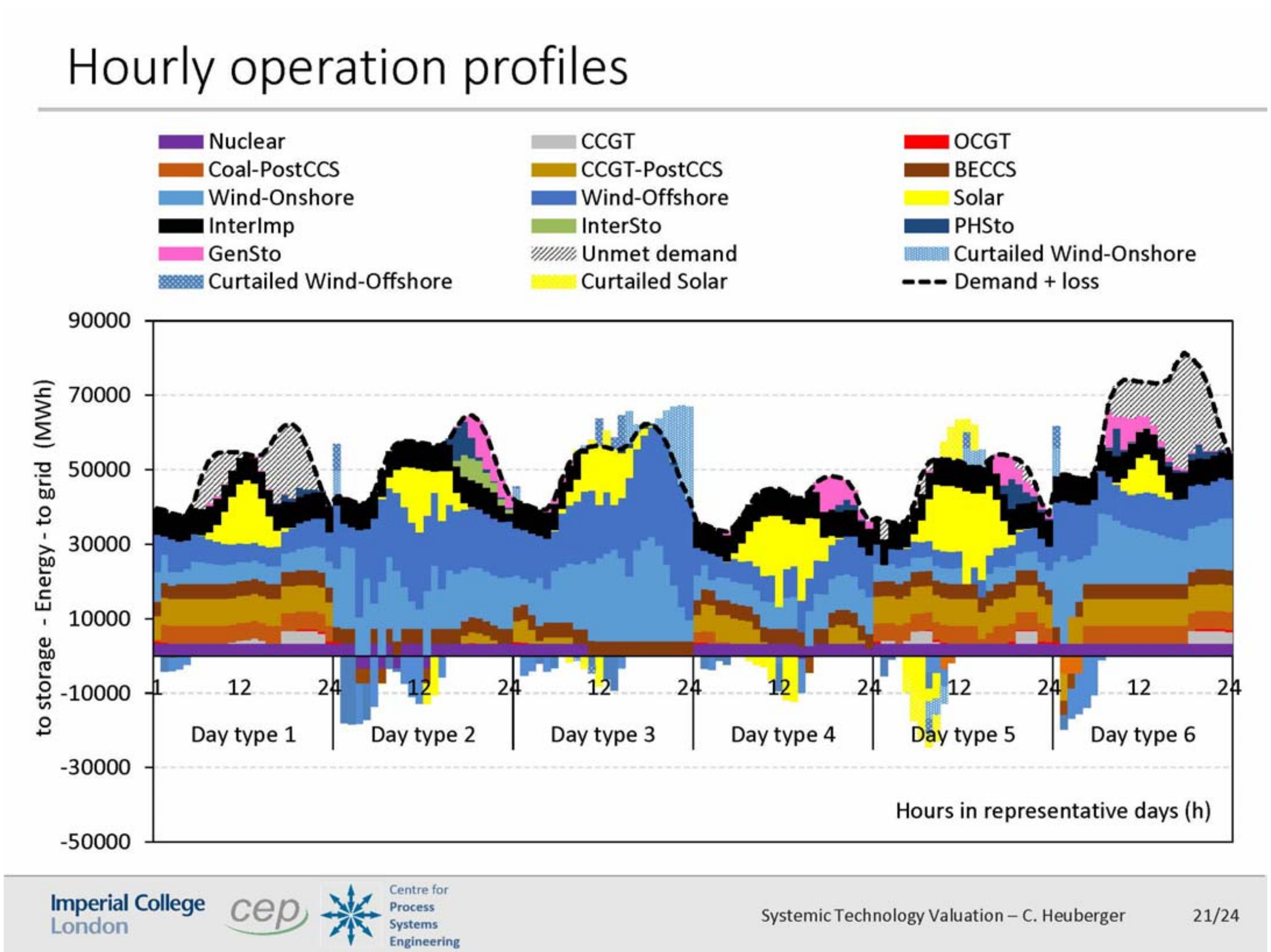
Hourly operation profiles
Nuclear
Coal-PostCCS
Wind-Onshore
InterImp
GenSto
Curtailed Wind-Offshore
CCGT
CCGT-PostCCS
Wind-Offshore
InterSto
Unmet demand
Curtailed Solar
OCGT
BECCS
Solar
PHSto
Curtailed Wind-Onshore
Demand + loss
to storage - Energy - to grid (MWh)
90000
70000
50000
30000
10000
-10000
-30000
-50000
Day type 1
Day type 2
Day type 3
Day type 4
Day type 5
Day type 6
Hours in representative days (h)
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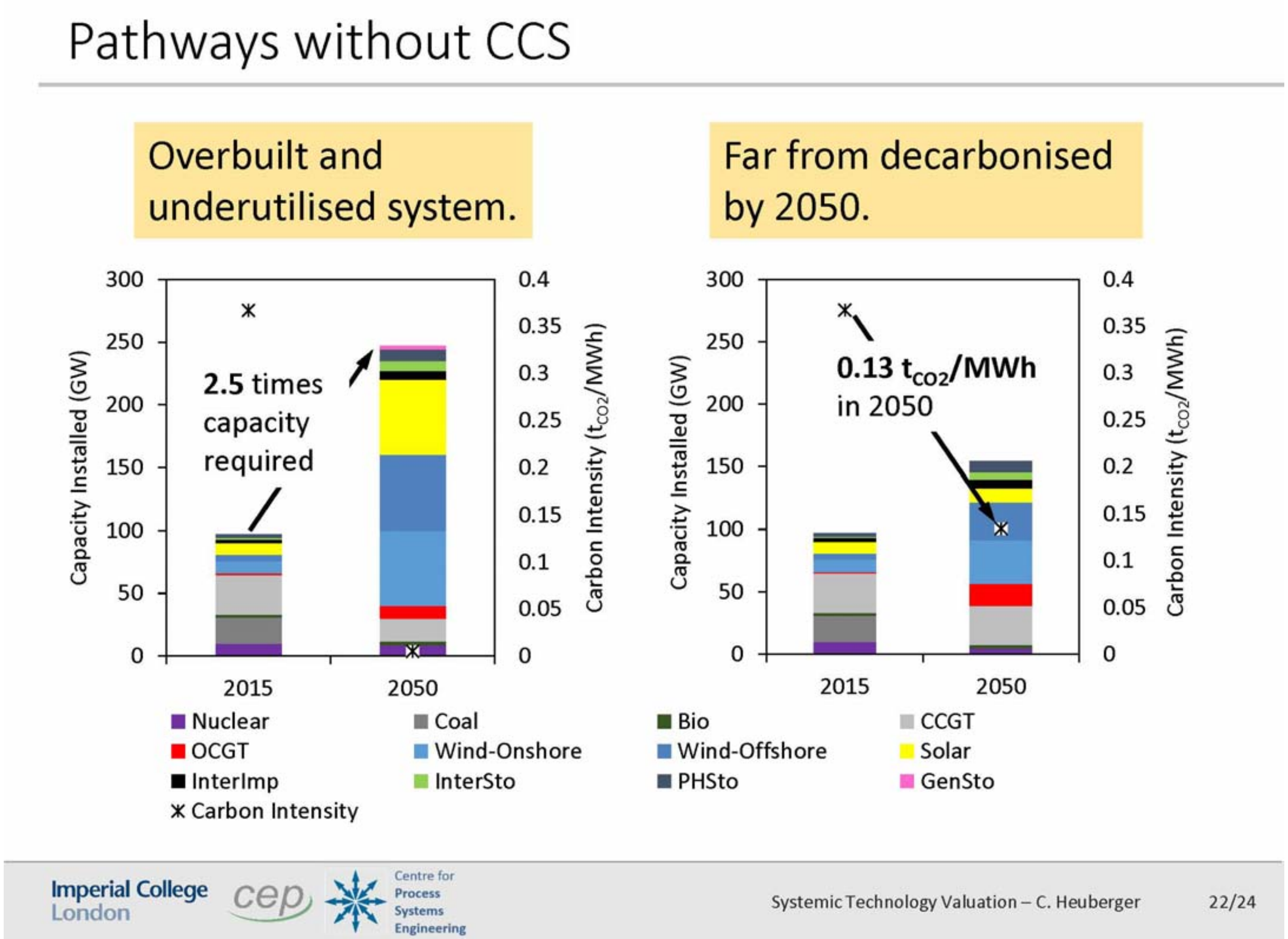
Pathways without CCS
Overbuilt and underutilised system.
Far from decarbonised by 2050.
300
250
200
150
100
50
0
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Capacity Installed (GW)
Carbon Intensity (t_{CO2}/MWh)
2.5 times capacity required
0.13 t_{CO2}/MWh in 2050
2015
2050
Nuclear
Coal
Bio
CCGT
OCGT
Wind-Onshore
Wind-Offshore
Solar
InterImp
InterSto
PHSto
GenSto
Carbon Intensity
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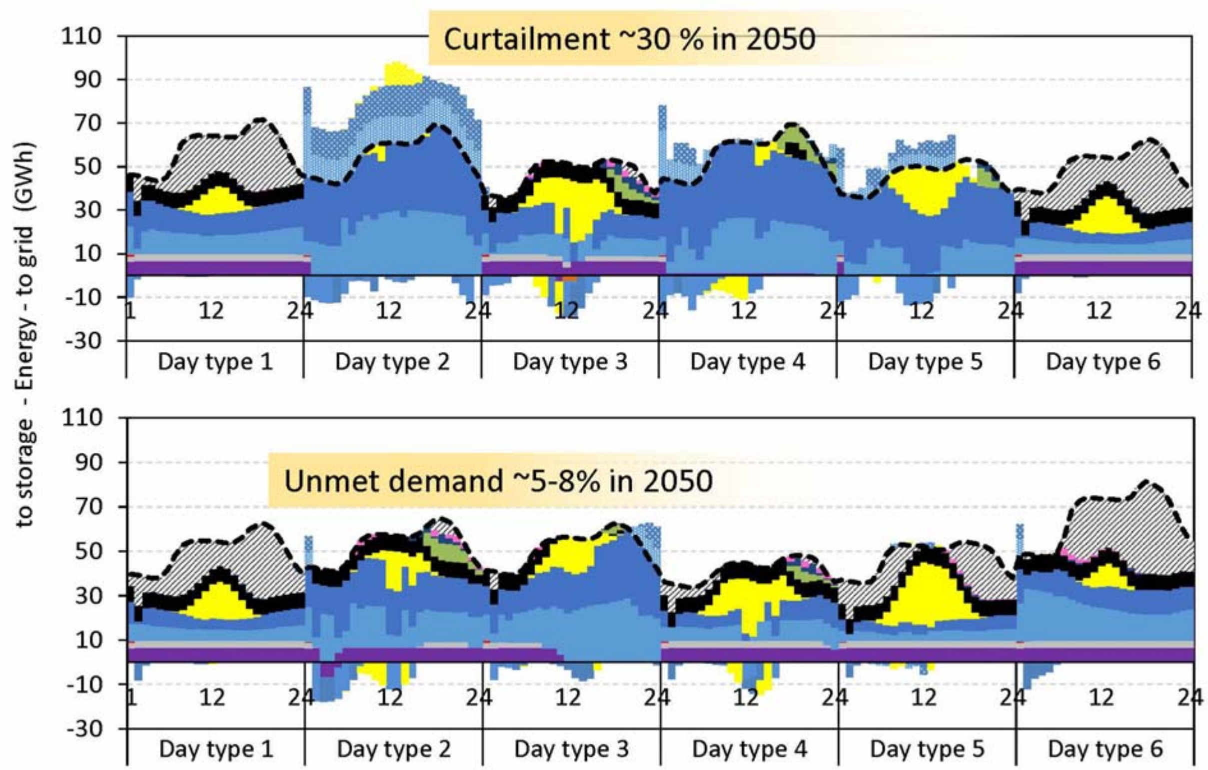
Compromising security of supply



Conclusions

The value of a power technology changes as a function of the penetration level and is dependent on the incumbent system conditions.

Flexible CCS technologies provide an additional value in being able to accommodate higher levels of intermittent renewable capacity and power generation.

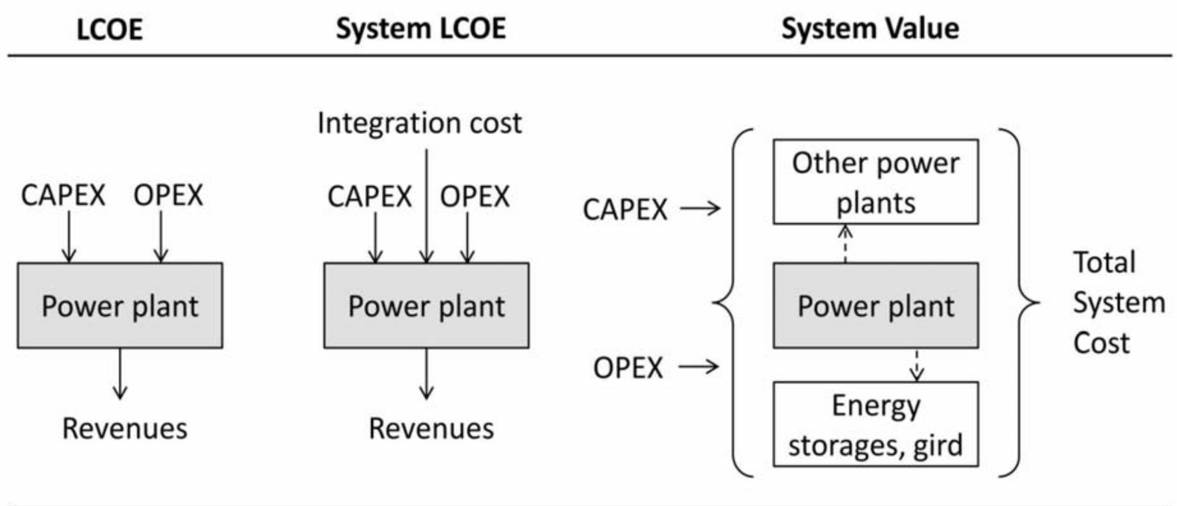
Total system cost by mid-century can be reduced when investments into low-carbon technologies are made now.

Thank you. Feel free to ask any questions.

Clara F. Heuberger, Iain Staffell, Nilay Shah, Niall Mac Dowell
Contact: c.heuberger14@imperial.ac.uk

BACKUP

LCOE, System LCOE, System Value

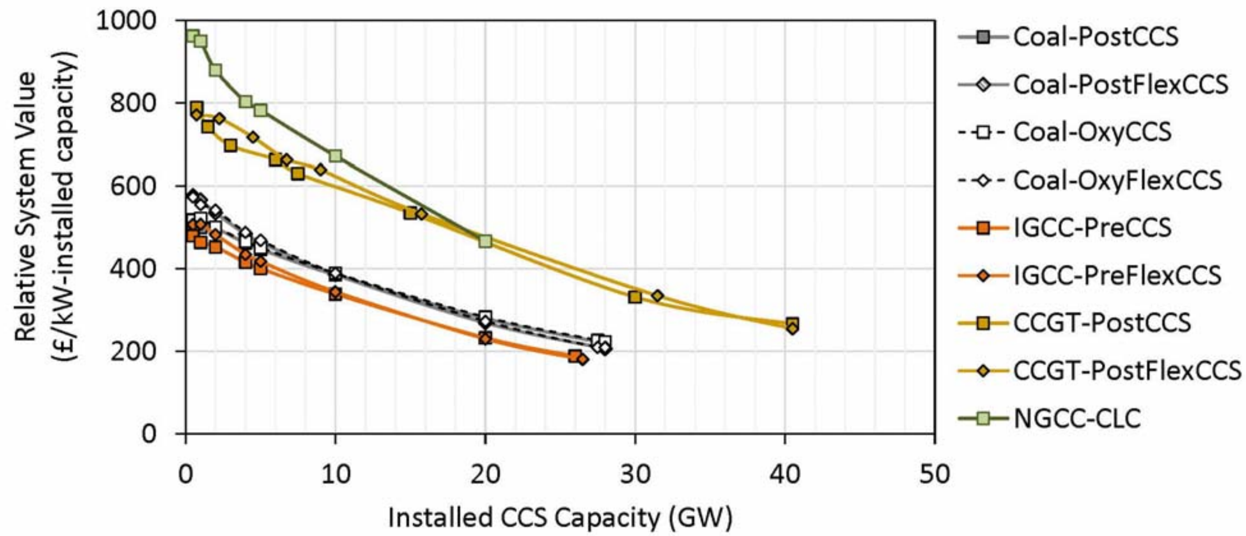


Economic calculation over power plant lifetime

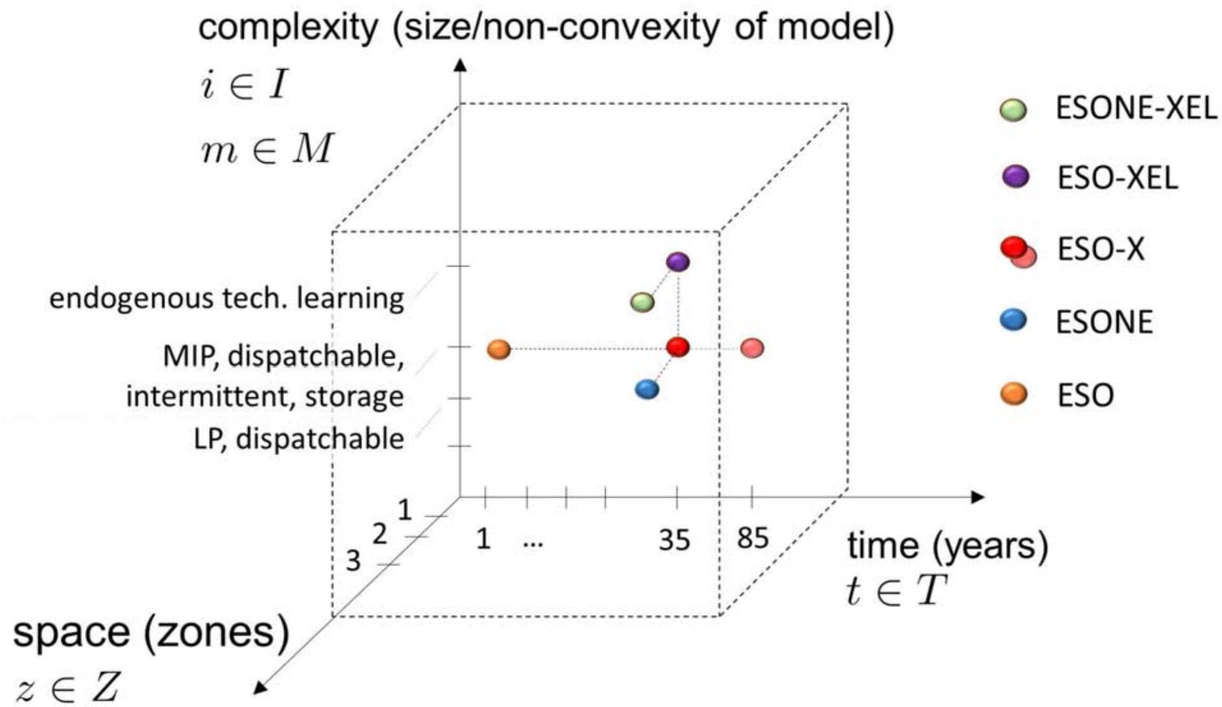
Mathematical model considering power plant under long-term system conditions

System Value – Summary for CCS Options

Flexible CCS technologies provide an additional value by accommodating higher levels of intermittent renewable capacity and power generation.



Power systems modelling - dimensions



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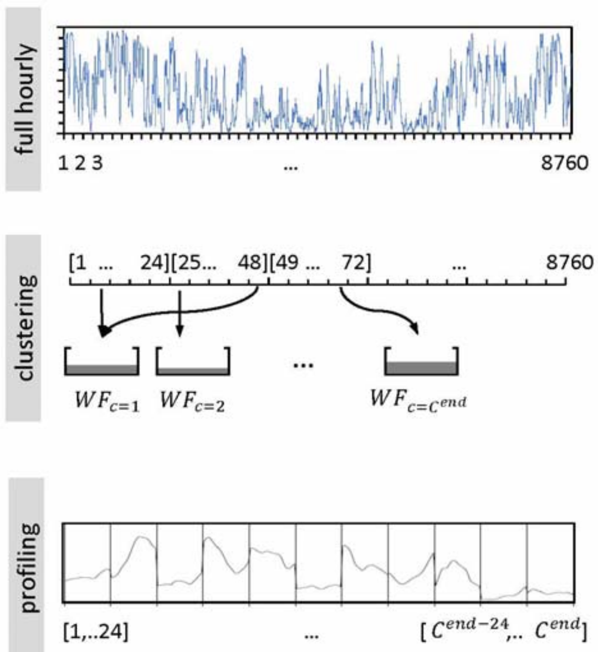
Modelling – Representation of Time



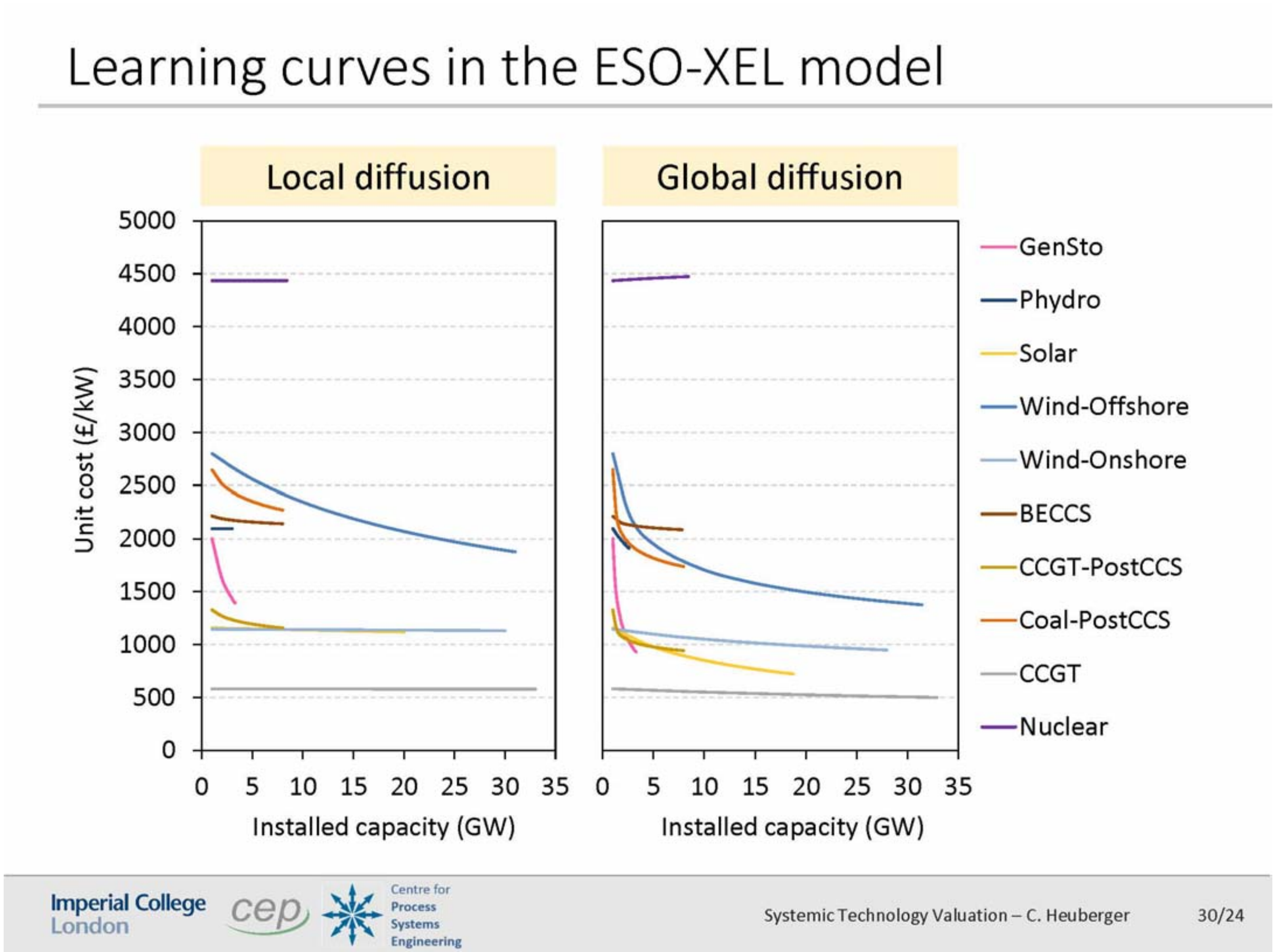
$8760\ hours \cdot 35\ years$
$= \mathbf{306,600}\ hours$

94 % size reduction

$21\ clusters \cdot 24\ hours \cdot 35\ years$
$= \mathbf{17,640}\ hours$

The average error in system-level results range from -1.7% to +2.5%.

CF Heuberger, E Rubin, I Staffell, N Shah, N Mac Dowell, Applied Energy, 2017, 204: 831–845


Learning curves in the ESO-XEL model
Local diffusion
Global diffusion
Unit cost (£/kW)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0 5 10 15 20 25 30 35
Installed capacity (GW)
0 5 10 15 20 25 30 35
Installed capacity (GW)
GenSto
Phydro
Solar
Wind-Offshore
Wind-Onshore
BECCS
CCGT-PostCCS
Coal-PostCCS
CCGT
Nuclear
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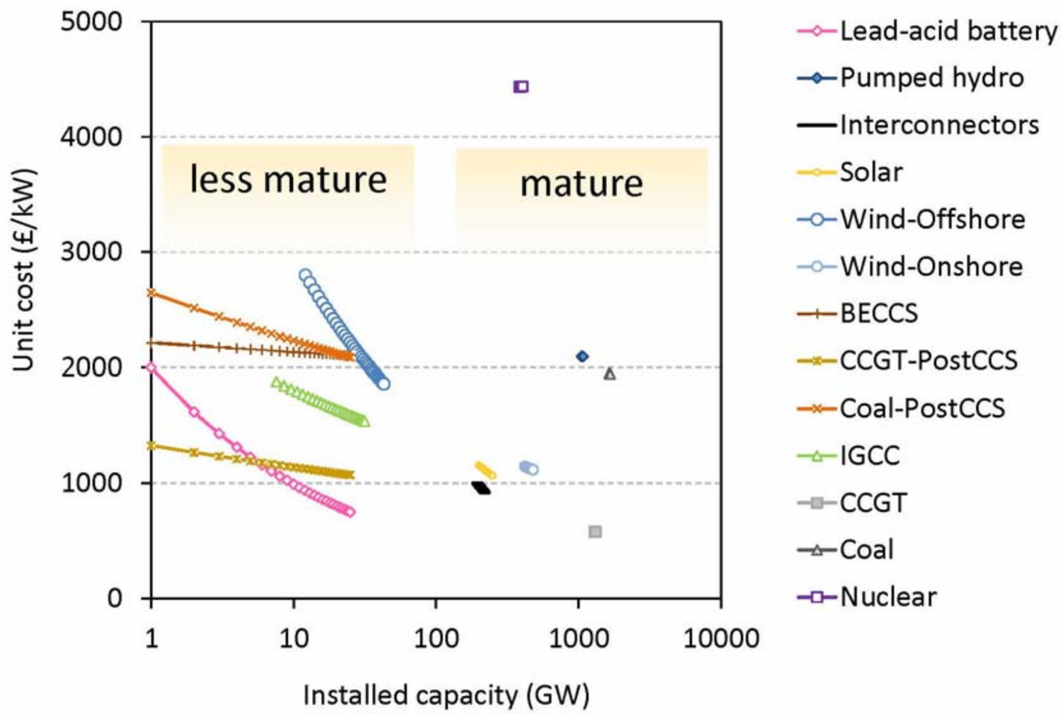
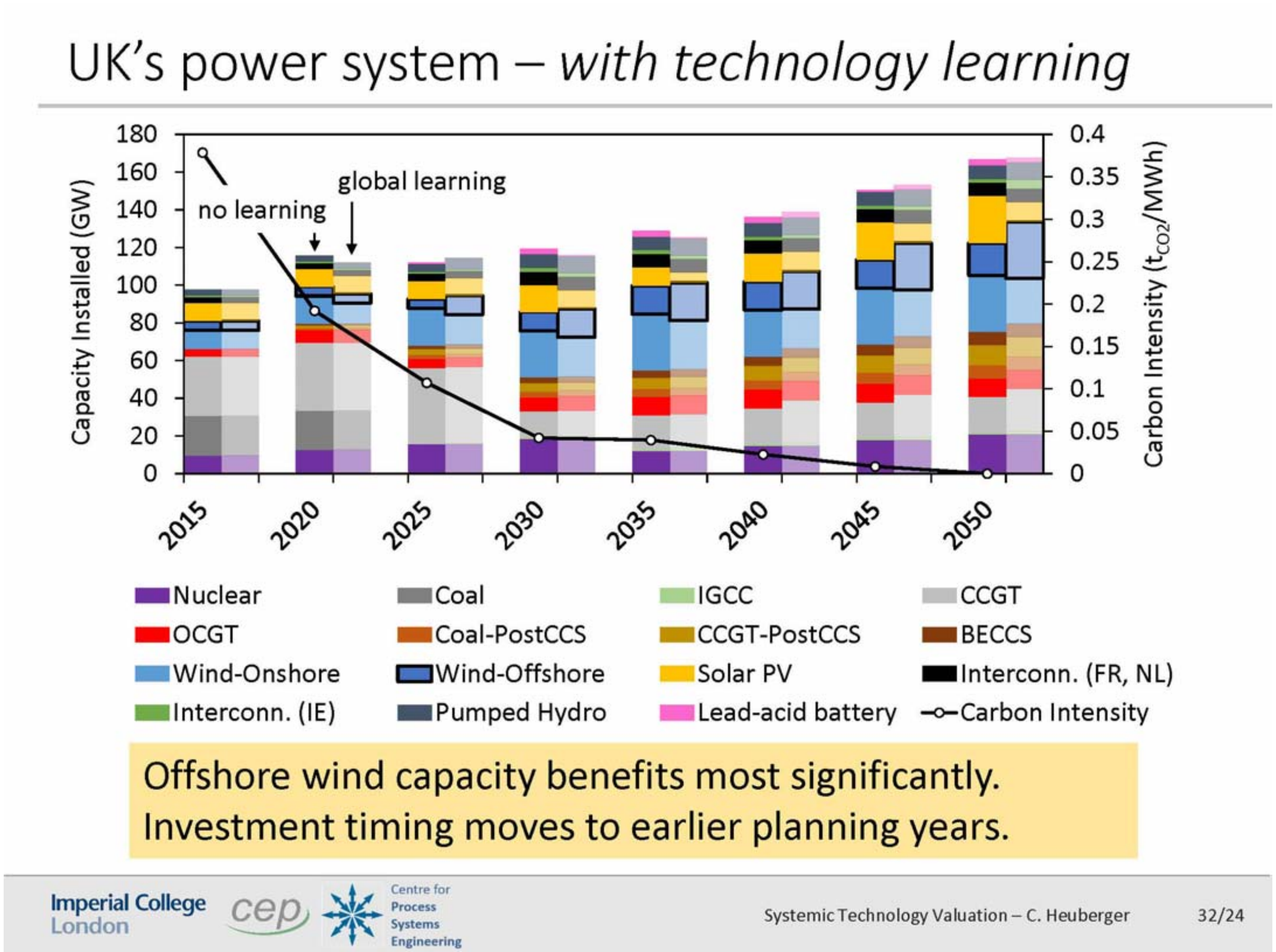
Nominal cost reductions



E Rubin, IML Azevedo, P Jaramillo, S Yeh, Energy Policy, 2015, 86: p. 198–218


UK's power system – *with technology learning*
Capacity Installed (GW)
Carbon Intensity (t_{CO2}/MWh)
no learning
global learning
180
160
140
120
100
80
60
40
20
0
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2015
2020
2025
2030
2035
2040
2045
2050
Nuclear
Coal
IGCC
CCGT
OCGT
Coal-PostCCS
CCGT-PostCCS
BECCS
Wind-Onshore
Wind-Offshore
Solar PV
Interconn. (FR, NL)
Interconn. (IE)
Pumped Hydro
Lead-acid battery
Carbon Intensity
Offshore wind capacity benefits most significantly.
Investment timing moves to earlier planning years.
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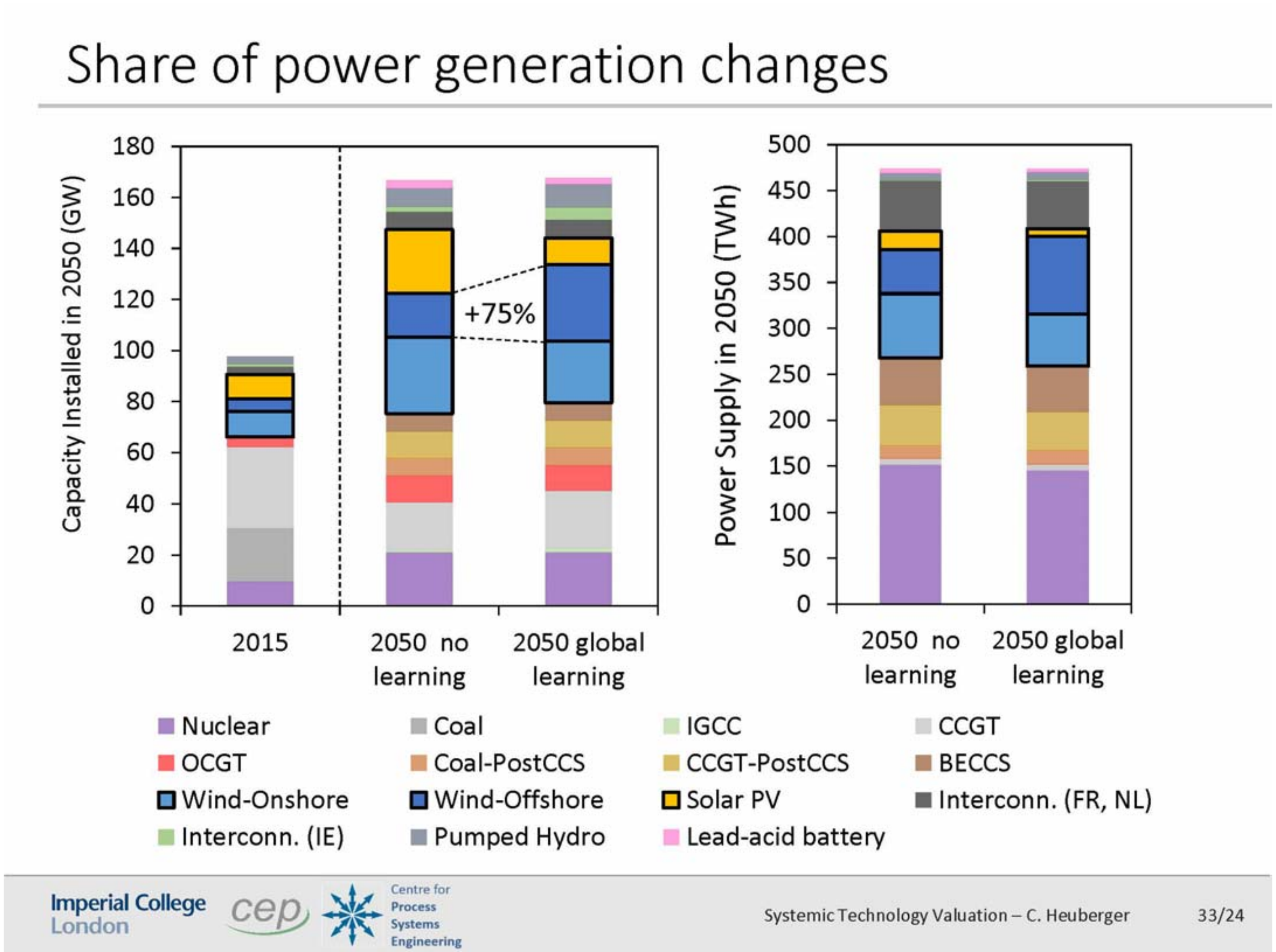
32/24


Share of power generation changes
Capacity Installed in 2050 (GW)
180
160
140
120
100
80
60
40
20
0
+75%
2015
2050 no learning
2050 global learning
Power Supply in 2050 (TWh)
500
450
400
350
300
250
200
150
100
50
0
2050 no learning
2050 global learning
Nuclear
Coal
IGCC
CCGT
OCGT
Coal-PostCCS
CCGT-PostCCS
BECCS
Wind-Onshore
Wind-Offshore
Solar PV
Interconn. (FR, NL)
Interconn. (IE)
Pumped Hydro
Lead-acid battery
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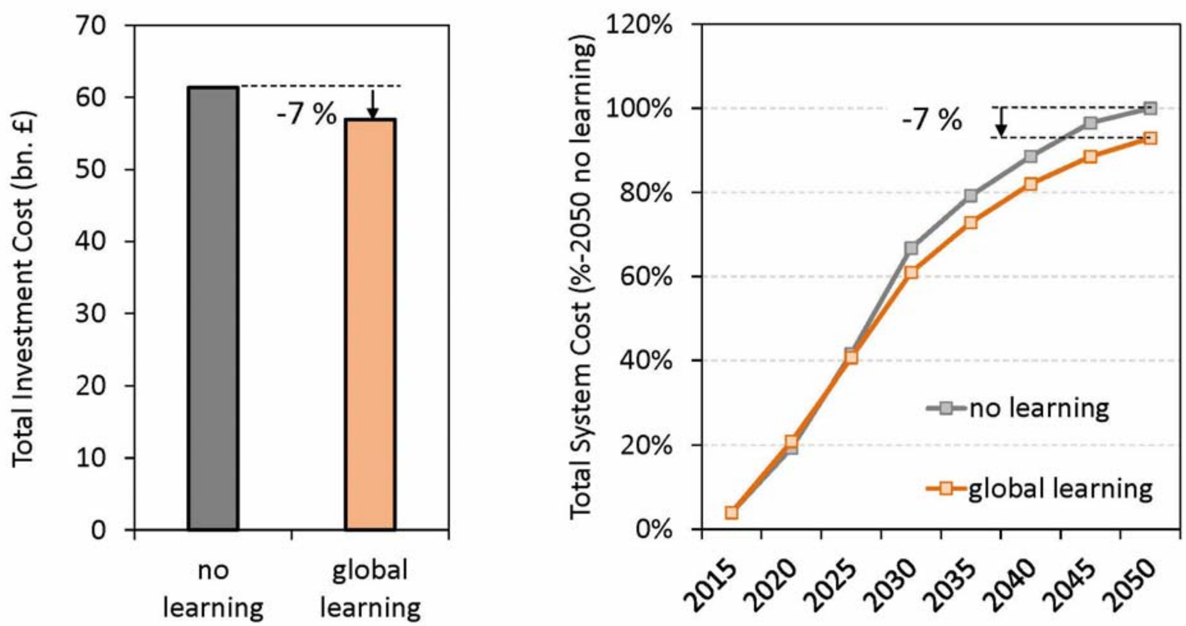
Total system cost reduce if learning is fostered



Investment cost and total system cost (2015-2050) can be reduced if technology learning encouraged.

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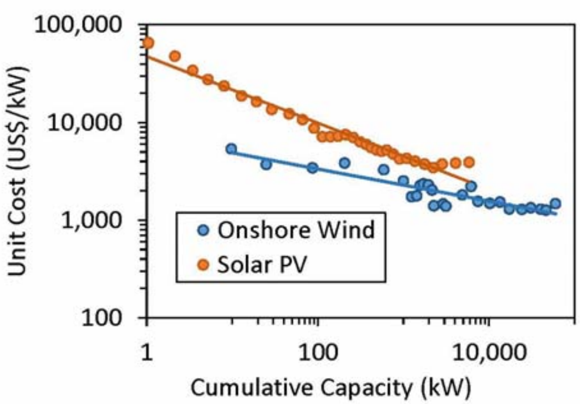
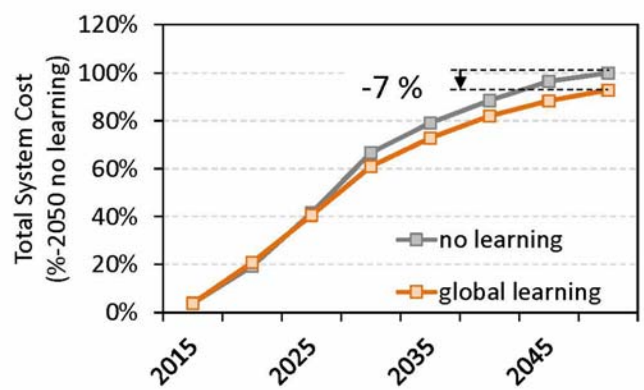
Modelling technology learning

Exogenous vs.	Endogenous
Cost reduction over ***time***	*Cost reduction upon* ***deployment***
→ *Input parameter*	→ *Model constraints*

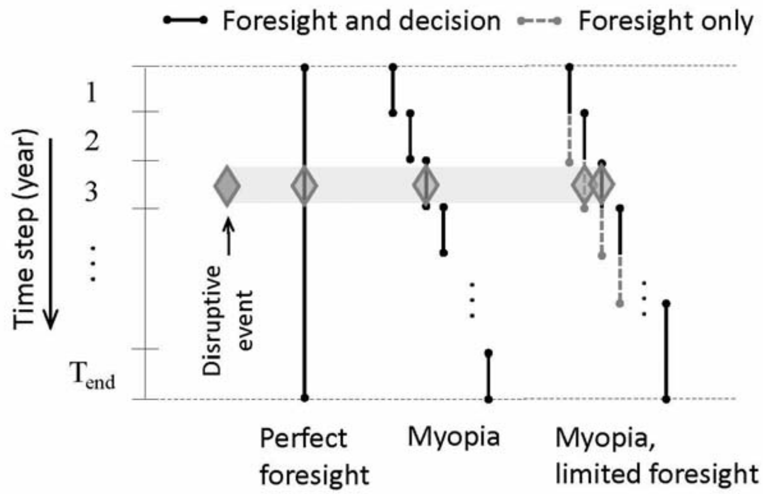


GF Nemet, Energy Policy, 2009, 37(3): p. 825–835

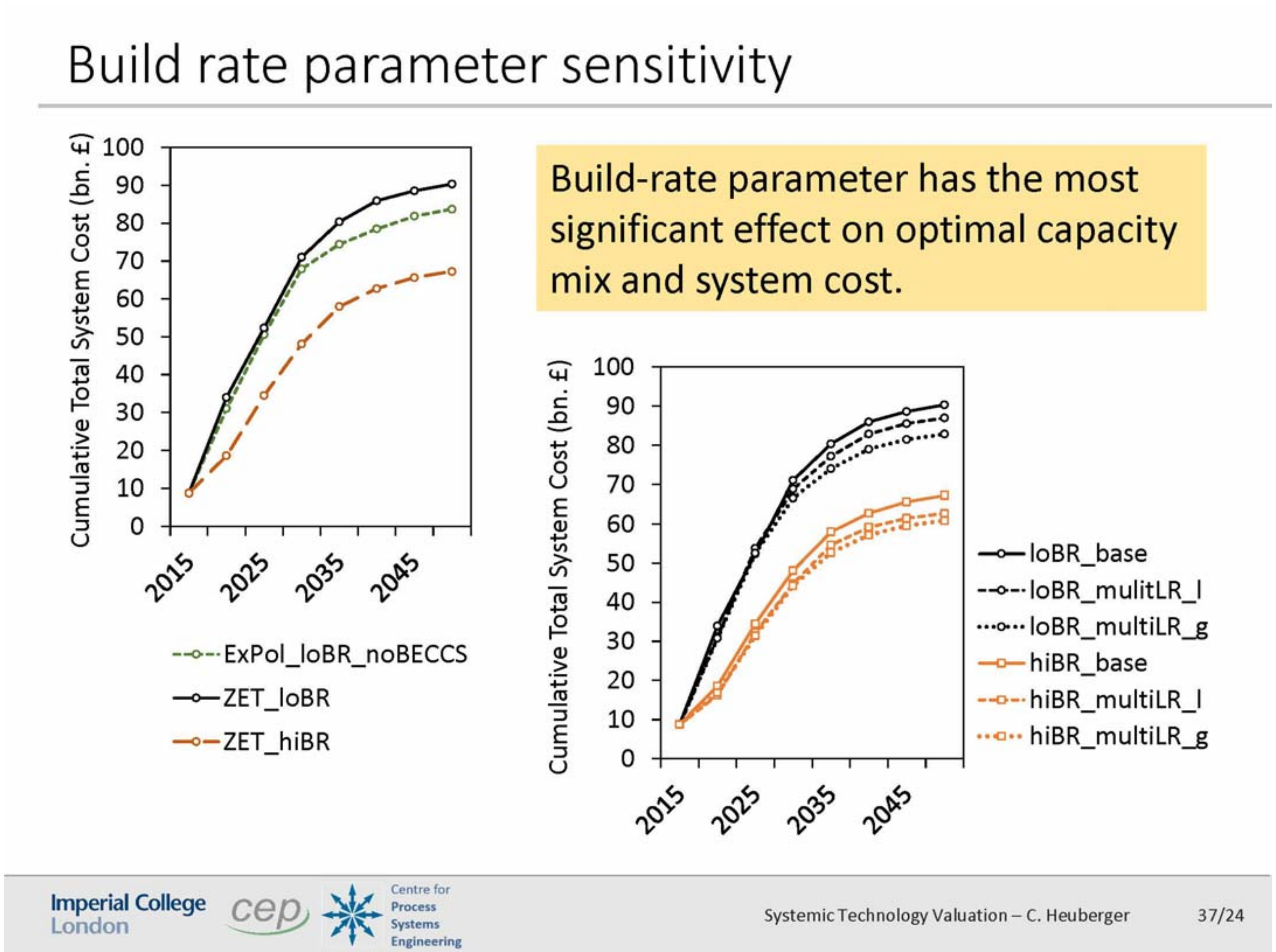


CF Heuberger, N Mac Dowell, Grantham Briefing Note 7, 2017

Perfect foresight vs. myopic planning



- Myopic decision making as rolling horizon optimisation
- Foresight horizon ≠ decision horizon
- Disruptive event can be assessed as part of the optimisation


Build rate parameter sensitivity
Build-rate parameter has the most significant effect on optimal capacity mix and system cost.
Cumulative Total System Cost (bn. £)
100
90
80
70
60
50
40
30
20
10
0
2015
2025
2035
2045
ExPol_loBR_noBECCS
ZET_loBR
ZET_hiBR
loBR_base
loBR_mulitLR_l
loBR_multiLR_g
hiBR_base
hiBR_multiLR_l
hiBR_multiLR_g
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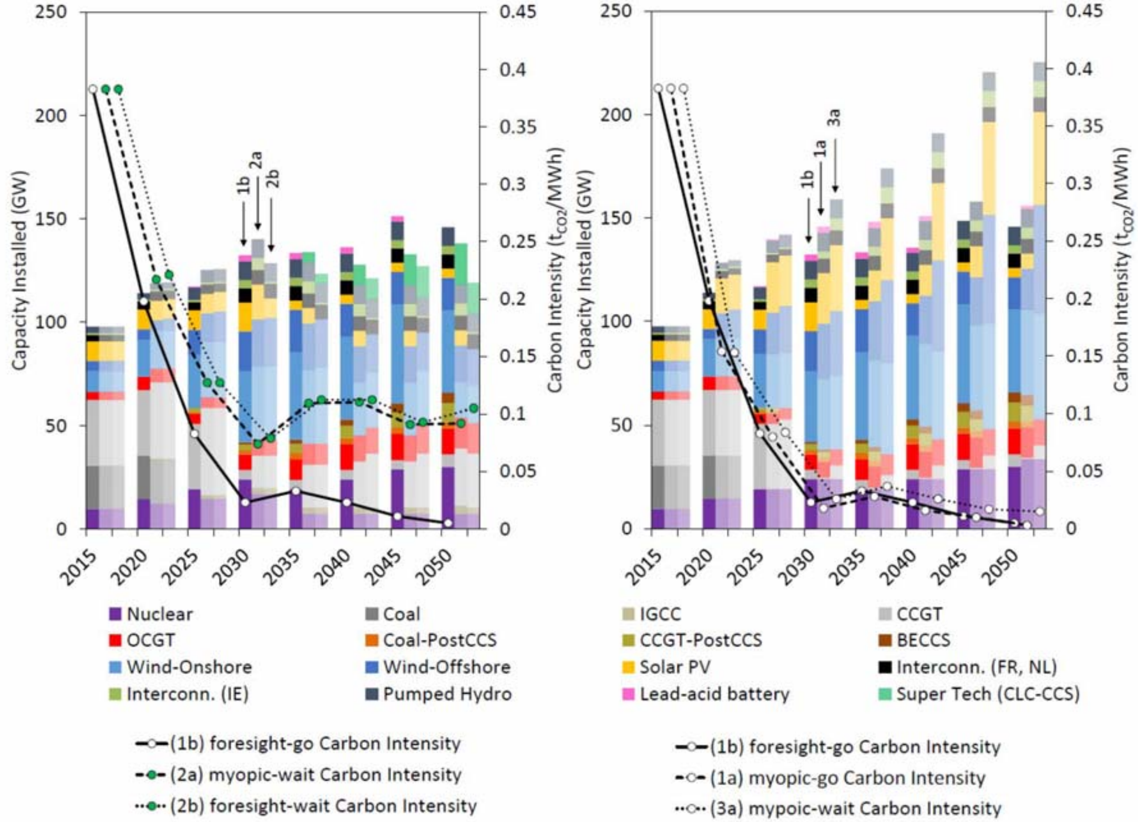
Super technology



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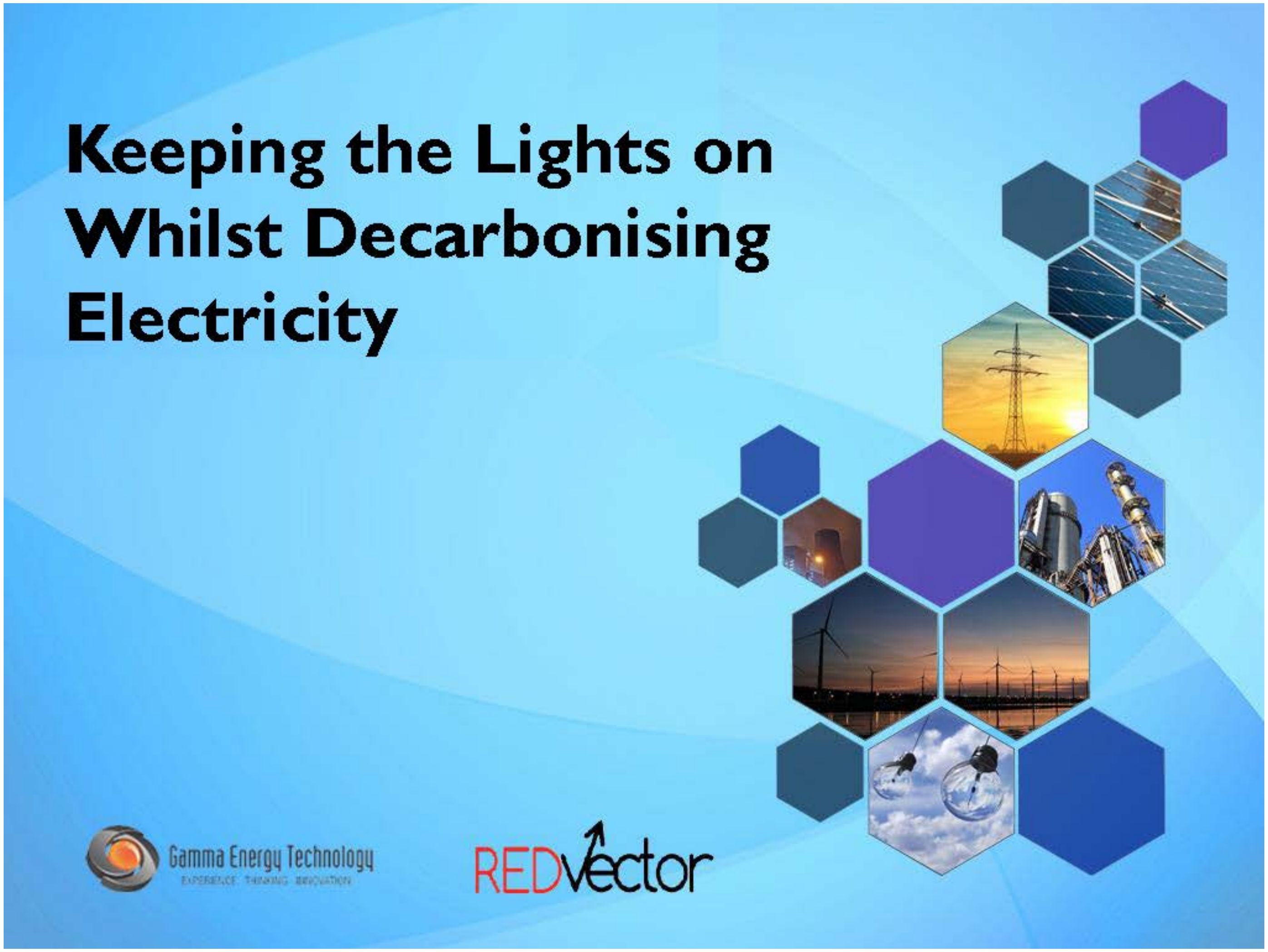
5b. Decarbonising the Australian National Electricity Market—Implications for CCS

Andy Boston, Red Vector


Keeping the Lights on Whilst Decarbonising Electricity
Gamma Energy Technology
REDVector

Acknowledgements

The authors wish to acknowledge financial assistance provided through Australian National Low Emissions Coal Research and Development (ANLEC R&D). ANLEC R&D is supported by Australian Coal Association Low Emissions Technology Limited and the Australian Government through the Clean Energy Initiative.

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- Head of Energy Research Partnership Analysis Team
- Technical Head of Modelling for E.ON UK
- Head of Business Modelling Team for PowerGen
- Thermodynamics, Central Electricity Generating Board

Dr Geoff Bongers CPChem GACID

Director of Gamma Energy Technologies

More than 13 years experience in working with Global Mining, Aluminium and Energy companies.

Steph Byrom

Gamma Energy Technologies

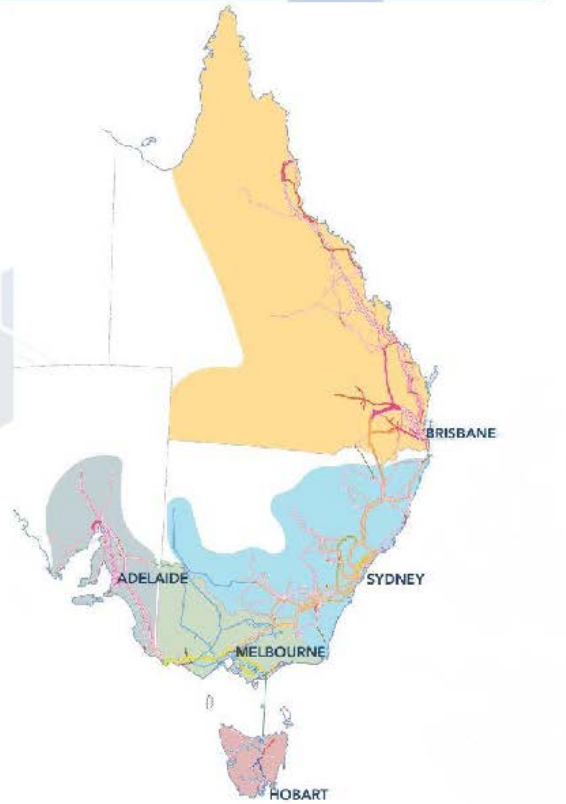
Four years at Rio Tinto specialising in energy and the environment

Context

The National Electricity Market has embarked upon a pathway to a gradual decarbonisation, driven at State and Federal Governments and some by commitments made in Paris.

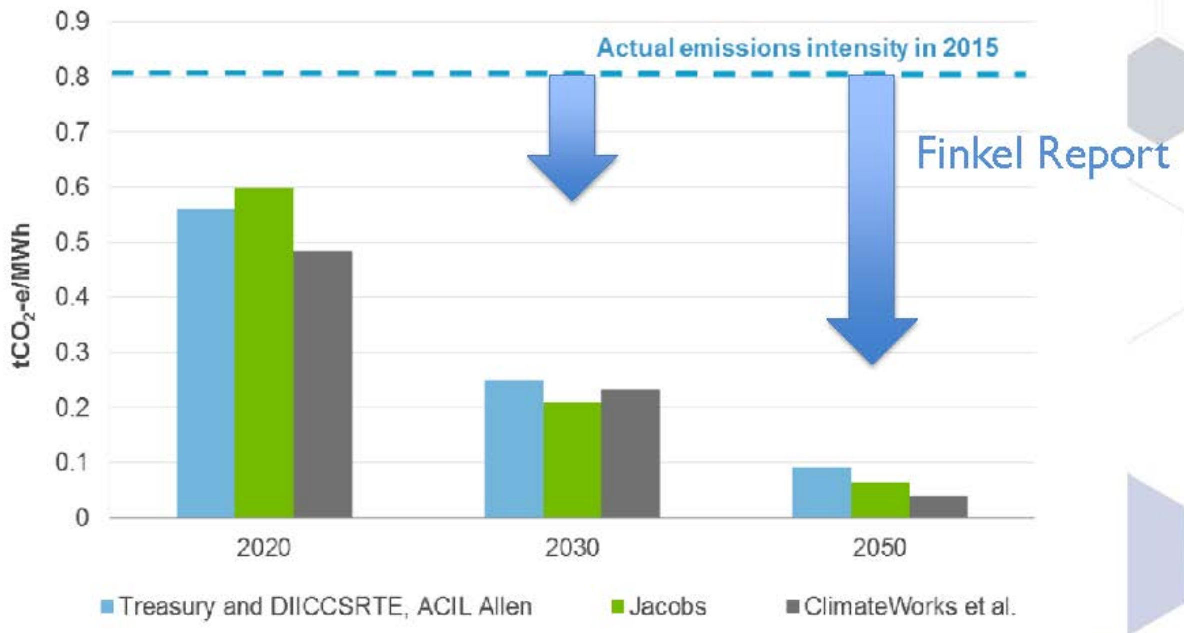
Key questions for existing generation fleet and new technologies:

Maintaining grid stability
Is there a silver bullet?
State vs NEM
Comparing tech cost
Cost to consumer



Meeting 2 degrees

Figure 5 Emissions intensity of electricity generation, 2 degree pathways



Policy Options for Australia's Electricity Supply Sector, By Climate Change Authority, Aug 2016

Overall Messages

It is important to consider the whole system across all timescales to 2050 and beyond

- The value of a technology depends on existing grid
- Chasing intermediate targets whilst ignoring the long term can be suboptimal
- Energy supply is only one of several grid services

A secure grid requires a range of essential services

- Traditional grid service suppliers are disappearing
- Services need valuing to reward existing providers and attract new suppliers
- Existing plant can provide many services if flexible
- Inflexible plant will struggle to survive

Overall Messages

The solution will be diverse

- To resolve the trilemma, a range of technologies will be required
- Each technology brings a different range of services
- Each state has unique problems and opportunities

Providing reliable low emissions electricity comes at a cost

- All low carbon energy forms are more expensive than existing assets
- Total system optimisation will lead to the lowest cost highest reliability outcomes

Modelling

MEGS: Modelling Energy & Grid Services

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MEGS balances several services essential to grid operation:

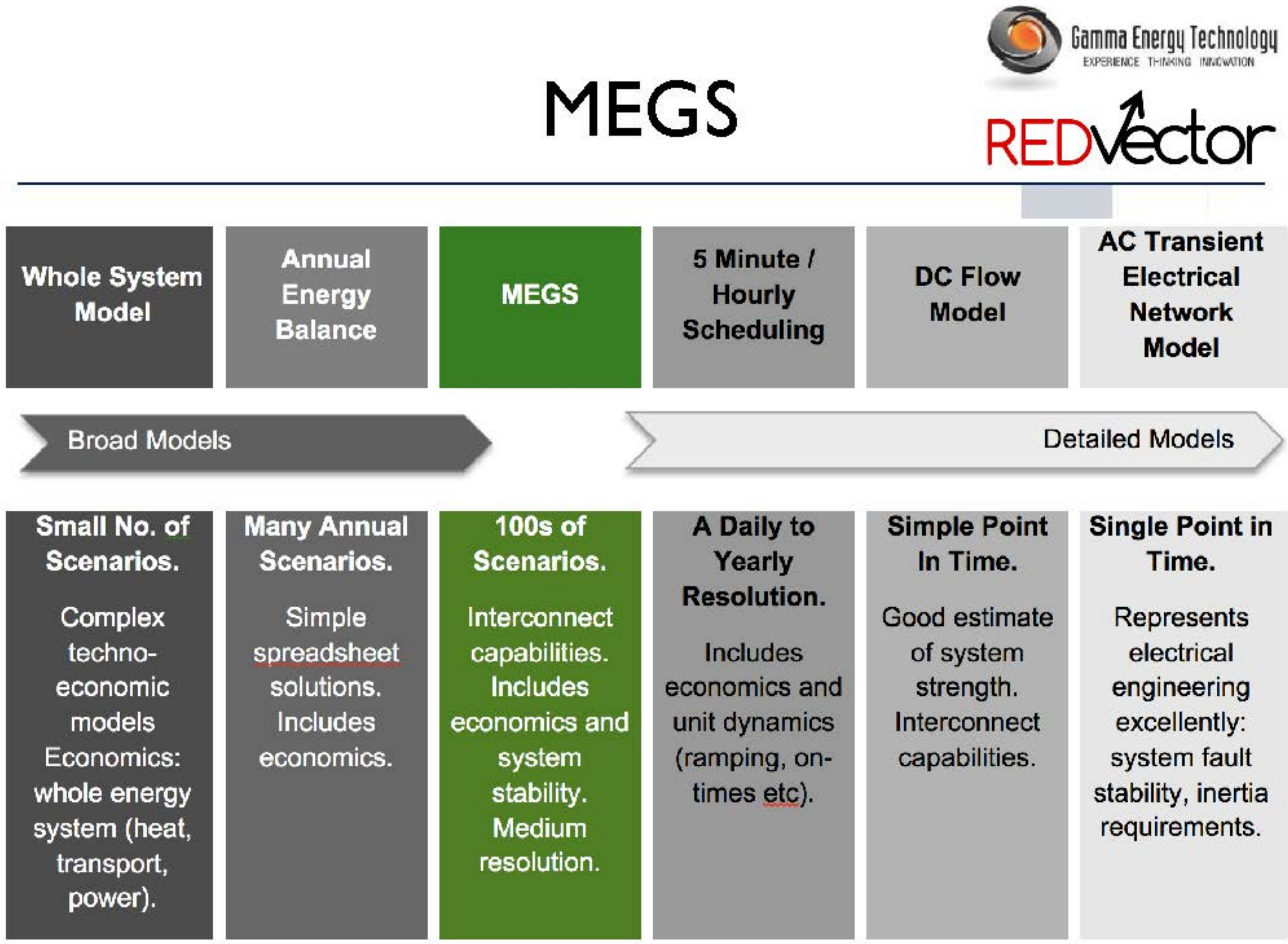
- Energy must balance.
- There is sufficient supply of reserve and response services.
- There is sufficient inertia
- There is sufficient reliable capacity to meet peak demand

Conservation of Energy

Managing imbalances

Stability: time to react

Keeping the lights on!


MEGS
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Whole System Model
Annual Energy Balance
MEGS
5 Minute / Hourly Scheduling
DC Flow Model
AC Transient Electrical Network Model
Broad Models
Detailed Models
Small No. of Scenarios.
Complex techno-economic models Economics: whole energy system (heat, transport, power).
Many Annual Scenarios.
Simple spreadsheet solutions. Includes economics.
100s of Scenarios.
Interconnect capabilities. Includes economics and system stability. Medium resolution.
A Daily to Yearly Resolution.
Includes economics and unit dynamics (ramping, on-times etc).
Simple Point In Time.
Good estimate of system strength. Interconnect capabilities.
Single Point in Time.
Represents electrical engineering excellently: system fault stability, inertia requirements.

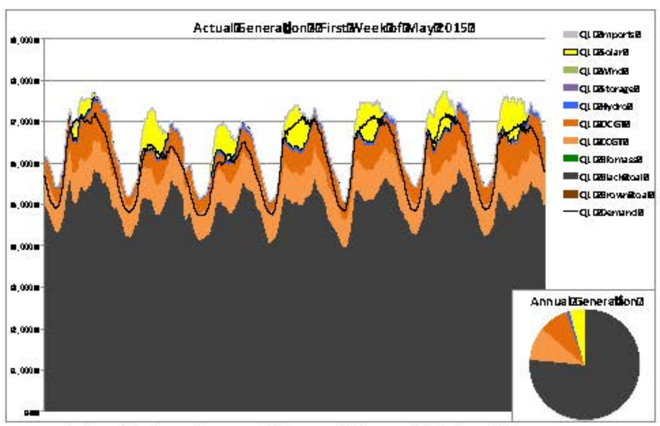
Validation - QLD

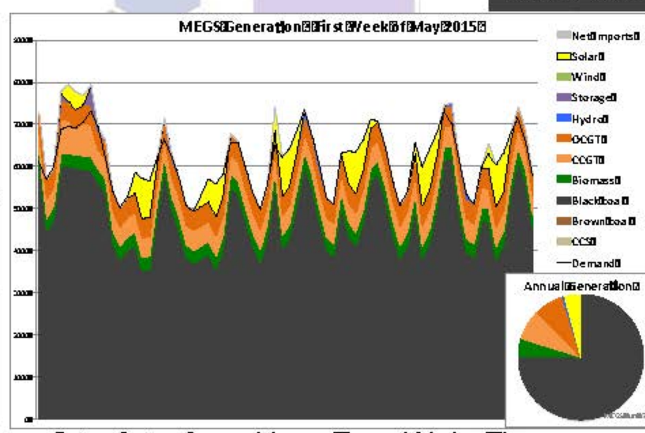
State by state comparison of modelled results and market data.

MEGS needed some adjustments for non-market behaviour (e.g. low priced gas contracts and running to support long grid lines)

Agreement for Queensland was good:

Solar
Storage
Hydro
OCGT
CCGT
Biomass
Black Coal

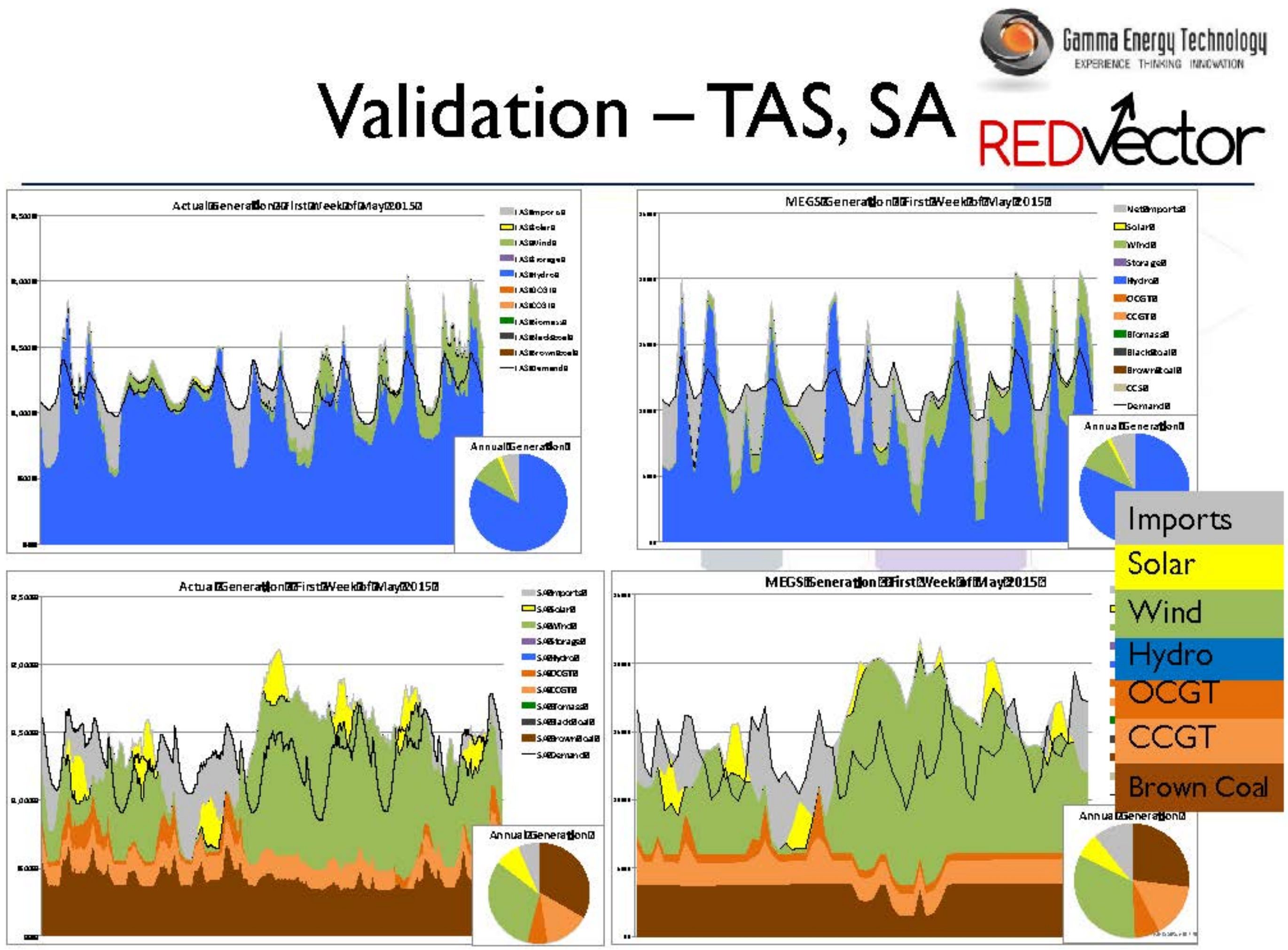




Fri Sat Sun Mon Tue Wed Thu

Fri Sat Sun Mon Tue Wed Thu

Queensland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Validation – TAS, SA
REDVector
Imports
Solar
Wind
Hydro
OCGT
CCGT
Brown Coal

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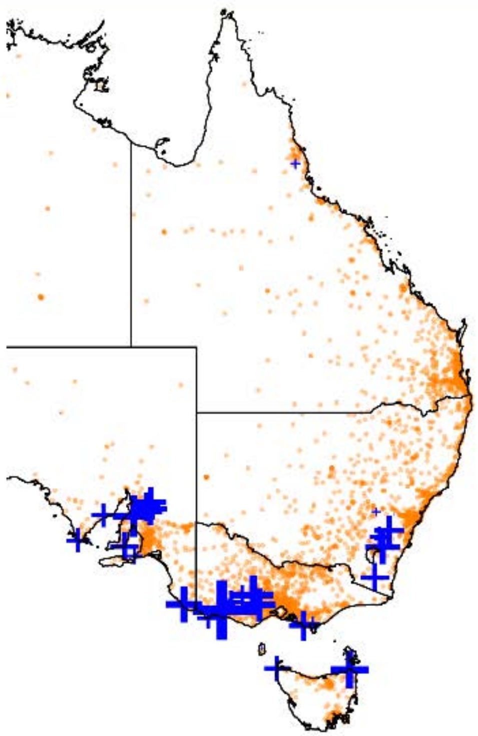
Weather

Renewables Ninja!



- Ninja takes historic weather records and simulates what wind and PV would've generated in those years.
- Has been validated against market data for NEM
- Known locations marked on map
- This project has 10 years of coincidental market and Ninja data

Anatomy of a Drought

This is 1 in 5 year wind drought for NEM.

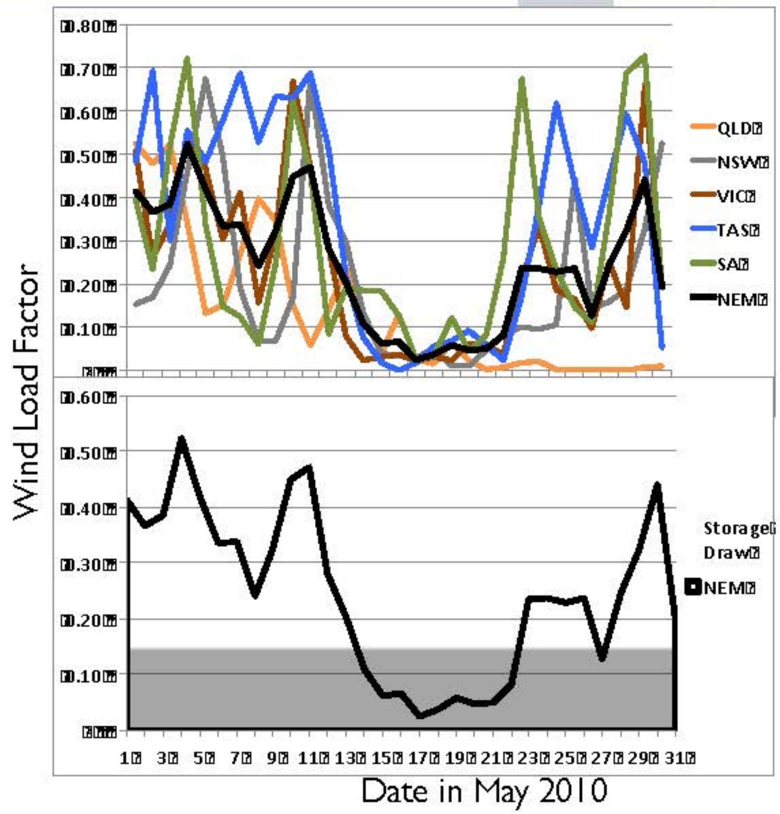
All states went down together for a week.

Assume system is OK with ½ of normal wind level.

Rest is made from storage

Would have to hold 14MWh per MW of wind for 5 years (red area).

So a 1GW windfarm would need 108 of Tesla's biggest batteries to "firm it up".



Anatomy of a Drought

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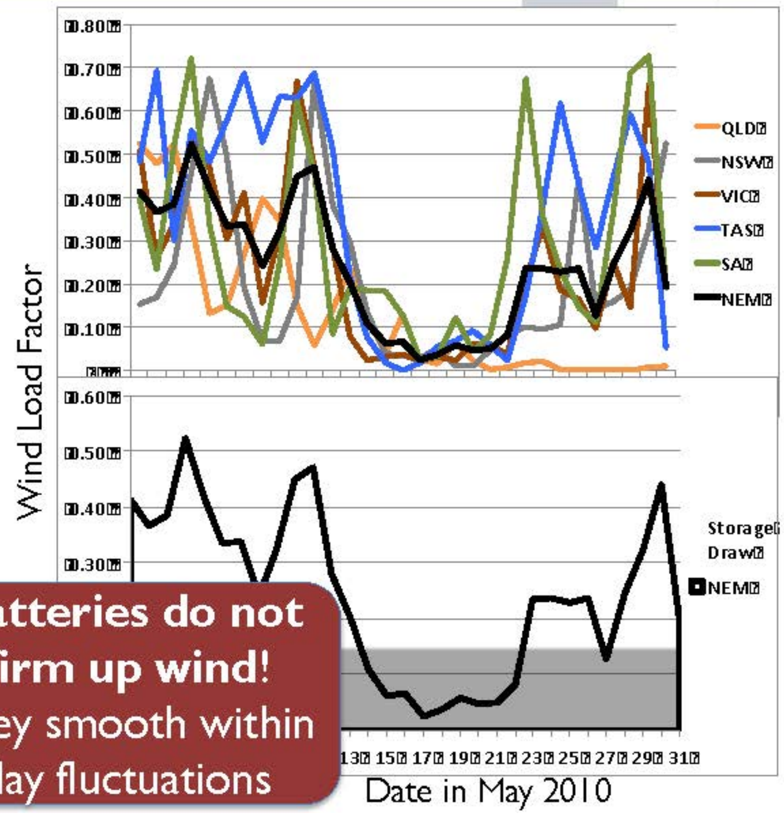
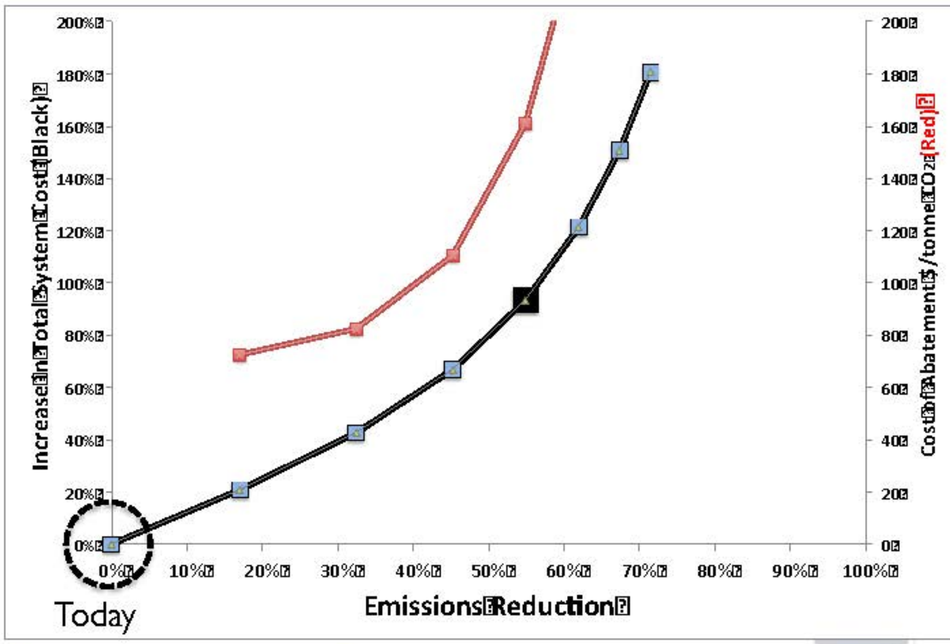
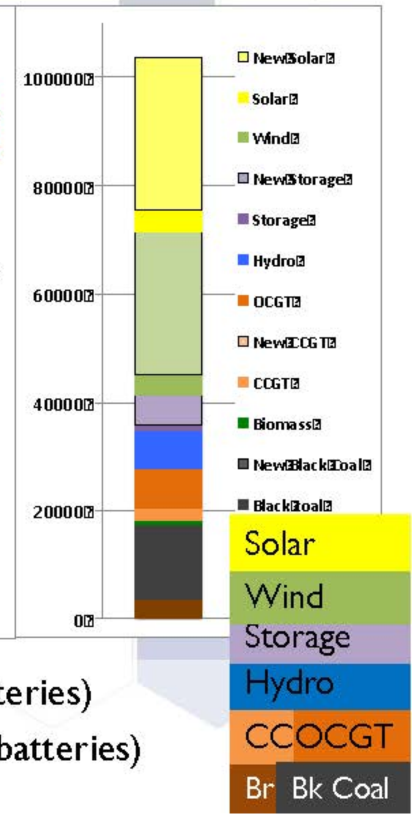


Batteries do not firm up wind!
They smooth within day fluctuations

Decarbonisation Pathways

Technology Options

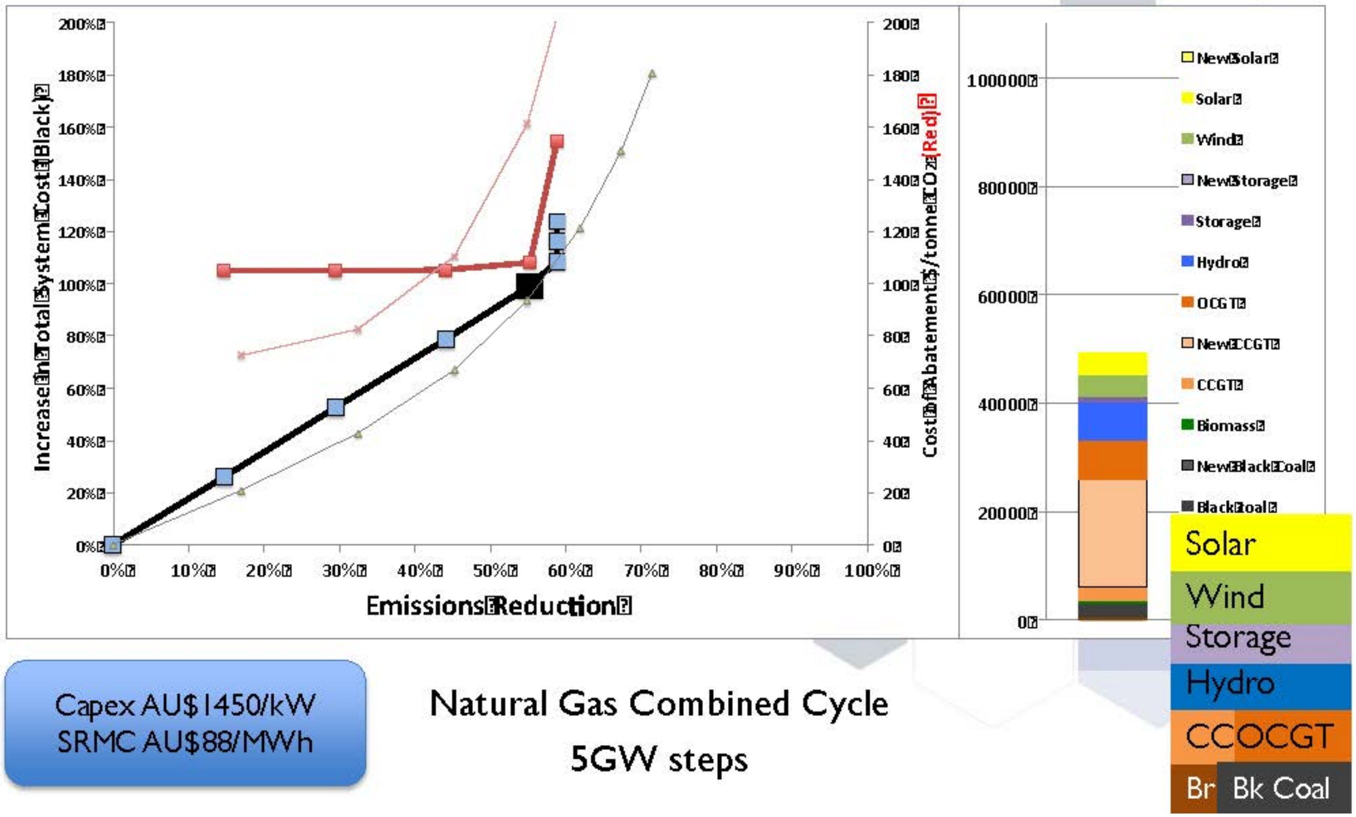




Wind AU$ 1900/ kW
PV AU$ 2100/ kW
Batteries AU$ 200/kWh

Renewables (wind & solar + batteries)
15GW steps (+1.5GW supporting batteries)

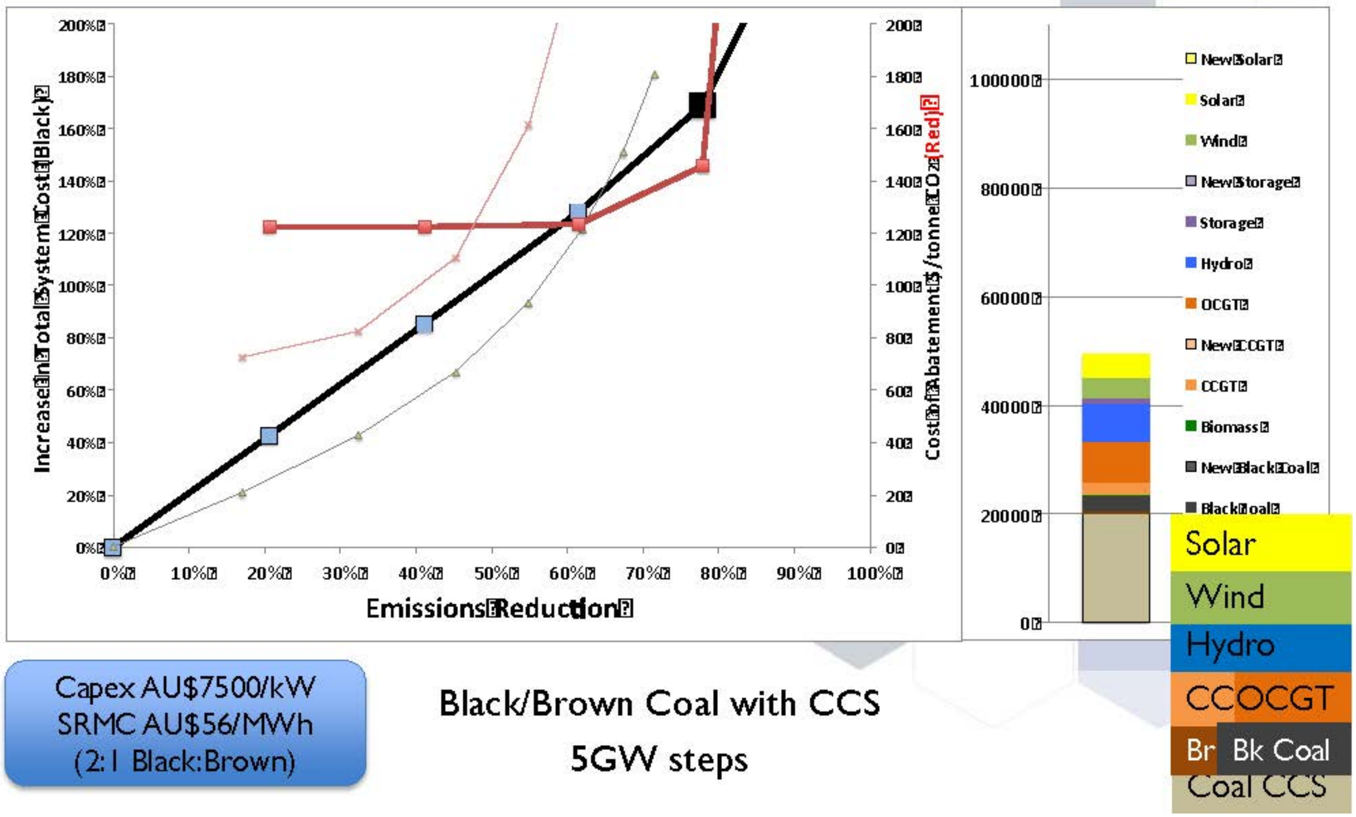
Technology Options



Capex AU$1450/kW
SRMC AU$88/MWh

Natural Gas Combined Cycle
5GW steps

Technology Options



Capex AU$7500/kW
SRMC AU$56/MWh
(2:1 Black:Brown)

Black/Brown Coal with CCS
5GW steps

Tech Option Conclusions

- The effectiveness of a technology depends on how much exists already
  - Costs increase in a **non-linear** fashion as they are added
  - Simple metric like LCOE can't explain or represent that behaviour
- Renewables appears to be cheapest for initial steps
  - But not for deeper decarbonisation (diminishing returns)
- Building gas is cheaper for mid levels of decarbonisation around 50%
- Only CCS can get to deep (>60%) decarbonisation levels
- The cost of gas CCS and coal CCS are similar at $12/GJ

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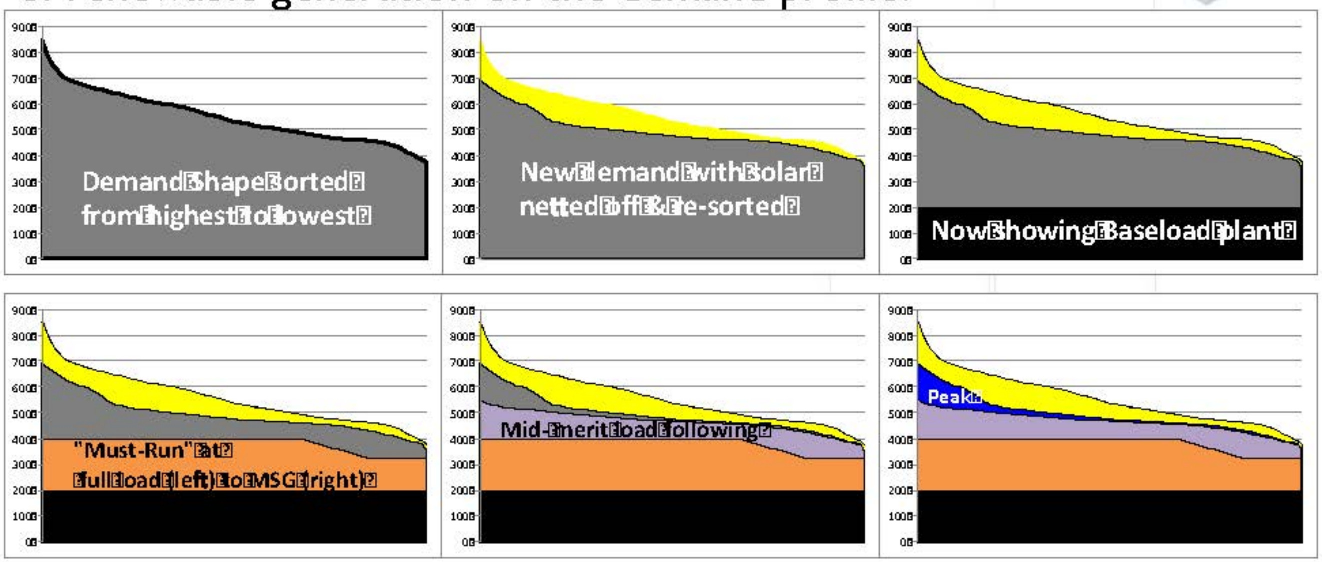
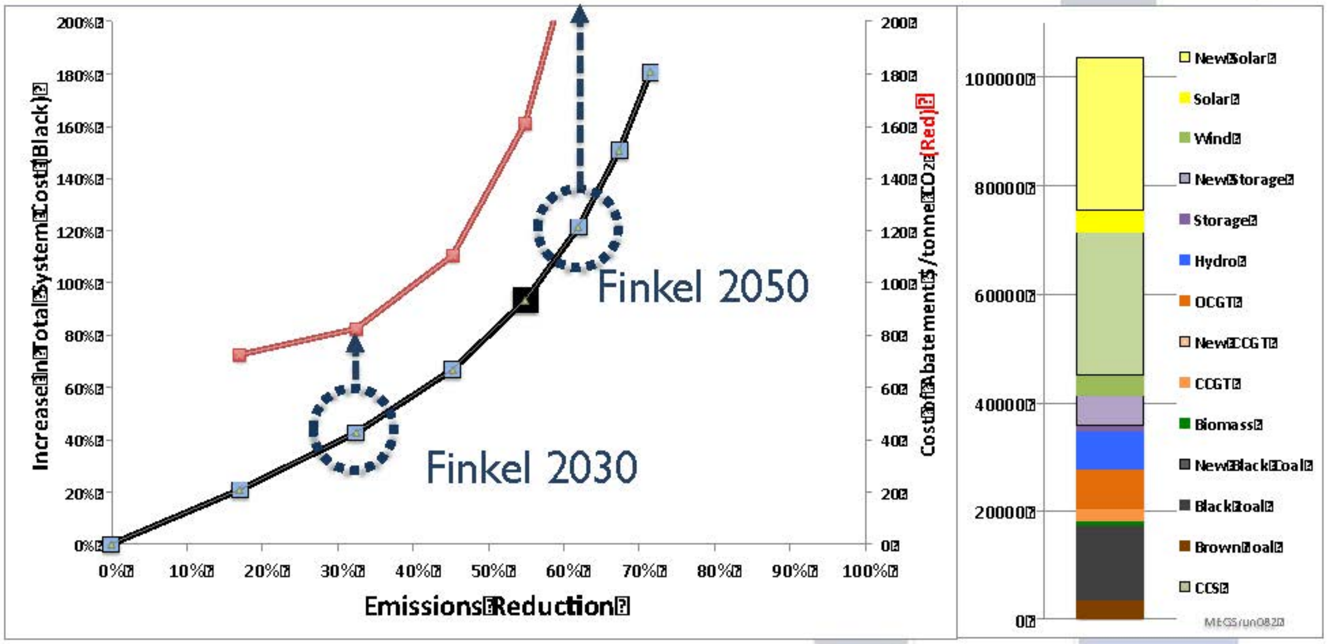
Finkel's Pathways

Load Duration Curves

Each line on the curve is compiled by sorting from highest on the left to lowest on the right. It neatly demonstrates the running pattern of different plant over the entire year, and shows the effect of renewable generation on the demand profile.



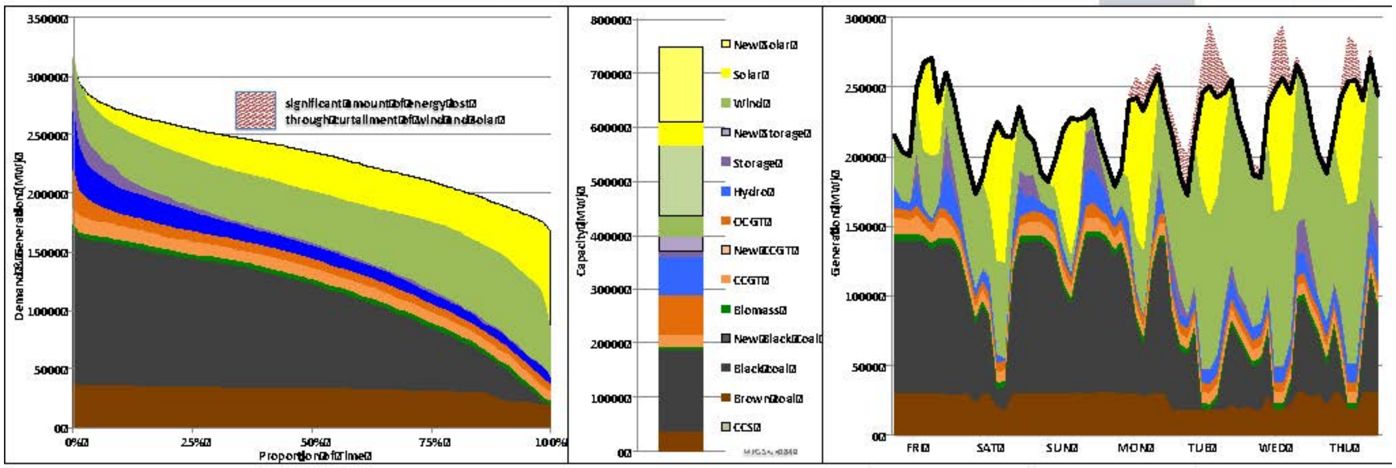
Finkel's Pathway



Renewables (wind and solar – with some additional storage)

15GW steps

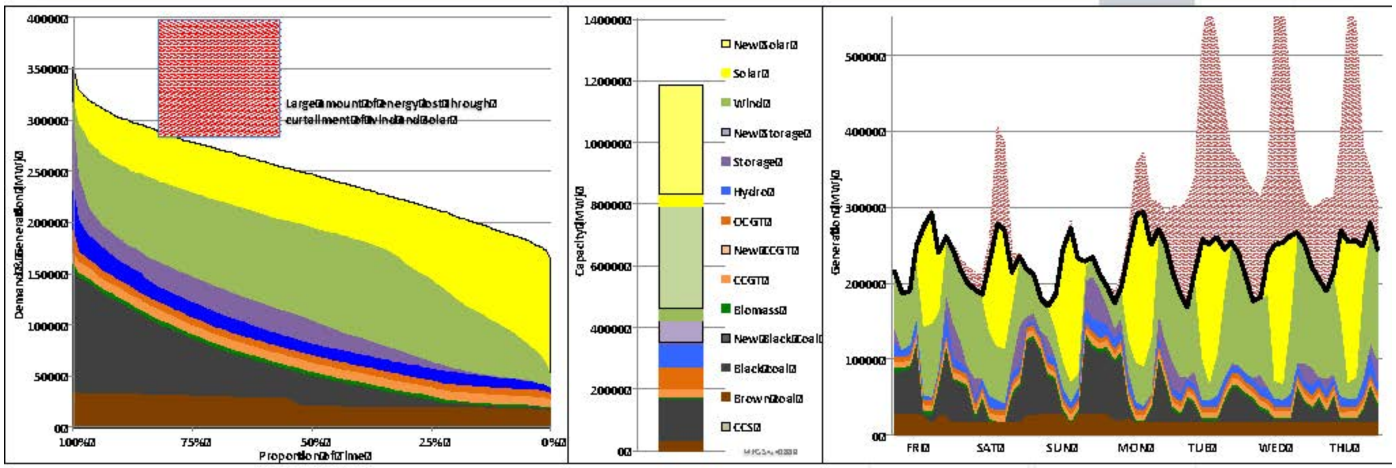
Finkel 2030



The solution here is technically feasible but not without difficulties:

- The baseload market has virtually disappeared
- Black Coal has to run very flexibly, often shutting down daily
- Some renewable output is lost through insufficient demand

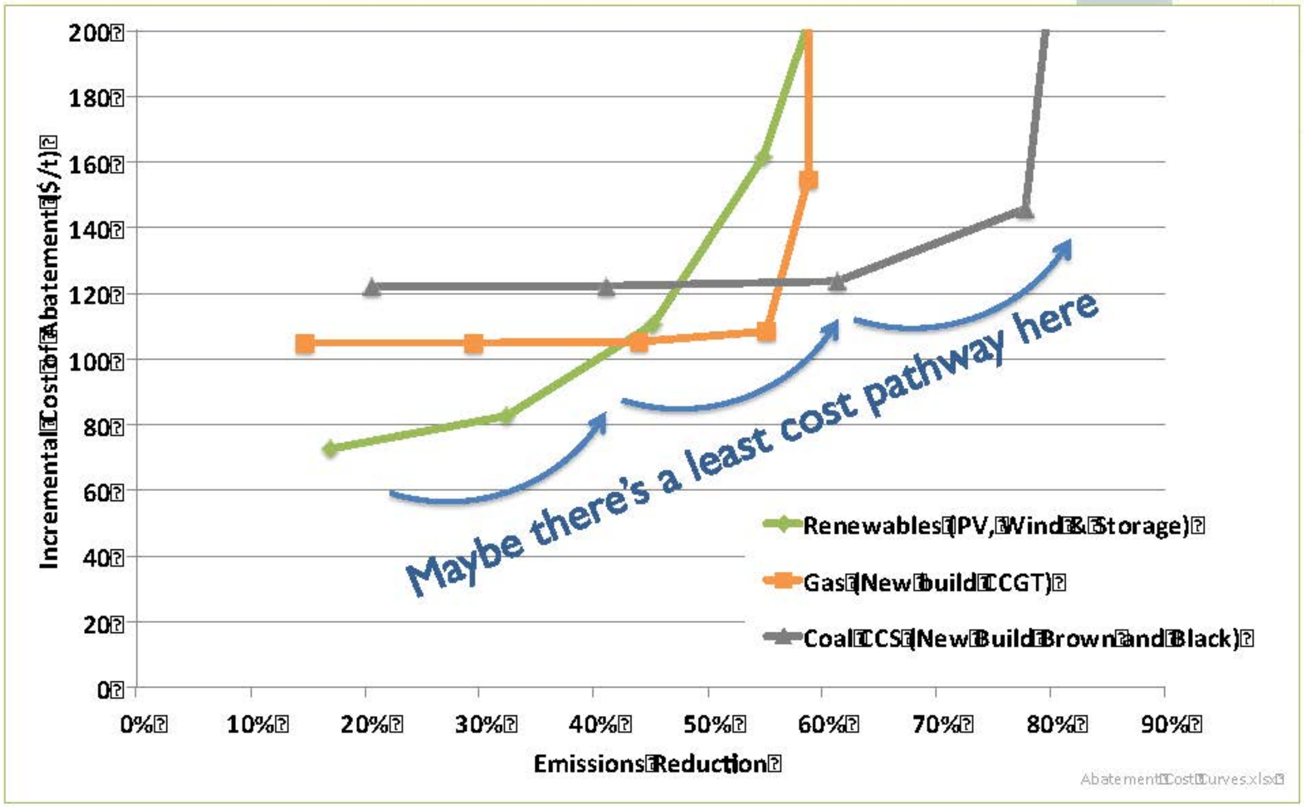
Finkel 2050



The solution here is costly:

- Curtailment (loss of renewable output) is huge
- Abatement cost of last step is 234 $/t
- This does not seem the best decarbonisation solution

Cost Curve Comparison



"Hybrid" 2050

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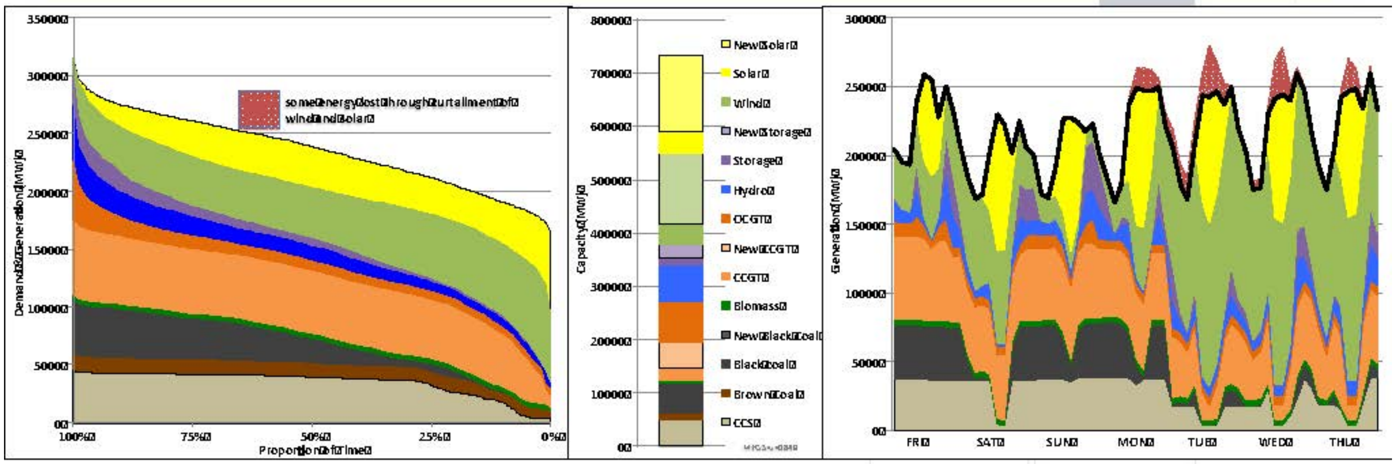

Retrofitted CCS plant occupies the near-baseload market, **but needs to be flexible,** and new gas has a high load factor. There is only a small curtailment of renewables. The remaining coal occupies the mid-merit position working flexibly with OCGT, hydro and storage at peaks.

The cost of abatement is $107/t for the final stages of this approach…

State by State 2030 Stories

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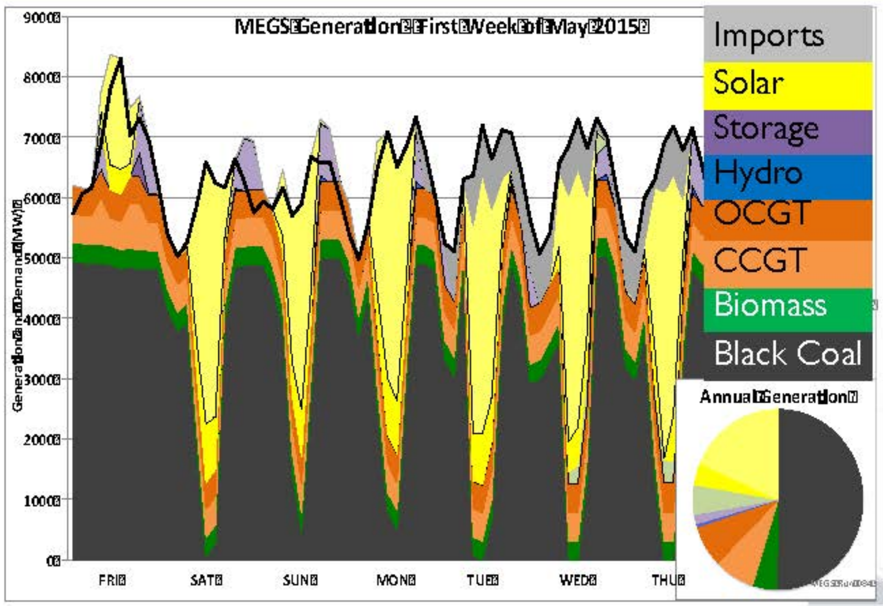
Queensland

REDVector



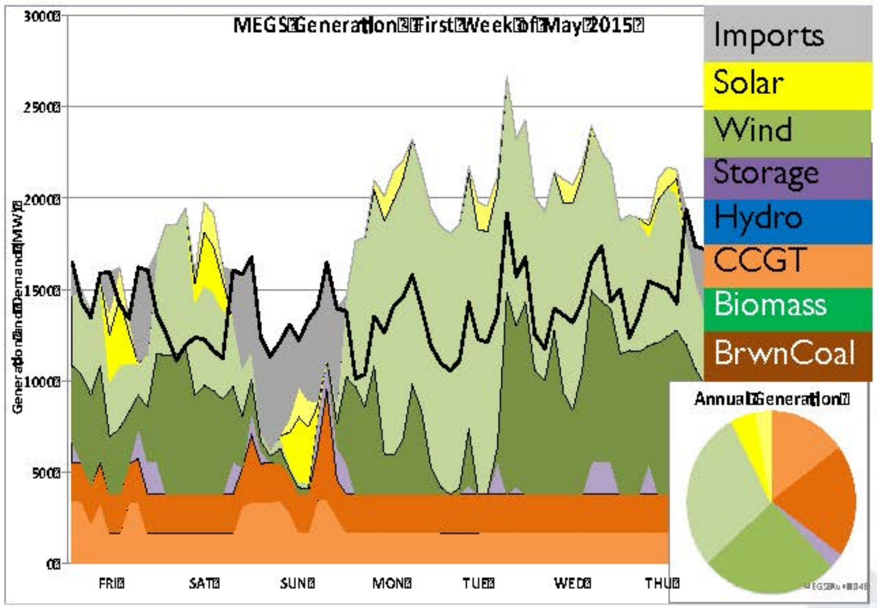
The Sunshine State

- Best place for PV
- PV can almost completely meet demand at noon most days
- Coal is night only running
- Exports Solar, Imports wind

- 300+ starts a year is a punishing schedule for old coal
- Likely to need significant work to prepare it for extra ongoing costs + lifetime consumption

CCS here would have to be very flexible

South Australia



The Windy State

- SA has best resource for wind
- But end of line grid needs support from gas plant
- Exports half of wind when windy
- Reliant on Victoria for imports when not

- There's not a great role for PV in SA
- Gas plant provides inertia and reserve in support of wind

Conclusions

Overall Messages

It is important to consider the whole system across all timescales to 2050 and beyond

- The value of a technology depends on existing grid
- Chasing intermediate targets whilst ignoring the long term can be suboptimal
- Energy supply is only one of several grid services

LCOE is helpful ✗

A secure grid requires a range of essential services

- Traditional grid service suppliers are disappearing
- Services need valuing to reward existing providers and attract new suppliers
- Existing plant can provide many services if flexible
- Inflexible plant will struggle to survive

Baseload Rules OK! ✗

Overall Messages

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The solution will be diverse

- To resolve the trilemma, a range of technologies will be required
- Each technology brings a different range of services
- Each state has unique problems and opportunities

One size fits all X

Providing reliable low emissions electricity comes at a cost

- All low carbon energy forms are more expensive than existing assets
- Total system optimisation will lead to the lowest cost highest reliability outcomes

Reliable & clean energy is cheap. X

END

“gap in the story”

Wind Droughts, MEGS and Renewables Ninja

State	Long term capacity factor	No of droughts > 1 week in 2006-2015	Length of “1 in 5 year” drought	MWh of storage, per MW of wind, to survive 1 in 5 year drought
QLD	16%	70	21 days	48 hours
NSW	31%	15	12 days	27 hours
VIC	31%	6	10 days	28 hours
TAS	38%	4	9 days	37 hours
SA	33%	5	9 days	23 hours
NEM	30%	1	6 days	14 hours

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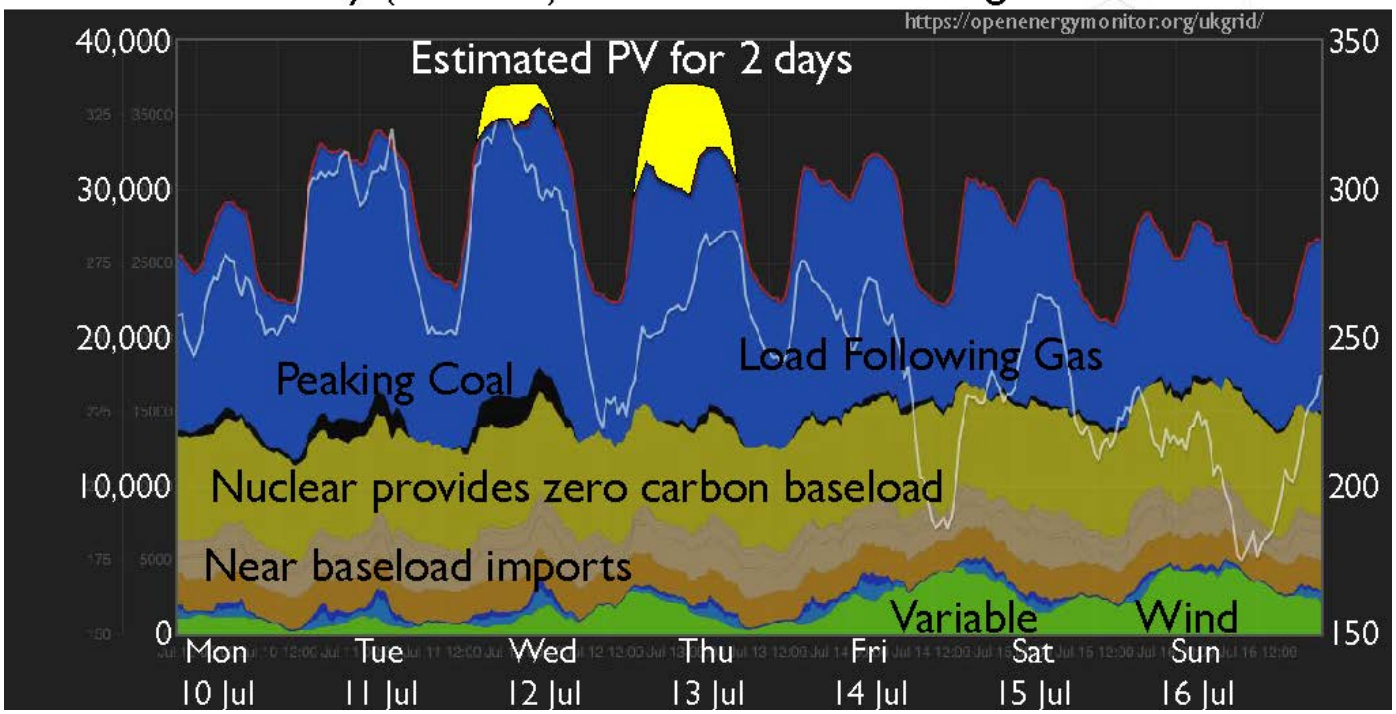
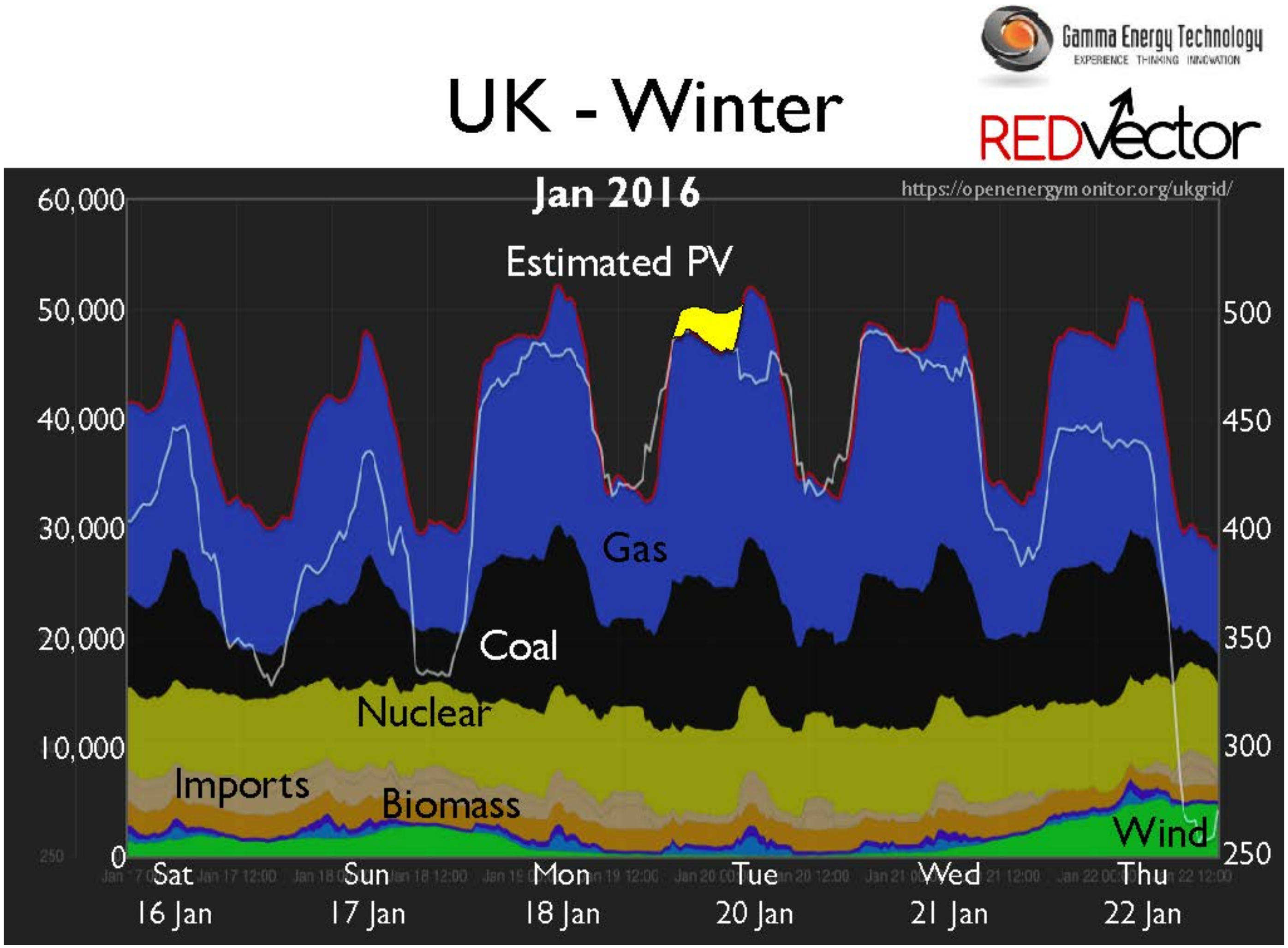
International Experience

UK - Summer

July 2017

Carbon Intensity (in white) varies from 180-320 kg/MWh




UK - Winter
Gamma Energy Technology
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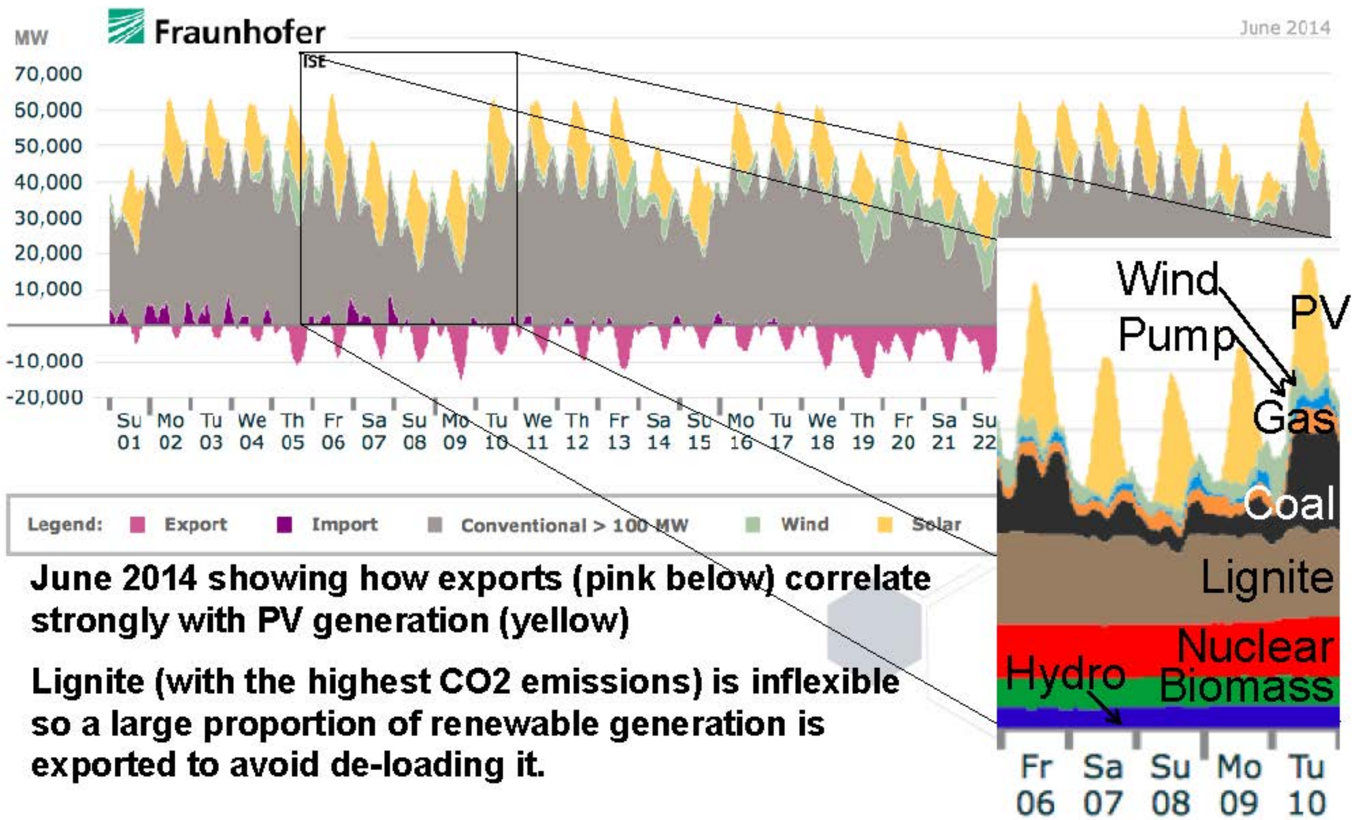
REDVector
Jan 2016
https://openenergymonitor.org/ukgrid/
Estimated PV
Gas
Coal
Nuclear
Imports
Biomass
Wind
60,000
50,000
40,000
30,000
20,000
10,000
0
500
450
400
350
300
250
Sat 16 Jan
Sun 17 Jan
Mon 18 Jan
Tue 20 Jan
Wed 21 Jan
Thu 22 Jan

Germany



June 2014 showing how exports (pink below) correlate strongly with PV generation (yellow)

Lignite (with the highest CO2 emissions) is inflexible so a large proportion of renewable generation is exported to avoid de-loading it.

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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