Proceedings: Workshop on Representing CCUS in Energy Systems Models

IEAGHG Technical Report
2019-08
August 2019

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 30 member countries and beyond. Within its mandate, the IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics. To date, there are 38 TCPs who carry out a wide range of activities on energy technology and related issues.

DISCLAIMER

The GHG TCP, also known as the IEAGHG, is organised under the auspices of the International Energy Agency (IEA) but is functionally and legally autonomous. Views, findings and publications of the IEAGHG do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries."

This report was prepared as an account of the work sponsored by IEAGHG. The views and opinions of the authors expressed herein do not necessarily reflect those of the IEAGHG, its members, the organisations listed below, nor any employee or persons acting on behalf of any of them. In addition, none of these make any warranty, express or implied, assumes any liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product of process disclosed or represents that its use would not infringe privately owned rights, including any parties intellectual property rights. Reference herein to any commercial product, process, service or trade name, trade mark or manufacturer does not necessarily constitute or imply any endorsement, recommendation or any favouring of such products.

COPYRIGHT

ACKNOWLEDGEMENTS AND CITATIONS

This report describes research ponsored by IEAGHG. This report was prepared by:

- University College Cork

The principal researcher was:

- James Glynn, University College Cork

To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager. The IEAGHG manager for this report was:

- Keith Burnard

The report should be cited in literature as follows:
'IEAGHG, "Proceedings: Workshop on representing CCUS in energy systems models", 2019/08, August 2019.'

Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG,
Pure Offices,
Cheltenham Office Park,
Hatherley Lane,
Cheltenham,
Glos.
GL51 6SH, UK

Tel: +44 (0)1242 802911
E-mail: mail@ieaghg.org
Web: www.ieaghg.org

Proceedings:
Workshop on Representing Carbon Capture Utilisation and Storage in Energy Systems Models

Location: College Park, Maryland, USA
Date: 17–19 October 2018

Contents

Acknowledgements

This workshop report reflects the expertise and dedication of the individuals who participated in the workshop, and who provided the perspective and broad thinking that enabled the conclusions in this report to be reached. The workshop participants were:

	Name	Surname	Affiliation
1	Mikhail	Adamantiades	EPA
2	Steve	Anderson	USGS
3	Jeff	Brown	Stanford University
4	Maxwell	Brown	NREL
5	Wonjun	Chang	CRA
6	Stuart	Cohen	NREL
7	Greg	Cooney	NETL LCA Team
8	David	Daniels	EIA
9	Casie	Davidson	PNNL
10	Jae	Edmonds	PNNL
11	Meredydd	Evans	PNNL
12	Rachel	Fakhry	NRDC
13	Allen	Fawcett	EPA
14	Sarah	Forbes	DOE
15	Timothy	Fout	NETL
16	James	Glynn	University College Cork
17	Timothy	Grant	NETL
18	Don	Hanson	Argonne National Laboratory
19	Hill	Huntington	Stanford University
20	Bob	Ivy	DOE
21	Gokul	Iyer	PNNL
22	Tony	Jones	EPA
23	Robert	Kaineg	CRA
24	Haroon	Kheshgi	Exxon
25	Sonny	Kim	PNNL
26	Nick	Macaluso	Canada
27	Daniel	Matuszak	DOE
28	Caitlin	Murphy	NREL
29	Pralit	Patel	PNNL
30	Ron	Sands	USDA
31	Ann	Satsangi	DOE-FE
32	Michael	Schaal	Energy Ventures Analysis, Inc.
33	Volker	Sick	University of Michigan
34	Jane	Stricker	BP
35	John	Thompson	CATF
36	Nadejda M.	Victor	NETL
37	Stephanie	Waldhoff	PNNL
38	Marshall	Wise	PNNL
39	Frances	Wood	On Location

Executive Summary

The US Department of Energy's Office of Fossil Energy (US DOE-FE) convened a workshop on 17-19 October 2018 in College Park, Maryland, USA, to provide a forum to review and exchange the latest understanding of carbon capture utilisation and storage (CCUS) and to improve the modelling approaches and representation of CCUS in energy systems models (ESMs) and Integrated Assessment Models (IAMs). This was the second workshop on this theme, following a previous workshop also hosted by US DOE-FE on 3-4 April 2017 in Washington DC, USA[1]. This second workshop was designed to grow and expand the number of research groups with expertise in up-to-date modelling of advanced fossil technologies and related market impacts, including application of US National Energy Technology Labs (NETL) cost and performance baseline data and CCUS expertise, tax implications of 45Q, EOR market feedback and information on international markets. It also sought to create a community of practice and to link CCUS technical experts with modellers and analysts.

The workshop brought CCS technology experts, CCS data providers, CCS process engineers and relevant stakeholders together with ESM and IAM modellers from policy, industry and academia. The attendees were largely from the USA. All attendees have been studying CO_2 capture, utilisation and storage, but most had not previously worked together. Many participants expressed their appreciation for the connections made through the workshop.

Accurate data provision is the core issue that was echoed at this workshop, repeating one of the outcomes from the previous April 2017 workshop. Data flow from CCUS technical experts to process modellers and onwards to energy systems and integrated assessment modellers is the mechanism that joins these communities of researchers and analysts. It is critical that the transaction cost between CCUS and integrated modellers is reduced. While NETL's recent release of new baseline process model databases was identified to be extremely useful in bridging this gap[2][3], some modellers lacked the expertise to interpret and appropriately utilise this data, illustrating why dialogue between technologists and modellers was valuable. Many models still lack the capability to model fiscal implications of 45Q policy, to represent the temporal dynamics of partial load CCS plants, or the resultant variable capture rates from CCS plants.

---

[1] IEAGHG, "Proceedings of US DOE Workshop: Energy-Economic Modelling Review", 2017/06, May, 2017. https://ieaghg.org/docs/General_Docs/Reports/2017-06_Proceedings_of_US_DOE_Workshop.pdf

[2] Natural Gas Combined Cycle Carbon Capture Retrofit database; https://www.netl.doe.gov/energy-analysis/details?id=2950

[3] Industrial Sources Carbon capture Retrofit Database; https://www.netl.doe.gov/energy-analysis/details?id=2951

There were many expressions of interest in holding additional similar workshops. Considerable work remained to develop the network and establish a robust community of practice that extended from technical research to integrated analysis capabilities.

IEAGHG are working with IEA-ETSAP to identify a process for sharing up-to-date CCUS data with IEA-ETSAP's ongoing energy technology ("SubRES") database project. NETL are also a critical data provider and their engagement in this process would be welcomed.

1. Introduction

The mitigation pathways in the recent IPCC special report on global warming of 1.5°C (SR1.5) highlights the increasing urgency for carbon capture and storage (CCS) deployment at scale to stabilise global mean surface temperatures towards 1.5C[4]. The use of bioenergy carbon capture and storage to achieve net-zero CO_2 emissions is a prevalent outcome of mitigation pathways[5] and given the reliance a CCS for climate stabilisation the appropriateness and uncertainties of model input data and modelling methodologies is increasingly scrutinised[6].

The US department of energy's office of fossil energy (US DOE-FE) convened a workshop on October 17th-19th 2018 in College Park, Maryland USA, to provide a forum for review and exchange the latest understanding of Carbon Capture Utilisation and Storage (CCUS) and to improve the modelling approaches and representation of CCUS in energy systems models (ESM) and Integrated Assessment Models (IAM). This was the second such workshop and followed a previous workshop also hosted by US DOE-FE in April 3rd-4th 2017 in Washington DC, USA[7]. This workshop was designed to grow and expand the number of research groups with expertise in up-to-date modelling of advanced fossil technologies and related market impacts, including the use of the US National Energy Technology Labs (NETL) cost and performance baseline data and CCUS expertise, tax implications of the revised 45Q, EOR market feedback, and international markets.

The workshop also sought to create a community of practice and to link CCUS technical experts with modellers and analysts. The workshop brought CCS technology experts, CCS data providers, CCS process engineers and relevant stakeholders, together with ESM and IAM modellers from policy, industry and academia. The attendees were largely from the USA. Modellers working on North American scenarios were encouraged to reach out and become involved in future CCS-related workshops. All attendees have been studying CO_2 capture, utilisation and storage, but most had not worked together previously. Many participants expressed their appreciation for the connections made as a result of the workshop.

---

[4] Rogelj et al., "Mitigation Pathways Compatible With 1.5°C in the Context of Sustainable Development."
[5] Rogelj et al., "Zero Emission Targets as Long-Term Global Goals for Climate Protection"; Hilaire et al., "Negative Emissions—Part 2"; Khanna et al., "Negative Emissions—Part 1: Research Landscape and Synthesis"; Kriegler et al., "Pathways Limiting Warming to 1.5°C: A Tale of Turning around in No Time?"; Rogelj et al., "Energy System Transformations for Limiting End-of-Century Warming to below 1.5 °C"; Luderer et al., "Residual Fossil CO2 Emissions in 1.5-2 °c Pathways."
[6] Van Vuuren et al., "Open Discussion of Negative Emissions Is Urgently Needed."
[7] IEAGHG, "Proceedings of US DOE Workshop: Energy-Economic Modelling Review", 2017/06, May, 2017. https://ieaghg.org/docs/General_Docs/Reports/2017-06_Proceedings_of_US_DOE_Workshop.pdf

The first session of the workshop was held the evening of October 17th. It provided an overview of the workshop, its goals, key questions to be addressed, and an opportunity for participants to get to know each other over a no-host dinner following the opening session.

Technical sessions on 18 October were divided into three, with goals to explore the state of the art regarding CO_2 capture (Session 1), utilisation (Session 2) and infrastructure, transport, and storage (Session 3).

The next day was focused on representing state of the art CCUS knowledge in models (Session 4) and particularly modelling U.S. policy and regulation. The session's discussions were guided by four questions:

1. What challenges have modellers identified in representing 45Q?
2. What lessons have we learned?
3. What are promising methods?
4. What conditions are required for investment in CCUS technologies?

In the final session on 19 October, delegates discussed a series of questions designed to identify a collective path forward:

1. What are issues on the horizon? Can we adequately model these? What additional model/data needs are required?
2. What are our most pressing needs for better representing CCUS in data, methods and analysis?
3. How can individual model strengths be leveraged, shared generalised functions, collaboration, etc.?
4. Should this workshop become a series? Should we create a web presence?

Each session started with a brief presentation setting the scene about the current state of the art in scientific knowledge to stimulate discussions and knowledge transfer. Discussion was framed around two key questions:

1. How can models better reflect the current state of the art?
2. What are the best sources of data for modellers to use?

The workshop was conducted under modified Chatham House rules. The agenda is outlined below.

2. Agenda

Wednesday 17th October 2018

18:00	Ann Satsangi	Overview and goals for the meeting
18:30	All	Self-Introductions
19:00	All	Adjourn for Dinner

Thursday 18th October 2018

9:00	All	Check in and orientation
9:30	Ann Satsangi	Welcome back
9:40	Keynote Address	Bob Ivy, Senior Advisor, Office of Fossil Energy at U.S. Department of Energy (DOE) Keynote: "The future of Fossil Energy and the role of CCUS and advanced fossil technologies in the evolving U.S. energy system"

10:00	**Chair** **Jae Edmonds**	**Session 1: CO_2 Capture**
9:40	*Speaker 1.1* Tim Fout	Modelling power generation with CCS: Overview of fossil energy baseline studies including: heat rates, capacity factors, differences between coal, gas, and the state of the art in the USA, costs, technology, standard end of pipe; Carbon capture retrofit database overview including retrofits to PC, NGCC and Modelling Industrial sources. And results from post-combustion membrane R&D sensitivity study.
10:45	*Comment 1.1* *Ron Sands*	Modeller 3-minute comment on CO2 capture (from seat, no PPT)
10:55	Comment 1.2 John Thomson	Modeller 3-minute comment on CO2 capture (from seat, no PPT)
11:05	Comment 1.3 Gokul Iyer	Modeller 3-minute comment on CO2 capture (from seat, no PPT)
11:15	All	**Discussion** Discussion question 1: How can models better reflect the current state of the art? Discussion question 2: What are the best sources of data for modellers to use?
12:00	Lunch Speaker James Glynn	National and International Perspectives of CCUS

13:20	**Chair** **Tim Grant**	**Session 2: CO_2 Utilisation**
13:20	Keynote **Greg Cooney**	Technology Review: Enhance Oil Recovery 101 – Enhanced Oil Recovery: EOR market feedback in economic model, reservoir availability data, spatial modelling international markets.
13:50	Speaker 2.1 Daniel Matuszak	Non-EOR CO2 Utilisation Options
14:10	Comment 2.1 Volker Sick	Modeller 3-minute comment on modelling EOR and other CO2 utilisation (from seat, no PPT)
14:20	Comment 2.2 Rachel Fakhry	Modeller 3-minute comment on modelling EOR and other CO2 utilisation (from seat, no PPT)
14:30	Comment 2.3 Nick Macaluso	Modeller 3-minute comment on modelling EOR and other CO2 utilisation (from seat, no PPT)
14:40	All	**Discussion**

		Discussion question 1: How can models better reflect the current state of the art? Discussion question 2: What are the best sources of data for modellers to use?
15:10	All	Open Discussion

15:30	**Chair** **Ann Satsangi**	**Session 3: CO_2 Infrastructure, Transport, and Storage**
15:30	Speaker 3.1 Tim Grant	Transport and Infrastructure: What's the current transport infrastructure in place? What infrastructure will be needed to support 45Q and potential extensions and expansion of the CO2 market. ESH issues. Cost implications. Implications for better modelling.
15:50	Speaker 3.2 Casie Davidson	Storage: Overview of storage reservoir types (deep saline reservoirs, depleted oil and gas wells, on shore offshore, coal seams, mineralisation), geology, grades, availability, and cost CO2 transport: technology, EHS issues, Cost. Best MMV practices, monitoring, regulation, short and long-term liability; implications for better modelling.
16:10	Comment 3.1 Steve Anderson	Modeller 3-minute comment on CO_2 storage and transport (from seat, no PPT)
16:30	Comment 3.2 Jane Stricker	Modeller 3-minute comment on CO_2 storage and transport (from seat, no PPT)
16:30	Comment 2.3 Jeff Brown	Modeller 3-minute comment on CO_2 storage and transport (from seat, no PPT)
16:40	All	**Discussion** Discussion question 1: How can models better reflect the current state of the art? Discussion question 2: What are the best sources of data for modellers to use?
17:10	All	Adjourn

Friday 19th October 2018

8:00	All	Check in and orientation
8:30	Ann Satsangi	Welcome back
8:40	**Chair** **David Daniels**	**Session 4: Modelling U.S. Policy and Regulation**
8:40	Keynote **Sarah Forbes**	Keynote: Challenges and Opportunities in modelling U.S. Policy and regulation. This presentation will focus on the challenges of modelling the U.S. energy system including, the new national 45Q, keeping up with technology, highly varied state policies such as caps, credits, RPSs, standards, and interactions with international energy markets.
9:10	Speaker 4.1 Marshall Wise	Model #1 Progress report on 45Q
9:30	Speaker 4.2 Frances Wood	Model #2 Progress report on 45Q
9:50	Speaker 4.3 Nadja Victor	Model #3 Progress report on 45Q
10:10	Speaker 4.4 Stuart Cohen and Caitlin Murphy	Model #4 Progress report on 45Q
10:30	All	**Discussion**

		Discussion question 1: What challenges have modellers identified in representing 45Q-CCS and CCU? Discussion question 2: What lessons have we learned? Discussion question 3: What are promising methods? Discussion question 4: What conditions are required for investment in CCUS technologies?
11:20	**Chair Allen Fawcett**	**Session 5: Future Directions, Needs and Opportunities** Discussion Questions 1: What are issues on the horizon? Can we adequately model these? What additional model/data needs are required. Discussion question 2: What are our most pressing needs for better representation of CCUS in data, methods and analysis? Discussion question 3: How can individual model strengths be leveraged, shared generalised functions, collaboration etc? Discussion question 4: Should this workshop become a series? Should we create a web presence?
11:20	Chairs	3-minute reflections on the session questions by the 4 session chairs
11:40	All	Flash Round – Each participant has 1 minute in which to identify one key modelling need and one key data or modelling opportunity
12:25	Ann	Closing Remarks
12:30	All	Adjourn

2.1. Session 1: CO_2 Capture

The initial CO_2 capture presentation provided an update on the state of the art about CO_2 capture from new fossil fuel power plants, retrofits to existing plants, and post-combustion membrane separation. The National Energy Technology Laboratory (NETL) has produced a series of reports that provide researchers with consistent costs for coal and natural gas power plants with and without CO_2 that are best utilised for technology comparisons and directing R&D decisions. Most recently National Energy Technology Labs (NETL) released several new baseline process model databases that are extremely useful in bridging the knowledge gap between technologist knowledge and modeller implementation[8]. Carbon capture retrofit costs are detailed in reports for coal and natural gas power plants along with high purity industrial sources. Capture system costs are available for advanced systems that approach Department of Energy targets for R&D (membrane sensitivity study). The presentation not only provided an update on the current state of the art, but also summarised the state of the art in ways designed to be accessible to the modelling community. Most usefully NETL presented variable costs of CO_2 capture for plants under partial load with variable capture rates from their CCS plant cost and performance baseline models. As recommended from the recent IEAGHG CCS in IAMs technical report, modellers requested NETL to provide cost curves for CO_2 capture by CCS technology type as a function of capture rate and capacity factor for better representation of operational plant dynamics in ESMs and IAMs.

The discussion that followed the presentation highlighted that there is scope for considerable improvement in the representation of CCUS in ESMs and IAMs. Models generally do not consider partial capture, partial load, co-firing CCS plants, or plant operational dynamics. Bioenergy Carbon Capture and Storage for both electricity generation, industrial and upstream applications were discussed as well as the competition of bioenergy with Agriculture and food production. The issue of stranded assets and cash flow modelling for plant operators at the day to day and week to week time resolution was also highlighted as a weakness in ESMs and IAMs– summarised in the phrase “the flaw of averages”.

2.2. Session 2: CO_2 Utilisation

Enhanced oil recovery (EOR) is the largest current user of CO_2 in the world. More than 60 percent of CO_2 used for human purposes is utilised for EOR. CO_2 can be used in the latter stages of an oil or gas well’s life to maintain production. Present systems generally mine CO_2 from natural reservoirs and pipe it to an oil field. There the CO_2 is injected along with water

[8] Natural Gas Combined Cycle Carbon Capture Retrofit database
https://www.netl.doe.gov/energy-analysis/details?id=2950
Pulverised Coal CCS retrofit database:
https://www.netl.doe.gov/energy-analysis/details?id=2949

to maintain well pressure. The USA 2018 Bipartisan Budget Act includes an amendment to the federal tax code, section 45Q, and provides for a credit to qualifying facilities for sale of captured CO_2 for use in EOR. The credit will increase linearly to $35/metric ton by 2026. 45Q creates the potential for CO_2 captured from qualifying facilities to be used for EOR. While EOR is by far the largest utilisation of CO_2 at present, CO_2 is used for other applications, e.g. in the production of aspirin, dry ice, freezing, fire extinguishers, and so forth. Some uses, for example, carbonisation of beverages simply exhaust CO_2 to the atmosphere with some delay. Other uses, for example, utilising CO_2 in building materials, potentially prevent re- release of the CO_2 to the atmosphere. One presentation explored the use of CO_2 as an energy feedstock. While energy is needed to break the carbon and oxygen bonds, the energy could be obtained from off peak power systems, and therefore be of economic interest as a means of load management. The release of the national academy of sciences report on CO_2 utilisation was highlighted[9].

Questions were raised during discussion about the ultimate scale of such systems compared to the volume of potential CO_2 streams. Some or all of the CO_2 captured in utilisation processes may also eventually be emitted to the atmosphere.

Modelling EOR is particularly challenging to modellers. Many systems come into play that are not always included by the current set of models. These include a CO_2 market where either captured or natural CO_2 can be used, oil field economics, alternative dispositions for CO_2, and finance. More work is needed to connect technical and financial expertise with modellers. Modellers generally do not have a good sense of how such markets work nor do they have access to good data to use to construct models. Similarly, other CO_2 utilisation technologies are generally not included in national-scale energy system models.

2.3. Session 3: CO_2 Infrastructure, Transport, and Storage

The United States has a robust pipeline system. There are about 3500 miles of pipelines, dozens of pipeline operators and EOR projects utilising CO_2 at scale. In general CO_2 is transported as a dense phase liquid. It is supercritical at 1,070 psi and 88°F, 55°F to 110°F and 1,250 psi to 2,200 psi range for transport. The pipeline usually employs a thicker wall pipe than for a natural gas pipeline. Between 1986 and 2008 12 accidents were reported caused by damage, corrosion, and leaks/blowouts. However, there were no injuries or fatalities reported. This is in part since CO_2 is not explosive. CO_2 represents about one to two percent of the cost of petroleum products. 45Q also provides a tax credit for capture and geologic storage of CO_2. Compared to other parts of the world, the United States storage potential is relatively well characterised. Reservoirs are defined by the rock type: sandstone, limestone, shale, coal beds, or basalts and by the fluids present in or co-produced from the system:

[9] Gaseous Carbon Waste Streams Utilisation - https://doi.org/10.17226/25232.

water, oil, or gas. Potentially geologic reservoirs for CO_2 storage need suitable porosity, permeability and thickness to sustain CO_2 injection at a meaningful rate and enough depth to maintain CO_2 in a supercritical state. A cap-rock/overburden is required to prevent injected CO_2 from migrating beyond the storage reservoir.

The cost of storage depends on the interaction of several elements: geology, potential ancillary benefits, e.g. EOR, and the cost of monitoring and compliance. While estimates of the cost of CO_2 storage vary site to site, rank ordering of source-sink pairings indicate that there are a few negative cost opportunities, but that costs are relatively flat near \$50/tonneCO_2 over a substantial range of potential storage locations & volume.

Discussion in this session brought out issues surrounding the regulatory environment, insurance, risk allocation & risk ownership, very long-term monitoring, and the relative scales of geologic storage compared to use of CO_2 for EOR. Insurance risks are potentially unbounded, and thus insurance costs can tend to infinity without regulation and backstop policy. European insurance companies were unwilling to underwrite projects. While induced seismicity is an issue, techniques are available to manage reservoir pressure.

CO_2 storage is new to most people and issues of social acceptance have already begun to emerge. In general uncertainty surrounding costs are difficult to quantify, but very real with large implications for financial feasibility of sequestration operations.

2.4. Session 4: Modelling U.S. Policy and Regulation

The U.S. energy policy scene is patchwork of federal, state and local policies and regulations. At the federal level, 45Q represents a new modelling challenge. While limits on both the period over which the tax credit is available and the time window in which qualifying facilities must come on line limit the economic attractiveness of the opportunity, potential changes to expand both limits could produce substantial participation. Similarly, interactions between California's Low Carbon Fuel Standard (LCFS -priced at \$100/tCO_2) and 45Q (priced between \$35-\$50/tCO_2) could induce substantial CCUS deployment.

Another modelling challenge is keeping up with the technology. Fossil fuel power generation technology is changing and improving rapidly, as is CO_2 capture, utilisation and storage technology. Bridges are needed to connect technology and finance experts with the modelling community.

Many USA based modelling teams are working to develop the ability to model 45Q. The enhanced 45Q legislation has now been enacted and hence, will need to be included in "reference" scenarios. Four teams reported on their progress in modelling 45Q within the context of the Stanford Energy Modelling Forum 34 (EMF-34) study group which is looking at both the current law and more stylised potential versions of the law.

The PNNL modelling team's presentation reported on work to model CO_2 markets at national scales using the Global Change Assessment Model (GCAM) that includes competition between natural and industrial CO_2 sources, between new and retrofit technology options for capture of CO_2, and between CO_2 demands from EOR and geologic storage. Analysis of the generic CO_2 study group policy showed that the EOR market would play a larger role in the near-term than in the long-term. Furthermore, industrial CO_2 supply would likely be dominated by CO_2 sourced from retrofit investments in existing coal plants.

On Location reported on work using the National Energy Modelling System (NEMS), which includes substantial detail. They reported work on four scenarios:

- Reference case with no 45Q sequestration tax credit, referred to as "No 45Q"
- Reference case with 45Q sequestration tax credits with sunset and 12 years of credit payments per current law, referred to as "45Q"
- 45Q sequestration tax credit extension case with no sunset provision and 12 years of credit payments, referred to as "45Q Ext"
- 45Q tax credit extension case with no sunset provision and lifetime (i.e., 30 years) of credit payments, referred to as "45Q Ext Life"

The scale of deployment of CCUS technology rose as the requirements to obtain the tax credit were relaxed. The more stringent versions of 45Q produced CO_2 that predominantly sold into the EOR market, but the "45Q Ext Life" scenario produced significantly more CO_2 than the other cases and significantly more CO_2 going to geologic storage. Like the GCAM results, much of the CO_2 utilised was captured from retrofitted coal-fired power stations.

NETL reported results for 45Q scenarios using their MARKAL-ANSWER CO_2-EOR model. Several issues emerged as part of the modelling. First the scale at which available CO_2-EOR data is different from the scale required by the models and the scale of the model output is rarely in tune with the scale at which decision makers require answers. Second, the rate at which EOR projects need CO_2 may not be steady, while powerplant CO_2 are often assumed to be produced at relatively constant rates. This mismatch may raise the cost of utilising industrial CO_2. Some preliminary findings included CO_2-EOR production could be as low as 2% (~0.3 MMBD) and as high as 14% (~1.1 MMBD) of total crude production and CO_2-EOR production can compete with shale oil production, but sensitivity analysis and low/high oil prices scenarios are required. They also found that as time went on natural sources of CO_2 were driven out of the market by industrial sources. Starting in 2040, 45Q generated a major increase in EOR production. Finally, they found substantial utilisation of coal retrofit opportunities for CO_2 capture.

The ReEDS model is an electric sector only model. They focused on power sector issues surrounding 45Q looking at utility sector incentives to capture CO_2 and geologic storage. They reported preliminary results which included the finding that CCS deployment scenarios in

ReEDS found little CCS deployment with either technology improvement or extending the 45Q credit alone, but tens to hundreds of GW of CCS capacity deployed when combining multiple technology and policy improvements including raising the CO_2 tax credit to $75/tCO2. CCS deployment in ReEDS is geographically dispersed and primarily installed on combined cycle natural gas-fired facilities, but the model's CCS representation does not represent regional differences in CO_2 transportation and storage prospects, and it does not include EOR and unit-specific retrofit costs that could reveal additional low-cost CCS opportunities. Finally, the ReEDS team reported on work to examine the implicating of House report language for the 2018 appropriations bill included a request for DOE to evaluate "the effects of a Zero Emissions Energy Credit that replaces existing renewable energy subsidies, once they phase out, with a graduated tax credit that is apportioned based on the total emissions profile… of energy production sources." This analysis request serves as a reminder that future legislation could influence the deployment of carbon capture systems in the power sector, potentially on a timescale that overlaps with the existing 45Q policy.

The discussion in Session 4 helped identify the types of important information needed to analyse the impact of policies affecting CCS such as 45Q. For example 45Q uses a tax credit rather than a tax as the inducement to deploy the technology which drives changes due to the carbon content differences between coal and gas. Mechanisms for financing are an important determinant of real-world technology deployment success or failure. Modelling challenges emerged between financial modelling of debt to equity ratios and the cost of capital, and the explicit lack thereof in ESM and IAMs. 45Q should now be treated as a core element of baseline scenarios rather than as a policy case. Potential extensions are policy scenarios. But there is still a question of how much you can really do in 5 years. At present the oil and gas industry seems to be interested. Models today don't have enough friction, technology specific lead in times or construction times in them for new technologies like CCS. For example, things like permitting issues take time that is generally not included in models.

2.5. Session 5: Future Directions, Needs and Opportunities

The meeting brought together researchers from a diverse set of backgrounds, all of whom have been studying CO_2 capture, utilisation and storage, but who had not worked together previously. Many participants expressed their appreciation for the connections. There were many expressions of interest in holding additional similar workshops. Considerable work remains to develop the network and establish a robust community of practice that extends form technical research to integrated analysis capabilities.

Data is an overriding issue which was brought up throughout the workshop by multiple participants. Modellers lack enough data to accurately incorporate key CCUS features. Similarly, uncertainty is poorly characterised.

Data interpretation was also mentioned by participants. Technical results may not be accessible to modellers. Communication between technical researchers and modellers is essential so that technical researchers can deliver knowledge in forms that can be utilised by modellers to faithfully represent CCUS in energy systems models and integrated assessment models.

Several participants expressed an interest in utilising future workshops to address other CCUS technologies such as CCS in combination with bioenergy for power or in the refining sector or oxy- combustion technologies.

Many models still lack the capability to assess CCUS issues such as 45Q. Several participants noted that having a place to go to find data that were presented in a way that could be easily accessed by modellers would accelerate the process of enhancing modellers' capabilities in the realm of CCUS. IEAGHG are working to share technical CCS data with IEA-ETSAP energy technology ("SubRES") database project. NETL are also a critical data provider and should be encouraged to be involved in this process.

Bibliography

Hilaire, Jérôme, Jan C Minx, Gregory F Nemet, Tim Beringer, Max W Callaghan, Thorben Amann, Gunnar Luderer, et al. "Negative Emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters* 13, no. 6 (2018): 063002. https://doi.org/10.1088/1748-9326/aabf9f.

Khanna, Tarun, Maria del Mar Zamora Dominguez, Joeri Rogelj, Jan C Minx, Tim Beringer, Gunnar Luderer, Gregory F Nemet, et al. "Negative Emissions—Part 1: Research Landscape and Synthesis." *Environmental Research Letters* 13, no. 6 (2018): 063001. https://doi.org/10.1088/1748-9326/aabf9b.

Kriegler, Elmar, Gunnar Luderer, Nico Bauer, Lavinia Baumstark, Shinichiro Fujimori, Alexander Popp, Joeri Rogelj, Jessica Strefer, and Detlef P. Van Vuuren. "Pathways Limiting Warming to 1.5°C: A Tale of Turning around in No Time?" *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376, no. 2119 (2018): 20160457. https://doi.org/10.1098/rsta.2016.0457.

Luderer, Gunnar, Zoi Vrontisi, Christoph Bertram, Oreane Y. Edelenbosch, Robert C. Pietzcker, Joeri Rogelj, Harmen Sytze De Boer, et al. "Residual Fossil CO_2 Emissions in 1.5-2 °c Pathways." *Nature Climate Change* 8, no. 7 (2018): 626–33. https://doi.org/10.1038/s41558-018-0198-6.

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, et al. "Mitigation Pathways Compatible With 1.5°C in the Context of Sustainable Development." In *Global Warming of 1.5°C. An IPCC Special Report [...]*, 82pp. Geneva: Intergovernmental Panel on Climate Change, 2018. http://www.ipcc.ch/report/sr15/.

Rogelj, Joeri, Gunnar Luderer, Robert C. Pietzcker, Elmar Kriegler, Michiel Schaeffer, Volker Krey, and Keywan Riahi. "Energy System Transformations for Limiting End-of-Century Warming to below 1.5 °C." *Nature Climate Change* 5, no. 6 (2015): 519–27. https://doi.org/10.1038/nclimate2572.

Rogelj, Joeri, Michiel Schaeffer, Malte Meinshausen, Reto Knutti, Joseph Alcamo, Keywan Riahi, and William Hare. "Zero Emission Targets as Long-Term Global Goals for Climate Protection." *Environmental Research Letters* 10, no. 10 (October 1, 2015): 105007. https://doi.org/10.1088/1748-9326/10/10/105007.

Vuuren, Detlef P. Van, Andries F. Hof, Mariësse A.E. Van Sluisveld, and Keywan Riahi. "Open Discussion of Negative Emissions Is Urgently Needed." *Nature Energy* 2, no. 12 (December 2017): 902–4. https://doi.org/10.1038/s41560-017-0055-2.

Appendix: Lunch Speaker – National and International Perspectives on CCUS

Presentation by Dr James Glynn, University College Cork

Carbon Capture and Storage in Climate Stabilisation Energy Scenarios

Dr James Glynn
Research Fellow MaREI Centre, University College Cork, IRELAND
@james_glynn | james.glynn@ucc.ie

17th October 2018 | University of Maryland, USA

EPMG ENERGY POLICY & MODELLING GROUP

MaREI Centre for Marine and Renewable Energy

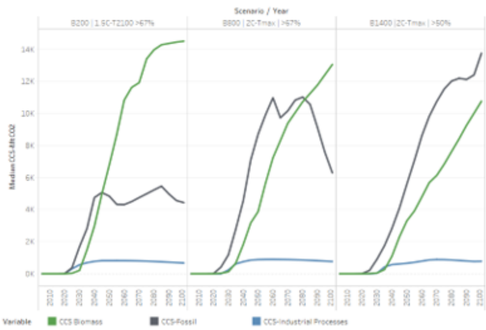
Environmental Research Institute

UCC University College Cork, Ireland Coláiste na hOllscoile Corcaigh

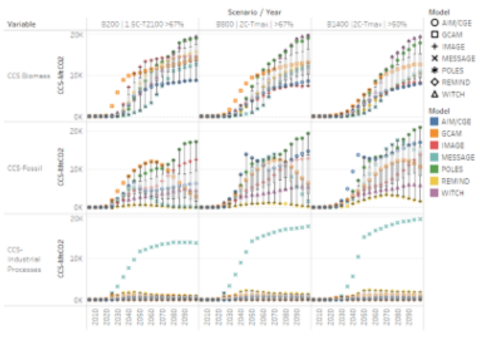
Aim of our "CCS in IAMs" study.

EPMG

- The aim of this study is to provide insight as to why the **projections and outcomes for carbon capture and storage** might differ among a selection of the more influential integrated assessment models (IAMS), by **exploring the assumptions, background calculations and input data**. The purpose of the study is to provide a transparent approach **to understanding model results**. It is not the intention of the study to advocate particular scenarios.



?



Project Consortium

EPMG

ieaghg | MaREI Centre for Marine and Renewable Energy | eci University of Oxford | Imperial College London

Contracting Party:
IEA GHG Ltd

Keith Burnard

MaREI Centre
Environmental Research Institutue,
University College Cork

Dr James Glynn
James.glynn@ucc.ie
Project contact point

Dr Paul Deane

Prof Brian Ó Gallachóir

Environmental Change Institute,
University of Oxford, UK

Prof Myles Allen

Dr Richard Millar

Imperial College London, UK

Dr Niall Mac Dowell

UCC University College Cork, Ireland Coláiste na hOllscoile Corcaigh

Outline

EPMG

- The role of CCS/CDR in stabilising the climate
- Context for non-modellers
  - Projections, Outlooks, Forecasts Vs Scenario Analysis
- Focus on CCS in the Shared Socioeconomic Pathways
- Diagnosing the dynamics of CCS in IAMs
  - (it's not just about using the right data – its how that data is used)
  - Direct and Indirect model assumptions
  - Model typology & responsiveness
- 6 Keypoints to take home
- 2 Recommendations for future work & collaboration

Science Foundation Ireland For what's next

MaREI Centre for Marine and Renewable Energy

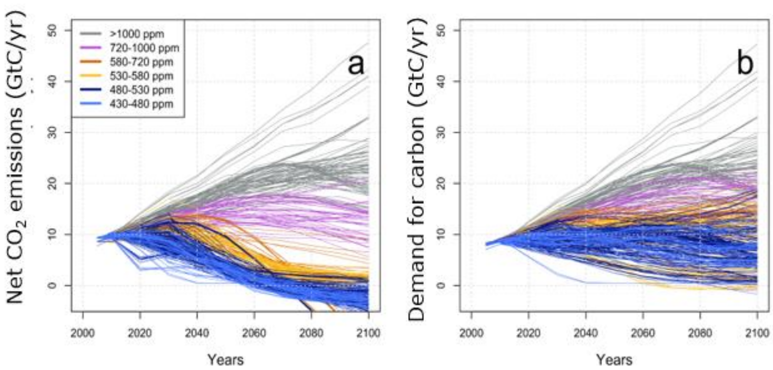
eri Environmental Research Institute

UCC University College Cork, Ireland Coláiste na hOllscoile Corcaigh

The role of CCS/CDR in stabilising the climate

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

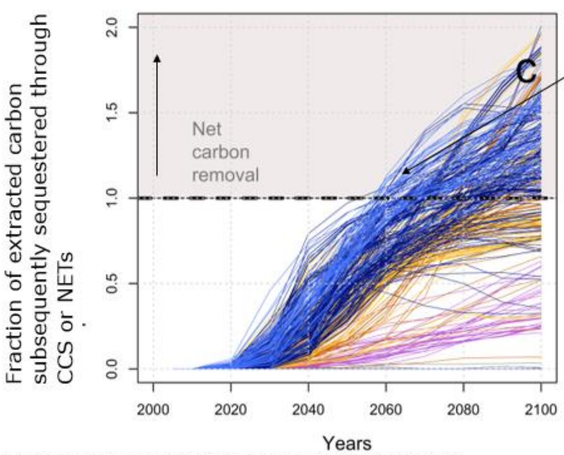
In AR5 scenarios with large emissions reductions, demand for carbon remains high



>66% chance below 2ºC
~50% chance below 2ºC

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

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



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

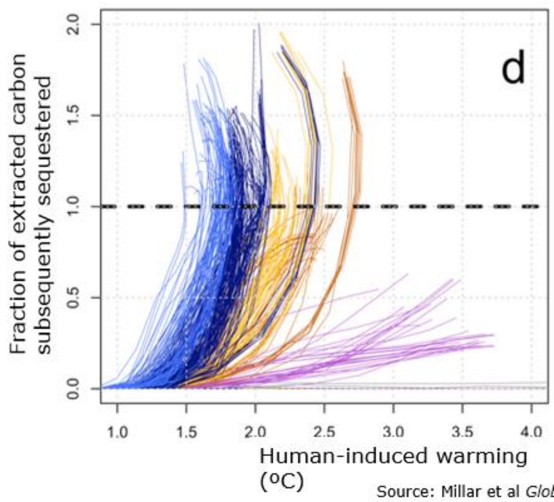
Sequestered fraction rises gradually and must reach 1.0 at some point in all scenarios that limit warming

>66% chance below 2ºC

~50% chance below 2ºC

EPMG

The fraction of CCS deployed is a well-constrained function of future warming in scenarios



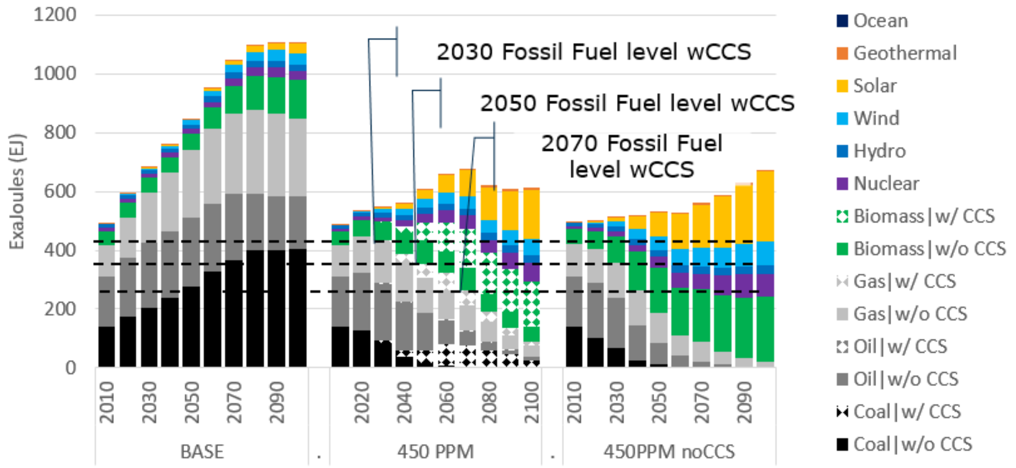
Scenarios show a steady upward curvature with warming beyond today, with peak warming occurring when the sequestered fraction reaches 1.

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

EPMG

Primary energy in the IPCC AR5 database for a BASE and 2C (EMF27) scenario with and without CCS

EPMG



UCC

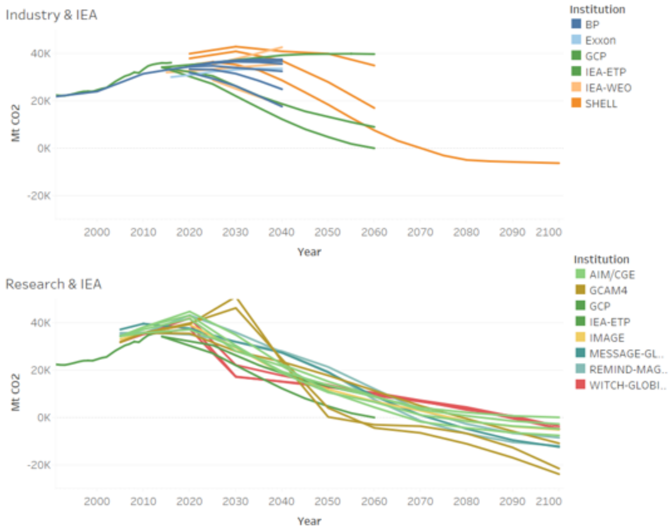
Context for non-modellers
Projections, Outlooks, Forecasts
Vs Scenario Analysis

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

CO_2 Projections, Outlooks and Forecasts Vs Scenarios

EPMG

- Purpose of IAMs is for robust insights from systems interactions not forecasts.
- Mathematical variation across IAM impacts model dynamics
  - Partial Equilibrium
  - General Equilibrium
  - Optimisation
  - Simulation
  - Perfect foresight
  - Dynamic Recursive with limited foresight
  - Myopic



Focus on CCS in the Shared Socioeconomic Pathways

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Deciding on what makes an IAM influential.

EPMG

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 (SR1.5) and into the future for IPCC 6th Assessment Report (AR6) are likely to be the Shared Socio-economic Pathways (SSP) marker models.

- SSP1 - Sustainability- IMAGE (PBL) – **Hybrid systems dynamics and General Equilibrium (GE)**
- SSP2 - Middle of the Road - MESSAGE-GLOBIOM (IIASA) – **Hybrid**
- SSP3 – Regional Rivalry - AIM/CGE (NIES) – **GE**
- SSP4 – Inequality - GCAM4 (PNNL) – **Partial Equilibrium (PE)**
- SSP5 - Fossil fuelled Development - REMIND-MAGPIE (PIK) – **GE**
- WITCH-GLOBIUM (FEEM) – **GE**

Science Foundation Ireland For what's next
MaREI
eri Environmental Research Institute
UCC University College Cork, Ireland

The Shared Socioeconomic Pathways of the energy sector

EPMG

- A new set of scenario narratives have been formulated to capture the uncertainty range of mitigation and adaptation challenges to the energy system, called SSPs, and is shaping future research within the IAM community to coordinate across climate research disciplines.

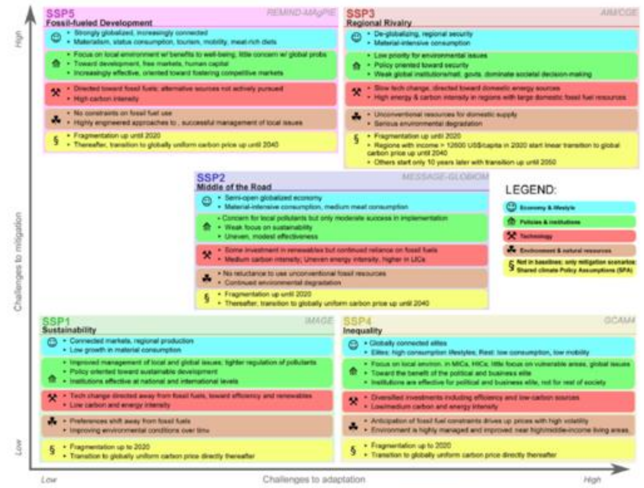
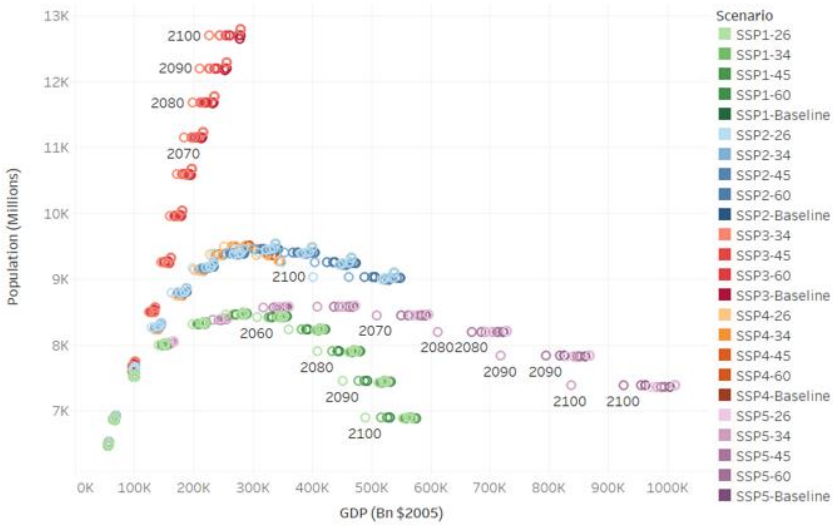


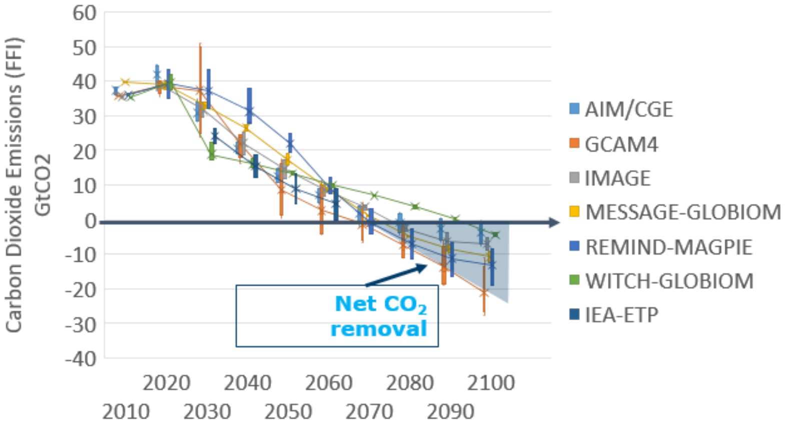
Fig. 1. Overview of *basic* SSPs, the energy sector elements of the narratives and the SPA specifications (O'Neill et al., 2016). HIC and MIC abbreviations for High and Medium Income Countries, respectively. The Shared Climate Policy Assumptions (SPAs), colored in yellow, are not used in the baseline 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.)

GDP, Population, Urbanisation data … and much more



Energy sector CO_2 emissions from the 6 SSP IAMs and IEA-ETP for 2°C (SSPx-2.6)

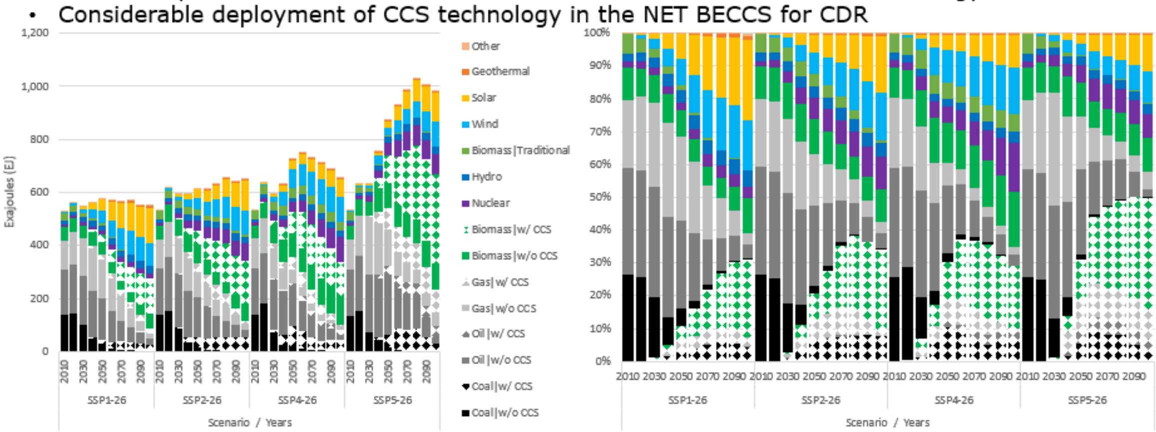
- Range of rates of decarbonisation observed illustrating each IAM's near term vs long term responsiveness.



Primary Energy Supply across SSPx-2.6 Scenarios

EPMG

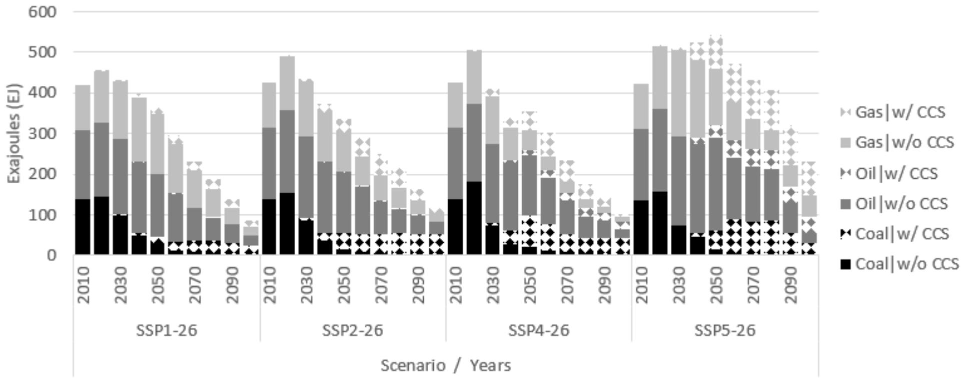
- Fossil Primary Energy Supply drops from 81% now to less than 20% across SSP1, 2 and 4 by 2100 for the 2°C scenario. 25% in SSP5
- There is a pervasive shift towards electrification from renewable electrical energy
- Considerable deployment of CCS technology in the NET BECCS for CDR



Primary Fossil Energy in SSPx-2.6 (2C) scenarios

EPMG

- SSP1, 2 and 4 show declining fossil fuel requirement in climate stabilisation scenarios from 2020 onwards, with increasing requirement for CCS on remaining fossil fuel supplies, largely in industry processes that are currently difficult to decarbonise.
- SSP5-2.6 shows medium term stabilisation in fossil fuel requirement at 400EJ, with declines in fossil fuel primary energy requirement from 2050, and coal from 2020

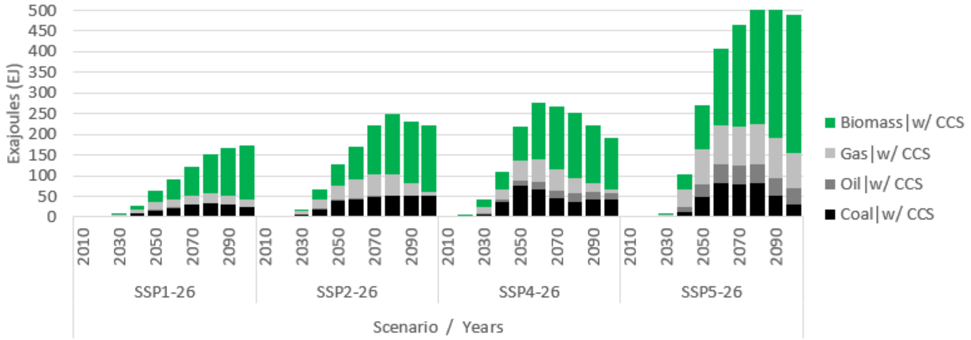


UCC

Primary Energy with CCS in SSPx-2.6 (2C) scenarios

EPMG

- CCS in conjunction with both fossil energy and bioenergy grows rapidly across the climate stabilisation scenarios for each of the SSPs from 1-5 (SSPx-2.6) starting from a low base and accounting for between 30-50% of primary energy by 2100 across scenarios.
- Primary energy supply from BECCS is larger than fossil CCS from mid-century. BECCS creates negative emissions removing CO2 from the atmosphere, but still requires sequestration storage space and infrastructure under the various SSP narratives



UCC

Variation of CCS deployment for each IAM for SSPx (2°C)

EPMG

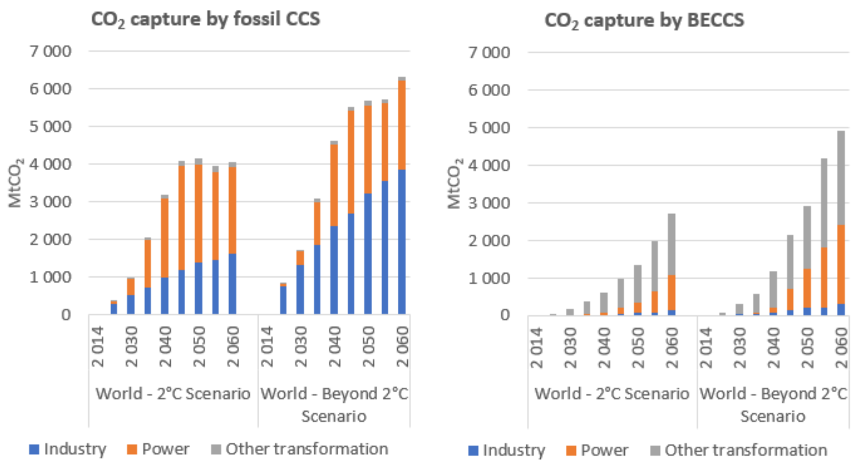
- Sustainable primary energy supply of bioenergy is limited to between 100EJ and 250EJ across SSP1-4 and up to a median value of 450EJ in SSP5-2.6.
- The supply of biomass is an upper constraint on BECCS deployment and the resultant level of negative emission the technology group could provide.
- Biomass is also used as a feedstock for various final liquid fuel consumption requirements as well as final gaseous fuels and electricity generation. The sustainable

CCS Capture from the SR1.5 DB (Luderer et al)

CCS Capture from the SR1.5 DB (Luderer et al)

IEA-ETP CO_2 – CCS's role in Industry is critical

EPMG



UCC

Diagnosing the dynamics of CCS in IAMs

- Direct and Indirect model assumptions
- Model typology & responsiveness

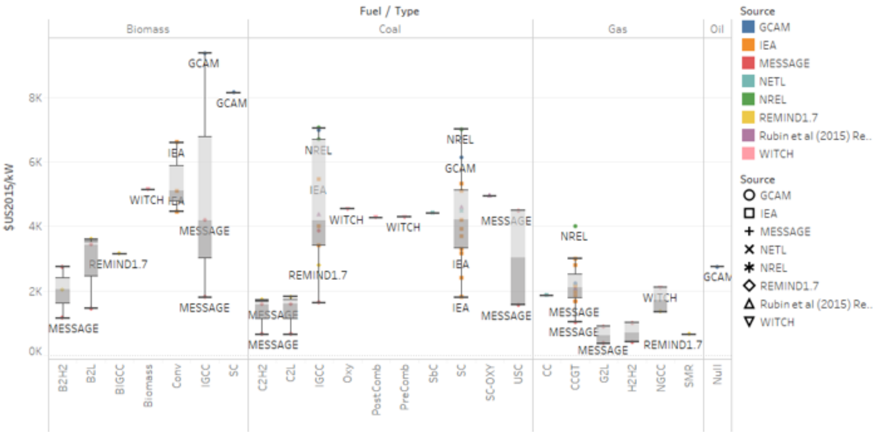
UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

IAM Input Data assumptions (& responsiveness)

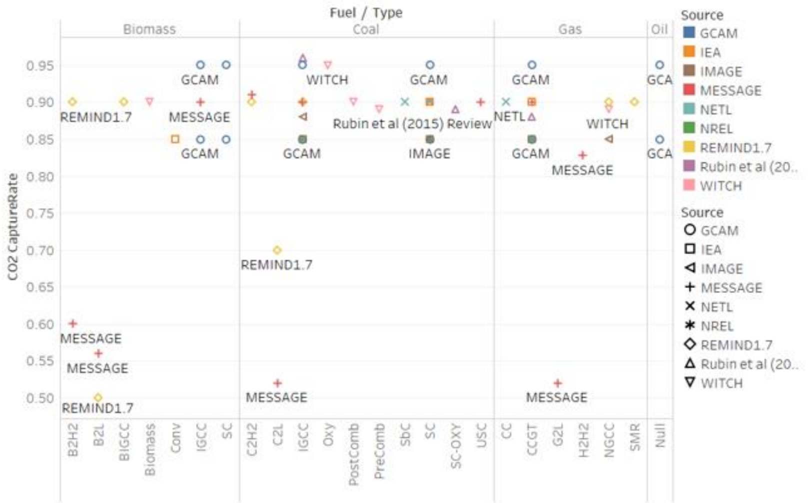
- There are a range of input assumptions that impact upon the deployment of CCS in integrated assessment models (IAMs), that can broadly be categorised into:
  - ✓ **Direct** input assumptions include CCS capex, fixed & variable opex, CO_2 capture rates, capacity factor, learning rates (reduction in cost for a doubling of installed capacity), build rates.
  - ✓ **Indirect** input assumptions can include fossil fuel cost curves, resource potentials, technology options, social acceptability, injection rate limits, residual emissions ….
  - ✓ **Responsiveness** to climate policy is an emergent property of an IAM dependent upon it's mathematical method, planning foresight and discounting of costs.

Direct CCS calibration input assumptions

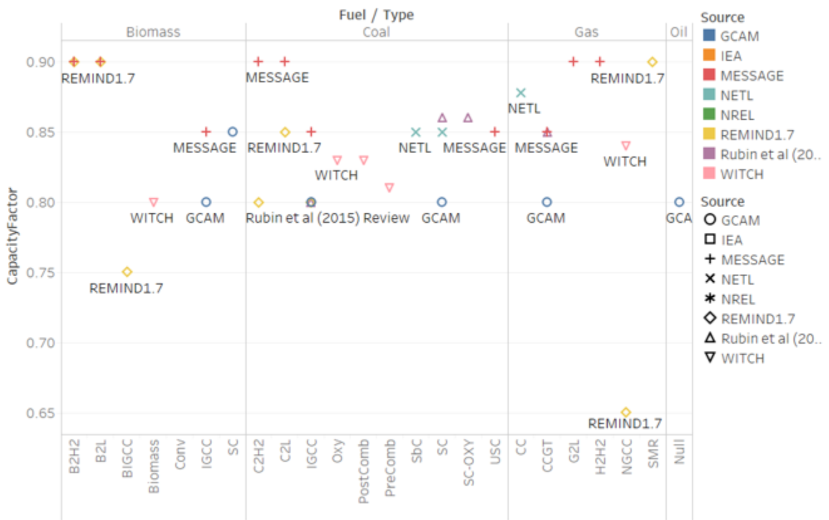
- CCS capacity cost by fuel and technology inflated to 2015 from each model base year using IHS CERA power capital cost index.



Direct Calibration factors – CO2 Capture Rate



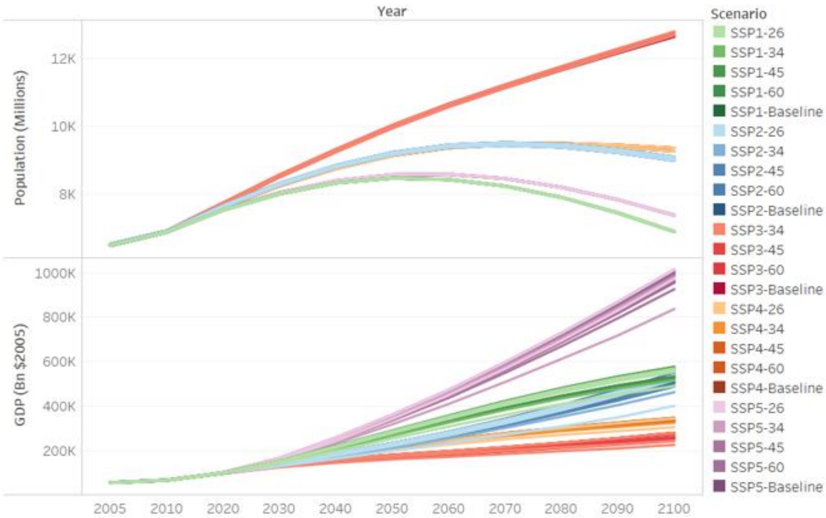
Direct Calibration factors – Capacity Factor (up time)



Other direct input assumptions for CCS technologies

- Capture rates (generally an upper limit of 90%)
- Capacity factors
  - (generally fixed, which causes high residual emissions from Fossil CCS)
- Learning rates (assumed slower than renewables)
  - Capacity cost reductions per doubling of installed capacity
  - Efficiency improvements over time wCCS
- Injection rate annual limits (regional variations?)
- Regional variation (capex, opex, learning)
- Cost discounting (3-6% per year)

Indirect Factors impacting CCS deployment



Indirect input assumptions from SSP narratives impact in CCS deployment

EPMG

- Qualitative **energy conversion technologies** elements of the SSPx narratives
  - Impacts on Learning rates & cost reductions
  - Impacts on acceptable growth rates.

SSP Element	SSP 1			SSP 2			SSP 3			SSP 4			SSP 5		
	Country Income Groupings														
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Fossil Fuel Conversion															
Technology Development		Med			Med			Med		Med	Med	Med		High	
Social Acceptance		Low			Med			High		High	Low	Low		High	
Commercial Biomass Conversion															
Technology Development		High			Med			Low		High	High	High		Med	
Social Acceptance		Low			Med			High		High	High	High		Med	
Non-bio Renewables															
Technology Development		High			Med			Low		Low	High	High		Med	
Social Acceptance		High			Med			Low		Low	High	High		Low	
Nuclear Power															
Technology Development		Med			Med		Low	Low	Med	High	High	High		Med	
Social Acceptance		Low			Med		High	High	High	High	Med	Med		Med	
CCS (only climate policy)															
Technology Development		Med			Med			Med		High	High	High		High	
Social Acceptance		Low			Med			Med		High	Med	Med		High	

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Indirect input assumptions from SSP narratives impact in CCS deployment

EPMG

- Qualitative **fossil fuel supply** elements of the SSPx narratives.

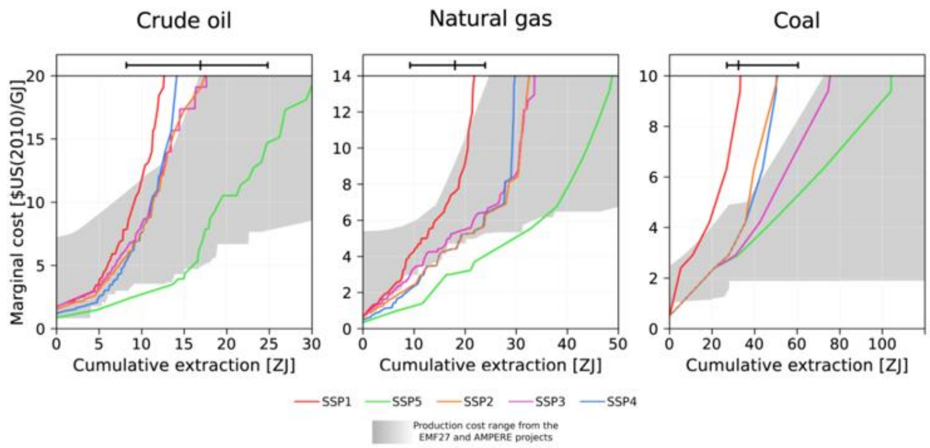
	SSP1 Sustainability	SSP2 Middle of the Road	SSP3 Regional Rivalry		SSP4 Inequality			SSP5 Fossil fueled development
			Country grouping		Country grouping by income			
			Exporter	Importer	Low	Medium	High	
Coal								
Macro-economy	cost driver	neutral	cost reducing		cost driver	cost driver	neutral	cost reducing
Technological progress	slow	medium	slow	fast	medium			very fast
National & environmental policy	very restrictive	supportive	very suportive		supportive	supportive	restrictive	very supportive
Conv. hydrocarbons								
Macro-economy	neutral	neutral	neutral		cost driver	neutral	cost reducing	cost reducing
Technological progress	medium	medium	medium		fast			very fast
National & environmental policy	restrictive	supportive	not supportive	supportive	supportive	supportive	restrictive	very supportive
Unconv. hydrocarbons								
Macro-economy	neutral	neutral	neutral		cost driver	neutral	cost reducing	cost reducing
Technological progress	slow	medium	slow	medium	medium			very fast
National & environmental policy	very restrictive	supportive	not supportive	very supportive	supportive	supportive	restrictive	very supportive
General								
Trade barriers	free trade	some barriers	high barriers		barriers			free

Source: Bauer, N. et al. Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. Global Environmental Change 42, 316–330 (2017).

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Indirect SSPx narrative input assumption
Example: Cost curves for fossil fuel production

EPMG



Source: Remind V.7 documentation (http://themasites.pbl.nl/models/advance/index.php/Fossil_energy_resources_-_REMIND).

Science Foundation Ireland For what's next
MaREI
Environmental Research Institute
UCC University College Cork, Ireland Coláiste na hOllscoile Corcaigh

Indirect input assumptions from SSP narratives impact in CCS deployment

EPMG

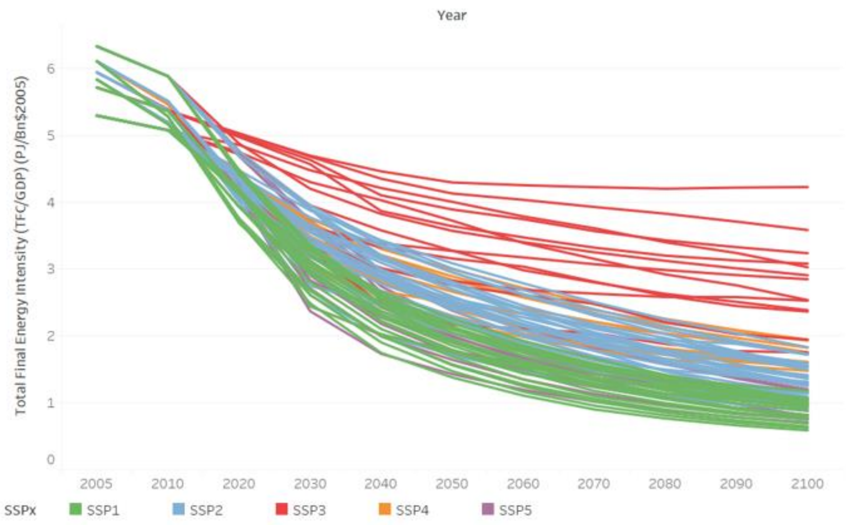
- Qualitative **final energy demand** elements of the SSPx narratives.
  - Energy Demand Intensity evolution

	SSP 1			SSP 2			SSP 3			SSP 4			SSP 5		
	Country Income Groupings														
SSP Element	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Non-climate Policies															
Traditional Fuel Use		fast phase-out, driven by policies and economic development			intermediate phase-out, regionally diverse speed			continued reliance on traditional fuels			continued traditional fuel use	some among low income households		fast phase-out, driven by development priority	
Energy Demand Side															
Lifestyles		modest service demands (less material intensive)			medium service demands (generally material intensive)			medium service demands (material intensive)			low service demands	modest service demands		high service demands (very material intensive)	
Environmental Awareness		high			medium			low			low	high		medium (low for global level/high for local level)	
Energy Intensity															
Industry		low			medium			high			high	low		medium	
Buildings		low			Medium			high			medium	low/medium		medium	
Transportation		low			Medium		medium		high		low/medium	low		high	
General Comments					some regional diversity retained										

Source: Bauer, N. et al. Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. Global Environmental Change 42, 316–330 (2017).

UCC University College Cork, Ireland Coláiste na hOllscoile Corcaigh

Example: Total final Energy Intensity of GDP by SSP



Discount Rates & Hurdle Rates

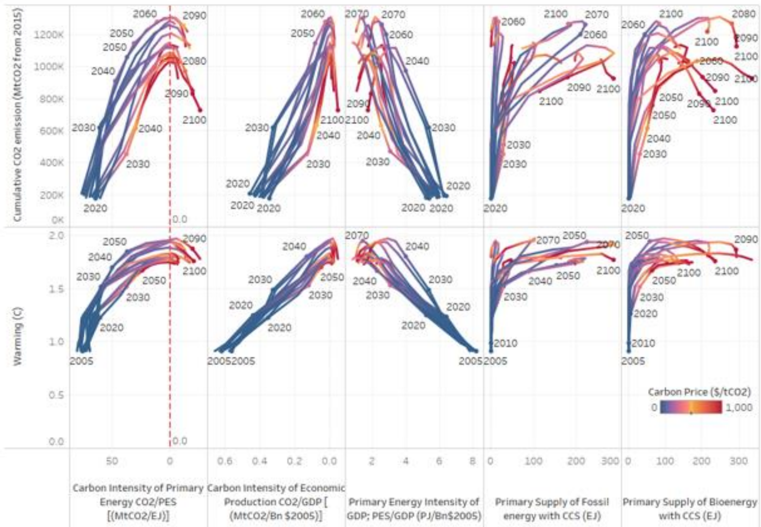
- Discounting effects
- Renewables with High CAPEX and Low OPEX learning rates interact with higher OPEX CCS plants with long term discounting

MODEL	DISCOUNT RATE
AIM	5%/yr, exogenous, constant over time
GCAM	5%/yr, exogenous, constant over time
IMAGE	5%/yr, exogenous, constant over time
MESSAGE	5%/yr, exogenous, constant over time
REMIND	Endogenous discount rate follows Keynes-Ramsey rule with PRTP = 3%/year and elasticity of marginal utility = 1. Consumption growth rates of 1-3% lead to 4-6% global discount rate, which slightly declines over time.
WITCH	Depends on marginal productivity of capital. It is related to the pure rate of time preference (3%/yr - declining by 0.257%/yr) and to the risk aversion (1) via the Ramsey rule, though not exactly, due to more complex nature of the economic growth engine in the model.

IAM responsiveness classification

Model Name	Equilibrium Type	Modelling Approach	Low Carbon Tech Supply Variety	Cost Per abatement value	Classification
AIM	Partial Equilibrium	Recursive Dynamic	High	TBD	PE - medium response
GCAM	Partial Equilibrium	Recursive Dynamic	High	Medium	PE - high response
IMAGE	Partial Equilibrium	Recursive Dynamic	High	Low	PE – high response
MESSAGE	General Equilibrium	Intertemporal Optimisation	High	Low	GE – high response
REMIND	General Equilibrium	Intertemporal Optimisation	High	Medium	GE – high response
WITCH	General Equilibrium	Intertemporal Optimisation	Low	Medium	GE – low response

IAM Dynamics Summary



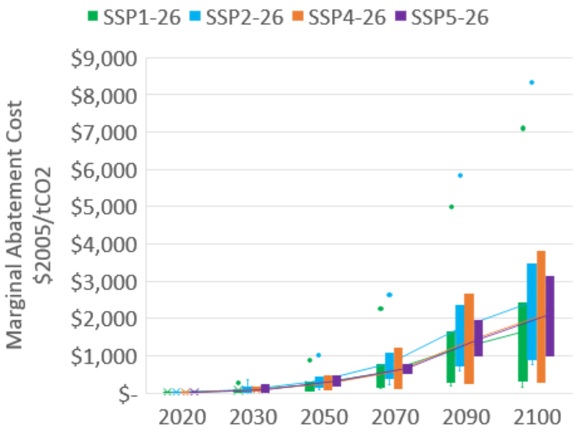
Key messages to take home

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Key Message 1 – System CO_2 cost >> CCS CO_2 Capture cost

EPMG

- CCS capture costs of less than $100/tCO2 in the power generation sector and less than $400/tCO2 in Industry, are considerably lower than the whole system marginal abatement costs of CO_2 by mid-century calculated in IAMS; hence, in these IAMs, there are other limiting and competing constraints on CCS deployment that are not solely related to the cost calibration input data of CCS in IAMs, but related to interdependent technical or modelling constraints listed in the following key-points.



University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Keypoint 2 – 90% capture rate is not a technical limit

- 90% capture is the upper limit for most CCS technologies across all the 6 SSP Marker IAMs reviewed except for WITCH and GCAM which have capture rates of up to 95% for some technologies. Note GCAM has the largest penetration of Gas-CCS in Primary energy supply across the SSP scenarios as well as typically having the deepest net-negative CO_2 emissions by the end of the century in the order of -25GtCO_2/year by 2100
- This 90% capture rate limit is not a technical limit to CO_2 capture
- Reliance on high deployment and high capture rates of CCS in IAMs is not prudent given the considerable gap between expected near-term deployment rates as a function of CCS projects in existing planning pipeline and the required near-term CCS deployment rates in IAMS ;
- however it is precautionary to significantly ramp up research, development and demonstration into higher capture rates given current CO_2 emissions trajectories and the mitigation rates now required to remain below 2°C .

Keypoint 3 – High Fossil CCS Residual emissions are incompatible with Paris agreement carbon budgets

- The 2°C scenarios (SSPx-2.6) have an inflexible upper limit (hard constraint) of cumulative CO_2 emissions allowable (Carbon Budget) in the range of 800-1,400GtCO_2. 1.5°C has a lower hard constraint on CO_2 emissions in the range of 200-800GtCO_2 . Residual CO_2 emissions from fossil CCS with 90% capture rates and fixed capacity factors become incompatible with such strict carbon budgets.
- The point here is that residual emissions from fossil CCS at 90% capture rates with inflexible operational regimes with fixed capacity factors become incompatible with such strict carbon budgets. Hence we see less and less fossil CCS deployment (assuming 90% capture and about 80-90% capacity factors) in scenarios with smaller and smaller carbon budgets representing lower and higher confidence temperature stabilisation targets.

Keypoint 4 – BECCS is a net energy positive CDR option

- BECCS provides the majority of negative emissions in IAMs (with CDR in the form of afforestation) that provide additional space within the remaining carbon budget, as long as there is remaining geological storage space under annual injection rate limits.
- Other CDR options such as Direct Air Capture (DAC) and Enhanced Weathering (EW) are beginning to be explored in IAMs, are not net energy positive , therefore do not contribute to energy service demand and require additional energy inputs to provide its CDR function. CDR by DAC and EW may be worth deploying in cases where resource limits do not constrain zero carbon heat, zero carbon electricity, water requirements, waste material processing requirements and where these technologies reduce the system wide marginal cost of abatement of carbon globally.

Keypoint 5 – BECCS CDR is limited via bioenergy supply

- BECCS has a limit of sustainable primary energy supply in the order of 120-300 EJ across the IAMs except in SSP5 scenarios where bioenergy primary energy supply is allowed to grow beyond sustainable levels to about 450 EJ. 450EJ of primary bioenergy is likely beyond a sustainable level absent of significant and, as yet, largely speculative, advances in 3rd- and 4th-generation biofuel technologies. Thus the volume of negative emissions BECCS can provide is also limited. The volume of residual fossil emission BECCS can negate is therefore also limited. The availability of up to 450 EJ of primary bioenergy supply is likely unsustainable, uncertain and unlikely without radical advances in afforestation

Keypoint 6 – without CCS/CDR/NETS demand reduction

- In the absence of further Negative Emissions Technologies (NETs) in the IAM SSP scenarios explored, and without further capture of CO_2, demand reduction, energy efficiency and deep near-term mitigation is the next considered option in the IAM literature when moving between 2°C and 1.5°C targets

Recommendations

Recommendation 1 of 2 – Centralised CCS Etech Brief

- Firstly, the IEAGHG may wish to coordinate the development of techno-economic specification for all CCS technology options in Power, Industry and upstream transformation processes with a range of capture rates with varying vintage technology options in a centralised database format to reduce the transaction cost of implementing the current state of the art of CCS technology in the influential IAMs.
- IAMs can have thousands of technology options, and so making CCS technology data available in a centralised location and useful format makes updating IAMs simpler and faster, reducing the need for continual technology review cycles from the IAM modeller perspective.
- This technology database should be designed in coordination with IEA-ETSAP in their current plans to update the ETSAP energy technology briefs ("Etech Briefs") and database as well as the Integrated Assessment Modelling Consortium (IAMC) to specify a useful data variable format for input into energy systems models and IAMs . This open database should further be maintained and regularly updated by CCS technologist experts, with regular communication between the CCS and IAM communities given their interdependence. The IEA-ETP data tables provided in the main body of the report as best practice gives an indication of useful data formats.

Recommendation 2 of 2 – Funded CCS MIP

- Secondly , a funded model inter-comparison project (MIP) with harmonised CCS input data assumptions involving the top 10 IAMs across the range of SSPx-RCP6-1.9 scenarios would remove the difficulties in transparently assessing and isolating the causes and effects of CCS calibration in IAMs.
  - We suggest that such a CCS/CDR MIP would focus on;
    - Learning rates as a function of research development spending and demonstration capacity for prospective ranges of future capture rates and reduction of residual emissions,
    - Sub-annual flexible capacity factors,
    - Feasible maximum industry build rates,
    - Maximum feasible injections rates.
  - The project scenario design and outputs could calculate the societal costs & benefits of CCS deployment in dollars savings of consumption and GDP growth against the counterfactual range of uncertain futures with limited CCS deployment such as low energy demand scenarios.
  - The project could calculate the revenues to fossil energy industry against the same uncertain CCS futures .
- Finally, the MIP could outline the scale of finance required to achieve the rates of learning and CCS deployment consistent with limiting global warming to below 2°C with updated and harmonised CCS input calibrations. This research could inform public-private funding of CCS RD&D and required infrastructure spending commensurate with the scale of the combined industry revenues and societal benefit of accelerated deployment of CCS as global mean temperature warming approaches 2°C.
- The goal is to achieve a net-zero carbon energy system well before 2°C is breached.


Thank You
QUESTIONS?
Science Foundation Ireland
sfi
For what's next
George Karbus

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Pure Offices, Cheltenham Office Park, Hatherley Lane,
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911

mail@ieaghg.org
www.ieaghg.org