Evaluating technology options to mitigate greenhouse gas emissions

IEAGHG Technical Report 2017-06

June 2017

Proceedings of US DOE Workshop: Energy-Economic Modelling Review

IEA GREENHOUSE GAS R&D PROGRAMME

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Proceedings of US DOE Workshop: Energy-Economic Modelling Review

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Acknowledgements

The idea for the workshop arose directly from the joint interests of the IEA Greenhouse Gas R&D Programme (IEAGHG) and the United States Department of Energy (US DOE) to explore how CCS is represented in energy-economic integrated assessment models. As energy-economic modelling provides important input to policy decisions, both IEAGHG and US DOE remain committed to ensure that CCS is represented appropriately.

IEAGHG would like to thank the US DOE for its leadership in planning and providing essential funding for the workshop. It would also like to thank the United States Energy Association (USEA) for providing the meeting facilities. The workshop was held on 3-4 April in the USEA's Washington DC offices. Particular thanks go to Ann Satsangi, US DOE, for her commitment to ensuring the success of the workshop.

This report was prepared by the project consortium contracted to undertake the IEAGHG study, "CCS in Energy and Climate Scenarios". The primary author was James Glynn, University College Cork. The content of the 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 to be reached.

The workshop participants were:

First Name	Surname	Institution
Mikhail	Adamantiades	Environmental Protection Agency
Steve	Andersen	US Geologic Survey
Praveen	Bains	DOE - Fossil Energy
José R.	Benítez	Energy Ventures Analysis, Inc.
Aaron	Bergman	DOE - Fossil Energy
John	Bistline	Electric Power Research Institute
Keith	Burnard	IEA Greenhouse Gas R&D Programme
Leon	Clarke	Pacific Northwest National Laboratory
Stuart	Cohen	National Renewable Energy Laboratory
David	Daniels	Energy Information Agency
Jarad	Daniels	DOE - Fossil Energy
Casie	Davidson	Pacific Northwest National Laboratory
Allen	Fawcett	Environmental Protection Agency
Sarah	Forbes	DOE - Fossil Energy
Doris	Fujii	British Petroleum
Kristin	Gerdes	National Energy Technology Laboratory
James	Glynn	University College Cork
Joseph	Goodenbery	National Rural Electric Coop
Lessly	Goudarzi	OnLocation Inc
Don	Hanson	Argonne National Laboratory
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Anhar	Karimjee	DOE - Fossil Energy
Jordan	Kislear	DOE - Fossil Energy
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Amishi	Kumar	DOE - Fossil Energy
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Christopher	Nichols	National Energy Technology Laboratory
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Sergey	Paltsev	MIT Joint Program
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John	Weyant	Stanford University
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Executive Summary

The US Department of Energy's Office of Fossil Energy (DOE-FE) organised an energy-economic modelling review workshop, held 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 IAM. 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 energy and 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 other relevant stakeholders, together with IAM modellers from policy, industry and academia with the objective to assess the methodologies, inputs, and assumptions of the energy-economic modelling capabilities we use to provide insights to inform policy direction, regulatory processes and program justifications. The desired outcomes of the workshop are a mapping of capabilities, and identification of gaps and opportunities for development. While some CCS and IAM experts came from Europe, workshop attendees were largely based in the United States. This geographic distribution of the attendees gave the workshop more of a US focus from the perspectives of data availability, CCS costs, and the IAMs presented at the workshop. The agenda included highlighting the CCS technology baseline data available from the US National Energy Technology Laboratory (NETL), updates on current CCS demonstration at scale plants (US DOE/IEAGHG), IAM overview presentations from US and global model developers, model inter-comparison projects (MIPs) from the Stanford Energy Modelling Forum (EMF), overview of the IEA Energy Technology Systems Analysis Programme (IEA-ETSAP), the energy system and CCS outlook from the IEA's Energy Technology Perspectives (ETP) analysis, as well as break-out discussion sessions.

The outcomes and actions from the workshop were as follows:

1. 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.

   Action: Based initially on attendance at the workshop, to establish and maintain a network of interested energy modellers and CCS experts. To establish an email list-serve for communication and information exchange among this group **(DOE/IEAGHG)**.

   Action: To arrange a follow up event to take place alongside the 2017 International Energy Workshop, which will be held in College Park, Maryland, USA, from 10-14 July **(IEA-ETSAP)**.

2. 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. It is largely focussed on US data sources but includes in-depth technology information relevant to international locations.

   Action: To schedule a series of NETL-led webinars on NETL's baseline data and other products. Suggest this is underway by June 2017, such that information is shared prior to next meeting **(NETL)**.

   Action: To provide a list of (and links to) NETL products, baseline evaluations and data **(NETL)**.

   Action: To review and make available NETL's database of industrial sources (including NEMS documentation) **(NETL)**.

3. 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.

   Action: To prepare a glossary of CCS/advanced fossil terminology to promote technical consistency. For example, how are the terms 'base plant', 'retrofit' and 'repowering' defined. What is included? What is required? What are the boundaries? **(DOE)**.

4. There are numerous IAMs, many of them with CCS represented in them to various levels of detail. For user confidence, it is important to gain an understanding of the assumptions, data and calculations that underpin the models.

   Action: To publish a review of CCS in IAMs **(IEAGHG)**.

Agenda

Day 1 Monday 3rd April 2017

08:00 Welcome and logistics

08:15 Opening remarks:
DOE-FE program highlights and progress
Jarad Daniels, US Office of Fossil Energy
IEAGHG: Global perspective on CCS
Keith Burnard, IEAGHG

09:00 **NETL Technology Baseline overview**
Kristin Gerdes and David Morgan, NETL

10:15 **Model Overview Presentations**

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

12:15 Working Lunch - Speaker: **"CCS Project updates and highlights: Kemper, ADM, NetPower"** Andrew Hlasko, Director Major Demos, DOE Office of Fossil Energy

1:30 **Model Overview Presentations**

Phoenix/ADAGE	EPA, Jim McFarland
ReEDS	NREL, Stuart Cohen
EPAUS9r	EPA, Dan Loughlin
MARKAL	NETL, Chris Nichols
REGEN	EPRI, John Bistline

3:10 Break

3:20 **Integrated Modelling Frameworks:**
SC/PNNL IMMM and IHESD
Bob Vallario, US DOE Office of Science
Ian Kraucunas, PNNL

4:00 **Model Overview Presentations**

MERGE	EPRI, Steven Rose
IEA-TIMES	IEA, Uwe Remme
ESO	ICL, Clara Heuberger
Irish-TIMES	UCC, Brian Ó Gallachóir

5:20 Conclusions

Day 2 Tuesday 4th April 2017

08:30 **Inter-model comparison:**
John Weyant, Stanford University

09:00 **US EIA modelling products**
David Daniels, EIA

09:30 **IEA Energy Technology Systems Analysis Programme,** Brian Ó Gallachóir, IEA-ETSAP/UCC

10:00 **IEA energy products and ETP**
Uwe Remme, IEA

10:00 Break

11:00 LCA modelling
Tim Skone, NETL

12:00 Lunch

1:30 **Break-out sessions:**
Map key model characteristics
Classify CCS, CO_2 and fossil technology representation
Identify model development gaps and opportunities

2:30 **Break-out sessions:**
Identify and compare cost assumptions and input
Identify data gaps and opportunities

4:00 **Report out and Wrap up**

5:00 **Adjourn**

1. Introduction

The 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) marked a milestone in the course of international efforts on global energy and climate action. World leaders agreed to set a goal of limiting global warming to less than 2˚C compared to pre-industrial levels. The agreement calls for zero net anthropogenic greenhouse gas emissions to be reached during the second half of the 21st century. In the adopted version of the Paris Agreement, the parties will also "pursue efforts to" limit the temperature increase to 1.5°C. While the global community has committed itself to holding warming below 2°C to prevent “dangerous” climate change, the Intergovernmental Panel on Climate Change[1] have highlighted that current policies could very likely lead to warming in excess of this level.

Integrated assessment modelling of possible 21st century energy system transitions by international research groups[1–8] highlight the importance of carbon capture and storage (CCS) and negative emissions technologies (NETs) in achieving substantial emission reduction on timescales relevant to the energy and climate goals of the Paris Agreement. In the latest Intergovernmental Panel on Climate Change (IPCC) assessment report (AR5)[1], 101 of the 116 scenarios that achieved a “likely” (>66%) chance of limiting warming to beneath 2°C relied on some deployment of the NET, bioenergy carbon capture and storage (BECCS), to achieve this goal as an essential complement to conventional mitigation.[9,10]

The United States Department of Energy’s Office of Fossil Energy (DOE-FE) 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 CCS technologies in integrated assessment models (IAMs). IAMs are computer models and vary in the mathematical approaches that underpin them, ranging from “top down” economic methods to “bottom up” engineering methods, or a hybrid combination of both. In general, IAMs incorporate representations of the energy, economy and Earth systems into one integrated framework. 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.

The models listed here were presented in the workshop, and include many of the most influential IAMs in the United States. There are, of course, many other notable global and national IAMs that were not represented at the 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	Uwe Remme
ESO	ICL	Clara Heuberger
Irish-TIMES/ETSAP	UCC/IEA-ETSAP	Brian Ó Gallachóir

2. Carbon Capture and Storage progress update

2.1. US DOE-FE programme highlights and progress

Jarad Daniels, Acting Deputy Assistant Secretary for Clean Coal and Carbon Management at the DOE-FE, gave an update on the research, development and current demonstration activities within the United States and the DOE's budget allocation towards advancing clean coal technologies. The current DOE budget for advanced power systems and CCS is in the order of $400 million annually. Carbon capture accounts for approximately $100m spend on pre-combustion gasification processes and post processing scrubbing flue gas etc. Most capture research has been on post-combustion chemistry in solvent, sorbent and membrane technologies. $40-$50m per year has been spent on material sciences research. A similar $100m spend on carbon storage, and $100m for advanced energy systems.

Demonstration activities have been driven by a combination of technology research development & demonstration (RD&D) push factors and market pull factors, such as the 65 million tons of CO_2 per year used to produce 300 000 barrels of oil in enhanced oil recovery (EOR) per day. Current major demonstration projects include the Kemper project (582 MWe coal-CCS with EOR) with operations having started in Q1-2017 at an estimated cost of $6.7 billion ($11 512/kW), Petra Nova CCS project (240 MWe coal-CCS with EOR) with full operation January 2017 at an estimated cost of $1 billion ($4 166/kW), the Air Products facility (steam methane reforming with CCS + EOR) in operation since December 2012 at an estimated cost of $431 million, and the Archer Daniels Midland bioethanol facility (with the captured CO_2 injected into the Mt Simon saline formation) expecting full rate injection in Q2-2017 at an estimated cost of $208 million. With the many industrial point emission sources in the United States, industrial sources could become early adopters of CCS technology, across chemical and refining, metal, minerals, waste management and agriculture.

The DOE engages nationally and globally to advance CCS technologies and is working with the IEAGHG in the working party on fossil fuels as well as the carbon sequestration leadership forum (CSLF). Technical efforts for the advancement of CCS is being carried out by the DOE-FE in multi-lateral collaboration with the Asia Pacific Economic Cooperation Expert Group on Cleaner Fossil Energy (APEC-EGCFE), the IEA Greenhouse Gas R&D programme (IEAGHG) and the IEA Clean Coal Centre (IEA CCC).

2.2. IEAGHG: Global perspectives on CCS

Keith Burnard from the IEA's Greenhouse Gas R&D Programme[i] (IEAGHG) gave a global perspective on CCS, starting from the context provided by the IPCC's 5th Assessment Report (AR5) highlighting 76% of GHG emissions sources originating from the energy system[11]. More mitigation measures are required via more end-use efficiency, greater use of low-carbon and no-carbon energy technologies including CCS, improving the available carbon sinks via increased afforestation and forestry management and finally lifestyle and behavioural change. Integrated assessment modelling referenced in the IPCC AR5 Synthesis Report (AR5 SYR) highlight that mitigation scenarios consistent with a 2˚C low carbon future are likely to have a 138%[ii] increase in total discounted mitigation costs if CCS is not a mitigation technology option. While the IPCC's AR5 Working Group III mitigation work focused on a 2˚C temperature rise ceiling, the stated goal of the Paris (COP21) Agreement ratified in 2016, is to keep temperature rise well below 2˚C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5˚C; this is a significant increase in mitigation ambition, than that analysed in IPCC AR5 Working Group III. The Intended Nationally Determined Contributions (INDCs) submitted to COP21 in 2015 are generally assessed to represent near-term mitigation that is less ambitious than that seen in cost-effective IAM scenarios limiting warming to "likely" below 2 degrees, with the result that CCS was mentioned in just 10 INDCs – albeit the countries covered by those 10 INDCs accounted for around two-thirds of global energy-related CO_2 emissions. ETP 2016[12] highlights that CCS has a considerable role to play in mitigation scenarios, providing 12% of cumulative mitigation to 2050 in transitioning from the 6DS to the 2DS or 15% from the 4DS to the 2DS, sequestering 6 billion tonnes CO_2 annually by 2050.

However, while SaskPower's Boundary Dam Coal-CCS power station in Canada, as well as Shell's Quest Hydrogen refining project and Petrobras's Lula project for offshore gas separation and EOR are each a step in the right direction, CCS is not "on track" globally to reach the 2DS by 2050. CCS has moved forward with increases in capture potential of the project pipeline, but is far from being consistent with a 2˚C pathway. IEAGHG has explored whether the industry will be able to build CCS quickly enough, with a new IEAGHG report on the topic due for release shortly. Secondly, the IEAGHG referenced the recent IEA report,

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i See www.ieaghg.org.

ii IPCC AR5 SYR: Synthesis Report (2014) Table 3.2

"20 years of carbon capture and storage: accelerating future deployment", stating stable policies including financial support are urgently required to provide the much-needed emphasis on CCS retrofitting, to cultivate early options for BECCS, to develop markets for "clean products" and disaggregating the CCS value chain to enable new business models to emerge.

3. NETL Technology Baseline Overview

Kristen Gerdes and Charles Zelek gave an excellent overview of data inputs for energy economy modelling from ongoing research within the National Energy Technology Laboratory (NETL). It became clear over the duration of the workshop that many IAMs use a simplified representation of CCS costs, often simplified to \$10/tCO_2 storage costs with an additional retrofit cost to conventional power generation and industrial processes. NETL provide multiple data sets to increase the accuracy of representation of CCS in IAMs. However, these data sets were not commonly known among IAM users present at the workshop.

The NETL "Cost and Performance Baseline for Fossil Energy Plants"[iii] include cost estimates for pulverised coal (PC), integrated gasification combined cycle (IGCC) and natural gas combined cycle (NGCC) plants with and without CO_2 capture. With state of the art technology adding 90% CO_2 capture and storage (CCS) increases the cost of electricity (COE) by between 45-65% for NGCC and circa 75% for PC. Lower capture rates of PC plants decrease the COE cost increase penalty but result in higher cost of CO_2 capture. For example, a supercritical PC plant with 16% capture may have a cost of capture of \$124/tCO_2, whereas the same plant with 90% capture may have a cost of capture of \$58/tCO_2[iv]. NETL conduct process performance and cost modelling incorporating supplier and vendor technology and economic data to provide these cost estimates. NETL's goal is to see a 30% cost of electricity reduction in greenfield coal power plants CCS by 2030. NETL also noted that labour costs are a sensitive variable in CCS cost, and that future learning by doing will reduce these costs.

The NETL "CO_2 Capture Retrofits Database" (CCRD) provides detailed cost and energy estimates for retrofits of existing coal and natural gas energy plants including capture and compression equipment and associated balance of plant. This data can be used to assess existing fossil fuel generation plant and the required incentives to retrofit CCS. NETL have provided data on "Costs of Capturing CO_2 from industrial sources" in January 2014, with varying CO_2 purity, across sectors and fuel types.[v]

The NETL CO_2 Pipeline Cost model provides spatially disaggregated transport cost estimates from point to point, and is freely available online[vi].

[iii] Cost and Performance Baseline for Fossil Energy Plants https://www.netl.doe.gov/research/coal/carbon-capture/analysis

[iv] See NETL's Cost and Performance Baseline for Fossil Energy Plants

[v] https://www.netl.doe.gov/research/energy-analysis/search-publications/vuedetails?id=1836

[vi] https://www.netl.doe.gov/research/energy-analysis/analytical-tools-and-data/co2-transport

NETL CO_2 Saline Storage Cost Model and the CO_2 Enhance Oil Recovery Resource and Cost model provide CO_2 storage potential and cost estimates for the US states, offshore and onshore. The model is still in development and expected to be posted with its data inputs and outputs to the NETL website.

4. Model Overview Presentation Summaries

4.1. GCAM - Leon Clarke, PNNL

The Global Change Assessment Model (GCAM[vii]) is a global IAM with 32 energy-economy regions, 283 land regions and 233 water basins. GCAM is a community model with data availability online. There is also a USA version of GCAM for analysis at the state level, GCAM-USA[13]. The presentation largely consisted of outputs of recent paper (M. Muratori et al (2017)) outlining CCS calibration in GCAM[14], giving estimates of CCS capital costs, efficiencies, CO_2 capture rates, capture costs and CO_2 avoided costs for representative coal, natural gas, oil and biomass plants. Interestingly PNNL noted the range in efficiencies and capital costs across IAMs; 26%-36% efficiency for coal CCS with capital costs ranging from $2 500/kW - $6 750/kW, while natural gas CCS has efficiency ranges from 34%-48% with capital costs from $1 100/kW – $3 800/kW. Where possible GCAM matches CCS sources and sinks to appropriately provide cost curve estimates, largely in the USA and China where data exists at useful spatial resolution. Finally, scenario results from Muratori et al, show critical role CCS must play under the post Paris Agreement conditions and with increased mitigation ambition scenarios. The mix of cumulative primary energy from CCS technologies may vary significantly, dependent on the rate of CCS cost reductions and rate of biofuel cost reductions.

4.2. IPM – EPA, Misha Adamantiades

The Integrated Planning Model (IPM) is a long-term capacity expansion model for the North American electricity power sector, thus its scope is not as broad as an IAM. IPM finds the least-cost solution to meet electricity demand subject to a range of operational constraints, and provides a detailed projection of electricity systems operations, electricity generation mix, new installed capacity, retirements, fuel choices etc. Data outputs are available at state, regional and national level over the model time horizon. CCS storage potential is aggregated at the state level. IPM uses a combination CO_2 transport costs and CO_2 storage costs developed in the geosequestration cost analysis tool (GeoCAT) model[viii]. The GeoCAT uses storage volumes for the United States documented by the US DOE National Carbon Storage Atlas (NATCARB V Atlas)[ix]. The EPA post the transport costs online as part of

vii wiki.umd.edu/gcam

viii https://www.epa.gov/sites/production/files/2015-07/documents/support_uic_co2_technologyandcostanalysis.pdf

ix https://www.netl.doe.gov/research/coal/carbon-storage/natcarb-atlas the base case documentation[x]. Their feasible CO_2 storage cost curves range exponentially up to \$50/tCO_2 for US national storage of 150 GtCO_2. CCS is currently an option on pulverised coal plants for retrofit only. Future CCS options are under consideration, including public perception.

4.3. NEMS-EEMS – EIA, David Daniels

The National Energy Modelling System (NEMS) is a group of modules that analyses supply, conversion, demand, economic and international elements of the US energy system and provides the integrated Annual Energy Outlook (AEO)[xi][xii] from the US Energy Information Administration (EIA) with a model horizon to 2040. NEMS has 9 demand regions commensurate with the US census divisions, 16 regions for natural gas, the coal market has 16 regions and the electricity module has 22 regions based on independent system operators (ISOs). Within NEMS, the Electricity Market Module (EEM) estimates regional electricity supply, by receiving electricity consumption, fuel prices and renewable electricity supply curves from NEMS and provides fuel consumption, electricity prices and capacity expansion back to NEMS. Prior to AEO-2017 EMM only had a limited representation of CCS technology. Coal with sequestration has been included in the model since 2004. As of AEO-2017, NEMS includes technology options for advanced combined cycle for oil and gas with sequestration, new pulverised coal CCS, and coal CCS retrofit[xiii]. Coal CCS with 90% capture is estimated to have a total overnight cost of \$5 562/kW and advanced combined cycle with CCS total overnight costs at \$2 153/kW. NEMS is open source and available online[xiv], however there is a steep learning curve with only a handful of users outside the US-EIA.

4.4. CTUS-NEMS – NETL, Charles Zelek

NETL use the standard release EIA-NEMS model and add their capture, transport, utilisation and storage model (FE/NETL CTUS)[xv]. Historical releases of NEMS had inadequate treatment of CO_2 storage for NETLs requirements, which was estimated at \$10/tCO_2. CTUS adds multiple site specific sources, sinks and EOR sites, estimates pipeline costs which aims to capture full energy economy interactions with CCUS infrastructure in model runs.

4.5. EPPA – MIT, Sergey Paltsev

The Emissions Prediction and Policy Analysis (EPPA) model from MIT is a top down computable general equilibrium (CGE) model with a focus on economic projection and policy

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[x] https://www.epa.gov/airmarkets/documentation-integrated-planning-model-ipm-base-case-v410
[xi] www.eia.gov/aeo
[xii] www.eia.gov/forecasts/aeo/assumptions
[xiii] https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf
[xiv] www.eia.gov/forecasts/aeo/nems/documentation
[xv] https://www.netl.doe.gov/research/energy-analysis/analytical-tools-and-data

analysis. EPPA is an 18-region global model with representations of all sectors of the economy, linking human systems and earth systems, with detailed US and Chinese coverage. The goals of the model are to provide projections of energy, electricity, economy, green-house-gas (GHG) and air pollutants. CCS is represented in EPPA as coal with CCS, natural gas with CCS and biomass with CCS, with dedicated studies published on bitumen upgrading, CCS in coal to liquids technology, and recently regional storage capacity[15]. Total overnight costs range from NGCC with CCS at $2 003/kW to IGCC with CCS at $6 277/kW. The key role for Bio-CCS under 2˚C scenarios was highlighted[xvi].

4.6. ESIM – ANL, Don Hanson

The Electricity Supply and Investment Model (ESIM) of Argonne national laboratory is an electricity supply model which is linked to a CGE model of the rest of US economy, AMIGA. The presentation highlighted the potential damage costs to power plants with increased cycling in correlation to increased variable renewable power generation[16].

4.7. Phoenix/ADAGE – EPA, Jim McFarland

The Phoenix Applied Dynamic Analysis of the Global Economy (Phoenix-ADAGE) model is also a nested CGE model, whose cost estimates are based from both the EIA-AEO modelling work from NEMS and IEA outputs. The presentation highlighted the importance of consistent data sets and that relative costs across technology databases are more important than individual technology data sets. Phoenix/ADAGE is participating in the EMF-33 on bioenergy potential for bioenergy CCS.

4.8. ReEDS – NREL, Stuart Cohen

The regional energy deployment system (ReEDS) is an electricity generation system model from the US national renewable energy laboratory (NREL). It simulates the expansion and operation of the US electricity generation and transmission system given projected load, fuel prices, technology costs and performance, alongside policies and regulations. It has high spatial and temporal resolution. Its major input assumptions come from the ABB velocity suite defining the existing generation fleet, NREL annual technology baseline for renewables, and the EIA-AEO for fossil and nuclear energy price and demand projections. CCUS is represented as a single technology option for coal and gas combined cycle, which assumes a 90% capture rate, cost and performance data from EIA-AEO, and applies capacity, heat rate and capital cost penalties to retrofitted coal-CCS plants. While there is not currently a detailed representation of CCUS in ReEDS, the models spatial and temporal resolution would enable detailed CCUS representation from capture locations, and transport to sink locations.

[xvi] https://globalchange.mit.edu/publications

4.9. EPAUS9r MARKAL – EPA, Dan Loughlin

The environmental protection agency's 9 census region (EPAUS9r) market allocation model (MARKAL) is a formulation of the whole US energy system. It is a technology rich bottom up model including energy processes from fossil fuel mining, renewable energy resources through conversion technologies, to demand technologies which satisfy societal energy service demands, and operates under operation constraints and environmental limits to find the least cost energy system. The source code development of MARKAL is overseen by the Energy Technology Systems Analysis Programme (IEA-ETSAP). EPAUS9r includes piece-wise linear approximations of regional storage costs vs cumulative capacity. Prior to the use of these cost curves storage costs had been estimated at \$9.7/tCO_2. CO_2 capture is included for existing pulverised coal, new PC, existing NGCC, new NGCC, IGCC and biomass gasification plants. CO_2 storage costs, capacity and locations come from the NETL CO_2 Saline Storage Cost Model[xvii] (2014). Transportation costs are not included in the model because the low costs estimates from the IPCC Special Report on CCS[17]. Illustrative model results show CCS has a strong role to play in the future CO_2 constrained US power sector.

4.10. MARKAL – NETL, Chris Nichols

Using the EPA 9R data base with MARKAL, NETL modelled a variety of CO_2 constrained scenarios based on the EMF22 scenarios with and without US DOE R&D goal success. These scenarios include a rate clean power plan (CPP), mass based CCP with high natural gas prices, 50% energy from clean sources, a \$25/t CO_2 tax with 5% escalation rate, and an 80% economy wide CO_2 reduction target by 2050. Meaningful deployment of CCS does not appear in most non-R&D scenarios, while R&D success does drive large scale deployments of CCS.

4.11. REGEN – EPRI, John Bistline

The US Regional Economy Greenhouse gas and Energy (US-REGEN) model, is the Electric Power Research Institute's (EPRI's) stylised electricity sector dispatch and capacity expansion model[xviii]. REGEN includes representations of coal retrofit with CCS, IGCC with CCS with capture rates of 55% and 90%, and NGCC with CCS. REGEN uses flat CO_2 storage costs of \$10/tCO_2

4.12. MERGE – EPRI, Steven Rose

MERGE is a global hybrid IAM with a detailed bottom up characterisation of energy technologies linked with an aggregated top down CGE representation of the rest of the economy. CCS technologies are represented in the power sector with coal, gas and biomass

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[xvii] https://www.netl.doe.gov/research/energy-analysis/analytical-tools-and-data/co2-saline-storage
[xviii] http://eea.epri.com/models.html

options and with cement process emissions in industry. Storage costs combine a novel approach of the market storage cost ($37/tCO_2$) with an external cost estimating public acceptance, which is a function of population density and cumulative storage (~$0.4 - $2/tCO_2$). Scenario analysis show that, with CCS, regional fossil generation could increase relative to today, in a carbon constrained future, and significantly affect generation mix, system size and decarbonisation beyond the electrical power sector.

4.13. ETP-TIMES – IEA, Uwe Remme

The energy technology perspectives (ETP) model within the International Energy Agency finds cost-effective investment and operation of energy technologies to meet energy demands from now to 2050/2060. The ETP team have carried out many investigations of CCS in their modelling exercises since 2004, ranging from "Prospects for CO_2 Capture and Storage" to most recently the "20 years of Carbon Capture and Storage; Accelerating Future Deployment"[xix]. Within the IEA-ETP 2016 publication, CCS is seen to account for 15% of the cumulative emissions reduction between a 4 degree scenario (4DS) and a 2 degree scenario (2DS) by 2050.

The ETP model specifies multiple carbon capture technologies in the power sector including pre-combustion capture, oxy-fuelling, and post combustion capture technologies with hard coal, and lignite, for electricity generation and combined heat and power (CHP). Natural gas for electricity generation or combined heat and power does not include pre-combustion processes. Biomass with CCS processes included, biomass integrated gasification combined cycle (BIGCC) for electricity and CHP, as well as co-firing with coal powered boilers. Each technology option has time dependent cost curves including learning, fixed operation and maintenance costs, associated gross efficiencies, and capture rates in the range of 85-90%.

The ETP model has further technology processes with CO_2 streams with carbon capture ranging from cement, iron and steel, chemicals and petrochemicals, pulp and paper and other sectors. ETP model results point to industrial applications account for more than 40% of CO_2 captured by 2050, with CCS being largely deployed in non-OECD countries accounting for 75% of CO_2 captured by 2050. Acknowledged weaknesses within the model approach are the aggregated representation of regional CO_2 transport and storage.

4.14. ESO – ICL, Clara Heuberger

The Electricity Systems Optimisation (ESO) framework is a long-term electricity power systems planning technology model from Imperial College London. ESO has high temporal resolution, and clustering compression to reduce model size and run-time. The model

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[xix] http://www.iea.org/etp/

formulation includes capacity expansion, system wide constraints, technology constraints, endogenous learning, and minimises the overall system costs. The novel element of this model is the detailed representation of CCS technology options and results point to flexible CCS technologies ability to provide additional value by accommodating higher installed levels of variable renewable capacity and reduced curtailment. The model explores advanced CCS technologies such as NGCC with chemical looping combustion CCS, making unabated CCGT and variable renewables less favourable, while coal-CCS, combined cycle gas turbine CCS, and BECCS remain part of the least cost pathway. Detailed CCS data inputs are sourced from IEAGHG publications.

4.15. Irish-TIMES – UCC, Brian Ó Gallachóir.

Irish-TIMES is the integrated energy system model for Ireland[18], developed in University College Cork, using the TIMES source code developed by the IEA-ETSAP technology collaboration programme. The presentation outlined the significant range of capital costs for both coal and gas CCS in recent literature reviews. CCS technology options are characterised in the model for power generation with coal, gas, and bio CCS options, as well as options for cement process emissions capture. Given the scale of the Irish land mass, recent studies with CCS in Irish TIMES can identify site specific locations for CCS retrofit or greenfield installation based on site specific capture costs, transport costs and storage costs.

5. Integrated Modelling Frameworks

Together, the US DOE Office of Science's **Bob Vallario**, and PNNL's **Ian Kraucunas** gave an overview of the next generation of integrated assessment modelling frameworks, which will incorporate multi-sector, multi-scale, multi-system (IM^3) dynamics. These new modelling frameworks aim to link IAMs with impact, adaption and vulnerability models (IAV) with earth systems models (ESM) to capture the dynamic multi-scale interactions among energy, water, land, weather/climate, socioeconomics, infrastructure and other sectors. Bob Vallario highlighted the point that the difference between an incremental effect and a disruptive effect (captured in IM^3) can push a fundamental shift in thinking of the portfolio requirements of the energy system; for example, nuisance flooding has increased by 900% in recent years in North West USA. DOE published cross cutting research on the Energy-Water-Nexus in 2014[xx]. However, a note of caution, with linking of IM^3 models there can be a proliferation of uncertainty throughout. A workshop was held on 24-26 May 2016 to explore these dynamics and future model frameworks[xxi]. Single sector models can misrepresent impacts and lead to poor decisions about energy and climate mitigation and adaption[19].

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xx https://energy.gov/under-secretary-science-and-energy/downloads/water-energy-nexus-challenges-and-opportunities

xxi http://www.globalchange.umd.edu/events/ia-iav-esm-workshop-2016/

6. Inter-model comparison

The energy modelling forum (EMF) is a lynchpin of the integrated assessment modelling research community, which published its first study in 1997. Its second EMF2 study was "Coal in Transition 1980-2000". Stanford University and the EMF has historically played a leading role in the International Energy Workshop (IEW) and the integrated assessment modelling consortium (IAMC), the meetings where energy systems modellers, and integrated assessment modellers discus research developments. The EMF is led by **John Weyant** and, in his presentation, he gave an overview of lessons learned through the past 20 years of EMF inter-model comparison studies, understanding model differences, strengths, weaknesses, identify insights for planning and government policy, and identify priority research areas in energy systems and integrated assessment modelling analysis. The EMF27 study focused on technology options and costs under climate mitigation scenarios and found that scenarios without CCS can increase costs in the order of 1.5 – 3.5 times that with CCS availabile[20–22]. EMF 24 showed the key role for CCS in the transition of the US electricity system in a mix with other low carbon energy options, particularly biomass with CCS and solar. EMF studies have shown that differing IAMs show differing short term and medium term dynamics in how they achieve that transition[23]. IAMs need to consider a broader range of uncertainties, do more diagnostic testing, better communication of results with potential users, and conduct more thought/work on forecasting rather than optimal futures projections. Lastly, IAMs need more implementation modelling and policy relevant metrics, and resultantly need more geographical disaggregation and better time resolution while tying high priority research areas directly into assessments.

7. US EIA modelling products

The US Energy Information Administration (EIA[xxii]) collects, analyses and openly disseminates immediate, short term, medium term and long term energy information for sound policy making, efficient market functioning and public understanding of energy interactions with the economy and their environment. **David Daniels**, Chief Energy Modeller, gave an overview of the outputs of the EIA's Annual Energy Outlook (AEO) and International Energy Outlook (IEO), and data availability from the EIA. Importantly the EIA operates an open data policy and thus provide critical data and projections which are used calibrate US IAMs and US sectors in global IAMs.

8. IEA Energy Technology Systems Analysis Programme

Brian Ó Gallachóir, Chair of IEA-ETSAP, gave an overview of the ETSAP, TIMES and MARKAL energy systems modelling frameworks developed and maintained collaboratively within IEA-ETSAP, an overview of the global integrated assessment model ETSAP-TIAM, and

xxii www.eia.gov

recent analysis within the IEA-ETSAP community integrating CCS in Spain, Portugal and North Africa.

IEA-ETSAP is one of 39 IEA technology collaboration programmes (TCPs), and was founded over 40 years ago in response to the first oil crisis under the need to develop energy systems analysis tools to better inform policy and markets. The modelling tools developed within IEA-ETSAP assist policy decision making globally and continually develop with novel modelling techniques through internal research and development programmes. The current Annex XIV programme aims at increasing understanding and facilitating the energy transition to achieve the well below 2°C goal. ETSAP is a unique network of energy modelling teams from almost 70 countries, in government, industry and academia.

The EU-FP7 project COMET investigated CCS infrastructure development scenarios for the integrated Iberian Peninsula and Morocco energy systems, to identify the most cost effective CO_2 transport and storage infrastructure to best serve the west Mediterranean area. Project results point to a strong role for CCS in the Iberian Peninsula under intermediate and strong mitigations scenarios. When mitigation targets become very stringent, CCS capture rates may become a limiting factor in deployment due to excessive residual emissions. Capture and transport network constraints appear to be strong determinants of CCS deployment levels compared to engineering costs and storage potentials.

IEA-ETSAP will hold its summer meeting together with 2017 International Energy Workshop (IEW), which will be held in University of Maryland in College Park, USA, on 10-11 July. It is proposed to have a follow up meeting on CCS integration in energy systems models at the IEA ETSAP workshop.

9. IEA energy products and ETP

Uwe Remme gave an overview of the IEA Energy Technology Perspectives (ETP[xxiii]) modelling and analysis, in the ETP global modelling framework, which incorporates the TIMES code developed within ETSAP, as well other sectoral models. IEA reports cover medium-term market report forecasts over the next 5 years, market-based scenario analysis out to 2040 in the World Energy Outlook from the world energy model (WEM), and long term planning scenarios out to 2060 from the ETP team. ETP policy reports cover statistics and trends on where we are today, scenarios and modelling on where we need to go, and technology roadmaps on how we get there

ETP scenario analysis shows that, to achieve the 2DS, global energy and process related CO_2 emissions must be more than halved by 2050 compared to today. 2°C requires a drop in the carbon intensity of primary energy. 70% of the cost-effective CO_2 abatement potential by 2050 is estimated to take place in cities. Urban technology infrastructure can either lock in existing inefficient systems or transition to sustainable energy use patterns for the coming

[xxiii] www.iea.org/etp

decades. While solar PV, onshore wind and electric vehicles are showing promise towards a 2°C scenario, efficient clean coal, carbon capture and storage or biofuels are not “on track”.

IEA ETP published the most recent CCS technology roadmap in 2013[xxiv]. While there is commonly a focus on CCS research in the power and upstream sectors, industry may become more of a focus in the future. ETP2017 results point to the potential scenario where industry and transport may account for 75% of remaining emissions in the 2DS in 2050, whereas they account for 45% of direct CO_2 emission today.

10. LCA modelling

Timothy Skone from The National Energy Technology Laboratory completed the presentations with his perspective on life cycle assessment (LCA) modelling of energy systems. This is a considerably different approach to that generally taken in IAMs. LCA is a comprehensive form of analysis that evaluates the environmental, economic and social attributes of specific energy processes ranging from extraction of raw materials, to the use of the energy carrier to perform work in the energy system, commonly referred to as the “life cycle” of a product. LCA is applied across all ranges of technology readiness level (TRL) in NETL, from identifying environmental impacts, risks and public perceptions to new technologies to determining environmental performance of existing technologies.

The presentation included novel data on life cycle greenhouse gas emission profiles per unit of electricity delivered for US power production for a portfolio of power generation technology options, among them were multiple CCS options. Interestingly advanced natural gas CCS and coal ccs with chemical looping compares positively with geothermal renewable electricity in this framework.

Key points from this presentation were that there is large variation in LCA emissions of CCS options, notably that advanced coal CCS options could compare positively relative to natural gas CCS in certain circumstances. This indicates the need for appropriate calibration of the (statistical) distribution of CCS plant characteristics in IAMs, so as not to bias model outcomes.

Following this presentation there was an interesting discussion highlighting the need for life cycle net-energy balance analysis in LCA and that IAMs need to include energy return on energy invested (EROEI) and exergy (useful energy) analysis in their frameworks.

11. Break-out discussions

Two break-out sessions had been planned on the agenda, but they evolved into a single 2.5-hour free flowing discussion around CCS representation in IAMs between the workshop

[xxiv] https://www.iea.org/roadmaps/

participants. This resulted in some useful workshop summaries, requests for information and recommended future actions.

The original break-out discussion briefing questions were as follows:

11.1. Break-out 1: Model characteristics, CCUS and fossil generation representation

- What aspects of CCS and advanced fossil technology are represented? For example, are new builds, retrofit upgrades, retrofit CCS, ramping, cycling effects, capacity, infrastructure, storage, EOR, industrial CCS, CO_2 markets and BECCS represented? What impact on outputs and messaging do differences in technology representation have?
- What are the key approaches that are used towards representing CCS, what constraints (i.e. CO_2 capture rate limit), how is implementation phased in, what are the approaches to learning, etc?
- Compare representation of interactions with other systems (e.g. global markets, fuel prices, industrial sector, water and biomass)? What impacts are most and least significant?
- How do the models treat regional differences? Where are regional interfaces critical? What are the advantages and disadvantages of various spatial and temporal scales?
- Identify gaps, barriers and opportunities for model development. What developments would help to better capture the potential of CCS and advanced fossil technologies?

11.2. Break-out 2: CCUS and fossil generation cost assumptions

- What are the primary data sources for economic, energy and emissions assumptions? What level of detail does each include? Are there gaps or shortcomings?
- Assess and discuss the impact of the differences in assumptions, data, sensitivities and calculations and explore how this relates to the messaging regarding CCS in its specific applications.
- List gaps, barriers and opportunities for data availability and data sharing for characterisation of CCS, advanced fossil technologies, as well as CO_2 transport, utilisation and storage. What developments would help to better capture the potential of CCS and advanced fossil technologies?

11.3. Break-out discussion session outcomes

1. Many IAMs have simplistic representation of CCS transport and storage costs, with a great variation in capture costs, depending upon what CCS technologies are represented in the model. Where data is available, IAMs should aim to have cost curves (and, potentially, learning rates) for capture, transport and storage.

2) 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.
3) There is insufficient good data on geological storage sites, their injection rates and dynamics over time.
4) Modellers need a cost curve on how capture rates (30% - 90%+) impact on capture costs.
5) IAMs need to ensure consistent/smart CO_2 market representation and not simply link CO_2 sources directly to sinks.
6) Semantics matter: some models introduce/produce a "carbon fee", others introduce/produce a "carbon tax"; be cognisant of policy maker's constraints and stakeholder perspectives.
7) Climate mitigating scenarios without CCS will be a lot more expensive; it is not clear why this has not garnered more public or policy support.
8) IAMs focus on broad systemic interactions, and as such CCS has not historically been a priority research area in IAMs.
    a. This meeting is an important step in addressing this issue.
    b. IAMs need a more functional representation of enhanced oil recovery, as well as water requirements, learning rates and hurdle rates for CCS in industrial processes and bioenergy CCS.
        i. Representing CCS plant cycling in IAMs may be difficult. How important is cycling to CCS?
    c. 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.

11.4. Break-out session recommended next steps

1) Create a data table with CCS representation compared for all influential IAMs :
    a. E-mail modellers and crowdsource the data input from the research community.
    b. List IAMs that have both retrofit and new capacity CCS options and the fuel sources they use.
2) Gather information on what the major efforts in CCS techno-economic characterisation are, who is working on it and who is being funded for this work. Share novel data sources.
3) NETL could host workshops or webinars to explain their models and make their data accessible to use as inputs into IAMs.

4) There could be a follow up meeting with the global energy systems modelling research community, who happen to be meeting near the DC area during the summer for the 2017 International Energy Workshop as well as the annual ETSAP meeting, both co-located at the University of Maryland College Park, MD, on 10-14 July.
5) IEAGHG will host its biennial CCS Costs Network workshop in September at Imperial College London. [Note: while several workshop attendees will attend this event in September, attendance is invitation only.]
6) Invite notable researchers from the US and from leading research institutes globally to attend future events.
7) The CCS technology experts and IAM modellers need to have regular meetings, potentially on a biannual basis.

12. Workshop conclusions

Following discussions between DOE, NETL, IEAGHG and workshop participants, the following actions were recommended.

1. 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.

   Action: Based initially on attendance at the workshop, to establish and maintain a network of interested energy modellers and CCS experts. To establish an email list-serve for communication and information exchange among this group **(DOE/IEAGHG)**.

   Action: To arrange a follow up event to take place alongside the 2017 International Energy Workshop, which will be held in College Park, Maryland, USA, from 10-14 July **(IEA-ETSAP)**.

2. 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. It is largely focussed on US data sources but includes in-depth technology information relevant to international locations.

   Action: To schedule a series of NETL-led webinars on NETL's baseline data and other products. Suggest this is underway by June 2017, such that information is shared prior to next meeting **(NETL)**.

   Action: To provide a list of (and links to) NETL products, baseline evaluations and data **(NETL)**.

   Action: To review and make available NETL's database of industrial sources (including NEMS documentation) **(NETL)**.

3. 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.

Action: To prepare a glossary of CCS/advanced fossil terminology to promote technical consistency. For example, how are the terms ‘base plant’, ‘retrofit’ and ‘repowering’ defined. What is included? What is required? What are the boundaries? **(DOE)**.

4. There are numerous IAMs, many of them with CCS represented in them to various levels of detail. For user confidence, it is important to gain an understanding of the assumptions, data and calculations that underpin the models.

   Action: To publish a review of CCS in IAMs **(IEAGHG)**.

13. Bibliography

1. IPCC. *Climate Change 2014: Mitigation of Climate Change*. (Cambridge University Press, 2014).
2. Smith, P. *et al.* Biophysical and economic limits to negative CO2 emissions. *Nature Clim. Change* **advance online publication,** (2015).
3. Fuss, S. *et al.* Betting on negative emissions. *Nature Clim. Change* **4,** 850–853 (2014).
4. UNFCCC. *Aggregate effect of the intended nationally determined contributions: an update*. 75 (United Nations Framework Convention on Climate Change, 2016).
5. Rogelj, J. *et al.* Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Clim. Change* **5,** 519–527 (2015).
6. Peters, G. P. *et al.* Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Clim. Change* **7,** 118–122 (2017).
7. Slade, R., Bauen, A. & Gross, R. Global bioenergy resources. *Nature Clim. Change* **4,** 99–105 (2014).
8. Schleussner, C.-F. *et al.* Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C. *Earth Syst. Dynam.* **7,** 327–351 (2016).
9. Jones, C. D. *et al.* Simulating the Earth system response to negative emissions. *Environ. Res. Lett.* **11,** 095012 (2016).
10. Gasser, T., Guivarch, C., Tachiiri, K., Jones, C. D. & Ciais, P. Negative emissions physically needed to keep global warming below 2 °C. *Nature Communications* **6,** 7958 (2015).
11. *Climate change 2014: synthesis report*. (Intergovernmental Panel on Climate Change, 2015).
12. International Energy Agency. *Energy Technology Perspectives 2016*. (OECD, IEA, 2016).
13. Zhou, Y. *et al.* Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. *Applied Energy* **113,** 1077–1088 (2014).
14. 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).
15. Kearns, J. *et al.* Developing a consistent database for regional geologic CO2 storage capacity worldwide. in *13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland* (Elsevier, 2016).
16. Hanson, D., Schmalzer, D., Nichols, C. & Balash, P. The impacts of meeting a tight CO2 performance standard on the electric power sector. *Energy Economics* **60,** 476–485 (2016).
17. *IPCC special report on carbon dioxide capture and storage*. (Cambridge University Press, for the Intergovernmental Panel on Climate Change, 2005).
18. Chiodi, A. *et al.* Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland's energy system. *Energy Policy* **53,** 169–189 (2013).
19. Harrison, P. A., Dunford, R. W., Holman, I. P. & Rounsevell, M. D. A. Climate change impact modelling needs to include cross-sectoral interactions. *Nature Clim. Change* **6,** 885–890 (2016).
20. Weyant, J. & Kriegler, E. Preface and introduction to EMF 27. *Climatic Change* **123,** 345–352 (2014).
21. Kriegler, E. *et al.* The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change* **123,** 353–367 (2014).

22. Krey, V., Luderer, G., Clarke, L. & Kriegler, E. Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Climatic Change* **123,** 369–382 (2014).

23. Wilkerson, J. T., Leibowicz, B. D., Turner, D. D. & Weyant, J. P. Comparison of integrated assessment models: Carbon price impacts on U.S. energy. *Energy Policy* **76,** 18–31 (2015).

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