Evaluating technology options to mitigate greenhouse gas emissions

CCS in Energy and Climate Scenarios

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CCS IN ENERGY AND CLIMATE SCENARIOS

Key Messages

- Integrated assessment models (IAMs) are used to quantify the interactions and trade-offs between societal demands for energy, economic, and environmental services, using a systems-based approach.
- To stabilise global average temperatures, i.e. to end global warming, net CO_2 emissions released to the atmosphere must be reduced to zero. CO_2 emissions must be completely decoupled from economic growth.
- The purpose of this study is to provide a transparent approach to understanding results from IAMs and, in particular, the role of carbon capture and storage (CCS). It is not the intention of the study to advocate particular scenarios.
- CCS, with either fossil or bioenergy inputs, is a resilient climate mitigation technology.[1] It is deployed at sizeable scale in the vast majority of IAM scenarios that apply carbon budgets consistent with the Paris Agreement goal of limiting the global mean temperature increase to 2°C and pursuing efforts to stay below 1.5°C.
- Bioenergy carbon capture and storage (BECCS) is deployed after fossil CCS, compensating for residual fossil CO_2 emission through net negative CO_2 emissions. BECCS, a negative emissions technology (NET), is one of a number of technologies designed to achieve carbon dioxide removal (CDR) from the atmosphere. Without NETs, permanent reduction in global temperatures following an overshoot would not be achievable. However, the extent of future BECCS deployment is uncertain due to concerns over the availability of sustainable biomass resource.
- CCS capture costs of less than $\$100/tCO_2$ in the power generation sector and less than $\$400/tCO_2$ in industry are considerably lower than the whole system marginal abatement costs of CO_2 by mid-century calculated in IAMS. In IAMs, therefore, there are limiting and competing constraints on CCS deployment that are not solely related to its cost.
- 2°C scenarios have an upper limit on the cumulative CO_2 emissions allowable (carbon budget) in the range of 800-1 400 $GtCO_2$. The carbon budget for 1.5°C scenarios is in the range of 200-800 $GtCO_2$. According to the models studied, CCS is deployed less in scenarios with more ambitious climate goals. This is, to a large extent, a result of the residual carbon emissions from fossil fuels with CCS.
- Residual CO_2 emissions from fossil CCS with 90% capture rates and fixed capacity factors become incompatible with strict carbon budgets. Importantly, a recent IEAGHG study[2] has concluded that the 90% capture rate cap is actually an artificial limit. It is an historical benchmark, originally chosen for illustrative purposes.[3] There are no technical barriers to increasing capture rates beyond 90% in the three classic capture

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[1] The diversity of mathematical approaches across the range of IAM typologies gives insights into the resilience of climate policy options across a range of scenarios and sensitivity analyses when combined across a range of models in a model inter-comparison project (MIP). Where the same technology deployments occur with the same scale and timing across the range of scenario analysis, this gives an indication of a resilient technology option across the range of input assumptions and uncertain future scenarios. Resilience is meant here in the sense that the technology option is consistently deployed across a range of uncertain scenarios, with a range of techno-economic specifications, giving an indication of a least-regrets investment option and is not overtly sensitive to an individual scenario.

[2] IEAGHG, "Towards zero emissions CCS from power stations using higher capture rates or biomass", 2019/02, March 2019.

[3] Personal communication from Dr. Niall Mac Dowell, Imperial College London, 16 May 2019.

routes (post-, pre- and oxyfuel combustion) or with the broad suite of CO_2 capture technologies currently available or under development.

- As well as capture rate and capacity factor, another direct assumption that influences the role of CCS in IAMs is investment costs for technologies. Figure 1 highlights the wide range of CCS capture costs by fuel type and technology type across power generation.

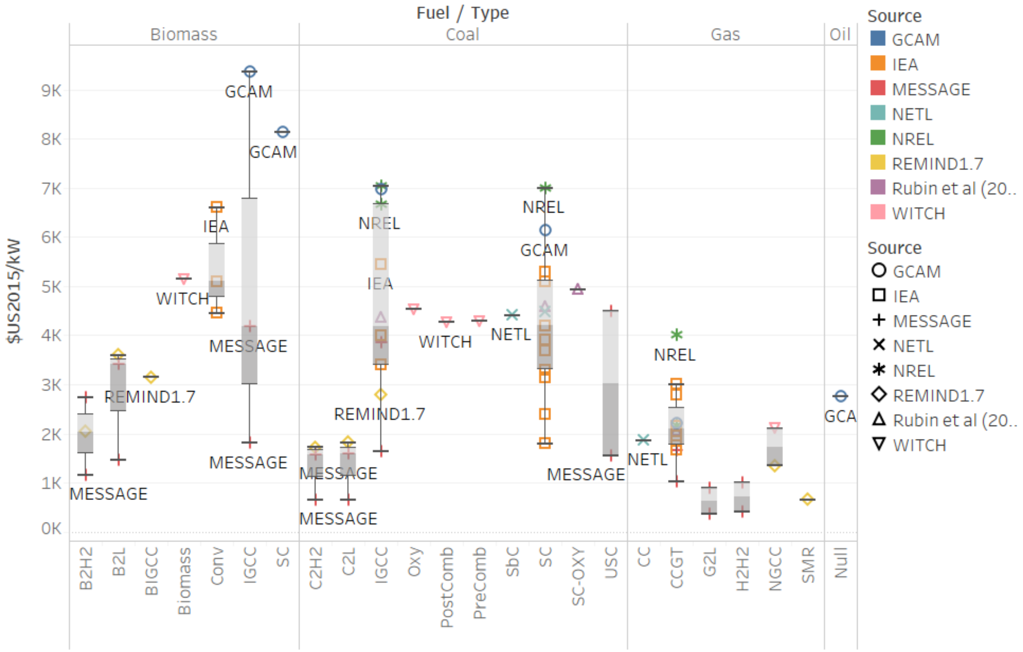

Figure 1. New investment costs/kW for CCS technologies.

- BECCS provides the majority of negative emissions in IAMs (with some CDR in the form of afforestation). It can provide additional space within the remaining carbon budget and may also compensate should global temperatures overshoot the target, but only as long as sufficient geological storage space remains under annual CO_2 injection rate limits.
- Actual CCS deployment to date is far removed from that depicted in the climate stabilisation pathways of most IAMs. There is a considerable gap between actual order books and the CCS deployment rates envisaged in most IAM scenarios to stabilise temperatures below 2°C.
- Only models that regularly update their base-year calibration, such as the IEA's Energy Technology Perspectives (ETP) model, can keep track of clean energy technology progress[4] and, accordingly, with the gap between actual CCS deployment and the required CCS deployment in temperature stabilisation scenarios.

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[4] IEA Tracking Clean Energy Progress (www.iea.org/tcep/)

Background to the study

The purpose of IAMs is to quantify the interactions and trade-offs between societal demands for energy, economic, and environmental services, using a systems approach. These systems are typically the energy system, the economy, the earth-land system, the water system and atmospheric climate system, although every IAM does not necessarily include all these systems and have varying degrees of completeness or complexity. The integrated systems interactions are assessed under the implementation of various socio-economic, demographic, technological and environmental constraints, and aim to use appropriate levels of engineering robustness, scientific completeness and economic theory to maintain a consistent and computationally tractable solution framework.

The mathematical approach underpinning each IAM can vary across the models. Classifications include whether a model's equations finds a partial equilibrium (in a single sector; here the energy sector) or general equilibrium (across the whole economy) between supply and demand of energy commodities and services, whether or not the model is attempting to optimise (the best case outcome) or simulate (the probable outcome) in its calculations subject to the model constraints, the range of sectors included in the model (such as land, energy, water, socio-economic systems, and climate), the treatment of discounting of costs, the temporal resolution and treatment of foresight; all of these influence the model dynamics and responsiveness in differing ways. Each IAM has its own strengths and weaknesses. Some industry medium-term models based on econometric simulation techniques describe their analysis as outlooks, implying a level of forecasting accuracy, while most research long-term IAMs do not claim to have forecasting capabilities as the future is too uncertain, and instead gain insights by describing sets of potential futures under scenario analysis covering a broad range of uncertainty in input assumptions.

CCS is represented in most IAMs and plays a key role in a large number of energy and emissions scenarios. While IAMs often align on high level messaging about the value and need for CCS, the actual role, impact and applications (e.g. power vs industrial, coal vs gas, CCS vs BECCS) vary considerably. Due to the nature of scenario making, the input data, background calculations and assumptions are not always presented, together with the results, in a clear and transparent manner. This can result in confusion and a lack of appreciation of the value of CCS (in both general and specific applications) within the energy sector, e.g. with manufacturers, policy makers, regulators and the general public. Inaction or inappropriate action is often the result.

It is also important to note that, while global results are often presented, for most policy makers it is the projections for countries and regions that are most meaningful. Thus the geographical granularity that underpins any particular IAM is of crucial importance. In many IAMs, this is not adequately addressed.

The study was undertaken by a consortium comprising University College Cork (study lead), Imperial College London and the University of Oxford.

Scope of Work

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 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.

Findings of the Study

Integrated assessment models

- Integrated assessment models (IAMs) are used to quantify the interactions and trade-offs between societal demands for energy, economic, and environmental services, using a systems approach.
- Each IAM has its own strengths and weaknesses. Some medium-term models based on econometric simulation techniques describe their analysis as outlooks, implying a level of forecasting accuracy. However, most long-term IAMs do not claim to have forecasting capabilities as the future is too uncertain and, instead, gain insights by describing sets of potential futures under scenario analysis covering a broad range of uncertainty in input assumptions.
- The usefulness of IAM scenario analysis is in the insights gained into the emergent logic of systems interactions, not typically of insights gained into the dynamics of an individual technology choice from a single scenario from a single model.
- In addition to the IEA's Energy Technology Perspectives (ETP) model, the six (of 30) most influential models that contributed to the IPCC's 5th Assessment Report and informed the majority of scenarios in the IPCC's Special Report on 1.5°C were investigated in this study to assess the role of carbon capture and storage (CCS).
- While not universal, the more influential IAMs are populated largely by relatively recent CCS data. Global storage volumes and transport costs, however, are still relatively aggregated, simplified and often rely upon 2005 IPCC data[5] in the absence of better regional data in the reviewed IAMs. There is ongoing work to create a global CCS storage geo-spatial database.
- To stabilise global average temperatures, i.e. to end global warming, net CO_2 emissions released to the atmosphere must be reduced to zero. Carbon emissions must be completely decoupled from economic growth.
- The purpose of this study is to provide a transparent approach to understanding results from IAMs and, in particular, the role of CCS. It is not the intention of the study to advocate particular scenarios.

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[5] IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2005, 442 pp.

Carbon capture and storage

- CCS, with either fossil or bioenergy inputs, is deployed at sizeable scale in the vast majority of IAM scenarios that apply carbon budgets consistent with the Paris Agreement goal of limiting the global mean temperature increase to 2°C and pursuing efforts to stay below 1.5°C. As such, CCS may be termed a resilient climate mitigation technology.[1] The cases that exclude CCS generally feature extensive near-term reductions in energy demand and, to accommodate rising population and income, would require extreme societal and behavioural changes to achieve the transformations needed.
- CCS technologies exist across multiple sectors in IAM temperature stabilisation scenarios, from power generation, to liquid fuel transformation and industrial processes.
- Bioenergy carbon capture and storage (BECCS) is deployed after fossil CCS, compensating for residual fossil CO_2 emission through net negative CO_2 emissions. BECCS, a negative emissions technology (NET), is one of a number of technologies designed to achieve carbon dioxide removal (CDR) from the atmosphere. Without NETs, permanent reduction in global temperatures following an overshoot would not be achievable. However, the extent of future BECCS deployment is uncertain due to concerns over the available sustainable biomass resource.
- In IAM temperature stabilisation scenarios, CCS is typically deployed with fossil energy feedstocks before mid-century. Following that, CCS is deployed with bioenergy feedstocks: these feedstocks are either transformed into low-carbon gaseous and liquid fuels offsetting emissions from difficult-to-mitigate sectors or used to provide the low and mid-range heat (<800°C) required in industry.
- In IAMs with low or no CCS deployment, substantial near-term reductions in energy demand coupled with considerable increases in energy efficiency would be required to achieve the Paris Agreement goals. Such demanding ambitions are usually considered unlikely to be realised.
- Deploying CCS gradually would likely be economically advantageous for minimising costs and risks rather than having to depend on ambitious climate policy later. While hugely ambitious, it would be advantageous to reach a position where at least 15% of the carbon being extracted from the ground was being sequestered by the mid-to-late 2020s.
- CCS capture costs of less than $100/$tCO_2$ in the power generation sector and less than $400/$tCO_2$ in industry are considerably lower than the whole system marginal abatement costs of CO_2 by mid-century calculated in IAMS. In IAMs, therefore, there are limiting and competing constraints on CCS deployment that are not solely related its cost.

Direct assumptions

- 2°C scenarios have an upper limit on the cumulative CO_2 emissions allowable (carbon budget) in the range of 800-1 400 $GtCO_2$. The carbon budget for 1.5°C scenarios is in the range of 200-800 $GtCO_2$. According to the models studied, CCS is deployed less in scenarios with more ambitious climate goals. This is largely a result of the residual carbon emissions from fossil fuels with CCS.
    - Notably, CO_2 capture rates from fossil fuel power plants applied in almost all IAMs, front-end engineering and design (FEED) studies, pilot plants, demonstration plants and technical analyses are currently capped at 90%, regardless of the technology type, the location or the fuel type.
    - In fact, 90% capture is the upper limit for most CCS technologies across the IAMs reviewed for this study, except for WITCH and GCAM which have capture rates of up to 95% for some technologies.
- Residual CO_2 emissions from fossil CCS with 90% capture rates and fixed capacity factors become incompatible with strict carbon budgets. Importantly, a recent IEAGHG study[2] has concluded that the 90% capture rate cap is actually an artificial limit. It is an historical benchmark, originally chosen for illustrative purposes.[3] There are no technical barriers to increasing capture rates beyond 90% in the three classic capture routes (post-, pre- and oxyfuel combustion) or with the broad suite of CO_2 capture technologies currently available or under development.
- Significantly, while the CO_2 capture unit at NRG's Petra Nova coal-fired power plant[6] operates as designed, capturing around 90% of the CO_2 from the slip stream, MHI Engineering, the designers of its KM-CDR capture process, has demonstrated a capture capability to 95%[7] and, further, has shown that 99.5% capture[8] is technically feasible with a modest increase in CAPEX and no increase in OPEX.
- Nonetheless, reliance on high CCS deployment and high capture rates in IAMs may not be prudent given the considerable gap between expected near-term deployment rates based on CCS projects presently in the planning pipeline and the required near-term CCS deployment rates in IAMs. However it is precautionary to significantly ramp up research and development, prioritising demonstration of higher capture rates, given current CO_2 emissions trajectories and the mitigation rates now required to remain below 2°C.
- Typically, capacity factors (the percentage time a CCS plant runs at its rated capacity) applied in most of the influential IAMs are established exogenously and range from 75% to 95%. Assuming fixed and high capacity factors for CCS may be inappropriate in cases where high penetration rates of variable renewable generation apply. Additionally, the ancillary services from dispatchable, grid balancing lower-carbon power offered by CCS plants are not valued.[9]
- As well as capture rate and capacity factor, another direct assumption that influences the role of CCS in IAMs is investment costs for technologies. Figure 1 highlights the

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[6] www.nrg.com/case-studies/petra-nova.html.

[7] www.powermag.com/japanese-conglomerates-rejigger-power-sector-strategies/?printmode=1.

[8] Y. Nakagami et al, Assessment of zero emission thermal power plant with advanced KM CDR Process, GHGT-14 Poster, October 2018. (https://az659834.vo.msecnd.net/eventsairwesteuprod/production-ieaghg-public/8b85f74f5f2448a69a7b019245aeb480)

[9] IEAGHG, "Valuing Flexibility in CCS Power Plants", 2017/09, November 2017.

wide range of CCS capture costs by fuel type and technology type across power generation.

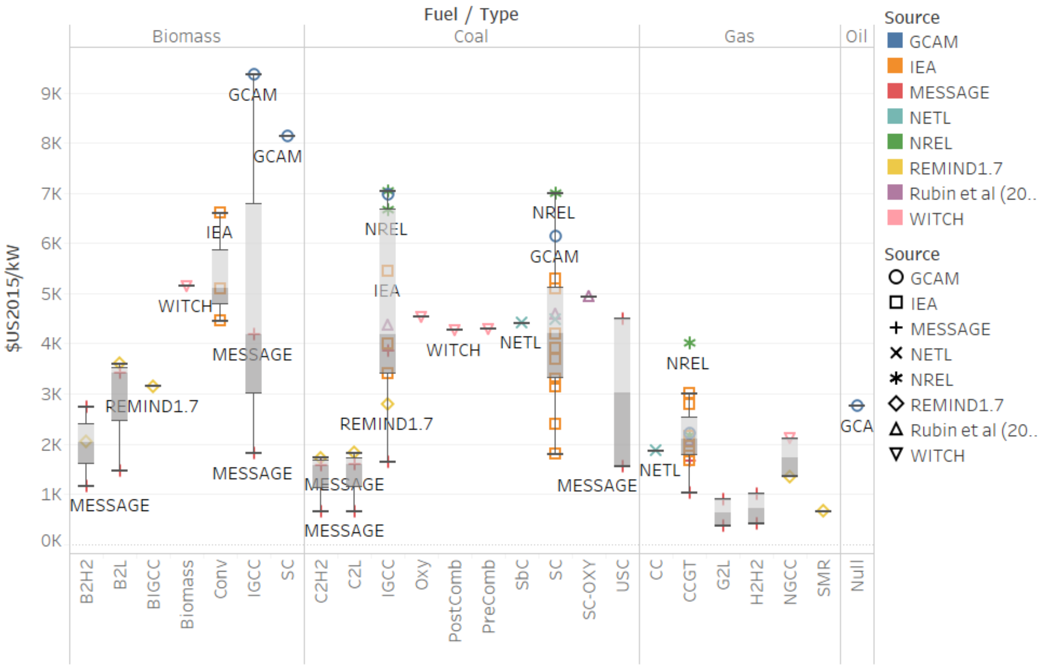

Figure 1. New investment costs/kW for CCS technologies.

- Yet other direct input assumptions may include learning rates and social acceptability, both of which are addressed as part of the overall narrative in the more influential IAMs.

Negative emission technologies

- BECCS provides the majority of negative emissions in IAMs (with some CDR in the form of afforestation). It can provide additional space within the remaining carbon budget and may also compensate should global temperatures overshoot the target, but only as long as sufficient geological storage space remains under annual CO_2 injection rate limits.
- Other CDR options such as direct air capture (DAC) and enhanced weathering (EW) are beginning to be explored in IAMs. As they are not yet net energy positive, however, they do not contribute to energy demand and, indeed, require additional energy inputs to provide their CDR function.
- BECCS has a limit of sustainable primary energy supply estimated at between 120 and 300 EJ across most IAMs explored. In pathways where adaptation dominates, bioenergy supply is allowed to grow beyond sustainable levels to about 450 EJ (which is considered unsustainable, uncertain and unlikely without radical advances in afforestation management). Thus, for the majority of IAMs, the volume of negative emissions BECCS can provide and, hence, the volume of residual fossil emission it can negate is limited.

Status of CCS deployment

- Actual CCS deployment to date is far removed from that depicted in the climate stabilisation pathways of most IAMs. There is a considerable gap between actual order books and the CCS deployment rates envisaged in most IAM scenarios to stabilise temperatures below 2°C.
- This gap in deployment rates between IAMs and real world construction is partially exacerbated as a result of the time lag in the development of IAM scenarios, their publication and subsequent updating of the model with real CCS deployment. For example, many current-generation IAM models have 2010 as a starting base year and allow CCS deployment in the years from 2010 to the present to rise at a rate that, in reality, has not occurred. Possibly, too much confidence was attributed to entries in order books that were, in fact, tentative or of low probability and that, ultimately, did not proceed.
- Only models that regularly update their base-year calibration, such as the IEA's ETP model, can keep up-to-date with the gap between actual CCS deployment and the required CCS deployment in temperature stabilisation scenarios.

Expert Review Comments

A review was undertaken by a number of international experts. The draft report was generally well received, with reviewers remarking on its valuable contribution to an important topic that has been underexplored.

A large number of comments and suggestions were made by the reviewers, all of which were addressed by the authors. Where appropriate, corrections and additions were either made to the text. In some cases, it was recognised that some recommendations lay outside the scope of the study.

Conclusions

CCS, with either fossil or bioenergy inputs, is deployed at considerable scale in the vast majority of IAM scenario analysis that apply carbon budgets, or allowable cumulative CO_2 emissions, consistent with the Paris Agreement goals of limiting global mean temperature increase to 2°C and pursuing efforts to stay below 1.5°C. Median fossil CCS capture rates range from 5-8 $GtCO_2$ per year by 2050, up to over 12 $GtCO_2$ per year by 2100 depending on the stringency of the climate target, and the compatibility of residual fossil emissions with the remaining carbon budget. BECCS is deployed after fossil CCS and reaches similar scales of capture as fossil CCS in 2°C scenarios, but larger median capture rates of 14 $GtCO_2$ per year by 2100 for the more stringent 1.5°C scenarios. BECCS provides accommodation for residual fossil CO_2 emission through net negative CO_2 emissions, commonly referred to as carbon dioxide removal (CDR) or negative emissions technologies (NETs). Cumulative removal of 640-950 $GtCO_2$ is required in representative scenarios to return end of century mean global warming to likely below 1.5°C. An alternative scenario is very rapid near-term energy demand reduction, such as the "Low Energy Demand" scenario of Grubler et al,[10] which limits the need

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[10] Grubler et al, A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies, Nature Energy, Volume 3, Pages 515–527 (2018).

for large-scale CCS through reducing global final energy demand by 40% relative to present, despite rises in population, income and economic activity.

The remaining carbon budget to meet the Paris agreement goals is uncertain but ranges between 570 $GtCO_2$ (67%) and 1080 $GtCO_2$ (33%) from 2018 onwards to return below 1.5°C by 2100 or between 1320 $GtCO_2$ (67%) and 2270 $GtCO_2$ (33%) for a 2°C scenario with non-CO_2 forcing and a response uncertainty of -400$GtCO_2$ to +200 $GtCO_2$. The probabilities associated with these ranges of carbon budgets range from 33rd to 67th percentile dependent on non-CO_2 forcing and response uncertainty; Table 2.2, Chapter 2 in the recent IPCC special report on 1.5°C[11] provides clarity on these uncertainties. Recent revisions to the global carbon budget suggest prior carbon budget figures may be conservative, but consistently indicate that net zero CO_2 emissions are likely to be required around mid-century, and net-negative CO_2 emissions thereafter, to meet the Paris goal of limiting warming to “well below 2°C” and “pursuing efforts” towards 1.5°C.

To stabilise global average temperatures, i.e. to stop global warming at any level, net CO_2 emissions released to the atmosphere need to reduce to zero. Therefore, the carbon intensity of economic activity (or tonnes of CO_2 emitted per dollar GDP) also needs to reach zero, i.e. carbon emissions need to be absolutely decoupled from economic growth.

The temperature at which warming stabilises is dependent upon the carbon budget emitted and whether NETs are deployed. Without NETs, permanent reduction in global temperatures following an overshoot is not achievable (temperatures can in principle be reduced temporarily through other measures, such as engineering planetary albedo but, without NETs, these reductions are only temporary and are quickly reversed should these measures be discontinued).

There are many low-carbon technologies to compete with fossil CCS in the power sector. IAMs show that variable renewable electricity generation technologies in conjunction with BECCS and nuclear power are projected to fulfil electricity demand at least cost. Gas-CCS remains in the electricity generation mix across some IAM scenarios but with considerably lower and less frequent deployment than BECCS. It is interesting to note, however, that the 90% cap on CO_2 capture rates adopted for power sector applications in almost all IAMs, front-end engineering and design (FEED) studies, pilot plants, demonstration plants and technical analyses, regardless of the technology, location or fuel type, has been exposed as an artificial limit.[2] In fact, to target net zero CO_2 emissions by around mid-century, minimising residual fossil fuel emissions by raising capture rates will be essential. Reflecting this in IAMs may well influence fossil CCS projections in the power sector.

Additionally, IAMs are not typically used to explore power grid stability other than minimum capacity factor requirements, nor are they used to explore issues such as intra-day electricity storage; these factors would have a bearing on the minimum stable levels of dispatchable generation that must remain installed.

It is important to note that to achieve zero carbon energy requirements in the industry sector, including zero carbon process emissions, IAM results place a heavy emphasis on fossil CCS.

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[11] IPCC, ‘Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C’, World Meteorological Organization, Geneva, Switzerland, 2018.

Without CCS, decarbonising some industries, such as chemicals, iron & steel and cement, presents a major challenge.

Historically, CCS has not benefitted from the level of subsidy or incentive enjoyed, say, by the renewables industry. Consequently, CCS deployment rates envisaged in 2°C and well below 2°C scenarios are very challenging compared to historical deployment rates of fossil, renewable or nuclear technologies and would be dependent on effective policy action to realise. Crucially, in IAM scenarios with low or no CCS deployment, significant reductions in energy demand and considerable increases in energy efficiency are required to not breach the carbon budget consistent with the Paris Agreement goals. If CCS is excluded as a mitigation option, the IPCC's 5th Assessment Report[12] reveals that the cost of limiting warming to below 2°C increases by 138%. The exclusion of CCS has a much greater impact on the cost of meeting 2°C than the exclusion of any other technology option.

A default median behaviour with regard to CCS deployment emerges from the majority of IAM temperature stabilisation scenarios: CCS is typically deployed with fossil energy feedstocks before mid-century. CCS is then deployed with bioenergy feedstocks to meet a limited amount of electricity generation but, more so, to transform bioenergy feedstocks into low carbon gaseous and liquid fuels both to offset emissions from difficult to mitigate sectors and to provide high temperature heat requirements in industry. As it is dependent on the available sustainable biomass resource, the extent of future BECCS deployment is uncertain and, thus, so too is the feasibility of the scenarios on which the level of deployment relies.

Recommendations

Two primary recommendations arise from this study.

1. IAMs may include thousands of technology options. Making CCS technology data available in a centralised location with a useful format would make updating IAMs simpler and faster, reducing the need for continual technology review cycles from the IAM modeller perspective. A centralised, accessible CCS database would reduce substantially the time and transaction costs associated with populating IAMs with current state-of-the-art CCS technology options. The database would essentially provide a techno-economic specification for CCS technology options in power, industry and upstream transformation processes and would include, e.g. equipment costs, capture rates and capacity factors.

   Such a database would likely be designed in coordination with appropriate bodies, e.g. the IEA ETSAP TCP, who themselves are updating their range of energy technology briefs ("Etech Briefs"). A format for input into energy systems models and IAMs would be specified. An open database would be maintained and regularly updated by CCS experts, with frequent communication between the CCS and IAM communities. Data tables maintained by the IEA's Energy Technology Policy Division are a good example of current best practice and provide an indication of useful data formats.

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[12] IPCC, 'Fifth Assessment Report of the Intergovernmental Panel on Climate Change', IPCC, Geneva, Switzerland, 2014.

2. A model inter-comparison project (MIP) with harmonised CCS input data assumptions would avoid difficulties in transparently assessing and isolating the causes and effects of CCS calibration in IAMs. Such an MIP would involve the top 10 IAMs across the range of scenarios consistent with limiting global warming to below 2°C.
    a. It is suggested the MIP would focus on:
        - Learning rates as a function of research development spend and demonstration capacity for increased capture rates and reduced residual emissions
        - Sub-annual flexible capacity factors
        - CO_2 capture cost curves as a function of varying capacity factor and capture rate
        - Feasible maximum industry build rates
        - Maximum feasible injections rates
    b. 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
    c. The project could calculate revenues to the fossil energy industry against the same uncertain CCS futures
    d. 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 data. This 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

Suggestions for further work

Two main recommendations follow from this study:

- To consider IEAGHG engagement in setting up a CCS database consistent with the needs of energy modellers.
- To consider what support IEAGHG might give to the setting up of and, if successful, to identifying data sources for the MIP discussed above.

Carbon Capture and Storage in Energy and Climate Scenarios

CONTENTS

EXECUTIVE SUMMARY

ES.1. AIM

The aim of this project 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.

ES.2. INTRODUCTION

The purpose of integrated assessment models (IAMs) are to quantify the interactions and trade-offs between societal demands for energy, economic, and environmental services, using a systems approach. These systems are typically the energy system, the economy, the earth-land system, the water system and atmospheric climate system, although every IAM does not necessarily include all these systems and have varying degrees of completeness or complexity. The integrated systems interactions are assessed under the implementation of various socio-economic, demographic, technological and environmental constraints, and aim to use appropriate levels of engineering robustness, scientific completeness and economic theory to maintain a consistent and computationally tractable solution framework.

The mathematical approach underpinning each IAM can vary across the models. Classifications include whether a model equations finds a **partial equilibrium** or **general equilibrium** between supply and demand of energy commodities and services, whether or not the model is attempting to **optimise** or **simulate** in their calculations subject to the model constraints, the range of sectors included in the model (such as land, energy, water, socio-economic systems, and climate), the treatment of discounting of costs, the temporal resolution and treatment of foresight, all of which influence the model dynamics and responsiveness in differing ways. Each IAM has its own strengths and weaknesses. Some industry medium term models based on econometric simulation techniques describe their analysis as outlooks, implying a level of forecasting accuracy, while most research long-term IAMs do not claim to have forecasting capabilities as the future is too uncertain, and instead gain insights by describing sets of potential futures under scenario analysis covering a broad range of uncertainty in input assumptions[1].

ES.3. CCS IN IAM SCENARIOS FOR THE 2°C AND 1.5°C GOALS OF THE PARIS AGREEMENT

Carbon capture and storage (CCS), with either fossil or bioenergy inputs, is deployed at considerable scale in the vast majority of IAM scenario analysis with carbon budgets consistent with the Paris Agreement[2] goals of limiting global mean temperature increase to 2°C and pursuing efforts to stay below 1.5°C. Median fossil-CCS ranges from 5-8 $GtCO_2$ per year by 2050, up to over 12 $GtCO_2$ captured per year by 2100 dependent upon the stringency of the climate target, and the compatibility of residual fossil emissions within a remaining carbon budget. Bioenergy carbon capture and storage (BECCS) is deployed after fossil CCS and reaching similar scales as fossil CCS in 2°C scenarios with larger annual capture rates of a median value of 14 $GtCO_2$ per year by 2100 for stringent 1.5°C scenarios. BECCS provides accommodation for residual fossil CO_2 emission through net negative CO_2 emissions, commonly referred to as carbon dioxide removal (CDR) or negative emissions technologies (NETs). Cumulative removal of 640-950 $GtCO_2$ is required in representative scenarios to return end of century mean global warming to likely below 1.5°C. An alternative scenario is very rapid near-term energy demand reduction, such as the “Low Energy Demand” scenario

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[1] Yue et al., ‘A Review of Approaches to Uncertainty Assessment in Energy System Optimization Models’.

[2] Rogelj et al., ‘Zero Emission Targets as Long-Term Global Goals for Climate Protection’; Rogelj et al., ‘Energy System Transformations for Limiting End-of-Century Warming to below 1.5 °C’, 5; Minx et al., ‘Negative Emissions—Part 1’; Strefler et al., ‘Between Scylla and Charybdis’; Rogelj et al., ‘Scenarios towards Limiting Global Mean Temperature Increase below 1.5 °C’; Luderer et al., ‘Residual Fossil CO 2 Emissions in 1.5–2 °C Pathways’; Luderer et al., ‘Deep Decarbonisation towards 1.5C - 2C Stabilisation. Policy Findings from the ADVANCE Project’; Kriegler et al., ‘Pathways Limiting Warming to 1.5°C’; IEA, *Energy Technology Perspectives 2017*; IEA, ‘Technology Roadmap: Carbon Capture and Storage’; International Energy Agency, ‘Tracking Clean Energy Progress’.

of Grubler et al (2018)[3], which limits the need for large-scale CCS through reducing global final energy demand by 40% relative to present, despite rises in population, income and activity.

The remaining carbon budget, or allowable cumulative CO_2 emissions, to meet the Paris agreement goals is uncertain but ranges between 570 $GtCO_2$ (67%) to 1080 $GtCO_2$ (33%) from 2018 onwards to return below 1.5°C by 2100 or 1320 $GtCO_2$ (67%) to 2270 $GtCO_2$ (33%) for a 2°C scenario with non-CO_2 forcing and response uncertainty of -400$GtCO_2$ to +200$GtCO_2$[4]. The probabilities associated with these ranges of carbon budgets range from 33rd to 67th percentile dependant on non-CO_2 forcing and response uncertainty; table 2.2 chapter 2 in the recent IPCC special report on 1.5C provides clarity on these uncertainties. Recent revisions to the global carbon budget (e.g. Millar et al, 2017; Goodwin et al, 2018; Tokarska and Gillett, 2018; Leach et al, 2018)[5] suggest prior carbon budget figures may be conservative, but consistently indicate that net zero CO_2 emissions are likely to be required around mid-century, and net-negative CO_2 emissions thereafter, to meet the Paris goal of limiting warming to "well below 2°C" and "pursuing efforts" towards 1.5°C.

To stabilise global average temperatures, i.e. to stop global warming, at any level, net CO_2 emissions released to the atmosphere need to reduce to zero. Therefore, the carbon intensity of economic activity (or tonnes of CO_2 emitted per dollar GDP) also needs to reach zero, i.e. carbon emissions need to be absolutely decoupled from economic growth.

The temperature at which warming stabilises is dependent upon the carbon budget emitted and whether negative emissions technologies (NETs) are deployed. Without NETs, permanent reduction in global temperatures following an overshoot is not achievable (temperatures can in principle be reduced temporarily through other measures, such as engineering planetary albedo, but without NETs, these reductions are only temporary and are quickly reversed should these measures be discontinued).

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[3] Grubler et al., 'A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies'.

[4] Millar et al., 'Emission Budgets and Pathways Consistent with Limiting Warming to 1.5 °C'; Luderer et al., 'Residual Fossil CO 2 Emissions in 1.5–2 °C Pathways'; Rogelj et al., 'Differences between Carbon Budget Estimates Unravelled'.

[5] Millar et al., 'Emission Budgets and Pathways Consistent with Limiting Warming to 1.5 °C'; Goodwin et al., 'Pathways to 1.5 °C and 2 °C Warming Based on Observational and Geological Constraints'; Tokarska and Gillett, 'Cumulative Carbon Emissions Budgets Consistent with 1.5 °C Global Warming'; Leach et al., 'Current Level and Rate of Warming Determine Emissions Budgets under Ambitious Mitigation'; Matthews et al., 'Estimating Carbon Budgets for Ambitious Climate Targets'.

Minimising residual fossil fuel emissions is also required, potentially with higher capture rates required across CCS technologies deployed. IAM results indicate that a fossil CCS focus on zero carbon energy requirements in the industry sector, including zero carbon process emissions, would be more cost effective and socially beneficial than in power generation. Variable renewable electricity generation technologies in conjunction with BECCS and Nuclear power is projected to fulfil electricity demand at least cost. Gas-CCS remains in the electricity generation mix across some IAM scenarios but with considerably lower and less frequent deployment than BECCS. IAMs do not typically explore power grid stability other than minimum capacity factor requirements, nor higher temporal resolution issues such as intra-day electricity storage, thus requiring minimum stable levels of dispatchable generation to remain installed.

Deployment rates envisaged in 2°C and well below 2°C IAM scenarios are very challenging compared to historical deployment rates of fossil, renewable or nuclear technologies and are dependent on stringent policy action to incentivise CCS[6].

In IAM scenarios with low or no CCS deployment significant reductions in energy service demand and considerable increases in energy efficiency are required to not breach the carbon budget consistent with the Paris Agreement goals[7].

The IPCC 5th Assessment report revealed that IAM scenarios show a substantial increase of 138% (29-297%) in the cost of limiting warming to below 2°C with a >66% chance, if CCS is excluded as a mitigation option[8]. The exclusion of CCS has a much greater impact on the cost of meeting a 2°C than the exclusion of any other technology option.

A default median behaviour with regard to CCS deployment emerges from the majority of IAM temperature stabilisation scenarios (See Figure ES.1). CCS is typically

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[6] Vaughan et al., ‘Evaluating the Use of Biomass Energy with Carbon Capture and Storage in Low Emission Scenarios’; Fuss et al., ‘Negative Emissions—Part 2’.

[7] Grubler et al., ‘A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies’; Vuuren et al., ‘Alternative Pathways to the 1.5 °C Target Reduce the Need for Negative Emission Technologies’.

[8] Clarke et al., ‘Assessing Transformation Pathways’; Strefler et al., ‘Between Scylla and Charybdis’.

deployed with fossil energy feedstocks before mid-century. CCS is then deployed with bioenergy feedstocks to meet a limited amount of electricity generation and more so the transformation of bioenergy feedstocks into low carbon gaseous and liquid fuels offsetting emissions from difficult to mitigate sectors, and high temperature heat requirements in industry. The extent of future BECCS deployment is uncertain as a function of the available sustainable biomass resource[9] and thus so too is the feasibility of the scenarios on which they rely.

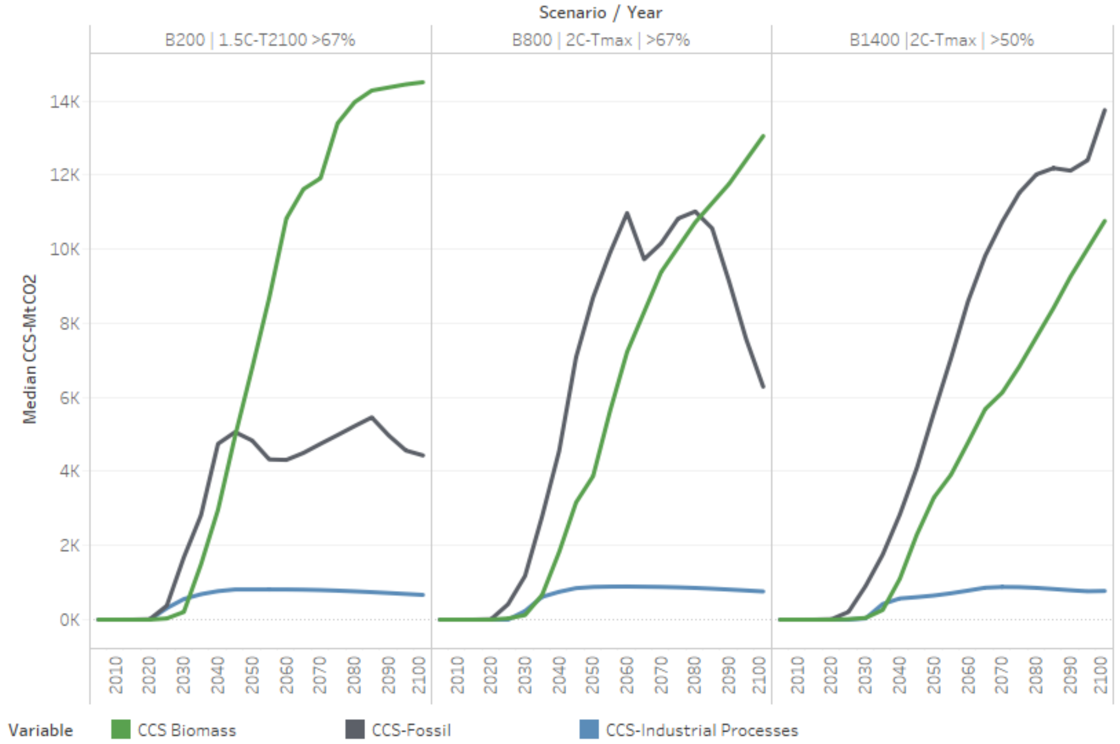

Figure ES.1 Median CCS deployment in $MtCO_2$ per year across 7 influential IAMs for carbon budget scenarios consistent with greater than 67% (200 $GtCO_2$ carbon budget 2016-2100) chance of limiting warming in 2100 to 1.5°C, greater than 67% (800 $GtCO_2$ carbon budget 2016-2100) of limiting warming to 2°C, and greater than 50% chance to limiting warming to 2°C (1400 $GtCO_2$ carbon budget 2016-2100); Data source: Luderer et al (2018)[10].

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[9] van Sluisveld et al., 'Comparing Future Patterns of Energy System Change in 2 °C Scenarios to Expert Projections'; Vaughan and Gough, 'Expert Assessment Concludes Negative Emissions Scenarios May Not Deliver'; Smith et al., 'Biophysical and Economic Limits to Negative CO2 Emissions'; Fuss et al., 'Betting on Negative Emissions'; Anderson and Peters, 'The Trouble with Negative Emissions'.

[10] Luderer et al., 'Residual Fossil CO 2 Emissions in 1.5–2 °C Pathways'.

ES.4. KEY MESSAGES

1) CCS capture costs of less than \$100/tCO_2[11] and learning towards \$45/tCO_2 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 of CCS in IAMs, but related to interdependent key-points listed below.

2) 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[12], and sensitivity to this calibration assumption is explored in ETSAP-TIAM in the scientific paper associated with this report. This work develops scenarios for the full energy system building on previous preliminary work exploring capture rates in the power sector[13]. 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.

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[11] Budini et al., 'Can CO2 Capture and Storage Unlock Unburnable Carbon'; Budinis et al., 'An Assessment of CCS Costs, Barriers and Potential'.

[12] Cousins et al., 'Towards Zero Emissions from Fossil-Fuel-Fired Power Stations'.

[13] Budini et al., 'Can CO2 Capture and Storage Unlock Unburnable Carbon'.

3) 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.

4) BECCS provides the majority of negative emissions in IAMs (with some 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, but 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.

5) 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. 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 management[14].

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[14] Smith et al., 'Biophysical and Economic Limits to Negative CO2 Emissions'; Vaughan et al., 'Evaluating the Use of Biomass Energy with Carbon Capture and Storage in Low Emission Scenarios'; Minx et al., 'Negative Emissions—Part 1'; Fuss et al., 'Negative Emissions—Part 2'; Vuuren et al., 'Alternative Pathways to the 1.5 °C Target Reduce the Need for Negative Emission Technologies'; Turner et al., 'The Global Overlap of Bioenergy and Carbon Sequestration Potential'.

6) 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 [15].

ES.5. RECOMMENDATIONS

The usefulness of IAM Scenario analysis is in the insights gained into the emergent logic of systems interactions, not typically into insights for the dynamics of an individual technology choice from a single scenario from a single model.

The diversity of mathematical approaches across the range of IAM typologies gives insights into resilient climate policy options across a range of scenarios and sensitivity analyses when combined across a range of models in a model inter-comparison project (MIP). Where the same technology deployments occur with the same scale and timing across the range of scenario analysis this gives an indication of a resilient technology option across the range of input assumptions and uncertain future scenarios. Resilience is meant here in the sense that the technology option is consistently deployed across a range of uncertain scenarios, with a range of techno-economic specifications, giving an indication of a least regrets investment option and is not overtly sensitive to an individual scenario.

CCS is a resilient climate mitigation policy as it is deployed at large scale in temperature stabilisation scenarios with all IAMs deploying BECCS and the majority deploying fossil CCS in the scenarios reviewed.

Real world CCS deployment to date is far off track compared to climate stabilisation pathways from IAMs. There is a considerable gap between the current industry growth rates

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[15] Grubler et al., 'A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies'; Vuuren et al., 'Alternative Pathways to the 1.5 °C Target Reduce the Need for Negative Emission Technologies'.

and the deployment rates envisaged in the current IAM SSP scenarios required for a temperature stabilisation scenario below 2°C[16]. The gap in deployment rates between IAMs and real world capacity construction is partially exacerbated as a result of the time lag in the development of IAM scenarios, publishing, and model base year calibration updates of the current state of CCS deployment. For example, many current generation IAM models have 2010 as a starting base year and allow CCS deployment in their model years between 2010 and 2018 at a scale that in reality has not occurred, largely as a result of the CCS demonstration projects that were envisaged previously to be online by now, have not been built as allowed the model scenarios. Therefore, there is a reduction in the perceptible gap between real world installed capacity deployment rates and the expected installed capacity in IAM climate stabilisation scenarios, and this perception gap grows the further back in TIME an IAM has its base year calibration; i.e. only models that regularly update their base year calibration, such as the IEA-ETP, can keep an up to date measurement of the progress and gap between actual CCS deployment and the required CCS deployment in scenarios for temperature stabilisation.

CCS technologies exist across multiple sectors in IAM temperature stabilisation scenarios, from power generation, to liquid fuel transformation and industrial processes.

The influential IAMs largely use up to date CCS specifications from IEAGHG technical briefs, IEA CCS roadmaps and Rubin et al[17] CCS techno-economic reviews. USA focused national energy systems models are often[18] heavily reliant on the 2005 IPCC Special report on CCS (IPCC SRCCS) [19] for data, but this is not the case for CCS technology cost estimates used in the influential global IAMs. Global storage volumes and transport costs are still relatively aggregated, simplified, and reliant upon the IPCC SRCCS in the absence of better regional data in the reviewed IAMs. There is ongoing work to create a global CCS storage geo-spatial database[20].

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[16] International Energy Agency, ‘Tracking Clean Energy Progress’.

[17] Rubin, Davison, and Herzog, ‘The Cost of CO2 Capture and Storage’.

[18] IEAGHG, ‘Proceedings of US DOE Workshop: Energy-Economic Modelling Review’.

[19] Metz and Intergovernmental Panel on Climate Change, *IPCC Special Report on Carbon Dioxide Capture and Storage*.

[20] Kearns et al., ‘Developing a Consistent Database for Regional Geologic CO2 Storage Capacity Worldwide’.

There are two primary recommendations from this project:

1. 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.
2. 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,
        - CO2 capture cost curves as a function of varying capacity factor and capture rate.

    - 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[21].
- 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.

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[21] Grubler et al., 'A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies'.

GLOSSARY

- AIM/CGE - Asia-Pacific Integrated Model with Computable General Equilibrium
- AR5 – IPCC 5th Assessment Report published in 2014/2015
- AR6 – IPCC 6th Assessment Report – due to be published in 2022
- BP – British Petroleum
- CMCC - Centro Euro-Mediterraneo sur Cambiamenti Climatici
- CDR – Carbon Dioxide Removal
- DAC – Direct Air Capture
- EJ – Exajoules
- ETP - Energy Technology Perspectives
- Exxon – Exxon Mobil
- EW – Enhanced Weathering
- FEEM - Fondazione Eni Enrico Mattei
- GCAM - The Global Change Assessment Model
- GCP – Global Carbon Project
- GDP – gross domestic product
- IAM - Integrated Assessment Models
- IEA - International Energy Agency
- IEA-ETP – International Energy Agency Energy Technology Perspectives
- IEAGHG – IEA Greenhouse Gas R&D Programme
- IEA-WEO – International Energy Agency World Energy Outlook
- IIASA – International Institute for Applied Systems Analysis
- IMAGE - Integrated Model to Assess the Global Environment
- IPCC – Intergovernmental Panel on Climate Change
- JGCRI - Joint Global Change Research Institute (JGCRI)
- MESSAGE-GLOBIOM – Model for Energy Supply Alternatives and their General Environmental Impact
- NET – Negative Emission Technology
- NIES - National Institute for Environmental Studies

- PBL - Netherlands Environmental Assessment Agency
- PES – Primary Energy Supply
- PIK - Potsdam Institute fur Klimafolgenforschung
- PNNL - Pacific Northwest National Laboratories
- RCP – Representative Concentration Pathway
- REMIND-MAgPie - Regional Model of Investments and Developments
- Shell – Royal Dutch Shell
- SR1.5 – IPCC special report on 1.5C requested at COP21 due in late 2018.
- SRCCS – IPCC special report on Carbon Capture and Storage published in 2005
- SSP – Shared Socioeconomic Pathways
- TFC – Total Final Energy Consumption/demand
- UN – United Nations
- UNFCCC – United Nations Framework Convention on Climate Change
- USD – United States Dollars ($)
- wCCS – with CCS
- WITCH-GLOBIOM - World Induced Technical Change Hybrid
- woCCS – without CCS

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 climate action. World leaders agreed to set a goal of limiting global warming to “well below” 2˚C above 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[22] highlight that current policies will very likely lead to warming far in excess of this level.

Modelling of possible 21st century energy system transitions by international research groups[23] highlight the importance of Negative Emissions Technologies (NETs) in achieving substantial emission reductions on timescales relevant to the climate goals of the Paris Agreement. In the latest Intergovernmental Panel on Climate Change (IPCC) assessment report[24], 101 of the 116 scenarios that achieved a “likely” chance of staying below 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[25]. 4 scenarios in the AR5 database solved a 2°C stabilisation scenario without CCS with a mitigation cost increase of 138% [26].

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[22] IPCC, *Climate Change 2014: Mitigation of Climate Change*.

[23] IPCC; Smith et al., ‘Biophysical and Economic Limits to Negative CO2 Emissions’; Fuss et al., ‘Betting on Negative Emissions’; UNFCCC, ‘Aggregate Effect of the Intended Nationally Determined Contributions: An Update’; Rogelj et al., ‘Energy System Transformations for Limiting End-of-Century Warming to below 1.5 °C’; Peters et al., ‘Key Indicators to Track Current Progress and Future Ambition of the Paris Agreement’; Slade, Bauen, and Gross, ‘Global Bioenergy Resources’; Schleussner et al., ‘Differential Climate Impacts for Policy-Relevant Limits to Global Warming’.

[24] IPCC, *Climate Change 2014: Mitigation of Climate Change*.

[25] Jones et al., ‘Simulating the Earth System Response to Negative Emissions’; Gasser et al., ‘Negative Emissions Physically Needed to Keep Global Warming below 2 °C’.

[26] IPCC, *Climate Change 2014*.

1.1 INTEGRATED ASSESSMENT MODELS: A PRIMER

The purpose of Integrated Assessment Models (IAMs) is to quantify the interactions and trade-offs between societal demands for energy, economic, and environmental services, using an integrated systems[27] approach. These systems are typically the energy system, the economy, the Earth land system, the water system and climate system, although every IAM does not necessarily include all these systems. Their interactions are assessed under the implementations of various socio-economic, demographic, technological and environmental constraints, and use appropriate levels of engineering robustness, scientific completeness and economic theory to maintain a consistent and computationally tractable solution framework.

A typical scenario analysis could consist of exploring how the global primary energy supply fuel mix may evolve under a diverse set of uncertainties with two primary constraints; meeting a climate stabilisation objective, and the availability (or lack) of CCS to lower hydrocarbon emissions and provide carbon dioxide removal (CDR) in the form of BECCS. Figure 1.1 shows the median primary energy supply from the IPCC 5th Assessment Report database for a *BASE* (business-as-usual) scenario, a scenario where atmospheric CO_2 concentrations are reduced to *450 PPM* by the end of the century (approximately consistent with a likely probability of limiting warming to beneath 2°C), and a *450PPM noCCS* case in which CCS is not available for deployment in the energy system of the IAMs. Under the imposition of a climate constraint there is a considerable reduction in the demand for primary energy brought about by a combination of efficiency alongside fuel switching between the continued use of fossil fuels with CCS and bioenergy with CCS, or in the case without CCS there is an earlier shift to bioenergy without CCS and a larger earlier deployment of renewable electricity generation.

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[27] Grubler et al., 'Chapter 1 - Energy Primer'.

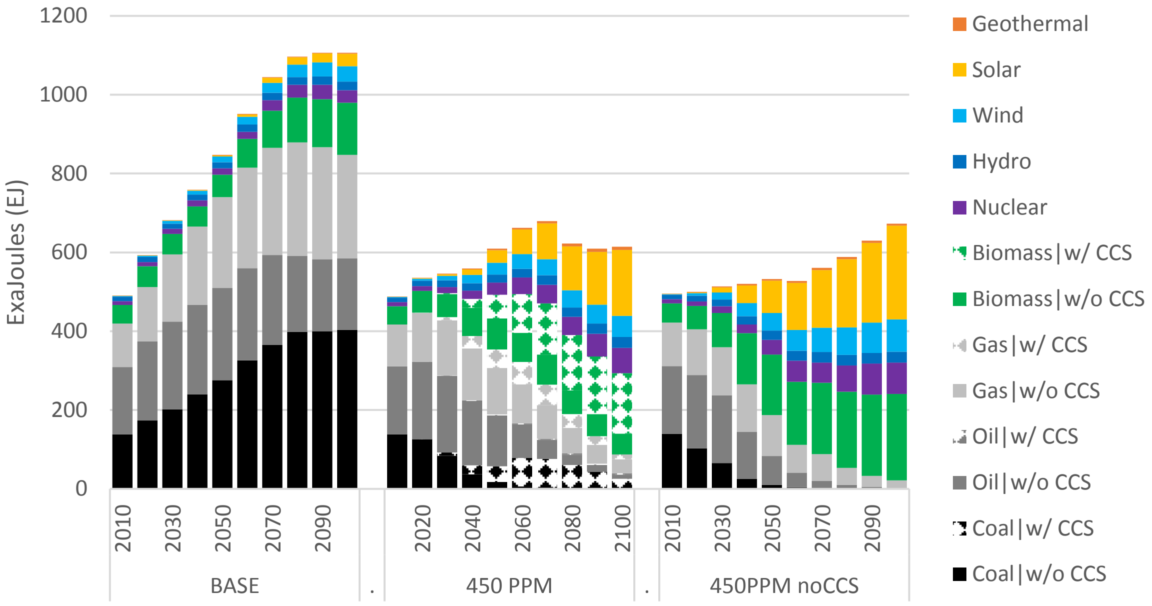

Figure 1.1 AR5 Global Primary Energy Supply (EJ) - MEDIAN base scenario compared with MEDIAN 450PPM climate scenarios with and without CCS

The mathematical approach underpinning each IAM can vary across the models. Classifications include whether a model equations finds a **partial equilibrium** or **general equilibrium** between supply and demand of energy commodities and services, whether or not the model is attempting to **optimise** or **simulate** in their calculations subject to the model constraints, the range of sectors included in the model (such as land, energy, water, socio-economic systems, and climate), and the treatment of foresight may vary. Each IAM has its own strengths and weaknesses. Some industry medium term models based on econometric simulation techniques describe their analysis as outlooks, implying a level of forecasting accuracy, while most research IAMs do not claim to have forecasting capabilities as the long-term future is too uncertain, and instead gain insights by describing sets of potential futures under scenario analysis covering a broad range of uncertainty in input assumptions. This uncertainty is treated differently across the range of industry outlook modelling teams from the oil majors, to the IEA’s World Energy Outlook and Energy Technology Perspective teams, and to the scenario analysis of the research institution based IAMs. The difference in approach to uncertainty analysis[28] is seen in the number of scenarios and the spread of future primary energy supply for Oil, Gas and Coal across each team's most recent analysis. There are also institutional and market confidence reasons not to display future uncertainty for policy analysis. Presenting too many scenarios can also become too confusing and the messages may get lost, in particular to a broader public or the policy maker directly. It can also be observed in Figure 1.2 that the oil majors and IEA's outlook overlap to a large extent with the climate mitigation scenarios from the influential models used in IPCC reports, and often envisage less fossil fuel based primary energy supply (PES) than the baseline scenarios from the research institution IAMs.

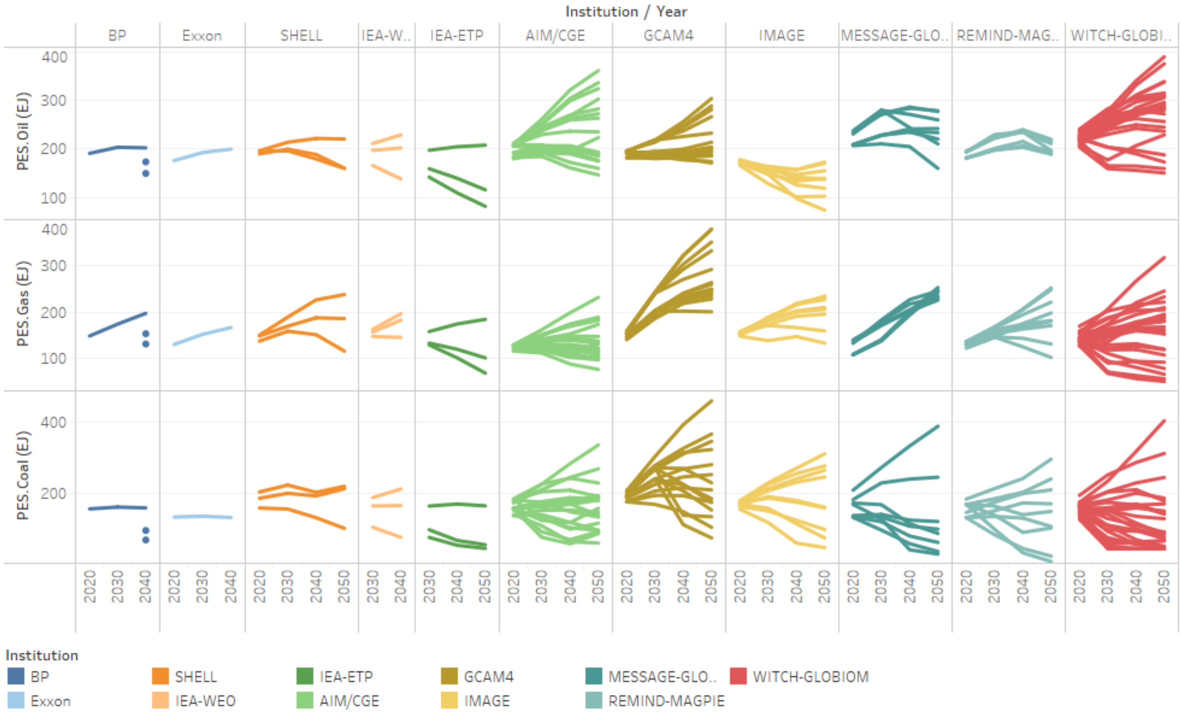

Figure 1.2 Range of Primary Energy Supply (PES) for Oil, Gas, and Coal across Industry, IEA and Research IAMs. Note IEA-ETP results show a scenario for well below 2°C scenarios (WB2DS), which the other models do not in this dataset. The Research IAMs have recently published Scenarios for overshoot and return to 1.5°C by 2100 in Rogelj et al [29] feeding into the IPCC Special Report on 1.5°C scenarios[30].

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[28] Yue et al., 'A Review of Approaches to Uncertainty Assessment in Energy System Optimization Models'.

[29] Rogelj et al., 'Scenarios towards Limiting Global Mean Temperature Increase below 1.5 °C'.

[30] Intergovernmental Panel on Climate Change, *Global Warming of 1.5°C*.

Broadly speaking the range of IAMs utilised at a global policy level can be categorised into groups as a result of 2 critical dimensions which characterise each model framework. These are the type of market equilibrium calculated in the framework, Partial Equilibrium (PE) or General Equilibrium (GE), and how the model treats time and information, typically either dynamic recursive, myopic, or intertemporal optimisation.

- PE models find price equilibrium within the energy system between supply and demand without feedback of the changes to demand or energy supply costs to the larger economy outside the energy system.
- GE models find an equilibrium between supply and demand for energy services within a whole economy framework, which results in feedback to the economy from the energy system and resultant demand for energy services, as prices for these services vary between scenarios.
- Dynamic recursive models have shorter solution time horizons and have reduced knowledge of the future available in that shorter time horizon representing real world myopic or limited foresight investment decision making processes.
- Intertemporal optimisation models generally have perfect foresight, thus perfect information of the future, and optimise the energy system costs in an ideal way with perfect market knowledge over the whole model time horizon.

Within these categories models can be grouped further into bottom-up (BU) engineering process modelling approach or top-down (TD) economic models with macro and micro economic theories underpinning them. Combining bottom up and top down approaches to achieve both a robust level of engineering detail in the model and also maintaining a general equilibrium of prices and commodity flows between an energy system and the macroeconomic system is known as a hybrid approach[31].

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[31] Glynn et al., ‘Economic Impacts of Future Changes in the Energy System—Global Perspectives’; Glynn et al., ‘Economic Impacts of Future Changes in the Energy System—National Perspectives’.

The level of technical completeness of the representation of any energy technology in an IAM, including CCS, is dependent upon the overall modelling approach, the time resolution, the endogenous explicitness of commodity and material flows in the model, and how well the available techno-economic input data for CCS fits the variables feasibly represented in the modelling approach. The treatment of time, discounting of future costs and the level of foresight the models have, from perfect foresight over the remainder of the century, to 5 year rolling horizon, all have influence on the model dynamics and the feasible rate of technological change within the energy system.

The BU process engineering models typically have more complete representation of the technical elements of an energy process, while TD models typically better represent the macro-economic dynamics, prices and demands for the services provided by an energy process the energy system impacts on GDP and consumption, but may have reduced functional forms of the technical representation of a process.

1.2 THE ROLE OF CARBON CAPTURE AND STORAGE IN CLIMATE SCENARIOS

The IPCC 5th Assessment report revealed that IAM scenarios show a substantial increase of 138% (29-297%) in the cost of limiting warming to below 2°C with a >66% chance, if CCS is excluded as a mitigation option [32]. The exclusion of CCS has a much greater impact on the cost of meeting a 2°C target than the exclusion of any other technology option. Whilst the existence of this result is becoming more widely known and was highlighted in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the underlying reasoning behind this result remains poorly understood[33].

Physically, the primary determinant of future climate change is the all-time cumulative emission of carbon dioxide (CO_2)[34]. Due to slow equilibration of the surface climate system to

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[32] Clarke et al., 'Assessing Transformation Pathways'; Strefler et al., 'Between Scylla and Charybdis'.

[33] Koelbl et al., 'Uncertainty in Carbon Capture and Storage (CCS) Deployment Projections'.

[34] Allen et al., 'Warming Caused by Cumulative Carbon Emissions towards the Trillionth Tonne'; Matthews and Caldeira, 'Stabilizing Climate Requires Near-Zero Emissions'.

radiative forcing, combined with the slow drawdown of carbon from the atmosphere into the upper and deep oceans[35], current understanding indicates that on cessation of CO_2 emissions temperatures will rapidly plateau and then hold approximately constant for at least several centuries[36]. Therefore, a physical necessity of limiting warming to achieve the long-term temperature goal of the Paris Agreement will require global emissions of CO_2 to be reduced to net-zero by or before the time human-induced warming reaches the temperature threshold interpreted to be "well-below" 2°C. Indeed, limiting warming to any threshold, be it 1.5°C, 2°C or higher, ultimately requires emissions of CO_2 to be brought to net-zero in all cases. In cases where there is a temperature overshoot above 1.5°C average warming, net-zero emissions may be achieved after the temperature stabilisation target is breached, by the use of carbon dioxide removal from the atmosphere to reduce future average temperatures, rather than stabilise at a given 2°C or 1.5°C limit.

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[35] Pierrehumbert, 'Short-Lived Climate Pollution'.

[36] Gillett et al., 'Ongoing Climate Change Following a Complete Cessation of Carbon Dioxide Emissions'; Joos et al., 'Carbon Dioxide and Climate Impulse Response Functions for the Computation of Greenhouse Gas Metrics'; Matthews and Caldeira, 'Stabilizing Climate Requires Near-Zero Emissions'; Solomon et al., 'Irreversible Climate Change Due to Carbon Dioxide Emissions'.

Figure 1.3 shows the evolution of a set of “cost-effective” scenarios (which minimise the present-day discounted cost of meeting a given CO_2 equivalent concentration target in 2100) in various metrics.

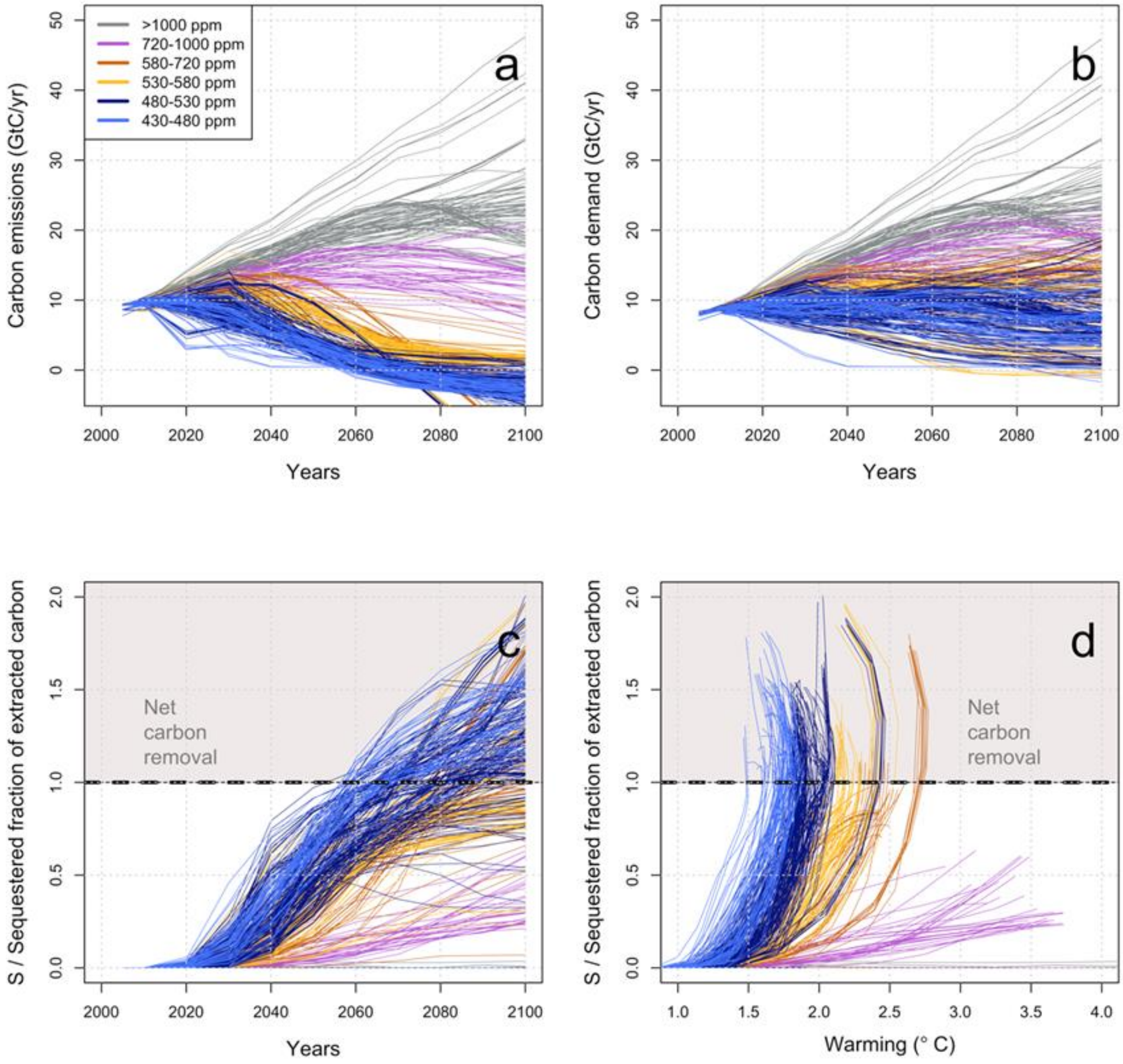

Figure 1.3 The evolution of annual global CO2 emissions (a) and underlying carbon demand or gross CO_2 emissions before capture or removal (b) of the scenarios in the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC-AR5) database. Lines represent scenarios coloured by IPCC-AR5 2100 radiative forcing categories. The evolution of the sequestered fraction of extracted carbon (S - sequestered fraction of carbon demand) in the individual scenarios is shown as a function of time (c) and realised warming (d). Background shading in panels (c) and (d) indicate net-removal of carbon from the atmosphere. Adapted from Millar & Allen 2018 (in press).

Despite the rapid declines in net emissions of CO_2 in these cost-effective mitigation scenarios (light and dark blue lines in Figure 1.3a), the underlying economic demand for carbon in these same scenarios remains high in many cases (Figure 1.3b). Fossil fuels and carbon based processes have many different economic uses in the global economy, and the need to reach net-zero emissions to limit warming requires that the most difficult-to-abate sources of emissions will therefore need to be either captured at source or subsequently removed from the atmosphere using NETs. These difficult to abate sources are likely to include particular industrial processes for which economically viable zero-carbon substitutes don't exist yet or are unlikely to be available at sufficient scale on timescales relevant to limiting warming to the ambitious long-term goal of the Paris Agreement. Similarly, despite declines in the carbon intensity of private transport, some forms of transportation, such as international air-travel, are likely to continue to be gross sources of CO_2 emissions to the atmosphere and therefore will have to be offset with NETs in order to reach a net-zero CO_2 emission world.

For many large-scale industrial point sources, CCS may be the only viable route to a net-zero emissions business model. CCS is likely to play a critical role in developing the technologies needed to implement NETs at large scales through either bioenergy with carbon capture and storage (BECCS) or direct air capture (DAC).

At a very high level, within cost-effective scenarios of future climate policy all mitigation pathways can be classified in terms of a two-dimensional space. Mitigation measures can either act to reduce the underlying economic demand for gross CO_2 emission (i.e. reducing the price of renewable energy can lower or remove demand for fossil carbon energy in the electricity generation system) or increase the fraction of carbon that is sequestered (removed from the active carbon cycle). An example of mitigation activities acting along this "sequestered fraction" axis are the deployment of fossil CCS or NETs (Figure 1.3). The physical necessity of reaching net-zero emissions to meet global climate goals requires either all demand for carbon within the global economy to be eliminated, or, more plausibly, for the sequestered fraction of the remaining carbon demand to reach 100% (the total amount of carbon that is extracted from the ground for combustion is equal to the total amount that is sequestered in any given year).

Figure 1.3c shows the evolution of the sequestered fraction in the same cost-effective scenarios of future climate policy as a function of time. As the economic demand for gross CO_2 emissions doesn't reach zero in most scenarios that succeed in limiting warming to beneath 2°C with >66% probability, the sequestered fraction of carbon (through CCS and NETs deployment) must reach unity in order to peak warming. In many cases the sequestered fraction rises above unity in the later part of the century indicating a net withdrawal of CO_2 from the atmosphere resulting in a decline of temperatures from their peak (see Figure 1.3d). The need to reach a sequestered fraction of unity to stabilise warming is required irrespective of how much non-fossil based energy is deployed in the meantime.

If the evolution of the sequestered fraction is expressed in terms of realised warming in the climate system, a consistent shape is seen for the evolution of the sequestered fraction in all cost-efficient scenarios (Figure 1.3d). Much of the variation across scenarios that is apparent in their annual CO_2 emissions pathways (Figure 1.3a) is now collapsed down to a single, approximately quadratic, profile for nearly all scenarios with the single degree of freedom (to a first order approximation) as the magnitude of peak warming reached in the scenario. When the sequestered fraction is thus expressed, it is clear that these cost-effective scenarios clearly simulate a smooth and steady increase in the sequestered fraction (through CCS and NETs deployment) with additional warming from today onwards and do not show a cliff-edge deployment of these technologies later in the century.

The advantage of such a high-level summary of the characteristics of CCS deployment profiles within IAMs are that they can be used as informative guiderails for policy implementation. A clear challenge for international climate policy is to help incentivise similarly smooth and progressive deployments of sequestering technology. The advantages of such a CCS deployment profile would be several-fold. Smooth and incremental deployment of CCS would allow learning to progress steadily before very large amounts of CCS capital is needed to be deployed in the second half of the century. This will be essential for reducing the cost of capital for capture and sequestration technologies, understanding the behaviour of geologically stored carbon, and, perhaps most importantly, establishing a social licence for large scale sequestration. Additionally, IAM scenarios that ramp up their sequestered fraction to higher fractions later in the century than others have greater overall costs of climate policy. This is likely associated with a greater required reduction in demand for carbon in some high economic value sectors, as cumulative CO_2 emissions are approximately constant within each scenario grouping, due to slower CCS and NETs penetration rates. Beginning a gradual deployment of CCS early is therefore likely to be economically advantageous strategy for minimising the costs and risks over ambitious climate policy.

A clear high-level conclusion that can be drawn from this framing of CCS in climate scenarios, is that while hugely ambitious, it would be advantageous for the globe to reach a position where it is sequestering at least 15% of the carbon that is extracted from the ground by the mid-to-late 2020s (when temperatures would be projected to be around 1.2°C above pre-industrial). Such a position would make a subsequent rapid scale up of the sequestered fraction both more plausible and affordable and would allow the option of keeping warming to beneath 1.5°C, particularly if the climate response turns out to be on the higher end of currently assessed distributions, on the table. Figure 1.4 highlights the differences between outlook projections of CO_2 emissions and CO_2 pathways scenarios that aim for temperature stabilisation at 2°C or below.

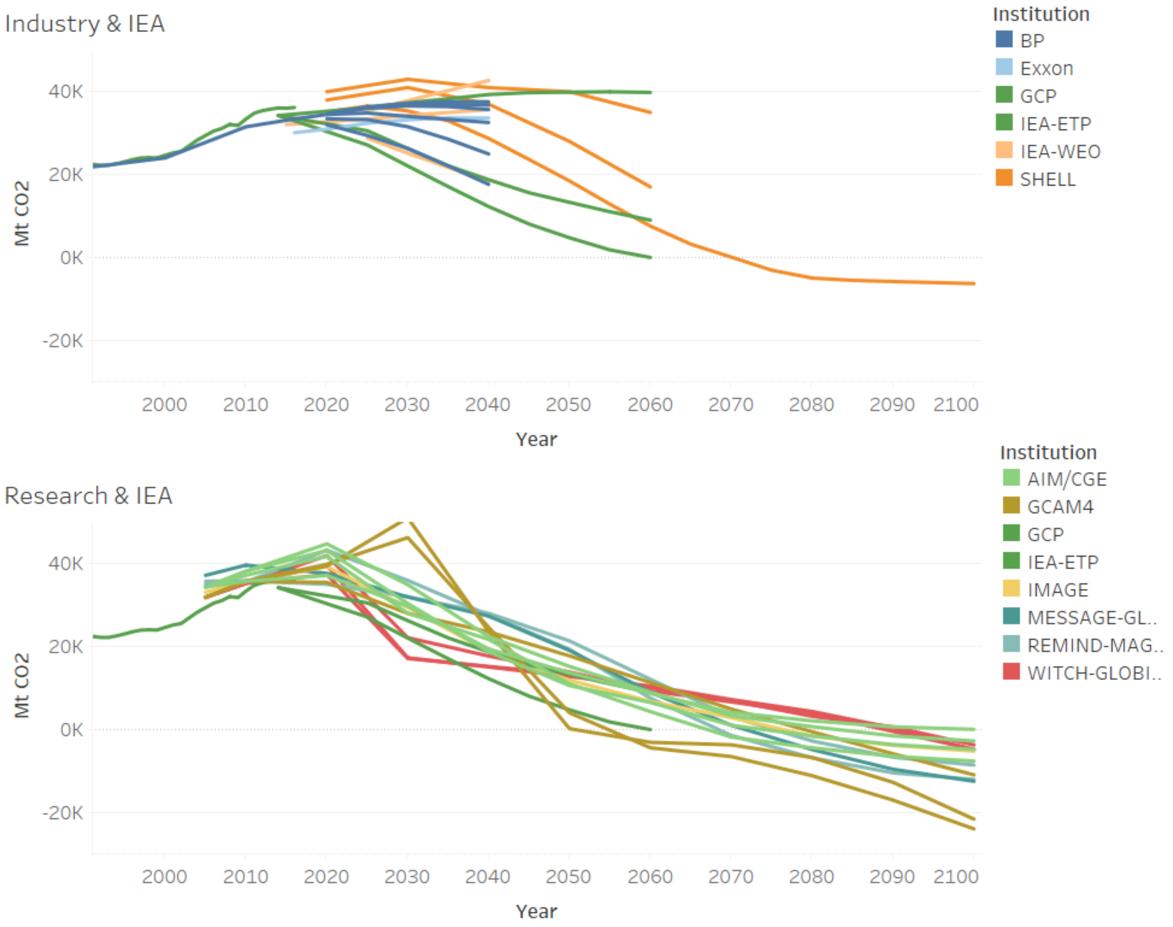

Figure 1.4 CO_2 Emissions ($MtCO_2$/year) from industry outlooks scenarios (top), and (bottom) research IAMs for shared socio economic pathways (SSP) which which stabilise temperature warming below 2°C (RCP2.6).

2 CURRENT INFLUENTIAL IAMS INFORMING GLOBAL CLIMATE POLICY

There are 30 integrated assessment models (IAMs) which contributed energy system scenarios to the Intergovernmental Panel on Climate Change (IPCC) working group 3 database[37], which underpins the analysis and policy outcomes of the IPCC's Fifth Assessment report (AR5)[38] [39]. Each of the scenarios within the database were published in peer reviewed journals, largely as results from completed (2014) Model Intercomparison Projects (MIPs), such as AME, AMPERE, EMF24, EMF27, LIMITS, POEM, and RoSE, to name a few. There are more than 30 other additional models and modelling frameworks that make up most of regional, industry and national policy analysis of energy and climate transitions, which are likely to have an increasingly prominent role in the IPCC 6th Assessment report given the restructuring of the mitigation analysis to include national pathways resulting from the national determined contributions.

The International Energy Agency (IEA) Energy Technology Perspectives (ETP)[40] publication is informed by a key advanced global energy system model, often used to benchmark the energy systems core of other Integrated Assessment Models. The ETP model focuses on technology explicit representation within their energy system framework and energy related CO_2 emissions, but does not endogenously include integrated assessment of climate, economy and land use change, and as such, is not an IAM in the same family of models that dominate the IPCC AR5 scenario database. The ETP team utilises a bespoke energy system assessment framework with 4 soft-linked technology rich models covering energy conversion, industry, transport and buildings. The ETP team's modelling analysis

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[37] https://secure.iiasa.ac.at/web-apps/ene/AR5DB/dsd?Action=htmlpage&page=about#references

[38] Clarke et al., 'Assessing Transformation Pathways'.

[39] These are process based IAMs which differ from the econometrically derived climate-economy models such as DICE, RICE and FUND as well-known examples of these other class of models sometimes also referred to as IAMs.

[40] IEA, *Energy Technology Perspectives 2017*.

underpins technology specific roadmaps from the IEA, including the 2013 CCS roadmap analysis[41].

In addition to the ETP model, we assessed the role of CCS in the influential IAMs that include energy and non-energy related CO_2 and other green-house-gases (GHGs). We defined influential IAMs to be those that contribute most scenarios to the AR5 database, or those that participated in the most model inter-comparison projects. Using this criterion, the 6 chosen IAMs, are those same chosen as the *marker models* for the next generation of scenario analysis within the IAM community; the shared socio-economic pathways[42] (SSPs) (See Table 2.1). These 6 IAMs– currently have scientific influence in the research community informing the majority of scenarios in the IPCC special report on 1.5°C[43] (SR1.5) and will continue to have an influential role informing the policy narrative for the transition to a net zero-carbon energy system at a global level[44].

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

Table 2.1 Most Influential IAMs in the IPCC Fifth Assessment Report Scenario Database

This report will focus on the most recently published model results from;

1. AIM[45] - Asia-Pacific Integrated Model (AIM) developed by the National Institute for Environmental Studies (NIES) in collaboration with Kyoto University and Mizuho Information and Research Institute,

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[41] IEA, ‘Technology Roadmap: Carbon Capture and Storage’.

[42] Riahi et al., ‘The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications’.

[43] Intergovernmental Panel on Climate Change, *Global Warming of 1.5°C*.

[44] Rogelj et al., ‘Scenarios towards Limiting Global Mean Temperature Increase below 1.5 °C’.

[45] http://www-iam.nies.go.jp/aim/about_us/index.html

2. *GCAM*[46] - The Global Change Assessment Model (GCAM) developed by the Joint Global Change Research Institute (JGCRI) in Pacific Northwest National Laboratories (PNNL) and the University of Maryland,
3. IMAGE[47] - Integrated Model to Assess the Global Environment (IMAGE) developed by the Netherlands Environmental Assessment Agency (PBL) and Utrecht University.
4. MESSAGE-GLOBIOM[48] – Model for Energy Supply Alternatives and their General Environmental Impact (MESSAGE) developed by the International Institute for Applied Systems Analysis (IIASA)
5. REMIND[49] - Regional Model of Investments and Developments (REMIND) developed by the Potsdam Institute fur Klimafolgenforschung (PIK)
6. WITCH[50] - World Induced Technical Change Hybrid (WITCH) developed by the Fondazione Eni Enrico Mattei (FEEM) and Centro Euro-Mediterraneo sur Cambiamenti Climatici (CMCC)
7. IEA-ETP[51] - Energy Technology Perspectives (ETP) model developed by the International Energy Agency (IEA)

2.1 SHARED SOCIO-ECONOMIC PATHWAYS – LATEST IAM SCENARIOS

The five Shared Socio-economic pathways (SSPs) are narratives used by IAMs to describe plausible but uncertain future changes in human development, economy and environment. These narratives make up the next generation of quantitative scenarios that describe the plausible solution space that integrated assessment models[52] occupy

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[46] http://www.globalchange.umd.edu/gcam/
[47] http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation
[48] http://www.iiasa.ac.at/web/home/research/modelsData/MESSAGE/MESSAGE.en.html
[49] https://www.pik-potsdam.de/research/sustainable-solutions/models/remind
[50] http://www.witchmodel.org/
[51] http://www.iea.org/etp/etpmodel/
[52] Riahi et al., 'The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications'.

when exploring socio-economic challenges to implementing climate mitigation, adaptation and sustainable development goals. Each SSP consist of quantitative projections of GDP[53], population[54] and urbanisation[55] (See Figure 2.1) along with resource and technology constraints consistent with an underlying qualitative narrative of potential future world development pathways independent of future climate policy. They have been developed as a cross community initiative between the mitigation and adaptation research communities to enable integrated analysis of future impacts of adaptation and mitigation measures using harmonised narratives[56].

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[53] Dellink et al., 'Long-Term Economic Growth Projections in the Shared Socioeconomic Pathways'.

[54] KC and Lutz, 'The Human Core of the Shared Socioeconomic Pathways'.

[55] Jiang and O'Neill, 'Global Urbanization Projections for the Shared Socioeconomic Pathways'.

[56] Moss et al., 'The next Generation of Scenarios for Climate Change Research and Assessment'; Kriegler et al., 'The Need for and Use of Socio-Economic Scenarios for Climate Change Analysis'; O'Neill et al., 'A New Scenario Framework for Climate Change Research'.

There is a considerable range of GDP growth and population projections explored in the uncertainty across the SSP narratives (See Figure 2.1).

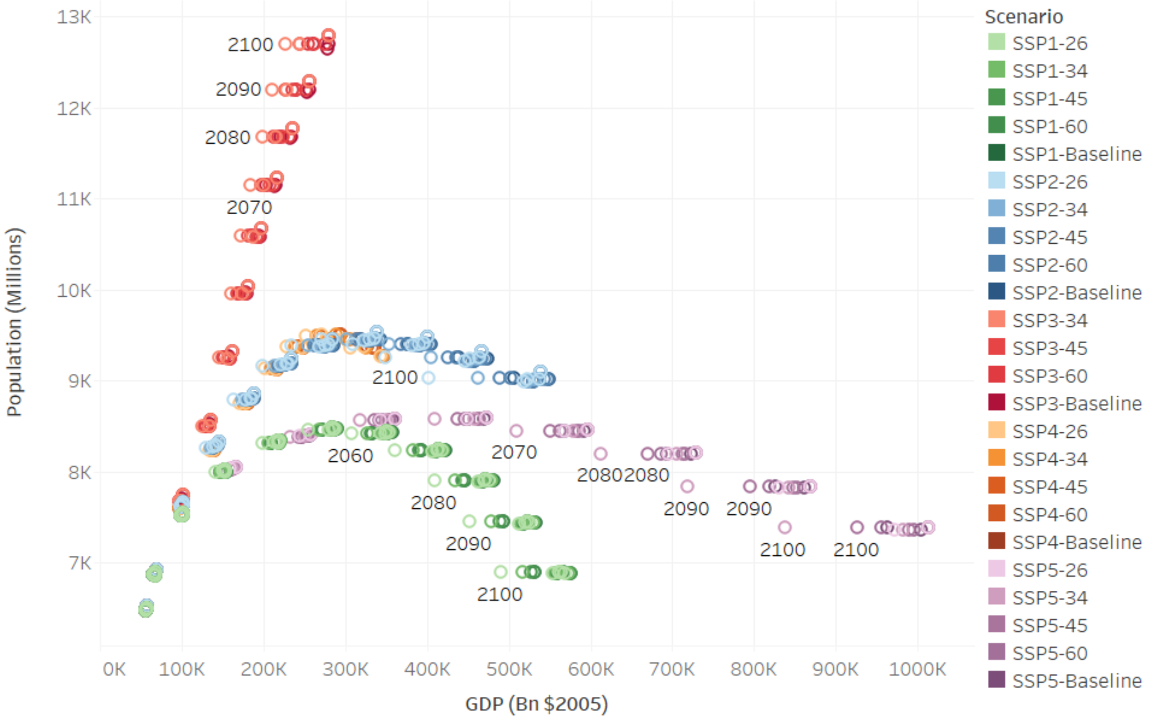

Figure 2.1 Primary Drivers for Energy Service Demands - World Population by SSP vs World GDP by SSP where 2.6, 3.4, 4.5, 6.0 and baseline refer to the representative concentration pathways and radiative forcing per scenario by 2100.

Six of the global integrated assessment model teams have developed and published marker model data sets[57] for the energy system and macroeconomic outcomes from each of the SSPs. Within each SSP a range of climate policy constraints are explored by reducing radiative forcing (a measure of the warming-inducing potential of changes to the atmospheric composition) from baseline levels, to 2.6W/m^2 by 2100, consistent with representative concentration pathway (RCP) used by the IPCC to assess a future emissions scenarios with a 66% probability of remaining below 2C warming[58]. The SSP

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[57] https://tntcat.iiasa.ac.at/SspDb/

[58] Calvin et al., 'The SSP4'; Fujimori et al., 'SSP3'; Kriegler et al., 'Fossil-Fueled Development (SSP5)'; Fricko et al., 'The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century'; van Vuuren et al., 'Energy, Land-Use and Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm'; Bauer et al., 'Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives'.

data sets and narratives underpin the outlook for CCS in IAMs in the state of the art climate scenarios, which include some explicit constraints as to the social acceptability of CCS, the environmental co-benefits from a life cycle perspective, and thus its rate of development and deployment across the various IAMs. These input assumptions will be explored later in Section 3.

2.1.1 SSP1 - SUSTAINABILITY – TAKING THE GREEN ROAD

SSP1, called "Sustainability – taking the green road", is a world making relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. Elements that contribute to this are a rapid development of low-income countries, a reduction of inequality (globally and within economies), rapid technology development, and a high level of awareness regarding environmental degradation. Rapid economic growth in low-income countries reduces the number of people below the poverty line. The world is characterized by an open, globalized economy, with relatively rapid technological change directed toward environmentally friendly processes, including clean energy technologies and yield-enhancing technologies for land. Consumption is oriented towards low material growth and energy intensity, with a relatively low level of consumption of animal products. Investments in high levels of education coincide with low population growth. Concurrently, governance and institutions facilitate achieving development goals and problem solving. The Millennium Development Goals are achieved within the next decade or two, resulting in educated populations with access to safe water, improved sanitation and medical care. Other factors that reduce vulnerability to climate and other global changes include, for example, the successful implementation of stringent policies to control air pollutants and rapid shifts toward universal access to clean and modern energy in the developing world[59].

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[59] van Vuuren et al., 'Energy, Land-Use and Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm'.

2.1.2 SSP2 - MIDDLE OF THE ROAD

In the SSP2 "Middle of the Road" world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. Development of low-income countries proceeds unevenly, with some countries making relatively good progress while others are left behind. Most economies are politically stable with partially functioning and globally connected markets. A limited number of comparatively weak global institutions exist. Per-capita income levels grow at a medium pace on the global average, with slowly converging income levels between developing and industrialized countries. Intra-regional income distributions improve slightly with increasing national income, but disparities remain high in some regions. Educational investments are not high enough to rapidly slow population growth, particularly in low-income countries. Achievement of the Millennium Development Goals is delayed by several decades, leaving populations without access to safe water, improved sanitation and medical care. Similarly, there is only intermediate success in addressing air pollution or improving energy access for the poor as well as other factors that reduce vulnerability to climate and other global changes[60].

2.1.3 SSP3 - REGIONAL RIVALRY – A ROCKY ROAD

SSP3, "Regional Rivalry – A Rocky Road" is a world that is separated into regions characterized by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. Regional blocks of countries have re-emerged with little coordination between them. This is a world failing to achieve global development goals, and with little progress in reducing resource intensity, fossil fuel dependency, or addressing local environmental concerns

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[60] Fricko et al., 'The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century'.

such as air pollution. Countries focus on achieving energy and food security goals within their own region. The world has de-globalized, and international trade, including energy resource and agricultural markets, is severely restricted. Little international cooperation and low investments in technology development and education slow down economic growth in high-, middle-, and low-income regions. Population growth in this scenario is high as a result of education and economic trends. Growth in urban areas in low-income countries is often in unplanned settlements. Unmitigated emissions are relatively high, driven by high population growth, use of local energy resources and slow technological change in the energy sector. Governance and institutions show weakness and a lack of cooperation and consensus; effective leadership and capacities for problem solving are lacking. Investments in human capital are low and inequality is high. A regionalized world leads to reduced trade flows, and institutional development is unfavourable, leaving large numbers of people vulnerable to climate change and many parts of the world with low adaptive capacity. Policies are oriented towards security, including barriers to trade[61].

2.1.4 SSP4 - INEQUALITY – A ROAD DIVIDED

SSP4, “Inequality – A Road Divided”, envisions a highly unequal world both within and across countries. A relatively small, rich global elite is responsible for much of the emissions, while a larger, poorer group contributes little to emissions and is vulnerable to impacts of climate change, in industrialized as well as in developing countries. In this world, global energy corporations use investments in R&D as hedging strategy against potential resource scarcity or climate policy, developing (and applying) low-cost alternative technologies. Mitigation challenges are therefore low due to some combination of low reference emissions and/or high latent capacity to mitigate. Governance and globalization are effective for and controlled by the elite, but are

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[61] Fujimori et al., ‘SSP3’, 3.

ineffective for most of the population. Challenges to adaptation are high due to relatively low income and low human capital among the poorer population, and ineffective institutions[62].

2.1.5 *SSP5 - FOSSIL-FUELLED DEVELOPMENT – TAKING THE HIGHWAY*

SSP5, “Fossil-fuelled Development – Taking the Highway”, stresses conventional development oriented toward economic growth as the solution to social and economic problems through the pursuit of enlightened self-interest. The preference for rapid conventional development leads to an energy system dominated by fossil fuels, resulting in high GHG emissions and challenges to mitigation. Lower socio-environmental challenges to adaptation result from attainment of human development goals, robust economic growth, highly engineered infrastructure with redundancy to minimize disruptions from extreme events, and highly managed ecosystems[63].

2.2 OVERVIEW OF CCS IN THE SHARED SOCIO-ECONOMIC PATHWAYS

Carbon Capture and Storage has a critical role to play in achieving the Paris agreement goals of limiting anthropogenic temperature increase well below 2°C and towards 1.5°C[64]. Figure 2.2 plots the reductions of energy system CO_2 emissions required by each model for the median and range of SSP1, SPP2, SSP4 and SSP5 for a mitigation scenario achieving a 2°C temperature stabilisation limit. IEA-ETP 2 degree Scenario (2DS) and beyond 2 degree scenario (B2DS)[65] CO_2 emissions are also included for comparison. Net Zero CO_2 emissions are required by 2070 on average (2050-2090). The 1.5°C temperature goal requires additional mitigation effort as well as the removal of at least 500GtCO_2 from the atmosphere over the century[66].

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[62] Calvin et al., ‘The SSP4’, 4.

[63] Kriegler et al., ‘Fossil-Fueled Development (SSP5)’, 5.

[64] Strefler et al., ‘Between Scylla and Charybdis’.

[65] IEA, *Energy Technology Perspectives 2017*.

[66] IEA; Rogelj et al., ‘Scenarios towards Limiting Global Mean Temperature Increase below 1.5 °C’; Luderer et al., ‘Deep Decarbonisation towards 1.5C - 2C Stabilisation. Policy Findings from the ADVANCE Project’.

It should be noted that in SSP3, a regionally fragmented world with limited investment in R&D or international cooperation, none of the IAMs that ran SSP3 were able find a feasible solution to limit warming to 2°C or 2.6W/m^2.

A range of simple model behaviours can be observed in the CO_2 emission pathways. Some IAMs under the same scenario conditions and constraints choose immediate and rapid mitigation in the short term allowing slower mitigation rates in the longer-term such as AIM and WITCH, whereas GCAM, REMIND, MESSAGE and IMAGE prefer slower rates of decarbonisation in the short and medium term with more ambitious rates of decarbonisation combined with larger deployment of negative emissions technologies in the long term by 2100. The IEA-ETP model runs to a 2060 horizon and chooses mitigation pathways within the medium-high responsiveness[67] range classification of the IAM range for the 2DS, and lower for the B2DS scenarios. Cumulative CO_2 capture in the IEA-ETP range from 150-250GtCO_2 by 2060[68].

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[67] Kriegler et al., 'Diagnostic Indicators for Integrated Assessment Models of Climate Policy'.

[68] IEA, *Energy Technology Perspectives 2017*.

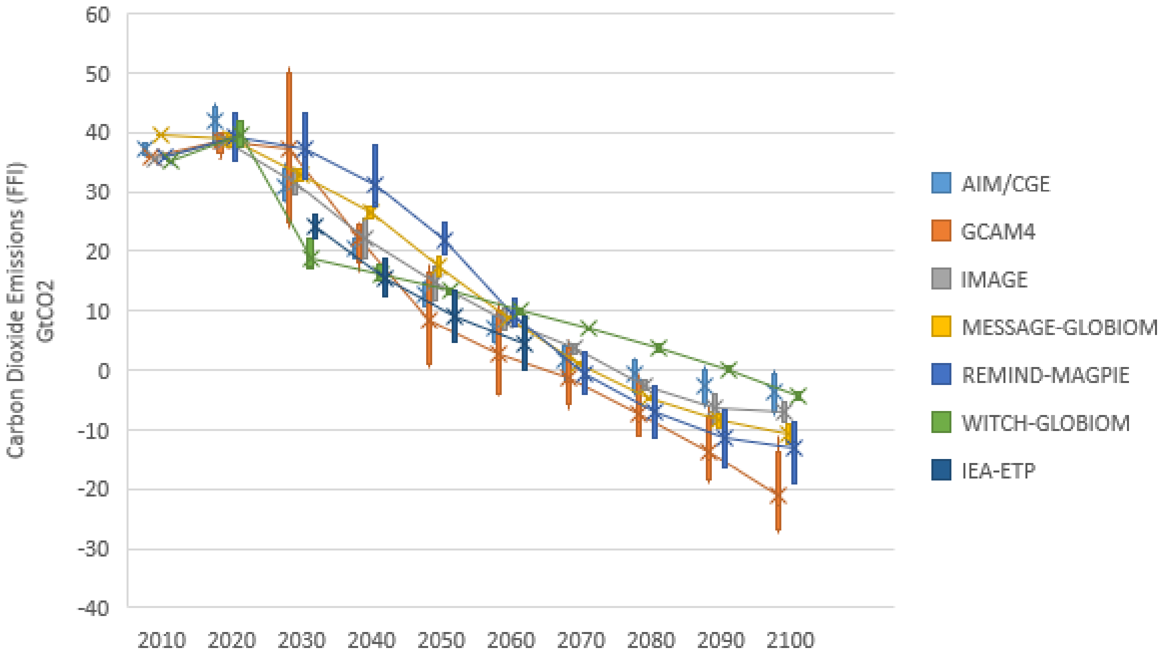

Figure 2.2 CO_2 Emissions reductions pathway by IAM for each SSP solution for a 2°C (RCP2.6) consistent scenario and for IEA-ETP 2017 2°C and B2°C scenarios. Trend line shows the mean of the feasible scenarios.

Stringent CO_2 reduction constraints induce a required restructuring of the primary energy supply (Figure 2.3) and the final energy consumption requirements of the global energy system (Figure 2.4). 81% of primary energy supply is currently fossil fuel based[69]. Fossil fuels share of primary energy supply drops to less than 20% across SSP1, 2 and 4 by 2100 for the 2°C scenario and makes up 25% of primary energy supply by 2100 in the fossil fuelled development scenario; SSP5 is a fossil fuel highly engineered and managed scenario, which retains higher levels of fossil fuel as a share of primary energy supply, but thus requires significantly more NETS in the form of BECCS to offset residual emissions from fossil energy supplies. There is a pervasive shift in final energy consumptions towards electrification, making up to 60% of final energy consumption, generated from nuclear, hydro power, and with rapid growth in bioenergy with CCS, wind and solar power. Total primary energy requirement varies from 530 exajoules (EJ) currently to over 1000 EJ towards the end of the

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[69] IEA, *World Energy Outlook 2017*.

century for SSP5. There are considerable demand reductions and energy efficiency improvements between the Baseline and SSPx-2.6 scenarios (See Figure 2.3).

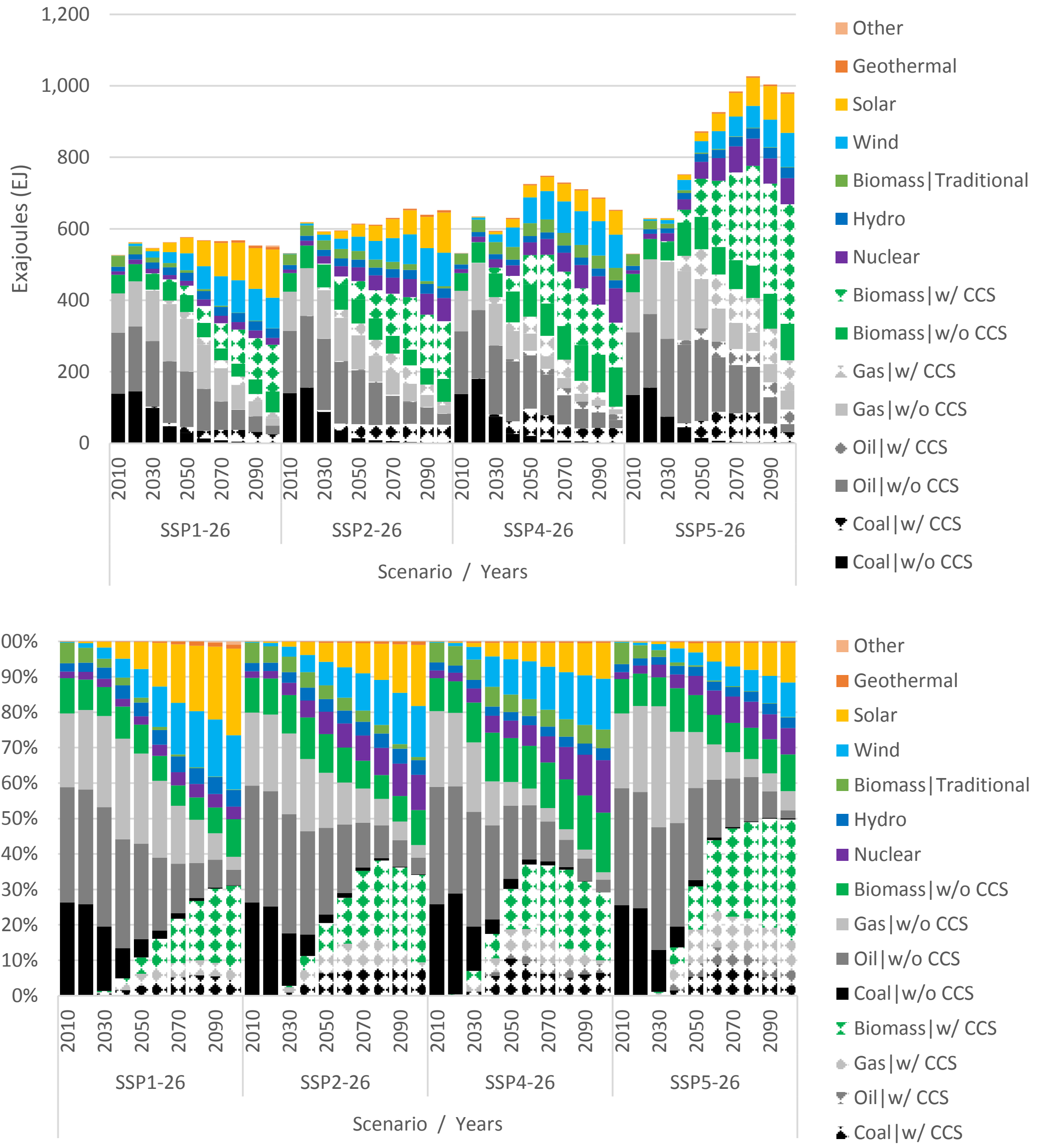

Figure 2.3 Primary energy supply across each SSP low temperature scenario for the median of the IAM range

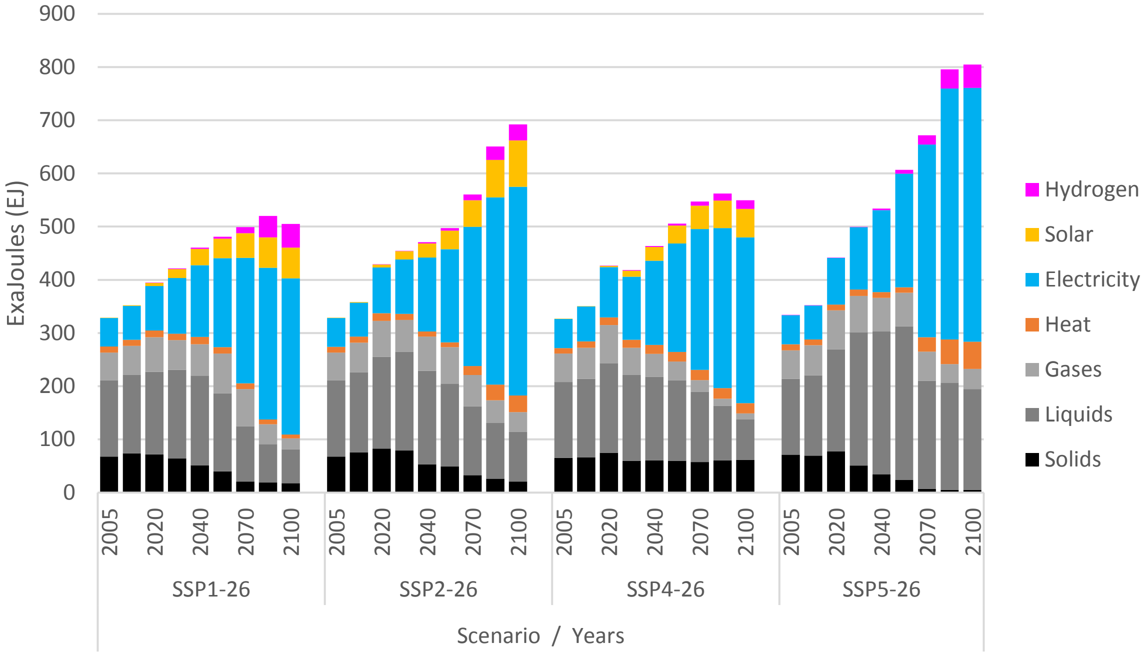

Figure 2.4 Final Energy Consumption across each SSP low temperature scenario for the median of IAM range

SSP1, 2 and 4 show (Figure 2.4) declining fossil fuel requirement in climate stabilisation scenarios from 2020 onwards, with increasing requirement for carbon capture and storage 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.

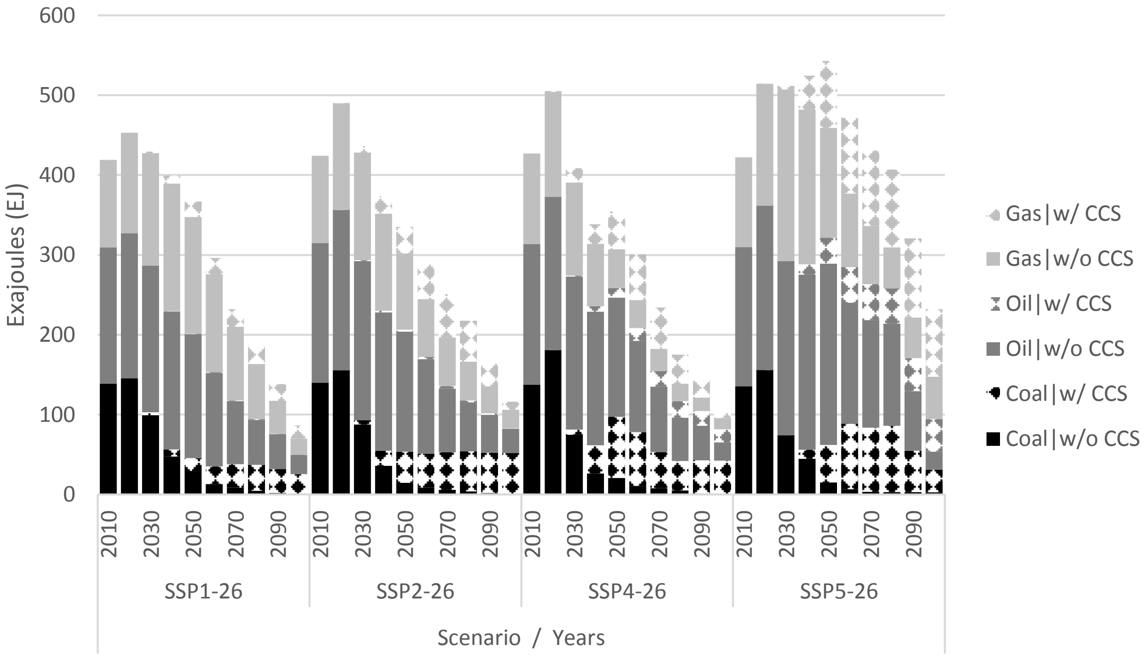

Figure 2.5 Fossil primary energy supply across each SSP low temperature scenario for the median of the IAM range

The use of 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 CO_2 from the atmosphere, but still require sequestration storage space and infrastructure under the various SSP narratives and geological surveys. The availability of bioenergy supply, the availability of geological storage, the build rate of infrastructure to utilise geological storage, and the feasible annual injection rates into geological storage all constrain the maximum potential of CDR from BECCS within a range of uncertainty.

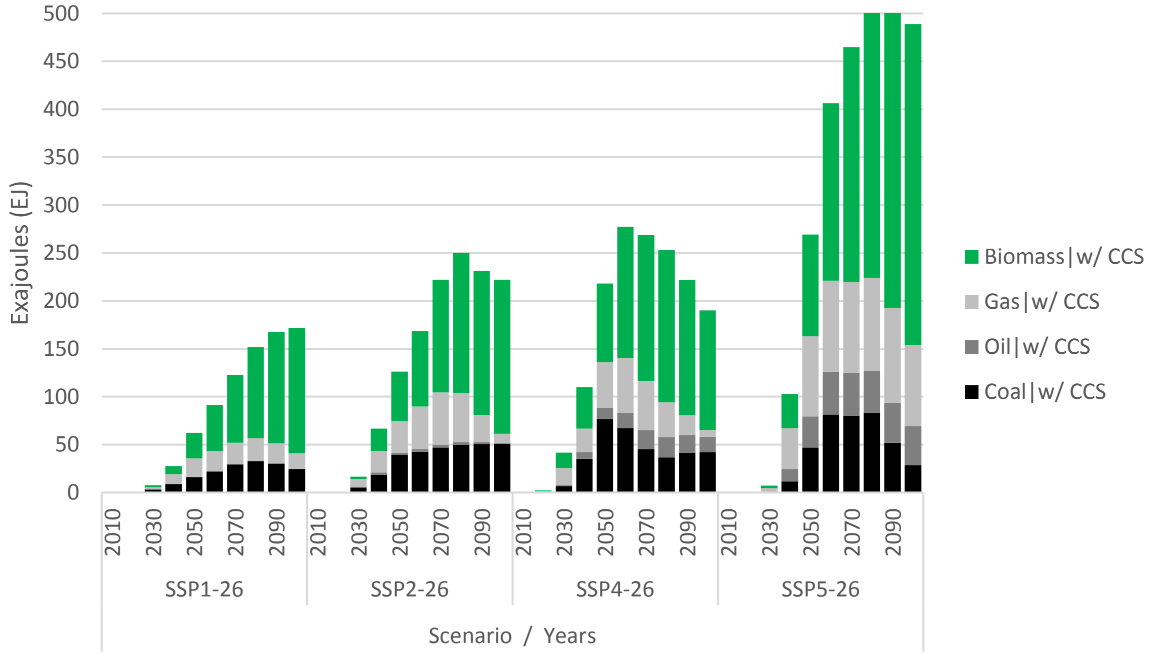

Figure 2.6 CCS in Climate Scenarios - Primary Energy Supply with (w/) CCS for Shared Socio-economic Pathways (1-5) using median values from the set of influential IAMs

The 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 as a function of land availability, water supply, food security, and bioenergy services, 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. There is a range in primary energy supply share by fuel type by each model shown below in Figure 2.8 and Figure 2.9.

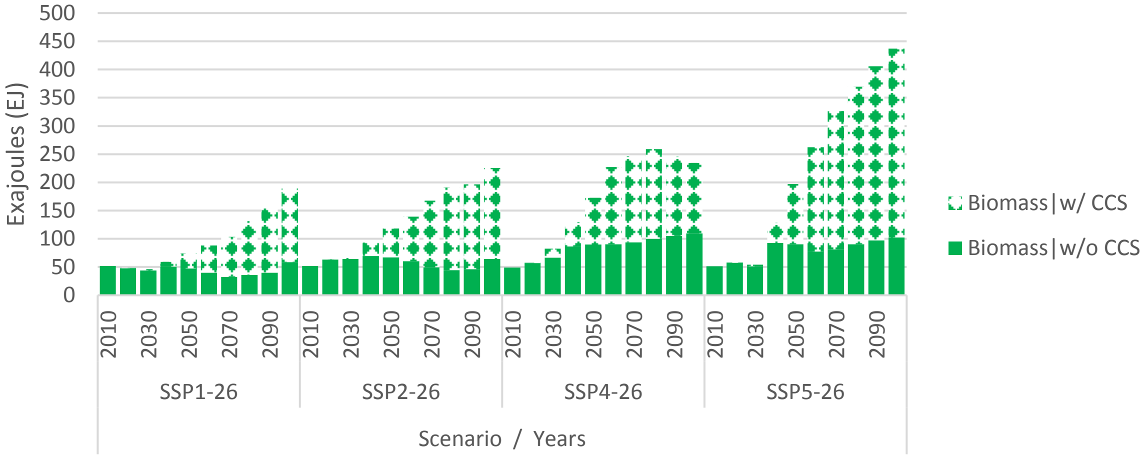

Figure 2.7 Primary Energy Supply of Bioenergy Supply with and without CCS across each SSP low temperature scenario for the median of IAM range

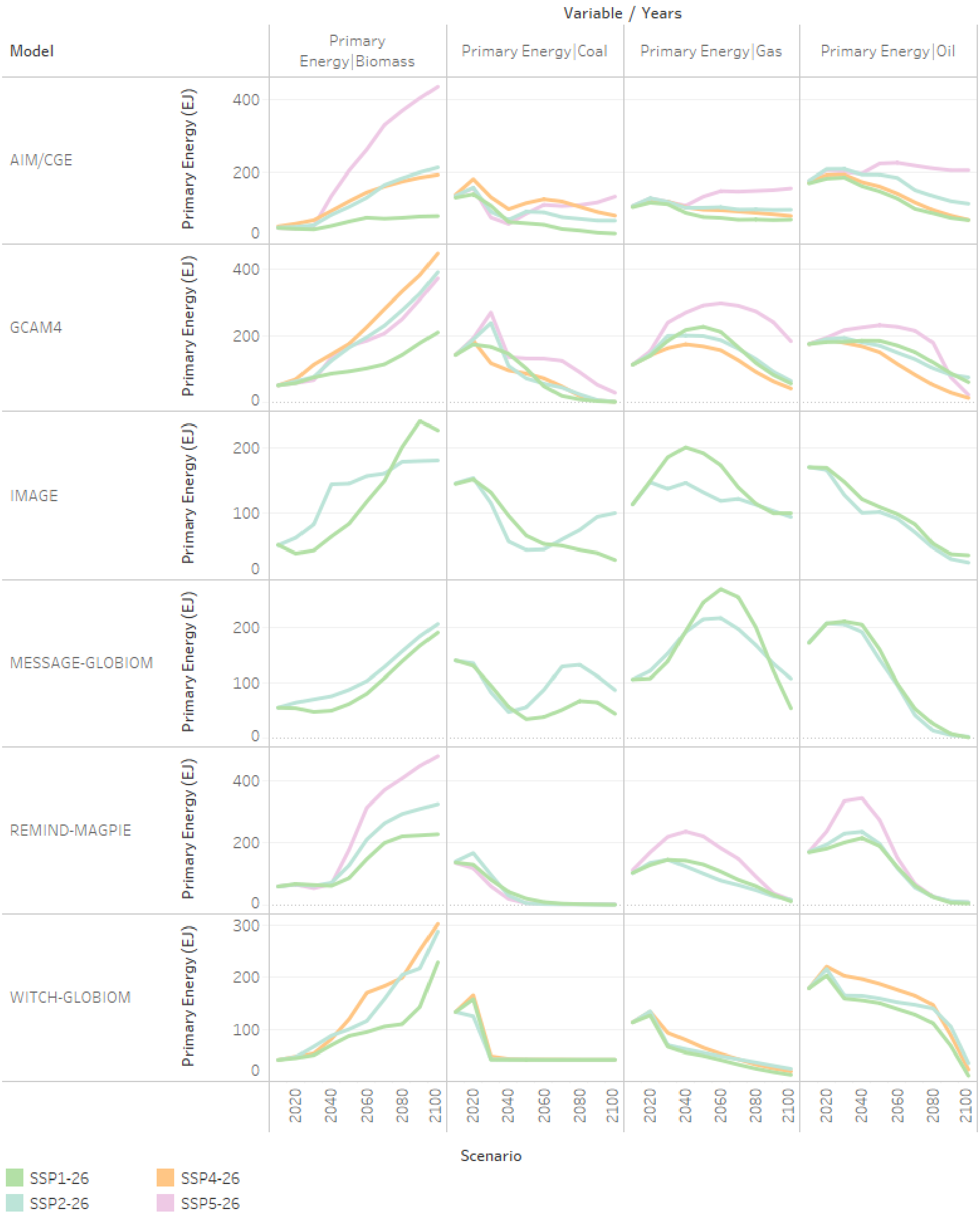

Figure 2.8 Range in Primary Energy Requirement (EJ) for Fossil energy and Bioenergy across the 6 influential IAMs for SSPx-2.6 low temperature stabilisation scenarios

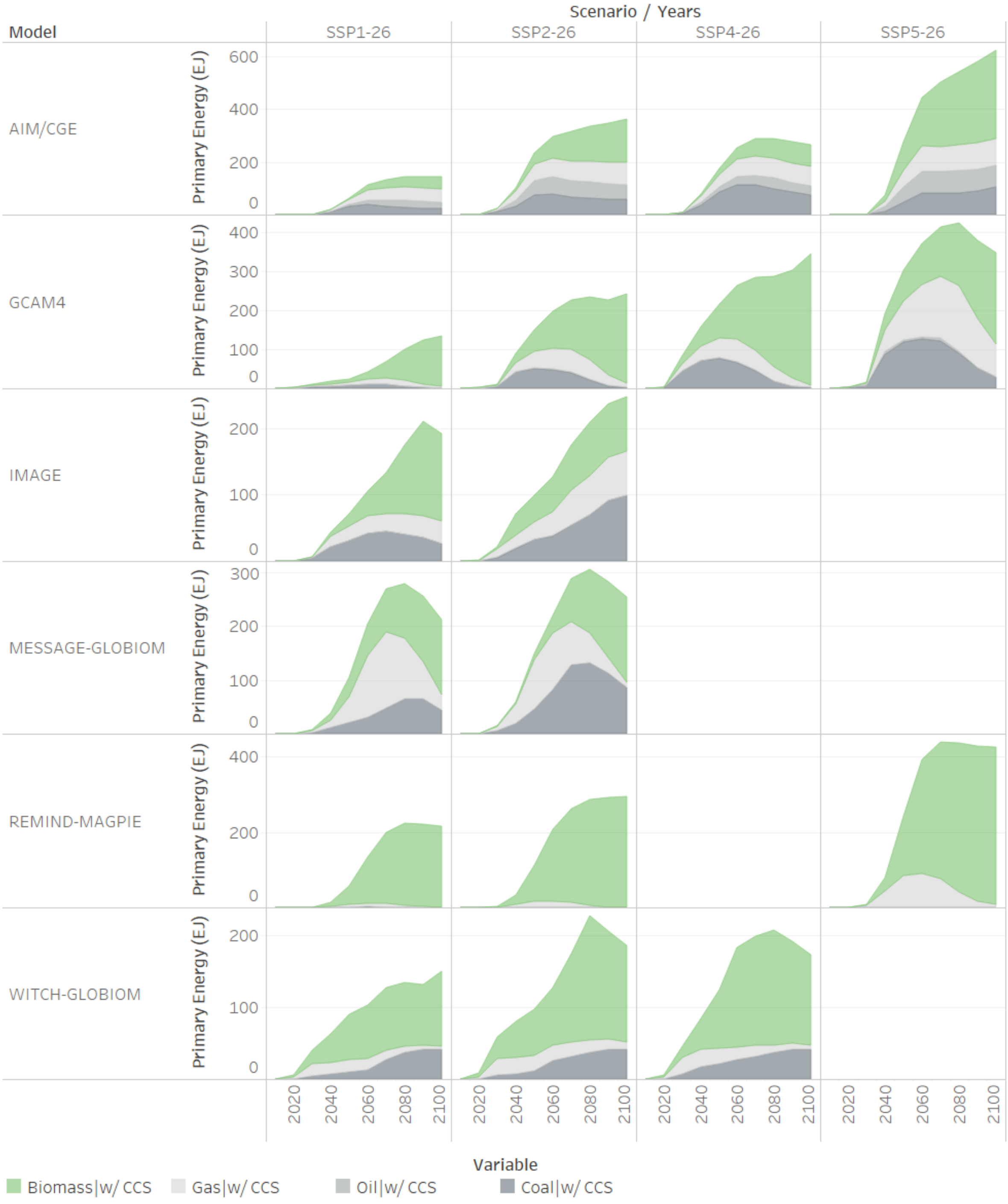

Figure 2.9 Range in Primary Energy Requirement (EJ) with CCS for Coal, Oil, Gas and Bioenergy across the 6 influential IAMs for SSPx-2.6 low temperature stabilisation scenarios

The emergent properties of each IAM's carbon intensity of primary energy, fossil primary energy and primary energy with CCS for each SSP scenario from a baseline scenario of global mean temperature warming of ~4°C reducing to SSPx-RCP2.6 with less than 2°C warming is illustrated in Figure 2.10. As the SSP scenarios approach the 2°C threshold the role of fossil primary energy rapidly reduces and is coupled with CCS and the role of BECCS rapidly increases. Again, note that, across all the SSPx-RCP2.6 scenarios, the carbon intensity of primary energy goes to zero to stabilise temperatures and then reduces further into negative carbon intensities reducing warming towards the end of the century.

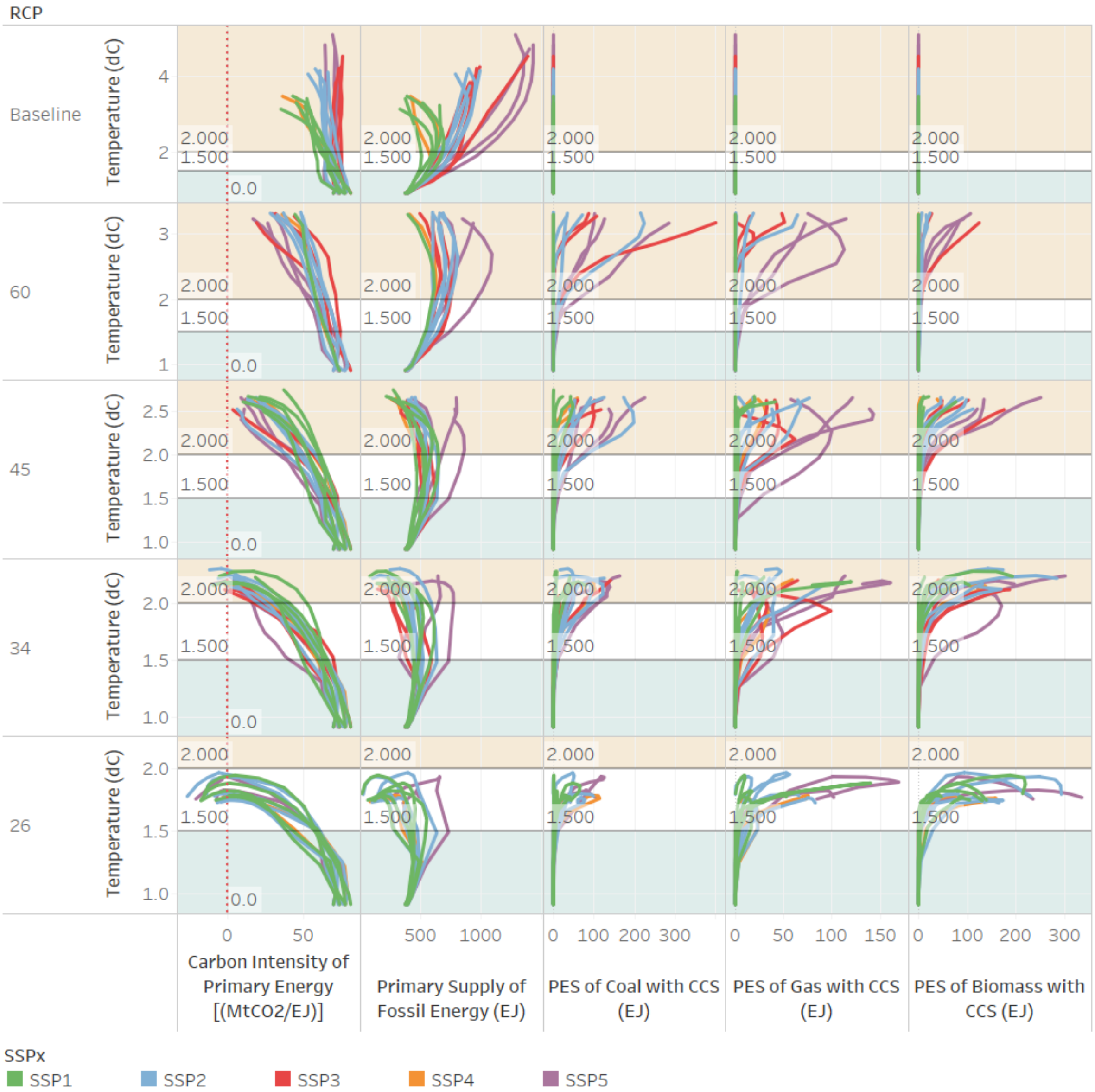

Figure 2.10 Primary Energy Supply Metrics as a function of temperature targets and coloured by SSP narrative: Carbon Intensity of Primary Energy Supply go to net zero in all temperature stabilisation scenarios. Primary Supply of Fossil Energy. Primary Supply of Coal, Gas and Biomass with CCS.

The calculated cost of carbon dioxide, or the marginal abatement cost of carbon to achieve the temperature stabilisation targets in the SSP scenarios are outlined below in Figure 2.11.

Each of the IAMs have a global carbon price across the SSP scenarios and temperature targets solved. The cost of carbon increases by an order of magnitude over the century ranging in the order of \$15-\$20 per tCO_2 in 2020 and rising to between \$140-\$7,099 per tCO_2 in 2100 for SSP1-2.6, the sustainable future, to between \$749-\$8321 per tCO_2 in SSP2-2.6 the middle of the road SSP. The IAM WITCH tends to be an outlier with regard to carbon prices, whereas the carbon prices for the remaining set of IAMs excluding WITCH, cluster across scenarios.

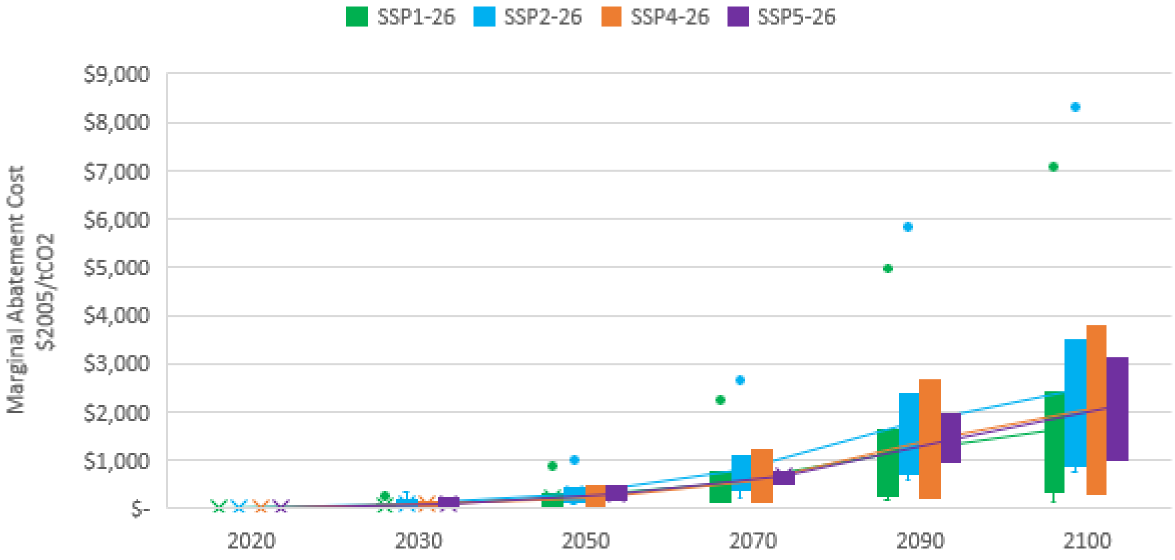

Figure 2.11 Carbon price range and mean for each SSP scenario across the selected influential IAMs

Given that the cost of CO_2 captured from CCS technologies[70] is an order of magnitude smaller than the marginal abatement cost of CO_2 from each of the IAM scenarios, therefore it is not cost input assumptions for those specific CCS technologies that are limiting the deployment of CCS within the scenarios, but more likely to be other technical parameters. Emergent penetration rates of CCS may be limited due to a number of constraints from social acceptability of CCS, social acceptability of fossil fuels, assumed maximum feasible rates of infrastructure construction growth, the availability of geological storage, maximum feasible rates of CO_2 sequestration, the availability of low carbon bioenergy feedstocks, maximum CO_2 capture rates in CCS plants, capacity factors (running time) of CCS plants, residual CO_2

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[70] Rubin, Davison, and Herzog, 'The Cost of CO2 Capture and Storage'.

emissions depleting the remaining carbon budget, and limited low carbon technology options for some energy service demands in industry and transport sectors.

2.3 OVERVIEW OF CCS IN INFLUENTIAL IAMS 2°C-1.5°C SCENARIOS.

The updated published SSP database recently added scenarios for well below 2°C, after the review period for this study. These scenarios are referred to as SSPx-1.9 in the scientific literature. Recent publications usefully outline the variation of CCS deployment in terms of Billion tonnes of carbon captured ($GtCO_2$), rather than in terms of primary energy deployed with CCS[71]. Focusing on Luderer et al (2018) with data reproduced below, they find *that minimising residual fossil fuel CO_2 needs to be a central policy priority* and that *residual fossil fuel CO_2 abatement is crucially limited by system inertia in all sectors and the extent to which end uses in industry and transport can substitute fossil based fuels.* In their analysis Luderer et al explore three carbon budget scenarios with the same set of influential IAMs plus another, POLES. They use threshold return carbon budgets (to peak and return to a specific temperature by 2100) of 200 $GtCO_2$ (B200) between 2016 and 2100 to represent a greater than 67% chance of returning below 1.5°C by 2100, 800 $GtCO_2$ (B800) for 67% chance to remaining below 2°C, and 1400$GtCO_2$ (B1400) for a 50% chance of remaining below 2°C.

Luderer et al find that fossil CCS deployment is higher in scenarios with lower probability of achieving the 2°C temperature limit, and that in the 1.5°C scenarios fossil CCS is limited to a mean value of 5 $GtCO_2$ per year as a result of the lack of space in the strict carbon budget for the residual emissions for fossil fuels even with CCS (note there is generally a 90% upper capture rate on CCS technology assumptions in IAMs). Bioenergy CCS is deployed earlier and more rapidly for Paris consistent 1.5°C scenarios to mean CO_2 levels of 14$GtCO_2$ per year by 2080 and plateauing thereafter (See Figure 2.12 & Figure 2.13). The total volume of CO_2 capture in 2100 across these scenarios ranges from 15$GtCO_2$ to 40$GtCO_2$ similar in scale

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[71] Rogelj et al., 'Scenarios towards Limiting Global Mean Temperature Increase below 1.5 °C'; Kriegler et al., 'Pathways Limiting Warming to 1.5°C'; Luderer et al., 'Residual Fossil CO 2 Emissions in 1.5–2 °C Pathways'.

to total current fossil fuel and industry emissions are of 36.8GtCO$_2$ ± 2GtCO$_2$ estimated for 2017[72].

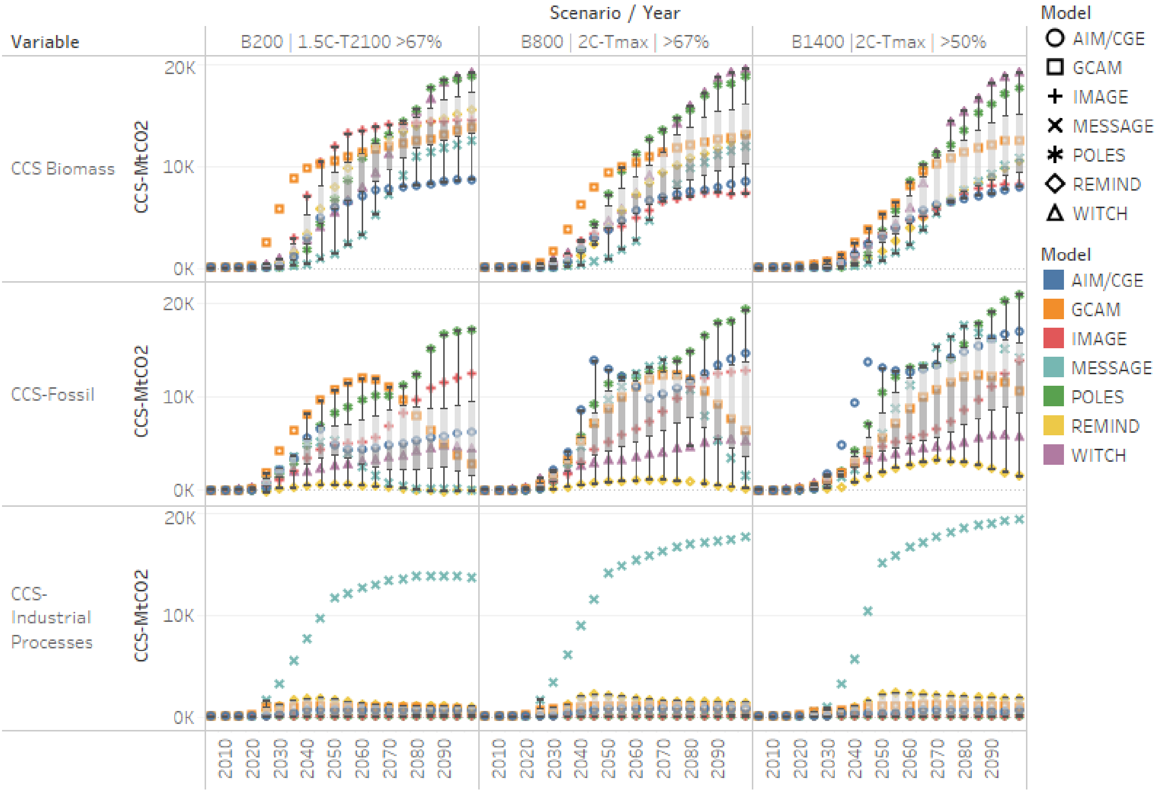

Figure 2.12. CCS CO$_2$ Capture by fuel type (BECCS, Fossil CCS or CCS in Industrial processes) and by carbon budget

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[72] Quéré et al., 'Global Carbon Budget 2017'.

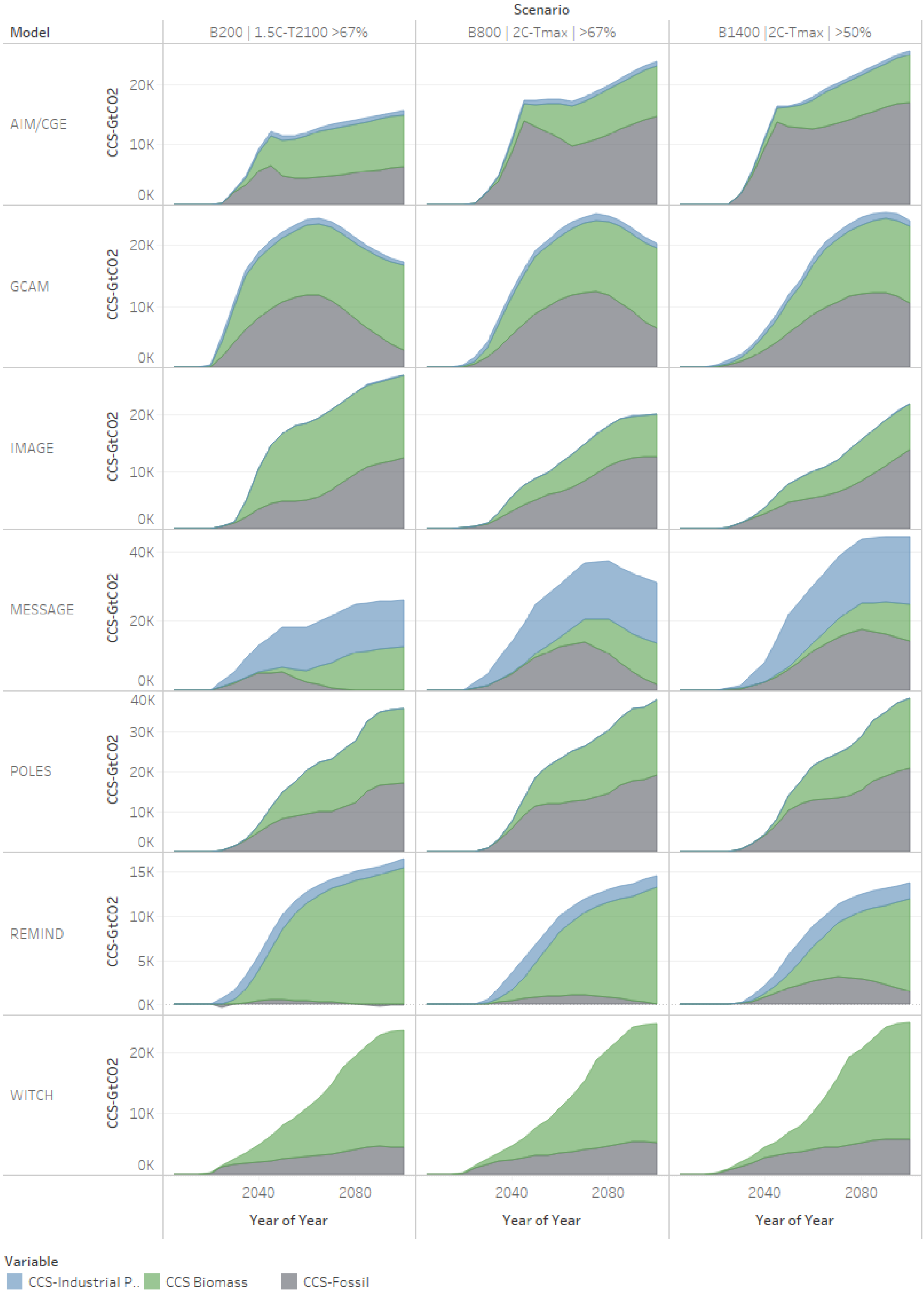

Figure 2.13. CCS Capture by BECCS, Fossil Fuel CCS and CCS in Industrial Processes by model by carbon budget

2.4 OVERVIEW OF CCS IN IEA-ETP CLIMATE SCENARIOS

The scenarios published in the most recent International Energy Agency's Energy Technology Perspectives have a chapter focusing on the role of CCS in temperature stabilisation[73], by exploring scenario pathways for a 2°C temperature stabilisation (2DS) and increasing the mitigation ambition to a below 2°C scenario (B2DS), towards that of the Paris Agreement goals. The primary energy supply mix across the IEA-ETP scenarios are consistent with the SSP2-2.6 scenarios (See Figure 2.14) with the most obvious difference being the increased role of nuclear energy and other renewables for electrification, in comparison the SSP IAMs have reduced energy demand and less renewables or nuclear for primary energy supply.

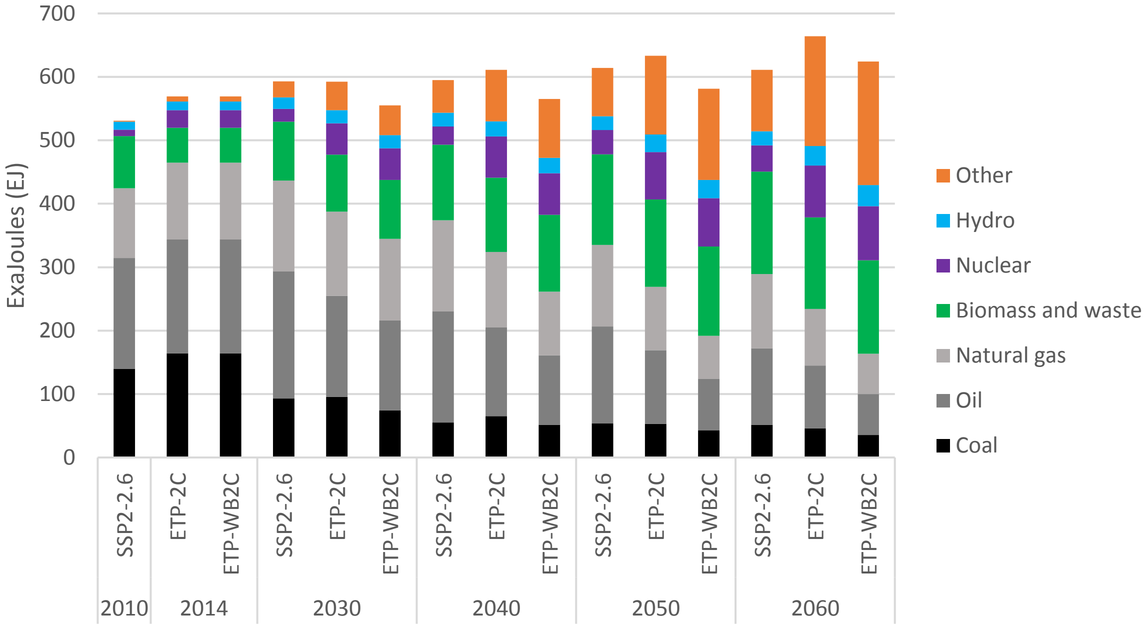

Figure 2.14 Primary Energy Supply across SSP2-2.6 IAM median values and IEA-ETP 2C and IEA-ETPWB2C scenarios

The IEA-ETP clearly outline growing role for CCS in the energy system, and more specifically in industry and upstream sectors to mitigate residual emissions in industry and transport (See Figure 2.15).

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[73] IEA, *Energy Technology Perspectives 2017*.

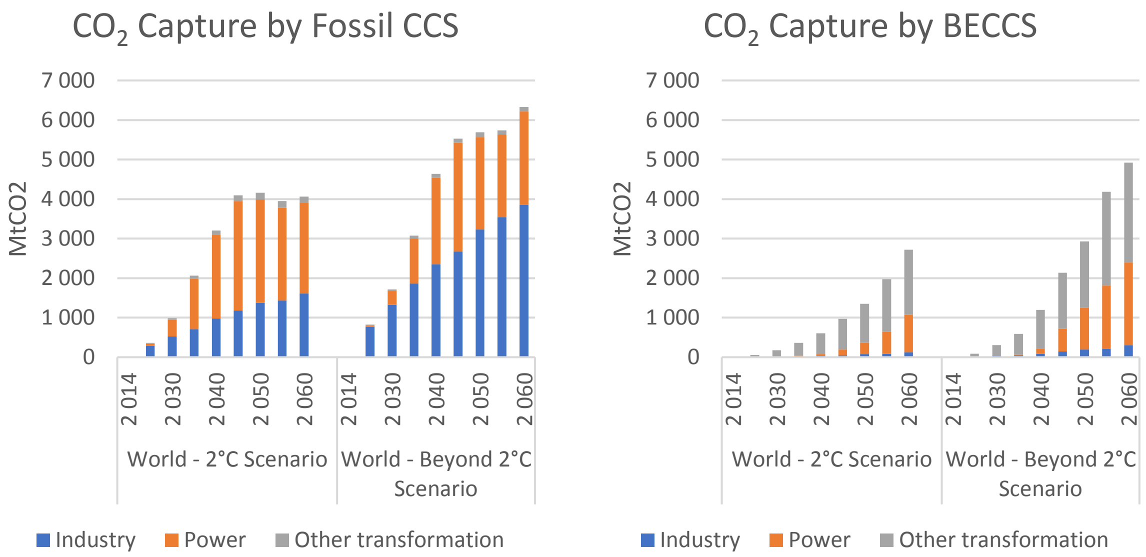

Figure 2.15 The role of CCS in IEA-ETP scenarios for 2°C and well below 2°C showing CO_2 capture by Fuel and by Sector. Other transformation includes upstream refining of low carbon liquid and gaseous fuels.

3 RECOGNISING INTEGRATED SYSTEMS CONSTRAINTS RESULTING FROM INPUT DATA ASSUMPTIONS IN IAMS

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, Indirect and emergent properties due to the Responsiveness of an IAM:

1. **Direct input** assumptions directly used to calibrate the representation of a CCS technology in an IAM, which could include CCS capex, fixed & variable opex, efficiency, CO_2 capture rates, capacity factor, learning rates (reduction in cost for a doubling of installed capacity) build rates, social acceptability, geological storage, injection rate limits, and efficiency.
2. **Indirect input** assumptions are those that calibrate other functions and technologies of an IAM and that interact with the energy service that CCS provides in an IAMs energy system. These indirect input assumptions can include carbon budgets, fossil fuel cost curves, resource potentials, technology options, residual emissions, the relative costs of competition technologies providing the same energy services, and various emergent systematic interactions.
3. **Responsiveness** to climate policy is an emergent property of an IAM dependent upon its mathematical method, its treatment of foresight, and the approach to discounting of costs. An IAM is characterised by its responsiveness to a carbon price, by the time-period the model chooses to mitigate (early or late), and how quickly the IAM can change the rate of net CO_2 emissions.

3.1 DIRECT INPUT ASSUMPTIONS

The data required to develop a specification for the representation of a particular CCS technology varies across each IAM dependent upon whether they are top down type IAMs or bottom up process engineering type models. Furthermore, the level of detail and dynamics of a CCS technology is also dependent upon the sub annual time resolution, if any, in each of the IAMs. For example, an IAMs ability to endogenously calculate the capacity factor from merit order dispatch of a power plant with CCS (wCCS), or whether or not the capacity factor is exogenously assumed, will have a considerable impact upon the flexibility to reduce residual emissions from CCS plant if both the capacity factor and the capture rates are exogenously fixed without intertemporal dynamics or technology learning[74] and improvement of costs, capture rates and efficiency over time.

3.1.1 INVESTMENT COSTS

The bottom up IAMs typically specify CCS on terms of investment costs per installed capacity both retrofit or new green field sites, while the top down IAMs specify CCS costs in terms of an additional CCS service cost per tonne of CO_2 captured. The investment costs outlined in Figure 3.1 highlight the range of CCS capture costs by fuel type and technology type across power generation and upstream liquid fuel transformation sectors. These costs are inflated to 2015 US dollars per kW using the IHS CERA Power Capital Costs Index[75]. The MESSAGE team have investment cost variation by region by SSP & by CCS technology. Data in the chart below is CCS initial costs for North America in SSP2. Where model data is missing, either the data was not found in published literature and databases or the model does not use this parameter in its input assumptions.

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[74] Riahi et al., 'Technological Learning for Carbon Capture and Sequestration Technologies'.

[75] Rubin, Davison, and Herzog, 'The Cost of CO2 Capture and Storage'.

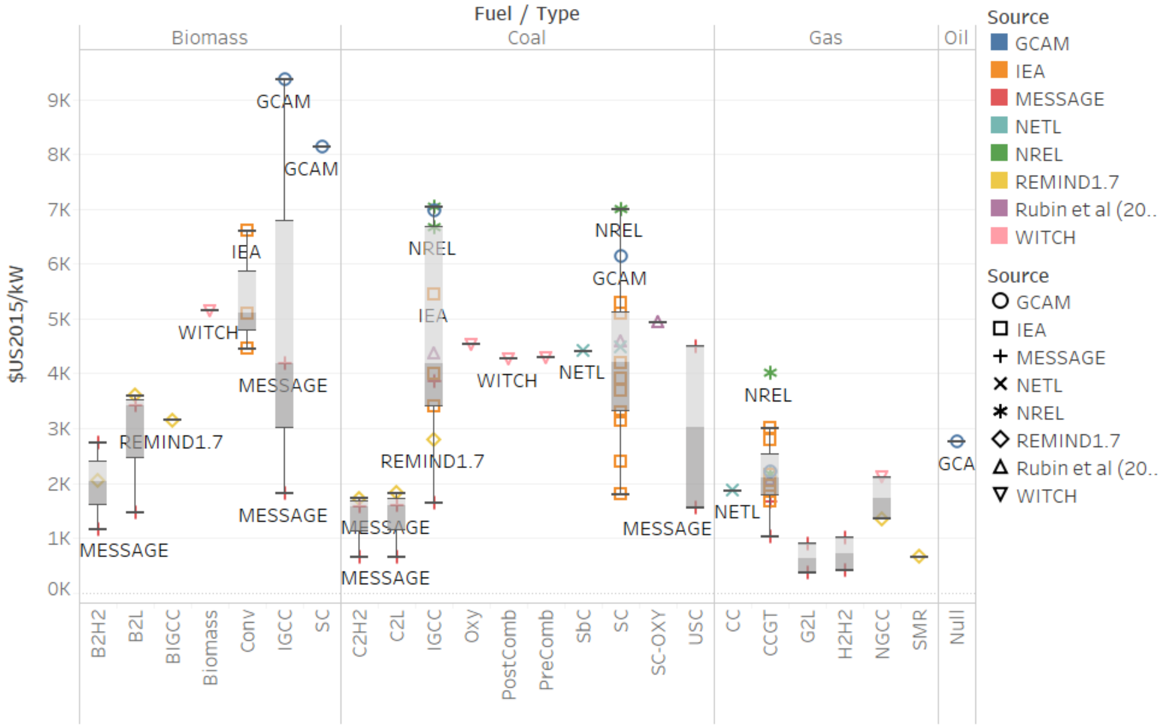

Figure 3.1 New investment capital per KW rate capacity for CCS technologies across Power Generation and Upstream transformation of low carbon liquid fuels.

3.1.2 CAPTURE RATES

Capture rates of CCS plants in IAMs typically are in the range of 85%-90% for power generation applications. Industrial CCS applications and upstream transformation of liquid fuels typically have lower capture rates in the order of 50-60% assumed flat across the time horizon. In the case of liquid fuel transformation, there is still carbon remaining in the liquid fuels which can be emitted later when these fuels are consumed; thus it is not possible to capture all the carbon during the transformation process of a liquid fuel. Notable exceptions to the flat capture rate assumption is GCAM which assumes an improvement in capture rates from 85% initially in the base year up to 95% by 2100, and WITCH utilising Rubin et al's review[76] for calibration have Coal Oxy combustion CCS and Coal IGCC CCS with capture rates

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[76] Rubin, Davison, and Herzog.

of 95% and 96%. IEA-ETP have capture rates of up to 94% in specific Iron and steel production technologies. Further to this point, note that GCAM tends to have the deepest negative emissions profile of all IAMs in the SSP database.

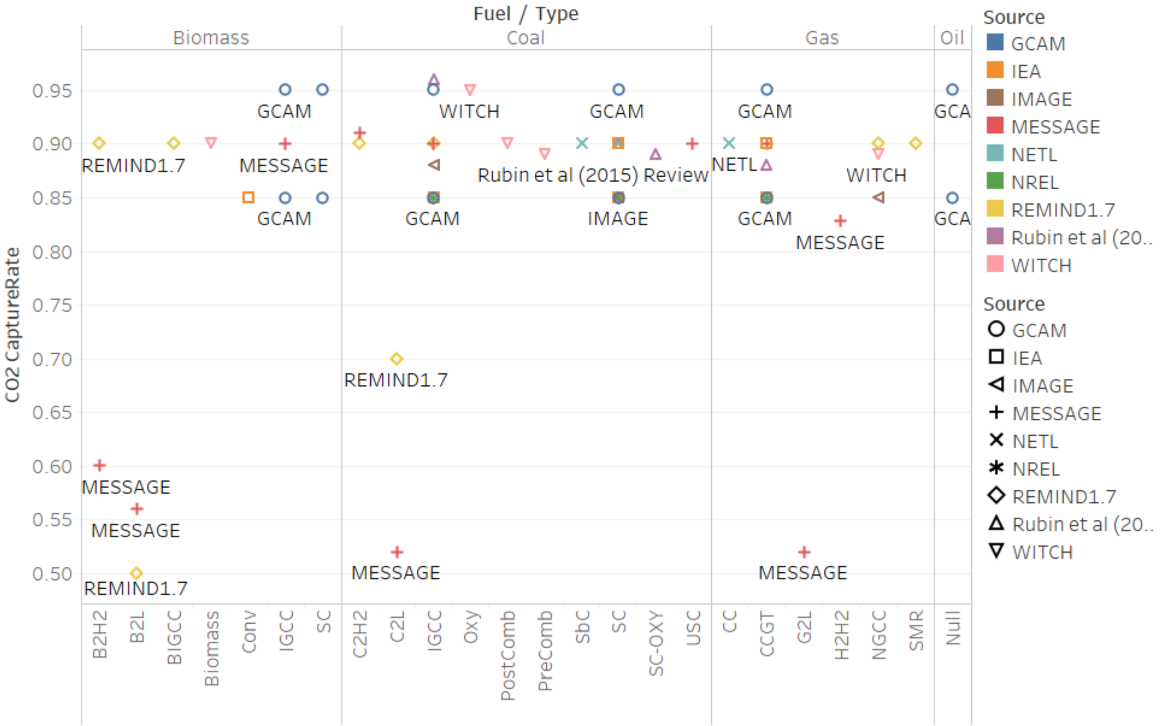

Figure 3.2 CCS CO_2 Capture rates for a range of CCS technologies represented in IAMs. Where models/data are missing, data could not be found in available literature.

3.1.3 CAPACITY FACTORS OF CCS PLANTS

While few of the IAMs have sub annual time slice resolution, most of the influential IAMs do not have sub annual time resolution and thus need to exogenously calibrate the capacity factor or the percentage time a CCS plant runs at rated capacity in their models. Typically, the capacity factors range from 75% to 95%. IAMs have recently aimed to improve temporal dynamics and variability of electricity dispatch using load duration curves for variable renewable generation[77], which could be expanded to CCS representation.

The emergent outcome of fossil fuel electricity generation plant with CCS that are calibrated with fixed capacity factors and an upper capture rate limit of 90%, is that residual

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[77] Pietzcker et al., ‘System Integration of Wind and Solar Power in Integrated Assessment Models’.

fossil CO_2 emissions become incompatible with the remaining carbon budget. Fixed and high capacity factors assumed for CCS conflict with high penetration rates of variable renewable generation, and don't value ancillary services from dispatchable grid balancing lower carbon power from CCS plants. In real world plant there is some operational flexibility with minimum economic capacity factors, as well as potentially higher capture rates for specific carbon capture and storage applications[78].

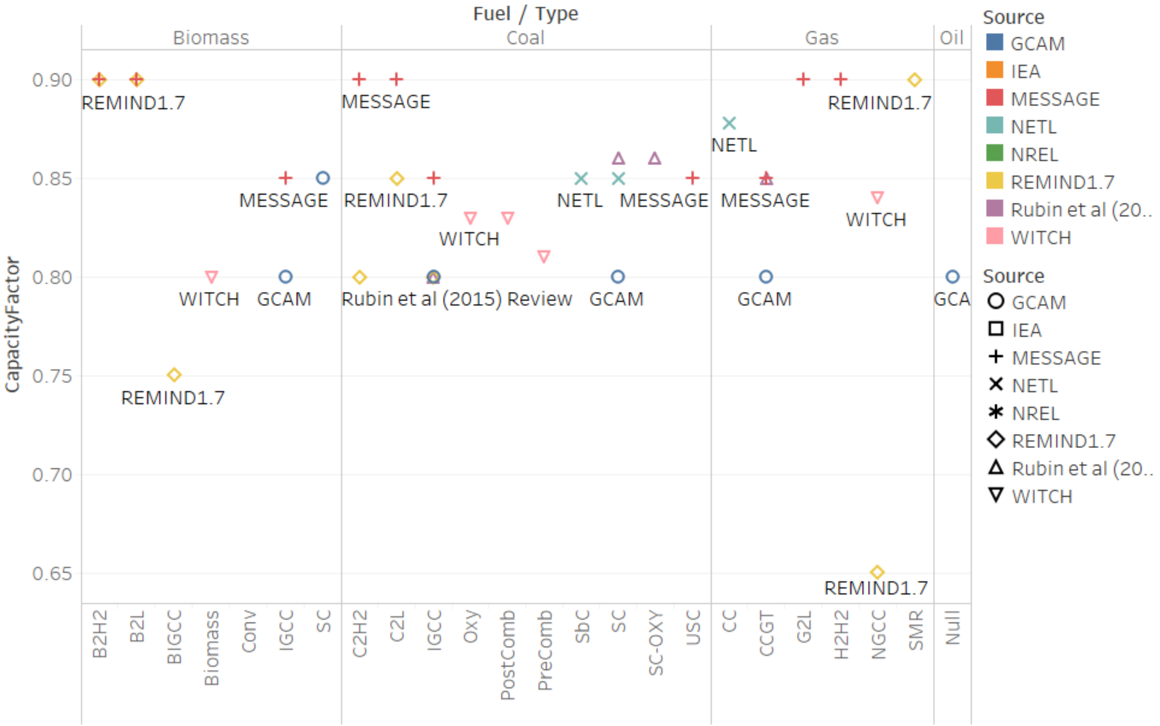

Figure 3.3 Capacity factors for CCS technologies represented in IAMs

3.1.4 LEARNING AND SOCIAL ACCEPTABILITY

Within the SSP narratives there are direct input assumptions on the maximum deployment rates of CCS as a function of both the technological learning rate consistent with the overall narrative of the individual SSP, and the social acceptability of fossil fuel CCS both an upper limit to the volume of CO_2 sequestration and a limit on acceptable rate of growth of

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[78] Energy technologies Institute and Foster Wheeler, 'Benchmarking and Performance Analysis of Future CO2 Capture Technologies – Benchmarking Study'; David Hawkins and George Peridas, 'Kemper County IGCC: Death Knell for Carbon Capture? NOT.'

that CO_2 sequestration. These limits vary across each of the modelling teams implementing the SSPs. SSP1 has low technology development for Fossil CCS and high technology development for Bioenergy CCS, which is implemented as cost reductions ranging from 0% in the case of Fossil CCS to 50% in the case of bioenergy CCS. SSP2 has medium learning cost reductions of 10-40% and SSP3 has low cost reductions of 10-27% for all CCS technologies. There is low social acceptance for CCS in SSP1 and high social acceptance for CCS in SSP5.

3.1.5 *OTHER CONSTRAINTS ON CCS DEPLOYMENT*

There are a range of other direct input assumptions to CCS specification across the range of IAMs, remembering again that the bottom up process based IAMs tend to have the more detailed representation at an engineering level, simulation system dynamics IAMs have less engineering detail, and top down CGE IAMs have even less technical detail.

Direct constraints explored in previous studies[79] & IEAGHG reports[80], but that do not appear to dominate CCS dynamics in IAMs include;

- Learning Floor CAPEX costs
- Diversity of CCS technology options across sectors
- Efficiency of CCS plants
- Available storage volumes
- Maximum Storage rates
- Storage cost by formation type
- Transport costs

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[79] Koelbl et al., ‘Uncertainty in Carbon Capture and Storage (CCS) Deployment Projections’; Koelbl et al., ‘Uncertainty in the Deployment of Carbon Capture and Storage (CCS)’.

[80] Budini et al., ‘Can CO2 Capture and Storage Unlock Unburnable Carbon’; Budinis et al., ‘An Assessment of CCS Costs, Barriers and Potential’.

3.2 INDIRECT INPUT ASSUMPTIONS EFFECTS ON CCS DEPLOYMENT – FOCUS ON SSP NARRATIVE CONSTRAINTS ON DEMAND, TECHNOLOGY PROGRESS AND SUPPLY [81]

Indirect input assumptions are quantitative calibration parameters in integrated assessment models that do not explicitly constrain the development of a process or technology, however, through systematic interdependencies within the energy system, socio-technical representation of the economy, and climate, indirect input assumptions can represent hard constraints on the deployment of a particular mitigation technology such as CCS. This fundamentally is the purpose of **Integrated** Assessment Models to expose and provide insights from the interactions between energy-economic-environment systems.

The shared socioeconomic pathway qualitative narratives have been quantitatively implemented across the 6 IAM teams published in a special issue[82]. The SSP narrative parameters that have the most prominent indirect impacts on CCS development are outlined below.

3.2.1 POPULATION AND ECONOMIC GROWTH AND URBANISATION

At the most fundamental level, population projections and sectoral economic growth drives demand for final energy services and the primary energy transformed in the provision of energy services (heating, transport, electricity etc.) The SSP narratives have a considerable variation across population growth ranging from 12 billion to less than 7 billion people by 2100. Economic growth ranges from 4 to 20 times current GDP by 2100. Primary energy supply/demand is a fundamental component of the engine of economic growth (Figure 3.4).

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[81] Bauer et al., 'Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives'.

[82] Kriegler et al., 'Fossil-Fueled Development (SSP5)'; Bauer et al., 'Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives'; Riahi et al., 'The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications'; Fujimori et al., 'SSP3'; van Vuuren et al., 'Energy, Land-Use and Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm'; Fricko et al., 'The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century'; Calvin et al., 'The SSP4', 2.

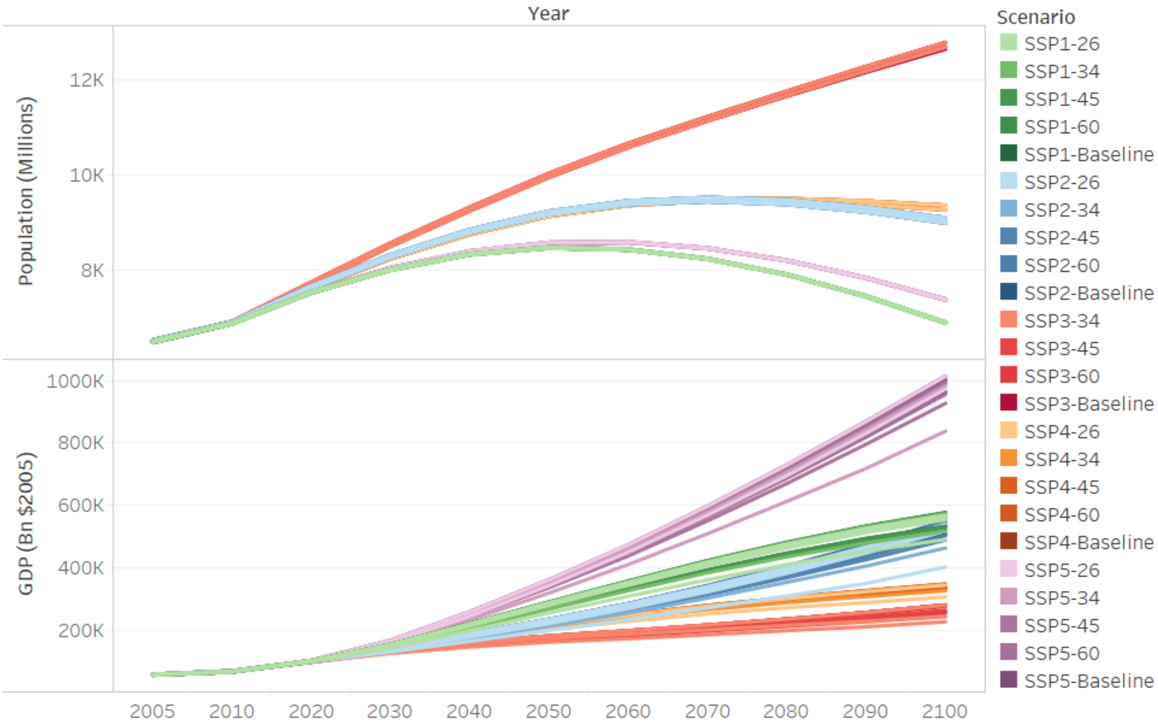

Figure 3.4 Global Population and Global GDP across the range of Shared Socioeconomic Pathways

Each of the influential IAMs have differing levels of completeness and complexity in how future energy service demands and end use sectors are represented. Final energy demand is an emergent output of some IAMs and an input driver to others. The conversion between macroeconomic and demographic growth drivers to energy service demands requires a coefficient of energy intensity to calculate future energy demand. These coefficients are based on historical trends and then extrapolated based on the SSP narratives. The range of energy intensity improvements are plotted below in Figure 3.5. SSP1, the sustainable future, has the most rapid improvement at 1.7% per year with regional variation of 1.3% to 2.45% per year across developed and developing regions. SSP3, the regionally fragmented world, having the slowest energy intensity improvements of between 0.3% to 0.9% per year [83].

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[83] Fricko et al., 'The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century'; Bauer et al., 'Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives'; van Vuuren et al., 'Energy, Land-Use and Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm'.

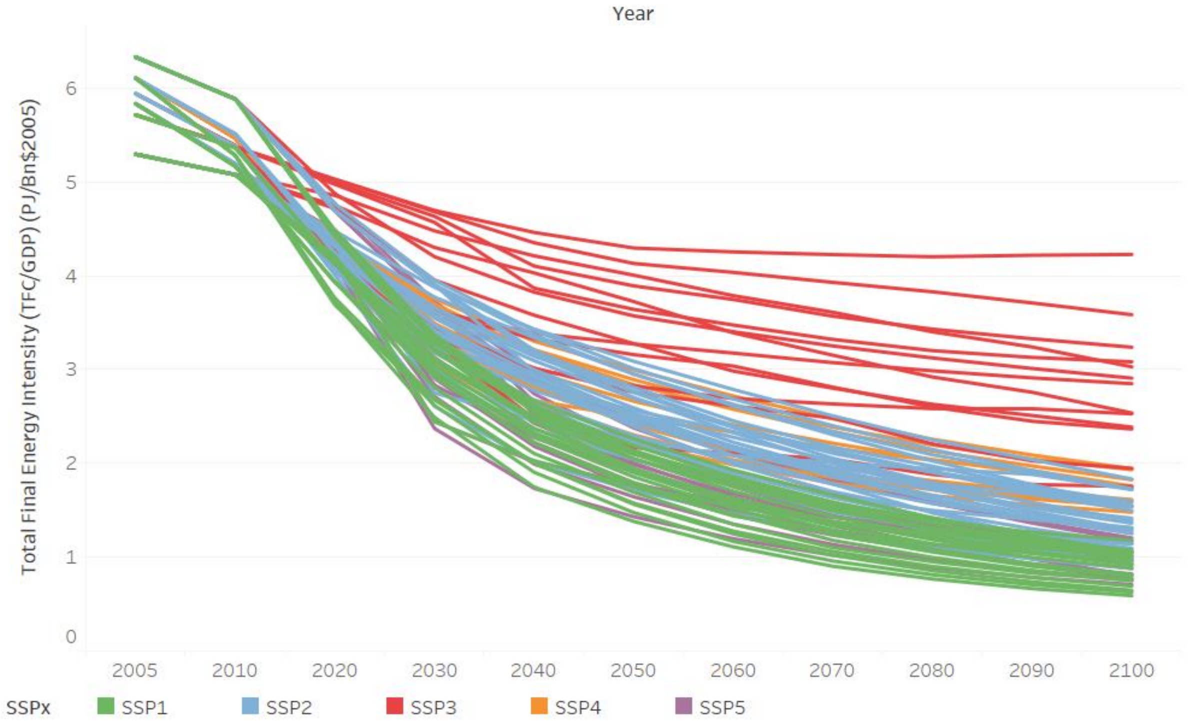

Figure 3.5 Range of global energy Intensity of GDP across the range of Shared Socioeconomic Pathways

3.2.2 CARBON BUDGETS & TEMPERATURE CONSTRAINTS

Climate and emissions-related constraints are important drivers of the evolution of energy systems in scenarios that have a good probability of achieving the long-term temperature goal of the Paris Agreement. Carbon budgets (estimates of the total amount of CO_2 emissions that could be emitted at a global level to have a certain chance of staying within a given level of warming) are conventionally used as proxy climate constraints. Meeting a fixed carbon budget requires net-zero CO_2 emissions to be achieved in order to limit emissions into the atmosphere. As the global temperature increase is currently around 1°C above pre-industrial levels and rising at about 0.17°C/decade, achieving the 1.5°C or 2°C Paris Agreement goals, requires rapid attainment of net-zero emissions or net negative CO_2 emissions to lower global surface temperature by removing carbon from the atmosphere after overshooting a carbon budget[84]. Due the short timescales and the small remaining carbon budgets replacing all sources of fossil carbon sufficiently quickly may not be possible, necessitating the deployment of carbon capture and storage at either concentrated stream of CO_2 associated with large point source emissions, or from the ambient air[85] in order to close the required carbon budget.

It has been well-documented that many IAMs rely heavily on bioenergy with carbon capture and storage in order to close their carbon budget over the remainder of the century, although some new IAM scenarios have dramatically reduced or eliminated their reliance on BECCS through very substantial demand side measures to reduce energy demand in the near-term[86]. As such, substantial levels of CCS deployment are envisaged in most scenarios to provide this source of negative emissions through BECCS. This conclusion is supported by in-depth studies within particular IAMs that indicate that total amount of CO_2 sequestered by fossil CCS and BECCS is correlated with increasing climate ambition[87].

3.2.3 Cost Discounting and Technology Hurdle Rates

Each IAM applies cost discounting over the time horizon of the model as an aggregation of various factors including time preferences of capital for the present over the future, cost of capital and risk aversion. Some of the IAMs have default discount rates as well as technology specific and sector specific discount rates also called hurdle rates. Some IAMs have regional variation of discount rates to include variations on the social time preferences. Discounting significantly reduces the cost of expensive investments in the future, and as a result, in a least cost energy systems IAM, expensive mitigation investments are delayed as long as possible as a function of the discount rate and competition between technologies for

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[84] Steffen et al., 'Trajectories of the Earth System in the Anthropocene'.

[85] Keith et al., 'A Process for Capturing CO2 from the Atmosphere'.

[86] Grubler et al., 'A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies'; Vuuren et al., 'Alternative Pathways to the 1.5 °C Target Reduce the Need for Negative Emission Technologies'.

[87] Vaughan et al., 'Evaluating the Use of Biomass Energy with Carbon Capture and Storage in Low Emission Scenarios'; Luderer et al., 'Residual Fossil CO 2 Emissions in 1.5–2 °C Pathways'.

provision of least cost energy services also driven in part by technology learning rates. Furthermore, there are competition impacts on technologies dependent upon when their costs are incurred throughout their lifetime. Pure capital technologies such as solar photovoltaic (PV) will experience relatively less discounting to competing technologies that have proportionally higher operational costs and fuel costs as a share of the total technology costs throughout their operational lifetime.

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.

Figure 3.6 Discount Factors across the SSP IAMs. Reproduced from Kriegler et al. [88]

A visual example of the effect of using undiscounted constant investment costs verses discounted costs is included below for clarity. Expensive investment costs are delayed until environmental and technical constraints require investment earlier to provide a least cost energy system. Note that WITCH has one of the lowest discount rates but generally the highest marginal abatement cost of CO$_2$.

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[88] Kriegler et al., ‘Diagnostic Indicators for Integrated Assessment Models of Climate Policy’.

	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
UNDISCOUNTED COST	100	100	100	100	100	100	100	100	100
DISCOUNTED @3%/YR	100	73.7	54.4	40.1	29.6	21.8	16.1	11.9	8.74
DISCOUNTED @5%/YR	100	59.9	35.8	21.5	12.9	7.69	4.61	2.76	1.65
DISCOUNTED @8%/YR	100	43.4	18.9	8.2	3.56	1.55	0.67	0.29	0.13

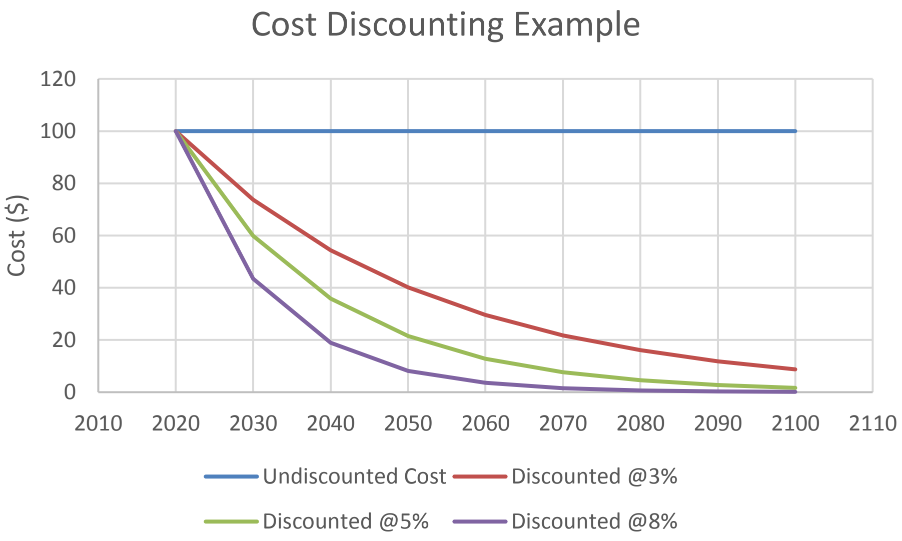

Figure 3.7 Example of cost discounting from a baseline cost of $100 per unit capacity in 2020, highlighting the effect of (investment) cost discounting over long time horizons.

3.2.4 FOSSIL FUEL SUPPLY CURVES

The fossil fuel supply curves which represent the production cost of a given fuel for a given cumulative volume of that fuel are adjusted within the SSP narratives. SSP2 as close to middle of the road projections for reserves, resources and costs of Coal, Oil and Gas, with medium cost assumptions for Coal and high resource availability for Oil and Gas. SSP1 has a high cost assumption for coal and a medium resource availability for other fossil fuels, while SSP3 has low cost assumptions for Coal and low resource availability of other fossil fuels. These trends are plotted below (Figure 3.8) for the REMIND model.

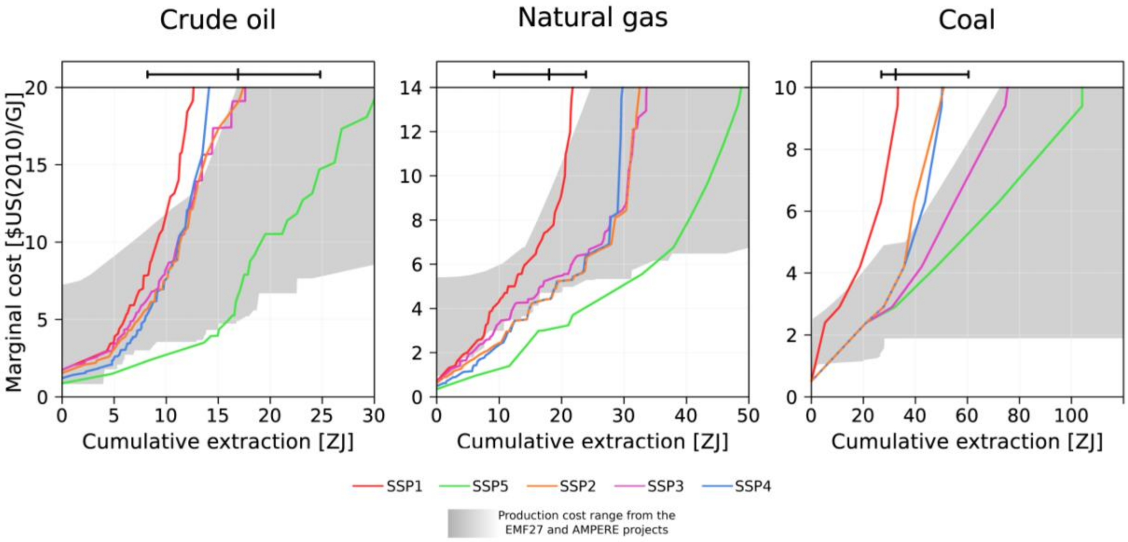

Figure 3.8 Fossil fuel production cost curves based on the SSP narratives. Reproduced from REMIND documentation[89] from PIK.

Following from fossil fuel supply curves, there are low technological learning rates for the extraction technologies of conventional and unconventional fossil fuel resources in SSP1, medium learning rates in SSP2 and a high learning rate for Coal and medium learning rate for production of other fossil fuels in SSP3.

3.2.5 *BIOENERGY SUPPLY CURVES*

Figure 3.9 outlines the global biomass supply potential and costs for SSP1, SSP2 and SSP3 in the IIASA IAM framework MESSAGE-GLOBIOM. Contrasting to current commercial biomass use of the order of 25EJ annually, future biomass potential ranges up to 80EJ per year by 2050 for less than 3$/GJ, which is a similar price to current coal production. The next 100 EJ estimated on the supply curve is significantly more expensive and ranges from 3-8$/GJ biomass supply. Maximum biomass potential in MESSAGE-GLOBIOM in 2050 is estimated at

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[89] REMIND 6 documentation - https://www.pik-potsdam.de/research/sustainable-solutions/models/remind/remind16_description_2015_11_30_final

less than 250EJ at a marginal cost of $13.5/GJ for the last tranche of biomass potential. The other IAMs have a variety of endogenous biomass supply land use models and exogenous biomass supply curves. Greater detail is available for each individual model in the new IAMC documentation website [90].

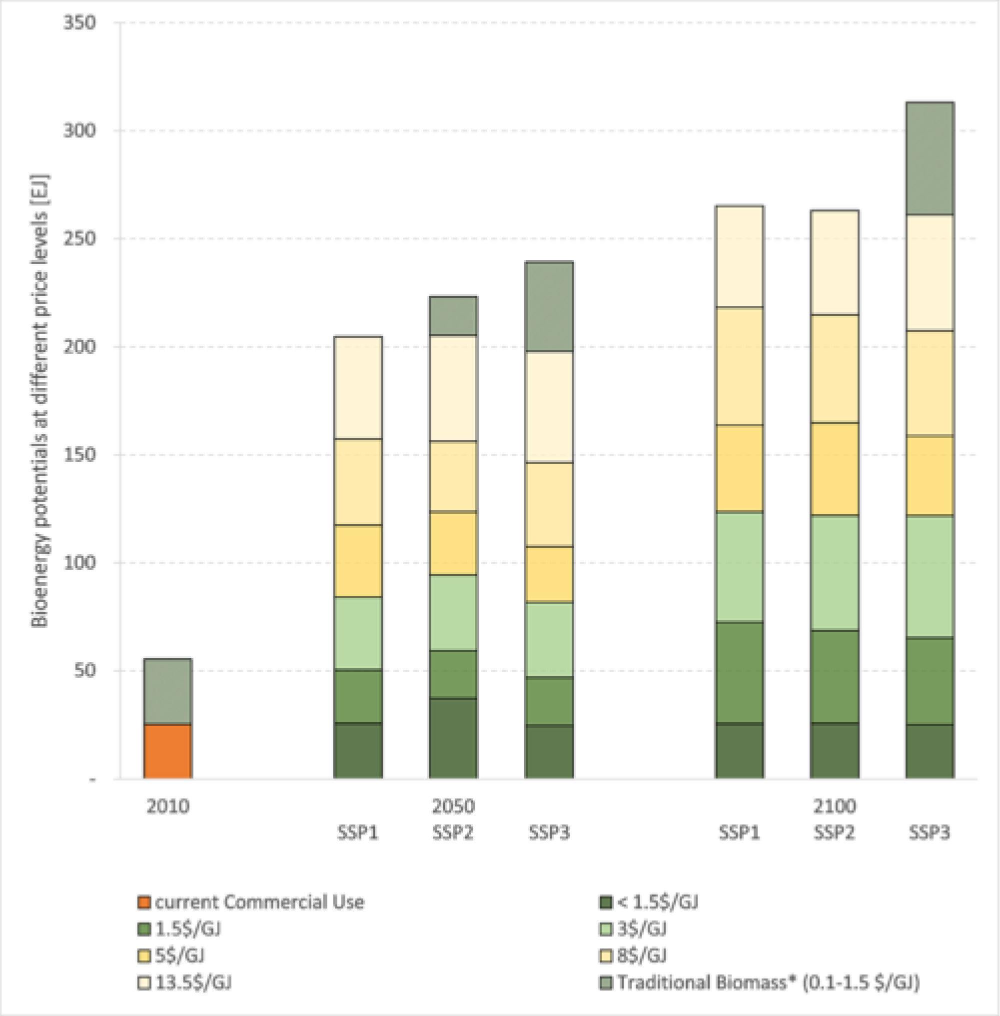

Figure 3.9 Availability of bioenergy at different price levels in the IIASA IAM framework for SSP1,2 and 3. Reproduced from Fricko et al (2017) [91]. Typically non-commercial biomass is not traded or sold, however in some cases there is a market -price range from 0.1-1.5$/GJ ($ equals 2005 USD)

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[90] The common Integrated Assessment Model (IAM) documentation - http://iamcdocumentation.eu/index.php/Bioenergy_-_MESSAGE-GLOBIOM

[91] Fricko et al., 'The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century'; Pachauri et al., 'Pathways to Achieve Universal Household Access to Modern Energy by 2030'. http://iamcdocumentation.eu/index.php/Bioenergy_-_MESSAGE-GLOBIOM#scite-4ee9ea6109fbc23ab07cf7f471d223b2

3.2.6 COMPETING TECHNOLOGY DEVELOPMENT, LEARNING & REGIONAL KNOWLEDGE TRANSFER

Bauer et al[92] transparently summarise the range of qualitative constraints in the SSP narratives including technology innovation, learning and knowledge transfer, which are described in more quantitative detail in each of the relevant market model papers[93], the supplementary material for Fricko et al and Van Vuuren et al. are particularly informative. In summary;

- Fossil fuel technologies have medium rates of technology development across all SSP1-4 with high rates of fossil fuel technology development in SSP5. Fossil fuel conversion has low social acceptance in SSP1, medium in SSP2, high in SSP3 and SSP5, with high social acceptance in low income regions in SSP4 and low acceptance in medium to high income regions in SSP4.
- Commercial biomass conversion has high rates of technology development in SSP1, SSP4, medium in SSP2 and low in SSP3. Social acceptance for commercial biomass conversion is high in SSP4 and SSP3, medium in SSP5 and SSP2, and low in SSP1.
- Carbon Capture and Storage technology which is only deployed in climate policy scenarios has high rates of technology development in SSP4 and SSP5, with medium rates in all other SSPs. Social acceptance for CCS is low in SSP1, medium in SSP2 and SSP3, high in SSP5, high in low income SSP4 regions and medium in other income groups in SSP4.

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[92] Bauer et al., 'Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives'.

[93] Calvin et al., 'The SSP4'; Fujimori et al., 'SSP3'; Kriegler et al., 'Fossil-Fueled Development (SSP5)'; Fricko et al., 'The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century'; van Vuuren et al., 'Energy, Land-Use and Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm'.

	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**
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	

Figure 3.10 Extended SSPs for energy conversion technologies, reproduced from Bauer et al[94].

These qualitative preferences are implemented quantitatively as growth limits and learning rates on the reduction of costs for each of the technologies specified. The narratives have an indirect influence on the outcome for CCS in each of the SSP narratives and further in how the narratives are implemented in each IAM.

3.3 IAM RESPONSIVENESS TO CLIMATE POLICY

Kriegler et al have characterised the main IAM dynamics using diagnostic indicators, an invaluable aid to characterising their inherent dynamics [95] and emergent properties. This work led further to the ADVANCE[96] project which developed the new generation of advanced IAMs for application to Post-Paris policy frameworks. The ADVANCE Diagnostics MIP has

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[94] Bauer et al., 'Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives'.
[95] Kriegler et al., 'Diagnostic Indicators for Integrated Assessment Models of Climate Policy'.
[96] http://www.fp7-advance.eu/; http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki

concluded and a new scenario database is completed but not currently available[97]. Kriegler et al (2015)[98] provide a useful diagnostic classification of the influential 6 IAMs by equilibrium type, modelling approach, technological variety, emergent cost of abatement and overall responsiveness to climate policy as a function of carbon pricing showing the structural variety across IAMs. Table 3.1 summarizes the modelling approach and equilibrium type of each IAM, the scale of variety of low carbon technology options, the emergent cost of carbon abatement and finally the classification as a low medium or high response model as a diagnostic indicator of the model's responsiveness and pace of change of investment decisions as a function of the price of carbon.

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[97] Luderer et al., 'Deep Decarbonisation towards 1.5C - 2C Stabilisation. Policy Findings from the ADVANCE Project'; Marangoni et al., 'Sensitivity of Projected Long-Term CO2 Emissions across the Shared Socioeconomic Pathways'.

[98] Kriegler et al., 'Diagnostic Indicators for Integrated Assessment Models of Climate Policy'.

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

Table 3.1 Classification of each of the influential IAMs by equilibrium type, modelling approach, low carbon technology supply variety represtented, cost per abatement, and overall responsivesness to climate policy.

3.4 IMPACTS OF INPUT DATA & IAM TYPOLOGY DYNAMICS ON CCS POLICY OUTCOMES

Figure 3.11 summarises insightful high-level indicators describing the dynamics of IAMs and the relevant outcomes for CCS for the SSPx-2.6 set of scenarios stabilising temperatures below 2°C, for the set of direct and indirect assumptions outlined in previous sections.

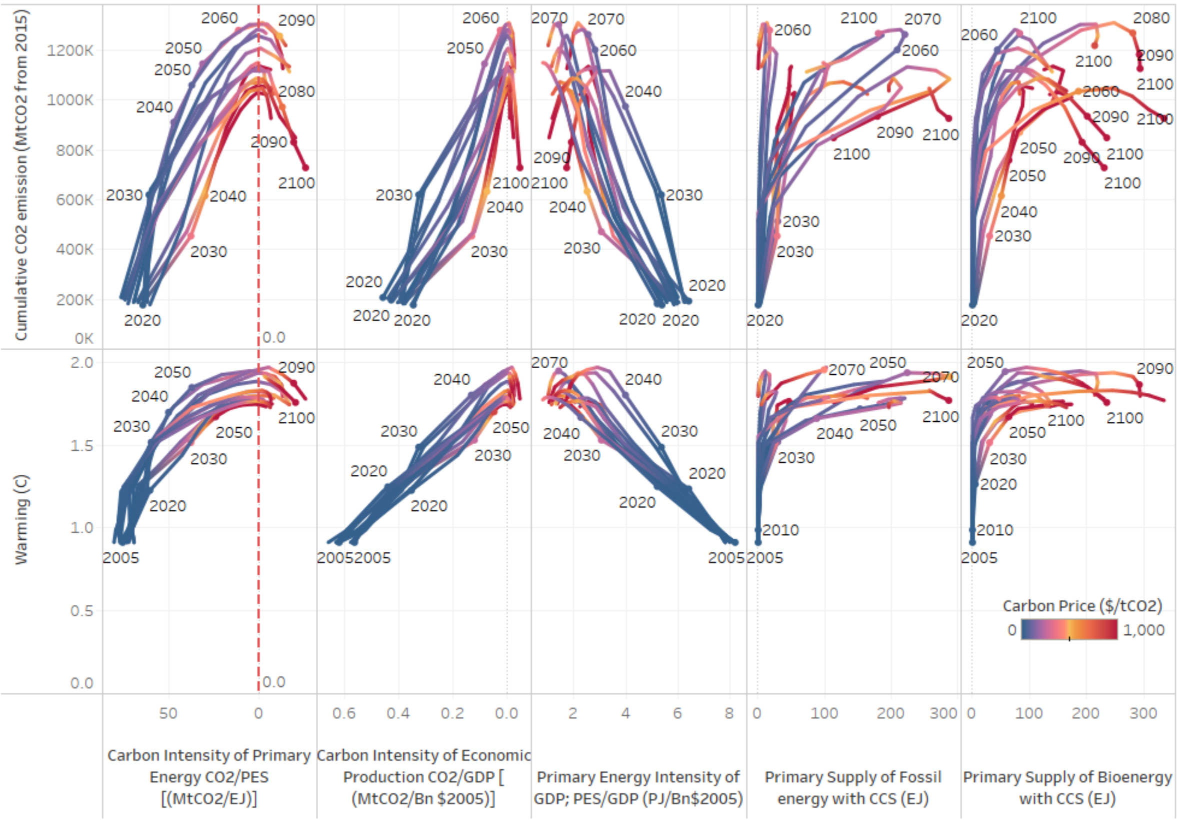

Figure 3.11 Energy System dynamics indicators under RCP2.6 (2°C temperature) constraints across the next generation of IAM scenarios the five Shared Socioeconomic Pathways (SSPx) for the 6 most influential IAMs in the Intergovernmental Panel on Climate Change (IPCC), showing cumulative CO_2 emissions from 2015 & global mean warming plotted against Carbon Intensity of Primary Energy, Carbon Intensity of GDP, Energy Intensity of GDP, Primary Energy Supply with CCS for both Fossil energy and Bioenergy

To stop temperature increase, and to stabilise temperatures at a specified level, requires cumulative CO_2 emissions not to breach a given carbon budget. This remaining carbon budget for a 2°C limit ranges from 800-1,400 $GtCO_2$ until 2100 as seen in the upper and lower left panel of Figure 3.11. The carbon intensity of primary energy must tend to zero by the time temperature is stabilised. Carbon dioxide removal technologies are required to reduce temperature where there is a temperature overshoot, to enable negative carbon intensity of primary energy supply and to compensate for remaining residual GHG emissions.

The carbon intensity, i.e. the amount of carbon used in producing a billion dollars of GDP, reduces from 0.6 $MtCO_2$ per BnUSD to zero $MtCO_2$ per BnUSD, again by the same time that temperature is stabilised under the assumption of continued economic growth.

In the SSPx-2.6 scenarios there is a 4 fold increase in energy efficiency as measured by the reduction of primary energy demand per unit of GDP, reducing from 8PJ per billion USD Gross domestic product to less than 2PJ per billion USD under projected economic growth rates.

Fossil CCS is deployed in conjunction with primary supplies of Gas and Coal reaching a maximum by 2050-2070, ranging from 50EJ in SSP1, 100EJ in SSP2, 145EJ in SSP4 and 225 EJ in SSP5. Beyond this mid-century maximum, both Fossil CCS deployment and Gross demand for fossil energy in primary energy supply declines to a combined total of less than 100EJ by 2100 across SSP1, 2 and 4.

Bioenergy CCS is deployed later than Fossil CCS in the medium term, but surpasses Fossil CCS deployment by mid-century and continues to rise and plateau under sustainable limits of bioenergy supply. Under stringent 1.5°C carbon budgets BECCS is not able to compensate for the residual fossil CO_2 emissions from fossil CCS and thus fossil CCS reaches an earlier and lower maxima by 2040-2050, and plateau's thereafter.

The diversity of pathway shapes and colour across each of the panel indicators in Figure 3.11 for each IAM SSPx-2.6 scenario, highlights the diversity of model dynamics and costs in aiming to achieve the same objective of limiting temperature below 2°C. Some models emergent dynamics choose earlier mitigation, with earlier higher costs, with less longer term CDR requirement, while others do the opposite with much larger cumulative CO_2 capture over the century in the same scale as the remaining carbon budgets, essentially doubling the remaining carbon budget.

There is a range of completeness of CCS technology representation, with some IAMs only representing CCS in the power sector, while others representing CCS across, Power, Industry, liquid fuels and hydrogen transformation with regional variation of capital costs, efficiency, learning rates, acceptable build rates limits corresponding to each SSP scenario[99].

With fixed capacity factors and fixed capture rates there is little flexibility in optimising residual emissions from CCS plants under stringent carbon budgets. Load duration curves which optimise CCS capacity factors similar to the optimisation of variable renewable penetration may help as a method to increase representation of CCS flexibility under strict carbon budgets[100].

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[99] Koelbl et al., 'Uncertainty in Carbon Capture and Storage (CCS) Deployment Projections'.

[100] Pietzcker et al., 'System Integration of Wind and Solar Power in Integrated Assessment Models'.

4 CONCLUSIONS

4.1 KEY MESSAGES

1) CCS capture costs of less than \$100/tCO2[101] and learning towards \$45/tCO_2 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 of CCS in IAMs, but related to interdependent key-points listed below.

2) 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[102], and sensitivity to this calibration assumption is explored in ETSAP-TIAM in the scientific paper associated with this report. This work develops scenarios for the full energy system building on previous preliminary work exploring capture rates in the power sector[103]. 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.

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[101] Budini et al., 'Can CO2 Capture and Storage Unlock Unburnable Carbon'; Budinis et al., 'An Assessment of CCS Costs, Barriers and Potential'.

[102] Cousins et al., 'Towards Zero Emissions from Fossil-Fuel-Fired Power Stations'.

[103] Budini et al., 'Can CO2 Capture and Storage Unlock Unburnable Carbon'.

3) 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.

4) BECCS provides the majority of negative emissions in IAMs (with some 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.

5) 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 management[104].

6) 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 [105].

4.2 BEST PRACTICE – IEA-ETP/MESSAGE

IEA-ETP & MESSAGE-GLOBIOM modelling teams demonstrate best practice from a technological perspective in how they represent CCS in their models but there is room for improvement, particularly incorporating next generation CCS vintages with improvements in capture rates, inclusion of the additional capital costs of higher capture rates, the cost of CO_2 captured[106] and sub annual flexible capacity factors, which could be implemented as load duration curves.

Current best practice is demonstrated by IEA-ETP and MESSAGE-GLOBIOM from an engineering perspective given the attention to regional variation, in CAPEX, OPEX, efficiency and capture rates for each CCS technology option considered in each model. The remaining IAMs either do not publish or do not consider that level of technical detail in their CCS specifications.

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[104] Smith et al., 'Biophysical and Economic Limits to Negative CO2 Emissions'; Vaughan et al., 'Evaluating the Use of Biomass Energy with Carbon Capture and Storage in Low Emission Scenarios'; Minx et al., 'Negative Emissions—Part 1'; Fuss et al., 'Negative Emissions—Part 2'; Vuuren et al., 'Alternative Pathways to the 1.5 °C Target Reduce the Need for Negative Emission Technologies'; Turner et al., 'The Global Overlap of Bioenergy and Carbon Sequestration Potential'.

[105] Grubler et al., 'A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies'; Vuuren et al., 'Alternative Pathways to the 1.5 °C Target Reduce the Need for Negative Emission Technologies'.

[106] Energy technologies Institute and Foster Wheeler, 'Benchmarking and Performance Analysis of Future CO2 Capture Technologies – Benchmarking Study'; David Hawkins and George Peridas, 'Kemper County IGCC: Death Knell for Carbon Capture? NOT.'

Up to date IEA-ETP specifications for CCS in the power sector is presented in the section below. CCS specifications within the Industry sector are uncertain and thus we point to the current literature for the range of capture costs per sub sector technology.

4.2.1 POWER SECTOR CCS DATA SET

The following data set is the power sector CCS techno-economic specification in IEA-ETP model for the 2017 version of the IEA energy technology perspectives[107]. The dataset exogenously provides up to date expected trends in efficiency, capex, and fixed operating and maintenance costs with expected learning per decade to 2060. The capture rate is constant in this specification but next generation CCS vintages with capture rate improvements are under exploration within IEA-ETP[108] modelling. The IEA costs below are within range of the Rubin et al (2015) review and in general CAPEX is higher than the IPCC 2005 Special report costs[109] (also lead by Ed Rubin) or the Ecofys cost of capture also commonly used in IAMs[110].

The Energy Technologies Institute (ETI) have previously published research on the estimated costs of carbon capture and storage in the power sector for increase capture rates up to 99%, with up to 7% increase in capex experienced for a 9%-point increase in capture rates from 90% to 99% [111]. Forthcoming work by CSIRO funded by IEAGHG is expected to provide greater detail and updated cost curves for CCS capture rates above 90% in the autumn of 2018[112].

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[107] IEA, *Energy Technology Perspectives 2017*.

[108] Uwe Remme, 'The Role of CCS in Deep Decarbonisation Scenarios'.

[109] Rubin, Davison, and Herzog, 'The Cost of CO2 Capture and Storage'; Metz and Intergovernmental Panel on Climate Change, *IPCC Special Report on Carbon Dioxide Capture and Storage*.

[110] Chris Hendricks, Wina Graus, and Frank van Bergen, 'Global Carbon Dioxide Storage Potential and Costs'.

[111] Energy technologies Institute and Foster Wheeler, 'Benchmarking and Performance Analysis of Future CO2 Capture Technologies – Benchmarking Study'.

[112] Cousins et al., 'Towards Zero Emissions from Fossil-Fuel-Fired Power Stations'.

			Efficiency (gross, LHV, %)					**Capture**
Region	*Fuel*	*Technology*	*2020*	*2030*	*2040*	*2050*	*2060*	**rate (%)**
USA	Hard coal	USC w/o CCS	46%	47%	48%	49%	49%	
		USC post-combustion	37%	39%	40%	41%	42%	85
		USC oxy-fuelling	37%	39%	40%	41%	42%	90
		IGCC w CCS	37%	40%	43%	44%	45%	85
	Natural gas	CCGT w/o CCS	59%	60%	61%	62%	62%	
		CCGT post-combustion	51%	52%	53%	54%	54%	85
	Biomass	BIGCC	45%	47%	49%	51%	51%	
		BIGCC w CCS	36%	39%	41%	43%	43%	85
INDIA	Hard coal	USC w/o CCS	41%	42%	43%	43%	43%	
		USC post-combustion	32%	34%	35%	36%	36%	85
		USC oxy-fuelling	32%	34%	35%	36%	36%	90
		IGCC w CCS	34%	37%	40%	41%	42%	85
	Natural gas	CCGT w/o CCS	56%	57%	58%	59%	59%	
		CCGT post-combustion	48%	49%	50%	51%	51%	85
	Biomass	BIGCC	43%	45%	47%	49%	49%	
		BIGCC w CCS	34%	37%	39%	41%	41%	85
CHINA	Hard coal	USC w/o CCS	45%	46%	47%	47%	47%	
		USC post-combustion	36%	38%	39%	40%	40%	85
		USC oxy-fuelling	36%	38%	39%	40%	40%	90
		IGCC w CCS	36%	39%	42%	43%	44%	85
	Natural gas	CCGT w/o CCS	57%	58%	59%	60%	60%	
		CCGT post-combustion	49%	50%	51%	52%	52%	85
	Biomass	BIGCC	44%	46%	48%	50%	50%	
		BIGCC w CCS	35%	38%	40%	42%	42%	85

Region	*Fuel*	*Technology*	**Specific investment costs, overnight (USD2015/kW)**				
			2020	*2030*	*2040*	*2050*	*2060*
USA	Hard coal	USC w/o CCS	2300	2300	2300	2300	2300
		USC post-combustion	5100	3700	3350	3250	3150
		USC oxy-fuelling	5300	3900	3550	3425	3300
		IGCC w CCS	5450	4000	3600	3500	3400
	Natural gas	CCGT w/o CCS	1000	1000	1000	1000	1000
		CCGT post-combustion	2800	1950	1750	1713	1675
	Biomass	BIGCC	3731	3516	3444	3376	3308
		BIGCC w CCS	6581	6366	5401	4800	4597
INDIA	Hard coal	USC w/o CCS	1400	1400	1400	1400	1400
		USC post-combustion	3600	2900	2400	2252	2103
		USC oxy-fuelling	3800	3100	2600	2425	2250
		IGCC w CCS	3850	3100	2600	2470	2341
	Natural gas	CCGT w/o CCS	700	700	700	700	700
		CCGT post-combustion	2450	1800	1650	1613	1575
	Biomass	BIGCC	3209	3024	2962	2903	2845
		BIGCC w CCS	5197	4807	4151	3901	3704
CHINA	Hard coal	USC w/o CCS	800	800	800	800	800
		USC post-combustion	3100	1900	1600	1532	1464
		USC oxy-fuelling	3200	2000	1700	1607	1514
		IGCC w CCS	3350	2150	1800	1733	1667
	Natural gas	CCGT w/o CCS	550	550	550	550	550
		CCGT post-combustion	2050	1300	1150	1113	1075
	Biomass	BIGCC	2388	2250	2204	2160	2117
		BIGCC w CCS	4136	3819	3250	3038	2873

			Fixed operating and maintenance costs (USD2015/kW)				
Region	*Fuel*	*Technology*	*2020*	*2030*	*2040*	*2050*	*2060*
USA	Hard coal	USC w/o CCS	69	69	69	69	69
		USC post-combustion	179	130	117	114	110
		USC oxy-fuelling	186	137	124	120	116
		IGCC w CCS	191	140	126	123	119
	Natural gas	CCGT w/o CCS	25	25	25	25	25
		CCGT post-combustion	84	58	53	51	50
	Biomass	BIGCC	131	123	121	118	116
		BIGCC w CCS	230	223	189	168	161
INDIA	Hard coal	USC w/o CCS	42	42	42	42	42
		USC post-combustion	126	102	84	79	74
		USC oxy-fuelling	133	109	91	85	79
		IGCC w CCS	135	109	91	86	82
	Natural gas	CCGT w/o CCS	18	18	18	18	18
		CCGT post-combustion	73	54	50	48	47
	Biomass	BIGCC	112	106	104	102	100
		BIGCC w CCS	182	168	145	137	130
CHINA	Hard coal	USC w/o CCS	24	24	24	24	24
		USC post-combustion	109	67	56	54	51
		USC oxy-fuelling	112	70	60	56	53
		IGCC w CCS	117	75	63	61	58
	Natural gas	CCGT w/o CCS	14	14	14	14	14
		CCGT post-combustion	61	39	35	33	32
	Biomass	BIGCC	84	79	77	76	74
		BIGCC w CCS	145	134	114	106	101

4.2.2 INDUSTRY

Leeson et al[113] provide the most recent review of CCS techno-economic costs in the industry sectors. There is a wide range of uncertainty of costs and applications of CO_2 capture in the industry sector in comparison to the power sector. IEA-ETP have a forthcoming review of CCS costs in their industry sector. IEAGHG technical reports continually update their techno-economic assessment reports of sector specific applications[114].

The iron and steel industry capture costs range from \$9.8/tCO_2 at a capture rate of 8%, up to \$147/tCO_2 CAPEX, \$9/tCO_2 fixed OPEX with a capture rate of 94%.

The cement industry have CCS options ranging from \$36/tCO_2 CAPEX, \$7.2/tCO_2 fixed OPEX at a capture rate of 60%, up to costs of \$271/tCO_2 CAPEX, \$15.9/tCO_2 fixed OPEX at a capture rate of 90%. Oxy-combustion with calcium looping has cost estimates at \$17/tCO_2 in the cement industry at a capture rate of 94%.

The paper and pulp industry have CCS cost estimates from \$59/tCO_2 with a capture rate of 62% up to \$380/tCO_2 at a 90% capture rate.

Finally, the petrochemical industry have a range of CCS technology options with cost estimates ranging from CAPEX of \$40/tCO_2 with a capture rate of 15% up to \$398/tCO_2 CAPEX, again ~\$10/tCO_2 fixed OPEX, with a capture rate of 90%.

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[113] Leeson et al., 'A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining and Pulp and Paper Industries, as Well as Other High Purity Sources'.

[114] IEAGHG technical report library; http://documents.ieaghg.org/index.php/s/YKm6B7zikUpPgGA

4.3 RECOMMENDATIONS

The usefulness of IAM Scenario analysis is in the insights gained into the emergent logic of systems interactions, not typically into insights for the dynamics of an individual technology choice from a single scenario from a single model.

The diversity of mathematical approaches across the range of IAM typologies gives insights into resilient climate policy options across a range of scenarios and sensitivity analyses when combined across a range of models in a model inter-comparison project (MIP). Where the same technology deployments occur with the same scale and timing across the range of scenario analysis this gives an indication of a resilient technology option across the range of input assumptions and uncertain future scenarios. Resilience is meant here in the sense that the technology option is consistently deployed across a range of uncertain scenarios, with a range of techno-economic specifications, giving an indication of a least regrets investment option and is not overtly sensitive to an individual scenario.

CCS is a resilient climate mitigation policy as it is deployed at large scale in temperature stabilisation scenarios with all IAMs deploying BECCS and the majority deploying fossil CCS in the scenarios reviewed.

Real world CCS deployment to date is far off track compared to climate stabilisation pathways from IAMs. There is a considerable gap between the current industry growth rates and the deployment rates envisaged in the current IAM SSP scenarios required for a temperature stabilisation scenario below 2°C[115]. The gap in deployment rates between IAMs and real world capacity construction is partially exacerbated as result of the time lag in the development of IAM scenarios, publishing, and model base year calibration updates of the current state of CCS deployment. For example, many current generation IAM models have 2010 as a starting base year and allow CCS deployment in their model years between 2010 and 2018 at a scale that in reality has not occurred, largely as a result of the CCS demonstration projects that were envisaged previously to be online by now, have not been

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[115] International Energy Agency, 'Tracking Clean Energy Progress'.

built as per the model scenarios. Therefore, there is a reduction in the perceptible gap between real world installed capacity deployment rates and the expected installed capacity in IAM climate stabilisation scenarios, and this perception gap grows the further back in TIME an IAM has its base year calibration; i.e. only models that regularly update their base year calibration, such as the IEA-ETP, can keep an up to date measurement of the progress and gap between actual CCS deployment and the required CCS deployment in scenarios for temperature stabilisation.

CCS technologies exist across multiple sectors in IAM temperature stabilisation scenarios, from power generation, to liquid fuel transformation and industrial processes.

The influential IAMs largely use up to date CCS specifications from IEAGHG technical briefs, IEA CCS roadmaps and Rubin et al[116] CCS techno-economic reviews. USA focused national energy systems models are often[117] heavily reliant on the 2005 IPCC Special report on CCS (IPCC SRCCS) [118] for data, but this is not the case for CCS technology cost estimates used in the influential global IAMs. Global storage volumes and transport costs are still relatively aggregated, simplified, and reliant upon the IPCC SRCCS in the absence of better regional data in the reviewed IAMs. There is ongoing work to create a global CCS storage geo-spatial database[119].

There are two primary recommendations from this project:

1. 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

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[116] Rubin, Davison, and Herzog, 'The Cost of CO2 Capture and Storage'.

[117] IEAGHG, 'Proceedings of US DOE Workshop: Energy-Economic Modelling Review'.

[118] Metz and Intergovernmental Panel on Climate Change, *IPCC Special Report on Carbon Dioxide Capture and Storage*.

[119] Kearns et al., 'Developing a Consistent Database for Regional Geologic CO2 Storage Capacity Worldwide'.

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.

2. 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,
        - CO2 capture cost curves as a function of varying capacity factor and capture rate.
        - 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[120].
  - 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.

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[120] Grubler et al., ‘A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies’.

5 PRELIMINARY ANALYSIS OF THE IMPACT OF CCS CAPTURE RATES ON RESIDUAL FOSSIL EMISSIONS UNDER STRINGENT CARBON BUDGETS IN ETSAP-TIAM

This preliminary analysis explores a perspective on the impact of the calibration input assumptions of carbon capture and storage (CCS) technologies in climate stabilisation scenarios in Integrated Assessment Models (IAMs). The interdependency between CO_2 capture rates for fossil fuel CCS and Bioenergy CCS (BECCS) Carbon Dioxide Removal (CDR) is explored using a perturbation scenario analysis varying the capture rates from default literature values by technology, up to 98% across more than 100 CCS technology options in the technology rich IEA Energy Technology Systems Analysis Programme's TIMES Integrated Assessment Model (ETSAP-TIAM). The sensitivity to maximum annual CO_2 injection rates as well as the role of Direct Air Carbon Capture and Sequestration (DAC) as an additional non-bioenergy CDR option is investigated.

In exploring least cost energy system mitigation pathways consistent with 2°C and towards 1.5°C Paris Agreement goals, hard constraints are observed between available fossil energy CCS options and BECCS CDR options under threshold avoidance carbon budgets for 2°C temperature stabilisation and threshold return carbon budgets for 1.5°C by 2100. The primary binding constraints appear to be the carbon budget, the feasible annual CO_2 sequestration volume - and as a function the total feasible cumulative sequestration volume - as well as the limited negative emissions feasible from the maximum sustainable bioenergy supply. These constraints bound the solution space, and the least cost optimisation occurs within this space. There does not appear to be a simple negative correlation between the amount of BECCS and Fossil CCS, as might be expected given a hard limit on CO_2 volumes cumulatively sequestered over the model horizon. The timing of installed BECCS CDR capacity over the model horizon depends upon the stringency of the temperature goal, and respective carbon budget.

Incrementally increasing CCS capture rates, particularly in the industry sector, can have significant impact upon reducing residual emissions in sectors with limited low carbon mitigation technology options, reducing the system wide marginal abatement cost of CO_2, and accelerating the feasible rate of decarbonisation. This analysis reinforces the call to expand research and development activity for industrial CCS technologies to enable least cost mitigation pathways by reducing residual emissions.

There is a range of CCS and NETS technologies represented in the influential IAMs across the range of sectors including power generation, industry, upstream transformation and land use. Capture options in power generation CCS include pre, post and oxy-combustion capture for conventional fossil fuels as well as for bioenergy combustion or gasification. Capture rates for CCS in power generation typically range from 70%-90% of gross CO_2 emissions as represented in IAMs as reviewed in the previous sections. More uncommonly discussed are the residual energy and process emissions captured in heavy industry (Steel, Cement Chemical, industrial Heat, Paper and Pulp) by CCS in IAMs. There is a range of CCS technologies conceptualised in IAMs for industry with capture rates ranging from 30% - 90% depending on the technology type and industry sector[121], and the number of technology options vary considerably from process type IAMs to top down IAMs[122]. Lastly there are CCS options utilised in the upstream oil and gas sector for enhanced oil recovery, processing of natural gas, capturing process emissions for refining of aviation fuels, and upstream technology options utilising CCS and BECCS for the gasification of bioenergy for the generation of low carbon hydrogenation fuels.

While technology learning takes place in most IAMs (either endogenously or exogenously), represented as a percentage cost reduction per doubling of installed capacity of an individual technology, upper limits on capture rates are generally not assumed to increase with technological learning in CCS options in IAMs; GCAM is an exception to this rule and assumes a growth to 95% capture across it's CCS technologies in electricity generation. Therefore, IAMs can have considerable residual emissions from sectors with limited alternative mitigation options which drives up the system wide marginal abatement cost and can result in demand reductions in those sectors with limited mitigation options and or

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[121] Leeson et al., 'A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining and Pulp and Paper Industries, as Well as Other High Purity Sources'; Larson, Li, and Williams, 'Chapter 12 - Fossil Energy'.

[122] Riahi et al., 'The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications'; Koelbl et al., 'Uncertainty in Carbon Capture and Storage (CCS) Deployment Projections'; Bauer et al., 'Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives'.

additional CDR where feasible. Residual emissions in industry, aviation and shipping often drive the requirement for negative emissions technologies in other sectors.

5.1 METHOD

This analysis explores the interdependency of residual emissions and the requirement for NETs as a function of CCS capture rates across all available CCS technology options in the technology rich IEA Energy Technology Systems Analysis Programme's TIMES Integrated Assessment Model (ETSAP-TIAM).

5.1.1 ETSAP-TIAM

ETSAP-TIAM independently calculates a dynamic inter-temporal partial equilibrium on global energy and emissions markets based on minimisation of total discounted energy system cost with perfect foresight to 2100[123]. The model has global coverage, with 15 regions, their resource potentials and energy trade connections. The model has been updated to use shared socioeconomic pathways (SSP2) drivers alongside sectoral outputs from the OECD ENV-LINKS[124] model as exogenous macroeconomic drivers to generate 45 price-elastic energy service demands across all sectors of the global economy. It has a rich technology database of over 1500 energy technologies, and their relevant commodities. TIAM encompasses a full cradle to grave representation of the energy system from resource production, refining, transformation, transport, trade, generation, consumption and sequestration of final energy commodities, environmental commodities and the investment, operation, maintenance, and decommissioning of intermediary technologies. Energy commodities include a full spectrum of resource potentials and their costs for fossil fuels, nuclear, bioenergy, both traditional and modern renewable technologies, while endogenously accounting for three main greenhouse gases emitted: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). An integrated climate module is calibrated to CMIP5 models greenhouse gas concentrations, radiative forcing and temperature changes.

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[123] Loulou and Labriet, 'ETSAP-TIAM'; Loulou, 'ETSAP-TIAM'.

[124] Dellink et al., 'Long-Term Economic Growth Projections in the Shared Socioeconomic Pathways'.

5.1.2 SCENARIOS

The scenario analysis presented focuses on the impact of varying the assumed capture rates across the available suit of CCS technologies in 2°C and 1.5°C temperature stabilisation scenarios.

The base case scenario is calibrated to SSP2 macroeconomic conditions with sectoral detail drivers from the OECD ENV-LINKS CGE model, which utilises consistent Population projections, GDP, sectoral gross value added for each of the 12 sectoral indicators which drive the 45 energy service demands in TIAM, along with household number estimates.

All Climate Policy runs are fixed to the reference (4°C) case scenario up to 2020, with subsequent carbon budgets applied from 2020-2100 of 1000 $GtCO_2$ for 2°C and 600 $GtCO_2$ for 1.5°C[125]. Non-CO_2 GHGs and other external climate forcing are imposed following a representative mitigation scenario.

We introduce Direct Air Capture as a technology option in ETSAP-TIAM following the most recent specification of the American Physical Society and Keith et al[126], including CAPEX, OPEX, electricity requirements and low temperature process heat requirements. We explore the cumulative CO_2 captured by Fossil CCS or BECCS, when increasing the CCS capture rates from the default base case, up to 60% and 70% in the industry sector only, or fixing all capture rates to 80%, 90% 95%, 98%, or 98% with direct air capture. Two DAC sensitivity variants are run, one with an exogenous non-linear reduction in cost of capture from \$600/tCO_2 in 2040 to \$150/tCO_2 in 2100, and lastly 98% CCS capture rate with low cost direct air capture with a constant floor price cost of \$150/tCO_2 available from 2040.

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[125] Rogelj et al., 'Differences between Carbon Budget Estimates Unravelled'; Millar et al., 'Emission Budgets and Pathways Consistent with Limiting Warming to 1.5 °C'.

[126] Keith et al., 'A Process for Capturing CO2 from the Atmosphere'; Mazzotti et al., 'Direct Air Capture of CO2 with Chemicals'; American Physical Society, 'Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs'.

5.2 RESULTS

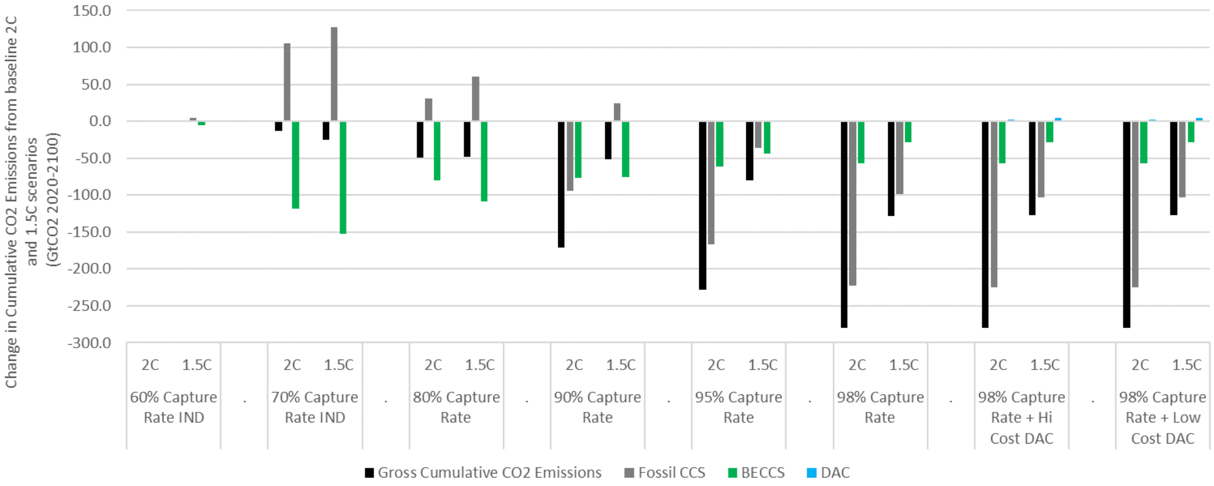

Figure 5.1 Change in cumulative CO_2 emitted and captured from standard 2°C and 1.5°C scenarios with increasing CCS capture rates and DAC availability.

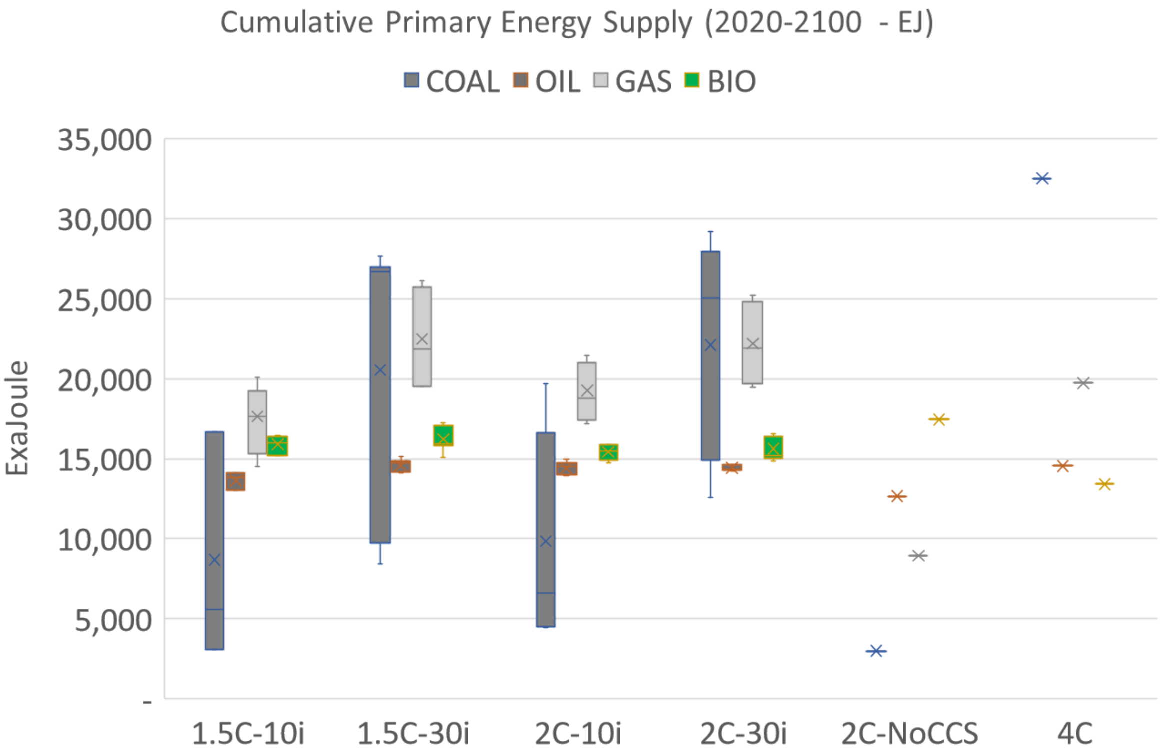

Figure 5.2 Cumulative Primary Energy Requirement (exajoules) of Fossil fuels and Bioenergy, for 1.5C and 2C scenarios, with no CCS, with a linear growth of sequestration rate from 30MtCO2 in 2020 to 10GtCO2 per year in 2100 (10i) or with a linear growth of sequestration rate from 30MtCO2 in 2020 to 30GtCO2 per year in 2100 (30i).

The CCS capture rate perturbation analysis shows two sets of correlations. In the first instance in scenarios with increased capture rates of 70% in industry and 80% across all sectors, a negative correlation between the additional volume of fossil fuel CO2 emissions captured via CCS and the lesser requirement for BECCS CDR of a similar volume under the same temperature targets and carbon budgets. As CCS capture rates increase from 90% to 98%, residual fossil emissions decline, and the requirement for both BECCS and fossil CCS capacity reduce under the same carbon budget constraints. There is a considerable decrease in the system wide marginal abatement cost of CO_2, resulting in a relatively cheaper energy system, reducing the pressure for energy demand reduction through relatively lower energy prices increases.

The deployment of higher CCS capture rates, reduces the rate of reduction in net emissions in the medium term to 2050 relative to the standard 2C and 1.5C cases, with relative accelerated reduction of net CO_2 emissions due to growing CCS capacity and higher effective capture rates beyond 2050.

Direct air capture is only deployed beyond 2080, when capacity costs have declined to the order of €150/tCO2. DAC provides 2.6-4.1 GtCO2 capture cumulatively over the model horizon, while its deployment is reduced in scenarios with higher CCS capture rates. Given that DAC does not meet an energy service demand, its marginal abatement cost is not directly comparable to infrastructure that does meet an energy service demand.

In scenarios with standard CCS capture rate assumptions, the fossil fuel share of primary energy supply decreases to between 60% and less than 30% by 2100 depending on the annual injection rates of CO_2 into geological storage. In cases with CCS capture rates up to 98% both the 2°C and return to 1.5°C scenario sees feasible annual increases of 50%-100% (~200EJ) in Fossil fuel primary energy supply by 2100.

5.3 DISCUSSION

Mission Innovation announced their seven innovation challenges at the 22nd Conference of the Parties in November 2016, one of which is to drive Carbon Capture

Innovation to enable near-zero CO_2 emissions from power plants and carbon intensive industries[127].

This analysis highlights the need for low carbon substitutes and or higher CCS capture rates in the industry sector, the benefits of reducing residual emissions with higher CO_2 capture rates, and, if achievable at reasonable costs, the potential benefits in reducing the marginal cost of CO_2 abatement. Scenarios allowing higher CCS CO_2 capture rates, even at higher costs, involve a considerably lower reliance on direct air capture than the current literature[128].

Access to onshore and offshore storage may become a constraining issue, impacted by both slow geological survey of national level storage locations, as well as social and political acceptance limiting the annual sequestration rate, below that which might otherwise be the cost effective mitigation option.

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[127] IEA, *Energy Technology Perspectives 2017*.

[128] Chen and Tavoni, 'Direct Air Capture of CO2 and Climate Stabilization'.

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Appendix A- SSP MARKER MODEL DESCRIPTIONS

Model descriptions are reproduced from Bauer et al[129] with further model description and documentation available at

http://iamcdocumentation.eu/index.php/IAMC_wiki .

A.1 AIM-CGE

The Asia-Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE)[130] is a recursive-type dynamic general equilibrium model that covers all regions of the world. The AIM/CGE model includes 17 regions and 42 industrial classifications. Likewise other CGE models, AIM/CGE deals with whole economic production and consumption behaviours with particular emphasis on the representation of energy in order to assess energy related CO2 emissions appropriately. In addition, agriculture and land use classifications have also high resolution in order to deal with the bioenergy and land use competition appropriately. The climate component is represented by the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC) and the emissions information generated from AIM/CGE is fed into MAGICC.

The production sectors are assumed to maximize profits under multi-nested constant elasticity substitution (CES) functions and each input price. The capital, labour, intermediate inputs and land are the input for each industrial activity. Household expenditures on each commodity are described by a linear expenditure system function. The saving ratio is endogenously determined to balance saving and investment, and capital formation for each good is determined by a fixed coefficient. The international traded goods are substitutable with the domestic production goods.

In addition to energy-related CO_2, CO_2 from other sources (land use), CH_4, N_2O, and F-gases are treated as GHGs in the model. Energy-related emissions are associated with fossil

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[129] Bauer et al., 'Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives'.

[130] Fujimori et al., 'SSP3'; Fujimori, Masui, and Matsuoka, 'Development of a Global Computable General Equilibrium Model Coupled with Detailed Energy End-Use Technology'; Fujimori, Masui, and Matsuoka; Fujimori et al., 'The Effectiveness of Energy Service Demand Reduction'; Fujimori, Masui, and Matsuoka, 'Gains from Emission Trading under Multiple Stabilization Targets and Technological Constraints'.

fuel consumption and combustion. The non-energy-related CO_2 emissions consist of land use change and industrial processes. Land use change emissions are derived from the difference of the forest area from that of the previous year multiplied by the carbon stock density. Non-energy-related emissions other than land use change emissions are assumed to be in proportion to the level of the activities (such as output). CH4 has various sources, but the main sources are the rice production, livestock, fossil fuel mining, and waste management sectors. N_2O is emitted as a result of fertilizer application and livestock manure management, and by the chemical industry. Air pollutant gases (BC, CO, NH_3, NMVOC, NO_X, OC, sulphur) are also associated with fuel combustion and activity levels. Basically, the emissions factors are changed over time according to the implementation of air pollutant removal technologies and relevant legislation.

A.2 GCAM4

The Global Change Assessment Model (GCAM)[131] is a global integrated assessment model with particular emphasis on the representation of human earth systems including interactions between the global economic, energy, agricultural, land use and technology systems. The GCAM physical atmosphere and climate are represented by Hector, an open source coupled carbon cycle-climate model. The GCAM is global in scope and disaggregated into 32 energy and economic regions and 283 agriculture and land use regions. GCAM is a dynamic-recursive market equilibrium model; as such, prices are adjusted to ensure that supplies and demands of all commodities are equilibrated in each model period. The model operates in 5-year timesteps from 1990 to 2100, with 2010 as its last historical year. The energy system model produces and transforms energy for use in three end-use sectors: buildings, industry and transport. Production is limited by resource availability, which varies by region. Fossil fuel and uranium resources are finite and depletable. Wind, solar, hydro, and geothermal resources are renewable. Bioenergy is also renewable but is treated as an explicit product of the agriculture-land-use portion of the model. The agriculture and land use model

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[131] Calvin et al., 'The SSP4'.

computes supply, demand, and land use for a variety of crops and other uses, including natural ecosystems. The model operates using an economic paradigm, where landowners allocate land among competing uses based on profitability. GCAM assumes a distribution of profits across each of the 283 regions, and thus, the fraction of each region allocated to each land use is the probability that use has the highest profit. GCAM computes anthropogenic emissions of 24 GHGs, short-lived species, aerosols, and ozone precursors. Emissions are associated with drivers and change in the future due to changes in drivers, income-driven pollution controls, or carbon-price driven abatement efforts. GCAM is open-source and can be downloaded at: www.globalchange.umd.edu/models/gcam/download/.

A.3 IMAGE3.0

The IMAGE/TIMER Integrated Assessment Modelling Framework,[132] consists of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as air pollution, climate change, and land-use change. The global energy model that forms part of this framework, TIMER, describes the demand and production of primary and secondary energy and the related emissions of GHGs and regional air pollutants. The land and climate modules of IMAGE describe the dynamics of agriculture and natural vegetation, and resulting climate change. For food and agriculture, the IMAGE system uses projections made by the computable-general-equilibrium MAGNET model. This model describes, in interaction with the main IMAGE framework, changes in food production and trade for a broad set of crops and animal products. The Terrestrial Environment System (TES) of IMAGE computes land-use changes based on regional production of food, animal feed, fodder, grass, bio-energy and timber, with consideration of local climatic and terrain properties. Climate change affects the productivity of crops and induces changes in natural vegetation with consequences for biodiversity. TES represents the geographically explicit modelling of and use. The potential distribution of natural vegetation

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[132] http://themasites.pbl.nl/models/image/index.php/IMAGE_framework/A_brief_history_of_IMAGE#
van Vuuren et al., 'Energy, Land-Use and Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm'.

and crops is determined on the basis of climate conditions and soil characteristics on a spatial resolution of 0.5 x 0.5 degree. It also estimates potential crop productivity, which is used to determine allocation of cropland to different crops. Emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere are also simulated. The Atmospheric Ocean System (AOS) part of IMAGE calculates changes in atmospheric composition using the emissions from the TIMER model and TES, and by taking oceanic carbon dioxide uptake and atmospheric chemistry into consideration. Subsequently, AOS computes changes in climatic parameters by resolving the changes in radiative forcing caused by greenhouse gases, aerosols and oceanic heat transport.

A.4 MESSAGE-GLOBIOM

Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) is an energy engineering model based on a linear programming (LP) optimization approach which is used for medium- to long-term energy system planning and policy analysis[133]. The model minimizes total discounted energy system costs, and provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, and inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. In addition to the energy system, the model also includes generic representations of agriculture and forestry, which allows incorporation of emissions and mitigation options for the full basket of greenhouse gases and other radiatively active substances[134]. MESSAGE is linked to a macro-economic model -MACRO[135] . In MACRO, capital stock, available labour, and energy inputs determine the total output of the economy

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[133] Riahi, Grübler, and Nakicenovic, 'Scenarios of Long-Term Socio-Economic and Environmental Development under Climate Stabilization'.

[134] Rao and Riahi, 'The Role of Non-CO2 Greenhouse Gases in Climate Change Mitigation'.

[135] Messner and Schrattenholzer, 'MESSAGE–MACRO'.

according to a nested constant elasticity of substitution (CES) production function. Through the linkage to MESSAGE, internally consistent projections of GDP and energy demand are calculated in an iterative fashion that takes price-induced changes of demand and GDP into account. MESSAGE is in addition coupled to agricultural model GLOBIOM for consistent projections of land-use. MESSAGE has also been linked to the GAINS model to provide estimates of air pollution[136]. Additional extensive model documentation can be found at http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_MESSAGE-GLOBIOM.

The Global Biosphere Management Model (GLOBIOM) has been developed at the International Institute for Applied Systems Analysis (IIASA) since the late 2000s. The partial-equilibrium model represents various land-use based activities, including agriculture, forestry and bioenergy sectors. The model is built following a bottom-up setting based on detailed grid-cell information, providing the biophysical and technical cost information. This detailed structure allows taking into account a rich set of environmental parameters. Its spatial equilibrium modelling approach represents bilateral trade based on cost competitiveness. The model was initially developed mostly for integrated assessment of climate change mitigation policies in land based sectors, including biofuels, and is increasingly being implemented also for agricultural and timber markets foresight, and economic impacts analysis of climate change and adaptation. Havlik's papers[137] provide more details on GLOBIOM.

A.5 REMIND-MAGPIE

The Regionalized Model of Investment and Technological Development (REMIND) is a global multi-regional integrated assessment model that couples a top-down macroeconomic

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[136] Riahi et al., 'RCP 8.5—A Scenario of Comparatively High Greenhouse Gas Emissions'; McCollum et al., 'Climate Policies Can Help Resolve Energy Security and Air Pollution Challenges'; Rao et al., 'Future Air Pollution in the Shared Socio-Economic Pathways'.

[137] Havlik et al., 'Global Land-Use Implications of First and Second Generation Biofuel Targets'; Havlík et al., 'Climate Change Mitigation through Livestock System Transitions'.

growth model with a detailed bottom-up energy system model and a simple climate model. By embedding technological change in the energy sector into a representation of the macroeconomic environment, REMIND combines the major strengths of bottom-up and top-down models. To obtain a detailed evaluation of the climate implications of the scenarios, the model is further coupled with the climate module MAGICC6[138]. Economic dynamics are calculated through inter-temporal optimization, assuming perfect foresight by economic actors. This implies that technological options requiring large up-front investments that have long pay-back times (e.g. via technological learning) are taken into account in determining the optimal solution. REMIND incorporates a detailed description of energy carriers and conversion technologies, including a wide range of carbon free energy sources as well as fossil and biomass conversion technologies in combination with carbon capture and storage. REMIND also represents trade relations and capital movements between eleven world regions, and also has a detailed representation of global markets for energy resources such as crude oil, coal and gas. Mitigation cost estimates thus take into account technological opportunities and constraints as well as macro-economic feedbacks and trade effects.

The **Model of Agricultural Production and its Impacts on the Environment (MAgPIE)** is a global multi regional partial equilibrium model of the agricultural sector. MAgPIE links demand for 10 economic world regions with spatially explicit biophysical inputs such as land, agricultural yields and water availability. The objective function of MAgPIE is the fulfillment of regional demand at minimum global production costs (cost minimization). Costs accrue for labor, capital, transport, land conversion and R&D investments. For meeting the demand, MAgPIE endogenously decides, based on cost-effectiveness, about the level of intensification (yield-increasing technological change), extensification (land-use change) and production relocation (international trade). In climate policy scenarios, GHG emissions from land-use and land-use change are priced. The resulting cost term enters the objective function of MAgPIE, which provides an incentive for endogenous abatement of land-related GHG emissions.

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[138] Meinshausen, Raper, and Wigley, ‘Emulating Coupled Atmosphere-Ocean and Carbon Cycle Models with a Simpler Model, MAGICC6 – Part 1’.

MAgPIE is solved in a recursive dynamic mode with a variable time step length of five or ten years on a timescale from 1995 to 2100.

REMIND and MAgPIE are coupled by exchanging price and quantity information on bioenergy and GHGs. First, REMIND is initialized with bioenergy supply curves and a GHG emission baseline derived from MAgPIE. Starting from this initialization, REMIND derives bioenergy demand and GHG prices consistent with a predefined climate target. MAgPIE takes bioenergy demand and GHG prices from REMIND as input and derives bioenergy prices and GHG emissions, which in turn serve as input for the next iteration of REMIND. REMIND and MAgPIE run iteratively until changes in prices and quantities of bioenergy and GHGs are sufficiently small.

A.6 WITCH-GLOBIOM

The World Induced Technical Change Hybrid model (WITCH), developed by the climate change modelling and policy group at FEEM is a hybrid top-down economic model with a representation of the energy sector of medium complexity. Two distinguishing features of the WITCH model are the game-theoretic set-up, which is particularly useful for analyzing fragmented international policy settings, and the representation of endogenous technological change. World countries are grouped into thirteen regions. Innovation spills across regions in the form of knowledge, with important repercussions on the optimal R&D investments that major economic actors decide to undertake. WITCH is an inter-temporal optimization model in which perfect foresight prevails over a time horizon covering the whole century. The model includes a wide range of energy technology options with different assumptions on their future development related to the level of innovation effort undertaken by countries. Special emphasis is put on the emergence of carbon-free energy technologies in the electricity and non-electricity sectors as well as on endogenous improvements in energy efficiency triggered by dedicated R&D investments contributing to a stock of energy efficiency knowledge.

WITCH is also coupled to the GLOBIOM model for the land-use sector and includes a module on air pollutant emissions. The full description is available at www.witchmodel.org/documentation/.

Evaluating technology options to mitigate greenhouse gas emissions

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