What relevant information do the integrated assessment models and scenarios from the 1.5 °C special report provide for Norway?

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4. desember 2019

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Financed by: The Norwegian Environment Agency (Miljødirektoratet)

Project: Nationally relevant information about IAM modelling frameworks and scenarios

Project Manager: Borgar Aamaas

Quality Manager: [Faktatekst]

Keywords: 1.5 °C, 2 °C, integrated assessment models, IPCC, scenarios

Abstract: The Norwegian Environment Agency (Miljødirektoratet) has requested a report to "get more detailed and nationally policy relevant information about the IAM-scenarios assessed in the Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5 °C global warming, and key features and assumptions in the modelling frameworks." We present information for scenarios consistent with 1.5°C and 2°C, but avoid scenarios with large-scale bioenergy with carbon capture and storage (as requested). Among the topics discussed in this report are emission pathways, carbon price trajectories, deployment of negative emission technologies, land use change, investment needs, deployment of key abatement options, demand for primary energy and base materials, portfolio of abatement options, and scenarios. The starting point is the emission scenario database linked to the special report on global warming of 1.5 °C. However, not all information asked for by the Norwegian Environment Agency is available in the scenarios database or produced by integrated assessment models. The emission scenarios are integrated pathways (trajectories over time) developed by global integrated assessment models that represent key societal systems and their interactions, such as the energy system, agriculture, land use, and the economy. Emission scenarios consistent with 1.5 °C and 2 °C of global warming are very demanding as these targets require large-scale transformations of society and its systems, including how energy is produced, how agricultural systems are organized, and how food, energy, and materials are consumed. Some aspects of all the scenarios can be considered as unrealistic, very difficult, or in conflict with other societal objectives. Some models cannot reach ambitious climate targets, particularly 1.5°C. Accompanied with this report, we also produce large Excel documents with numerous sheets and figures on the topics discussed here.

Language of Report: English

Cover picture: Alf Ove Hansen / CICERO

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Summary

The Norwegian Environment Agency (Miljødirektoratet) has requested a report to "get more detailed and nationally policy relevant information about the IAM-scenarios assessed in the Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5 °C global warming, and key features and assumptions in the modelling frameworks." We present information for scenarios consistent with 1.5°C and 2°C, but avoid scenarios with large-scale bioenergy with carbon capture and storage (as requested). Among the topics discussed in this report are emission pathways, carbon price trajectories, deployment of negative emission technologies, land use change, investment needs, deployment of key abatement options, demand for primary energy and base materials, portfolio of abatement options, and scenarios. The starting point is the emission scenario database (Huppmann et al. 2018) linked to the special report on global warming of 1.5 °C (V. Masson-Delmotte 2018). However, not all information asked for by the Norwegian Environment Agency is available in the scenarios database or produced by integrated assessment models.

The emission scenarios are integrated pathways (trajectories over time) developed by global integrated assessment models that represent key societal systems and their interactions, such as the energy system, agriculture, land use, and the economy. Emission scenarios consistent with 1.5 °C and 2 °C of global warming are very demanding as these targets require large-scale transformations of society and its systems, including how energy is produced, how agricultural systems are organized, and how food, energy, and materials are consumed. Some aspects of all the scenarios can be considered as unrealistic, very difficult, or in conflict with other societal objectives. Some models cannot reach ambitious climate targets, particularly 1.5°C.

The models that have produced the emission scenarios and discussed in this report include: AIM/CGE 2.0 (or 2.1), C-ROADS-5.005, GCAM 4.2, IMAGE 3.0.1, MESSAGE V.3, MESSAGE-GLOBIOM 1.0, MESSAGEIX-GLOBIOM 1.0, POLES EMF33, REMIND 1.7, REMIND-MAgPIE 1.7-3.0, WITCH-GLOBIOM 3.1, and WITCH-GLOBIOM 4.4. Groups of scenarios with similar characteristics are rarely statistical samples of all hypothetical scenarios, as often some models or model structures are overrepresented or not all possible scenarios are explored. The REMIND and AIM/CGE models contribute with many of the scenarios in the SR15 database, while some other models provide only one or a few. Groupings of scenarios give an indication of the range of outcomes, but care is required not to over interpret the statistical samples.

Most 1.5°C scenarios require large-scale use of bioenergy with carbon capture and storage (BECCS), but this has become controversial as it may be infeasible or unsustainable. As a consequence, the Norwegian Environment Agency, wanted scenarios with unsustainable levels of BECCS removed. There is no clear-cut definition of what a sustainable level of BECCS is. The special report on land gives a wide range of BECCS deployment, but the nature for which it is deployed is important for sustainability concerns. After assessing several approaches, we decided to

use the Norwegian Environment Agency criteria of 500GtCO$_2$ cumulative BECCS this century and 12GtCO$_2$/yr BECCS in 2100. After applying these criteria, there remain 23 scenarios consistent with 1.5 °C (with no or low overshoot) and 53 scenarios with 2°C (with a 66% chance). This selection of scenarios is discussed in detail throughout the report.

Emission pathways show that at the global level CO$_2$ emissions (not including other greenhouse gases) reach net-zero around 2050 for the selected 1.5 °C scenarios and 2075 for the selected 2°C scenarios. Different regions reach net-zero in different years, based on cost optimizing mitigation. Latin America is often the first region to reach net-zero (median 2042) due to its ability to provide CO$_2$ removal, while OECD is generally after the global average (median 2058). The modelled pathways do not consider equity. For 2 °C pathways, the net-zero year is about 15 years later than for 1.5 °C pathways at the global level, with some variation at the regional level. For all GHGs combined, net zero emissions (in CO$_2$-equivalent terms) is reached around 2070 for 1.5 °C pathways and after 2100 in 2°C pathways. The Paris Agreement calls for net-zero GHG emissions in the second half of the century (Article 4), but only about half of the assessed 2°C scenarios reach net-zero in that period. Consequently, the Paris net-zero constraint indicates a pathway more consistent with 1.5 °C than 2 °C. The year of net-zero in OECD for GHGs is very close to the global average. While the OECD has capacity for mitigation, this region does not mitigate faster or earlier than other regions, which is a consequence of the cost-optimizing model framework that does not introduce concepts of equity. Since models cut emissions where they are cheapest, regional variations should not be over interpreted given equity concerns.

There is a large variation in carbon prices across models, socioeconomics, and temperature outcomes. The carbon prices vary little between regions, and most scenario designs use global carbon prices which exclude regional variations. Depending on the model, socioeconomics, and climate target, carbon prices rise close to exponential over the century. Carbon prices are higher for 1.5°C and 2°C, with some models showing steep increases in carbon prices for 1.5°C scenarios indicating this pathway is close to the feasibility limit of the model. The carbon prices are outcomes of the model structure and are therefore very model dependent. Very high prices reflect the difficulty of reaching targets, though care should be taken when comparing carbon prices across models as they may not always be comparable. Models rarely consider variations in carbon prices at the sector level and are weak on innovation. This means carbon prices from models may not be useful for guiding policy on innovation or first-of-the-kind technologies.

Most scenario databases and publications only report and present net emissions, but models distinguish gross positive emissions (from the burning of fossil fuels, industry, and net deforestation) and gross negative emissions (CO$_2$ removal like BECCS and afforestation). Negative emissions start being deployed in models almost immediately, even though net-negative emissions may not be reached until after 2050. Negative emissions can be separated into two, one part to cancel out residual emission and one part to reduce global temperatures after overshooting. In most 1.5 °C scenarios, the second dominates, which is partly due to the model set up where such a temperature overshooting is allowed. The discount rate also has a major impact on the amount of negative emissions. Models use a mix of BECCS and afforestation, but BECCS is more productive at removing carbon for a given area of land. In general, the considered scenarios remove twice as much CO$_2$ from BECCS than from afforestation. Models with less BECCS, often use more afforestation.

The land use impacts of BECCS and afforestation are immense, though it is not possible to characterize the quality of the land-use in scenarios. Some models have poor representation of land-use, and the analysis is therefore dominated by only a few different models. The land use impacts are generally greater for afforestation than BECCS in the assessed scenarios. Further, BECCS takes up about four times as much CO$_2$ per unit area than afforestation, since yield improvements generally apply to bioenergy but not afforestation. The additional land use for afforestation and BECCS comes from yield improvements in crops and pastures. The changes in land use are

immense in both 1.5°C and 2°C scenarios and will potentially lead to trade-offs and conflicts. Regionally, the OECD generally uses more land for bioenergy, while most afforestation happens in the tropics.

Investment needs are provided in detail only in some models. Those few models indicate larger investments in energy supply compared to energy efficiency. The investment level is not very different between 1.5 °C and 2 °C as the energy infrastructure is to be replaced anyhow.

On key abatement options, many of the mitigation measures are related to the energy sector as most of the models are built from detailed energy models. Specific models are unlikely to consider all technologies and measures. The models are different, such as representing the technologies differently and with large differences in the costs of electricity generation technologies. The demand side measures can typically be divided into energy-related and food-related measures. The supply-side measures are linked to the energy sector. Costs on carbon capture and storage (CCS) are typically based on studies in the energy supply sector. Most of the models include BECCS and Afforestation and reforestation (AR) as negative emissions. Both depend heavily on land use change and in most models both technologies are modeled explicitly and endogenously to compete with other land use purposes such as production of energy and food crops. First-of-kind technologies and innovation processes are rarely modelled in these types of scenarios. Thus, these models are not useful tools to model initial investments required to scale up new technologies.

We present future demand for primary energy by source, but no data is available on the demand for base materials. Fossil fuel use declines rapidly in 1.5 °C scenarios but does not decline to zero. Fossil fuels are quickly replaced by non-fossil sources, such as solar, wind, and hydro. Coal drops strongly in all scenarios, oil has a more gradual decline, while natural gas has a large variation between scenarios with some indicating a decline and others indicating a rise before declining a few decades into the future. Relative to baseline scenarios, coal, oil, and gas use declines substantially. Oil use in the OECD drops by 30% by 2030 and 80% by 2050. For gas, the average indicates a decline of 20% by 2030 and 50% by 2050 in the OECD region.

Abatement options in the industrial sector are difficult to identify in the scenarios as most of the models have modelled the economic activities at an aggregate level. Basically, there are no mitigation measures specific for the industrial sector although CCS technologies are considered in industrial processes in some models.

We also show relevant literature for further reading on the models and scenarios. Accompanied with this report, we also produce large Excel documents with numerous sheets and figures on the topics discussed here. Users of the emission scenarios should be aware of the limitations and that the perspective taken in the modeling are important for how they are framed.

1   Introduction

1.1   Mandate

The Norwegian Environment Agency (Miljødirektoratet) has requested a report to "get more detailed and nationally policy relevant information about the IAM-scenarios assessed in the Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5°C global warming, and key features and assumptions in the modelling frameworks."

Specifically, information was required for two groups of scenarios

- 1.5°C-scenarios with no or limited overshoot (Below-1.5°C and 1.5°C-low-OS), and
- Below 2°C-scenarioes (Lower-2°C).

In addition, use of bioenergy with carbon capture and storage (BECCS) is constrained to include only scenarios that have less than 12 $GtCO_2$ of BECCS per year in 2100, and less than 500 $GtCO_2$ cumulatively to 2100. For the two groups of scenarios, the topics to be covered are as follows.

a)   Emission pathways by region and sector, both for all GHGs and CO_2 only

b)   Carbon price trajectories (calculated in 2019-USD), preferably for the energy and industry sectors in the EU/EEA for the purpose of comparison with EUA-price trajectories. Alternatively, information should be provided to serve this purpose, such as marginal abatement cost over time for relevant sectors. The same should be done to assess CO_2-price trajectories for other sectors as a group, for the purpose of comparison with current non-ETS climate policy.

c)   Deployment of negative emission technologies on a global and regional level.

d)   Land use change on a global level and regional level.

e)   Investment needs on a global level and regional level.

f)   For each sector a description of the deployment of key abatement options, including the cost of first-of-a-kind and cost-curves, and other important assumptions if relevant. Most importantly, we need information about CCS in the industry and energy sectors in EU/EEA, or the region most closely covering EU/EEA. Assumptions about CCS in different modelling frameworks must be described.

g)   As far as possible, demand for primary energy and base materials (such as oil, gas, coal, different kinds of bioenergy, renewable electricity, cement, iron and steel, aluminum, and chemical products such as ammonia, ethylene, methanol). Most importantly, we need information about the demand for oil and gas globally and in Europe.

h)   A detailed description of the portfolio of abatement options available in different models for different industrial sectors (such as iron and steel, chemicals, non-metallic minerals, pulp and paper, non-ferrous metals), and the most important assumptions about these options - such as cost and technological maturity.

i)   A list showing which scenarios are included in each selection, and references to relevant studies and publications.

1.2   Context

In October 2018, the IPCC published a special report with the title *Global Warming of 1.5 °C, an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (V. Masson-Delmotte 2018). Mitigation pathways consistent with 1.5 °C and 2 °C global warming were produced by the research community ahead of the special report and assessed in the special report. In addition, an emission scenario database was also produced as an addition to the special report (Huppmann et al. 2018). This is the starting point of this report and is used to address the topics in the mandate.

The emission scenarios are integrated pathways developed by global integrated assessment models (IAMs) that represent key societal systems and their interactions, such like the energy system, agriculture, land use, and the economy. These models often include simple representations of interactions with the geophysical system, for instance with the carbon cycle and climate models. All emission sectors and regions are covered in the models, though not necessarily modelled individually. Pathways consistent with 1.5 °C and 2 °C are very demanding as these targets require large-scale transformations of our society and systems, including how energy is produced, how agricultural systems are organized, and how food, energy, and materials are consumed.

The Norwegian Environment Agency has previously commissioned several reports on related emission pathways. van Vuuren et al. (2015) presented implications around 2050 of pathways consistent with the 2 °C target from the IPCC's fifth assessment report (IPCC 2014). Among points raised in the report are the need for negative emissions and bioenergy with carbon capture and storage (BECCS) in order to keep within carbon budgets, and whether this is possible in terms of sustainability. Rogelj (2016) followed up on mitigation needed in order to be consistent with 2 °C. In 2017, the Norwegian Environment Agency (Andresen and Gade 2017) synthesized what these emission pathways mean for the industry sector and what carbon prices in the EU and technology development are needed to follow up. All these reports were published before the special report on global warming of 1.5 °C. This report is, hence, a follow-up of these previous studies by applying the most recent emission pathway dataset and putting these pathways into context that is relevant for Norwegian policy. We address the topics asked for in the mandate by utilizing the emission scenario database linked to the special report, literature review, and expert opinion from researchers in CICERO and other research institutes working on the emission database. However, information available is limited for several of the topics asked for in the mandate.

1.3   Structure of the report

First, we briefly introduce the Excel document produced in this project. Second, we present the models involved in the emission database that are relevant for this report. Third, we discuss scenario selection. Fourth, we address the topics a) through i) chronologically. The letters in parenthesis in the titles indicate what topic in the mandate is presented. Not all details asked for in the task description of the mandate are possible to identify given available dataset and current knowledge. Fifth, we discuss the limitations and relevance for Norway, before we conclude.

2   About the Excel document

As part of the delivery, we also produce three Excel workbooks with numerous sheets. Data relevant for the topics a)-i) are provided. The first sheet contains general information relevant for all the sheets. The following sheets provides data for topics a)-i) chronologically. The sheets contain selection criteria as extra columns, so that for instance all scenarios can be looked at or those that meet the BECCS criteria discussed later in the report.

3 Models involved in the target scenarios

In the following sections, we will routinely be referring to different models. Because of this, we first outline models that have been used to generate at least one of the target scenarios: AIM/CGE 2.0 (or 2.1) (Liu et al. 2018); C-ROADS-5.005 (Holz et al. 2018); GCAM 4.2 (Riahi et al. 2017); IMAGE 3.0.1 (Riahi et al. 2017; Luderer et al. 2018; McCollum et al. 2018; van Vuuren et al. 2018); MESSAGE V.3 (Rogelj et al. 2013a; Rogelj et al. 2013b; Rogelj et al. 2015); MESSAGE-GLOBIOM 1.0 (Bauer et al. 2018; Luderer et al. 2018); MESSAGEIX-GLOBIOM 1.0 (Grubler et al. 2018); POLES EMF33 (Bauer et al. 2018); REMIND 1.7 (Strefler et al. 2018); REMIND-MAgPIE 1.7-3.0 (Bauer et al. 2018; Bertram et al. 2018; Kriegler et al. 2018); WITCH-GLOBIOM 3.1 (Riahi et al. 2017); and WITCH-GLOBIOM 4.4 (McCollum et al. 2018). The numbers in the end of the model names indicate the model versions used in the scenarios. Below we present a brief introduction of all the models as a background to under the target scenarios.

 AIM/CGE 2.0/2.1

AIM/CGE is a general equilibrium model with technology explicit modules in power sectors (Fujimori et al. 2014). The model is developed to analyze the climate mitigation and impact. The energy system is disaggregated to meet this objective in both of energy supply and demand sides. Agricultural sectors have also been disaggregated for the appropriate land use treatment. The model is designed to be flexible in its use for global analysis.

C-ROADS-5.005

C-ROADS takes future population, economic growth and GHG emissions as scenario inputs specified by the user and currently omits the costs of policy options and climate change damage (Holz et al. 2018). The model aims to improve public and decision-maker understanding of the long-term implications of international emissions and sequestration futures with a rapid-iteration, interactive tool as a path to effective action that stabilizes the climate.

GCAM 4.2

Global Change Assessment Model (GCAM) 4.2 is a global integrated assessment model that represents the behavior of, and complex interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate[1].

The core operating principle for GCAM is that of market equilibrium. Representative agents in GCAM use information on prices, as well as other information that might be relevant, and make decisions about the allocation of resources. These representative agents exist throughout the model, representing, for example, regional electricity sectors, regional refining sectors, regional energy demand sectors, and land users who have to allocate land among competing crops within any given land region. Markets are the means by which these representative agents interact with one another. Agents pass goods and services along with prices into the markets. Markets exist for physical flows

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[1] https://jgcri.github.io/gcam-doc/v4.2/

such as electricity or agricultural commodities, but they also can exist for other types of goods and services, for example tradable carbon permits.

IMAGE 3.0.1

IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes that result[2]. More specifically, the model aims 1. to analyze interactions between human development and the natural environment to gain better insight into the processes of global environmental change; 2. to identify response strategies to global environmental change based on assessment of options and 3. to indicate key inter-linkages and associated levels of uncertainty in processes of global environmental change.

The IMAGE framework can best be described as a geographically explicit assessment, integrated assessment simulation model, focusing a detailed representation of relevant processes with respect to human use of energy, land and water in relation to relevant environmental processes.

MESSAGE V.3

MESSAGE V.3 is a hybrid model (energy engineering partial equilibrium model soft-linked to macro-economic general equilibrium model), which is an integrated assessment framework designed to assess the transformation of the energy and land systems vis-a-vis the challenges of climate change and other energy-related sustainability issues. It consists of the energy model MESSAGE, the aggregated macro-economic model MACRO and the simple climate model MAGICC6. The global model description is available at https://wiki.ucl.ac.uk/display/ADVIAM/MESSAGE.

MESSAGE-GLOBIOM 1.0 and MESSAGEix-GLOBIOM 1.0

MESSAGE-GLOBIOM is an integrated assessment framework designed to assess the transformation of the energy and land systems vis-a-vis the challenges of climate change and other sustainability issues (Fricko et al. 2017). It consists of the energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregated macro-economic model MACRO and the simple climate model MAGICC6. The global model description is available at http://data.ene.iiasa.ac.at/message-globiom/.

POLES EMF33

POLES is a partial equilibrium model and was originally developed to assess energy markets, combining a detailed description of energy demand, transformation and primary supply for all energy vectors. It provides full energy balances on a yearly basis using frequent data updates to as to deliver robust forecasts for both short and long-term horizons. It has quickly been used, in the late 90s, to assess energy-related CO2 mitigation policies. Over time other GHG emissions have been included (energy and industry non-CO2 from the early 2000s), and linkages with agricultural and land use models have been progressively implemented.

REMIND 1.7

The regionalized model of investment and development (REMIND) is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector[3]. It allows analyzing technology options and policy proposals for climate mitigation, and

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[2] https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation
[3] https://www.pik-potsdam.de/research/transformation-pathways/models/remind

models regional energy investments and interregional trade in goods, energy carriers and emissions allowances.

REMIND-MAgPIE 1.7-3.0

The is a version linking the REMIND model to the model of Agricultural Production and its Impact on the Environment (MAgPIE), which is a global land use allocation model. MAgPIE derives future projections of spatial land use patterns, yields and regional costs of agricultural production[4].

WITCH-GLOBIOM 3.1/4.4

WITCH is a hybrid economic optimal growth model, including a bottom-up energy sector and a simple climate model, embedded in a game theory framework[5]. The model evaluates the impacts of climate policies on global and regional economic systems and provides information on the optimal responses of these economies to climate change. The model considers the positive externalities from leaning-by-doing and learning-by-researching in the technological change.

Table 1: Key characteristics of the models that will be analysed in the following sections. The model classification diagnostics are from Kriegler et al. (2015).

Model Name	Equilibrium Type	Modelling Approach	Classification diagnostics
AIM/GCE	General equilibrium	Recursive dynamic	Medium response
C-ROADS	No equilibrium	Recursive dynamic	Not assessed
GCAM	Partial equilibrium	Recursive dynamic	High response
IMAGE	Partial equilibrium	Recursive dynamic	High response
MESSAGE	General equilibrium	Intertemporal optimization	High response
POLES	Partial equilibrium	Recursive dynamic	Medium response
REMIND	General equilibrium	Intertemporal optimization	High response
WITCH	General equilibrium	Intertemporal optimization	Low response

Note: Partial equilibrium models provide detailed description of processes and markets in one or more sectors, e.g. the energy sector, assuming the rest of the economy is unaffected by any change in the focused sectors. General equilibrium models cover the full economy allowing interactions among all the sectors. Non-equilibrium models are not based on standard economic theory and do not consider any equilibrium in the market of any economic sector.

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[4] https://www.pik-potsdam.de/research/projects/activities/land-use-modelling/magpie
[5] https://www.witchmodel.org/

4   Methods of scenario selection

There are a multitude of ways to select scenarios from a scenario database, and the criteria can vary across a wide range of dimensions. In this section, several aspects of scenario selection will be discussed: the method of classifying scenarios, challenges with interpreting the selected scenarios, and different methods to refine the scenario selection.

A "pathway" and "scenario" are often used interchangeably, but they are defined slightly differently. From SR15, the two terms are defined as:

- **Emission pathways**: Modelled trajectories of global anthropogenic emissions over the 21st century are termed emission pathways.
- **Scenario**: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts but, are used to provide a view of the implications of developments and actions.

In short, a scenario has a set of assumptions, while a pathway is just the trajectory over time.

4.1   Scenario classification

IPCC AR5 (Clarke et al. 2015) put scenarios into groups based on their CO_2-equivalent concentrations in 2100: Category 1 (430-480ppm CO_2-eq), Category 2 (480-530ppm CO_2-eq), and so on. AR5 used an addition set of sub-classifications such as carbon budget, scale of negative emissions, overshoot, technology restrictions, and policy restrictions.

Scenarios in SR15 were initially classified in a similar way to AR5 but used temperature and its level of overshoot (**Table 2**). The SR15 classification of scenarios into groups was also specifically associated to characteristics of 1.5°C and 2°C pathways. Similar detail was not used for scenarios around, say 3°C. SR15 additionally classified scenarios using a range of other criteria, but with less detail than in AR5. Most of the additional criteria are simply summaries of variables that can be estimated using the scenario database (e.g., year of peak temperature) and so they are much less useful.

Table 2.1 | **Classification of pathways that this chapter draws upon, along with the number of available pathways in each class.** The definition of each class is based on probabilities derived from the MAGICC model in a setup identical to AR5 WGIII (Clarke et al., 2014), as detailed in Supplementary Material 2.SM.1.4.

Pathway group	Pathway Class	Pathway Selection Criteria and Description	Number of Scenarios	Number of Scenarios
1.5°C or 1.5°C-consistent**	Below-1.5°C	Pathways limiting peak warming to below 1.5°C during the entire 21st century with 50–66% likelihood*	9	90
	1.5°C-low-OS	Pathways limiting median warming to below 1.5°C in 2100 and with a 50–67% probability of temporarily overshooting that level earlier, generally implying less than 0.1°C higher peak warming than Below-1.5°C pathways	44	
	1.5°C-high-OS	Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1–0.4°C higher peak warming than Below-1.5°C pathways	37	
2°C or 2°C-consistent	Lower-2°C	Pathways limiting peak warming to below 2°C during the entire 21st century with greater than 66% likelihood	74	132
	Higher-2°C	Pathways assessed to keep peak warming to below 2°C during the entire 21st century with 50–66% likelihood	58	

* No pathways were available that achieve a greater than 66% probability of limiting warming below 1.5°C during the entire 21st century based on the MAGICC model projections.

** This chapter uses the term 1.5°C-consistent pathways to refer to pathways with no overshoot, with limited (low) overshoot, and with high overshoot. However, the Summary for Policymakers focusses on pathways with no or limited (low) overshoot.

Table 2: Table 2.1 from SR15 showing the main classification of scenarios used in the report.

The temperature classification in SR15 was based on a simple climate model (MAGICC6), but another observationally constrained simple climate model (FAIR) was also used. MAGICC6 was used as it is well known, was used in AR5, and is familiar to the IAM community. FAIR is a new model and gives a much lower temperature response than MAGICC6. **Figure 1** shows the temperatures response for the 'Lower 2°C' scenarios for MAGICC6 and FAIR. For this grouping, MAGICC6 gives a 66% probability of staying below 2°C, while FAIR gives a temperature increase below 1.5°C. In effect, the 'Lower 2°C' scenarios using MAGICC6, would be below 1.5°C using FAIR. SR15 has a discussion on these points and the differences between MAGICC6 and FAIR but decided to use MAGICC6 for SR15 as the model is well known and has been involved in many peer reviewed publications. However, the introduction of FAIR has highlighted a potential issue with over reliance on MAGICC6 and this has instigated a model intercomparison of similar models to feed into AR6 (https://www.rcmip.org/). The results in this report will be exclusively based on the MAGICC6 classification, as used in SR15, but it is important to highlight that temperature-based classifications may depend on the simple climate model used.
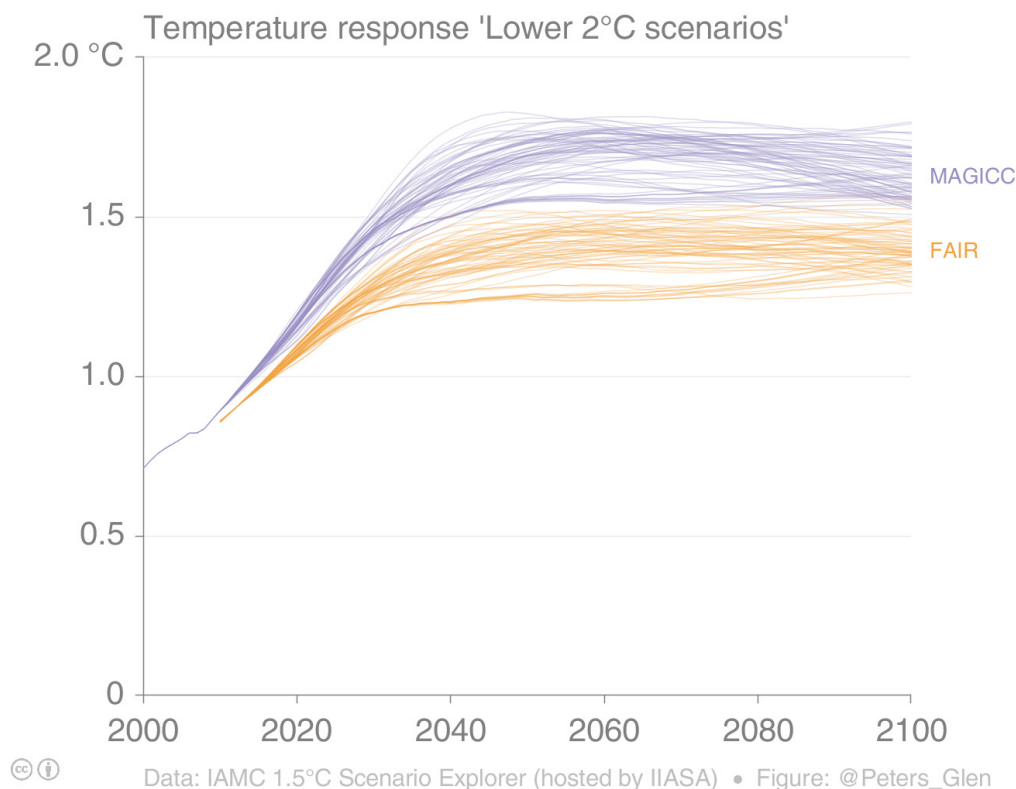
Figure 1: Lower 2°C pathways using MAGICC6 and FAIR from SR15. The scenario classification in SR15 was done using MAGICC6, but FAIR gives a much lower temperature response.

4.2 Interpreting classified scenarios

One challenge with working with selected groups of scenarios is that they are not a statistical sample of all possible scenarios, and thus, may be biased from the hypothetical statistical distribution of all scenarios. These biases may be exacerbated when selections are taken from an already biased scenario subset. In the case of SR15, 529 scenarios in total were submitted to the scenario database for analysis. Of those, 118 scenarios were removed from the scenario database as they did not satisfy certain criteria (e.g., not full century, missing data, or values inconsistent with history). In total, after including reference data, the publicly available database has 416 scenarios available for assessment.

Within the public SR15 scenario database, there is a biased distribution of model families, **Figure 2**. The REMIND and AIM/CGE models are represented by a much larger number of scenarios compared to the much more widely known IEA scenarios (one submitted from the World Energy Outlook and one from the Energy Technology Perspectives). Some models, such as REMIND and AIM/CGE, submitted many sensitivity cases, which provides useful analysis to the scenario database, but introduces bias. GCAM, a widely known IAM, had most of its scenarios removed from the scenario database based on selection criteria (of which the GCAM modellers disagree with, based on personal communication). Thus, if using the scenario database as a statistical ensemble, it will be greatly skewed towards the outcomes of REMIND, AIM/CGE, and other over-represented models, at the expense of other models. There are now ongoing discussions on how to adjust for these biases, and this may feed into the ongoing IPCC AR6.
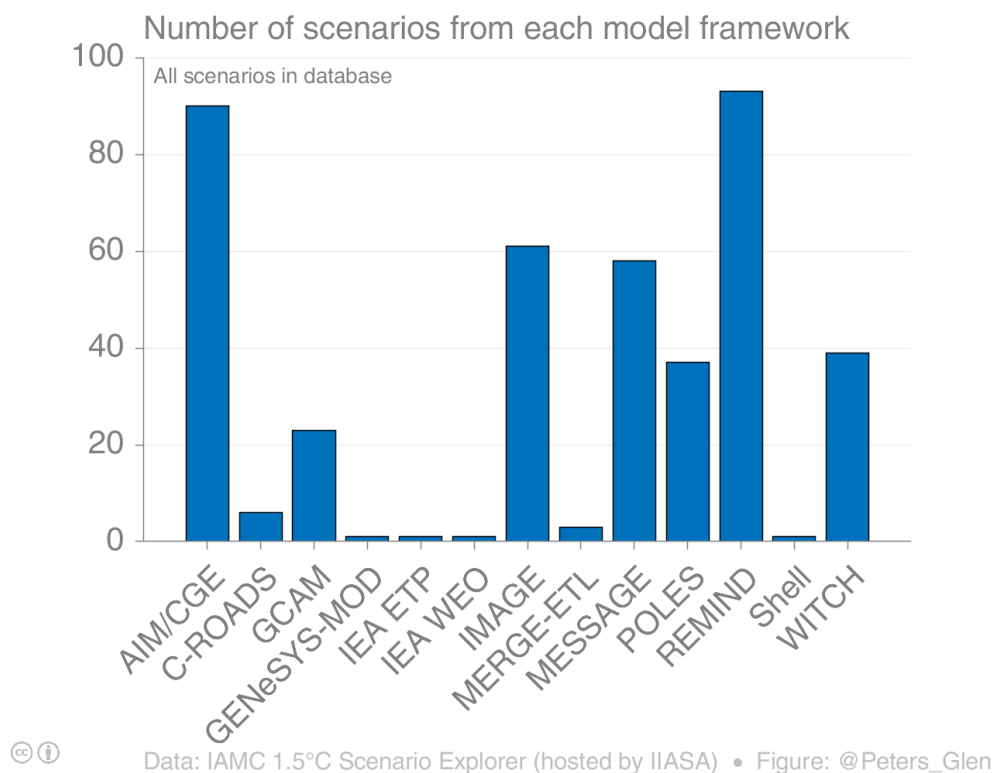
Figure 2: The distribution of model families across scenarios in the entire SR15 scenario database open for public assess.

When selecting subsets of scenarios the biases can be further exacerbated, such as on specific climate criteria '1.5°C with no or low overshoot' (**Figure 3**) or 'lower 2°C' (**Figure 4**). In the 1.5°C grouping, REMIND is represented the most, while AIM is far more represented in the 2°C grouping. Comparing across these different scenario groups may give misleading results, since the statistical representation underneath is not consistent. As a *hypothetical* example, if the 'lower 2C' scenarios were skewed towards a model that uses a lot of CCS, while the '1.5°C with no or low overshoot' is skewed towards a model that uses little CCS, then it may look statistically like 1.5°C requires less CCS than 2°C even though this is not true in each individual model. Using a group of scenarios does give an appreciation for the range of outcomes across scenarios, but care is needed not to overinterpret the statistical samples.

Number of scenarios from each model framework

1.5C low overshoot
Below 1.5C
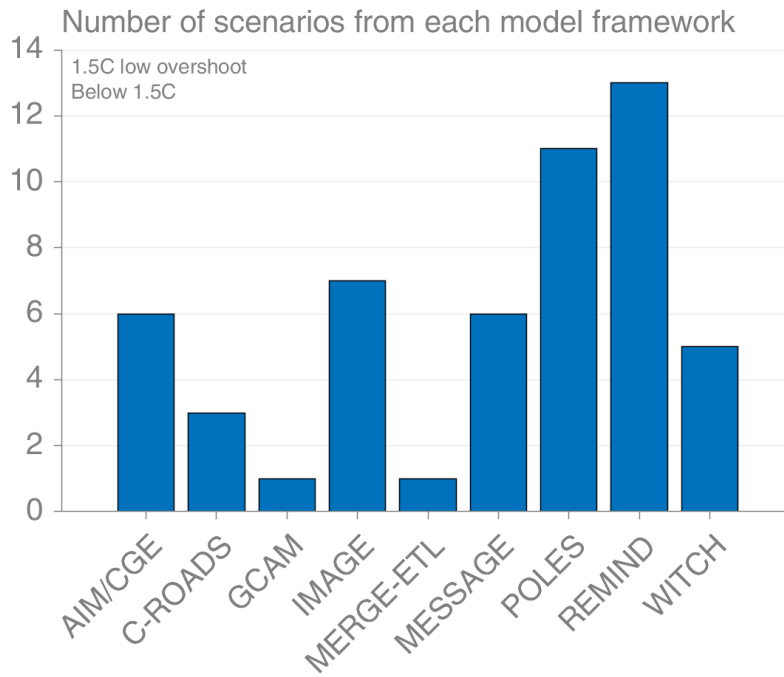
Data: IAMC 1.5°C Scenario Explorer (hosted by IIASA) • Figure: @Peters_Glen

Figure 3: The distribution of models with no or low overshoot of 1.5°C, see **Table 2** for definitions.

Number of scenarios from each model framework
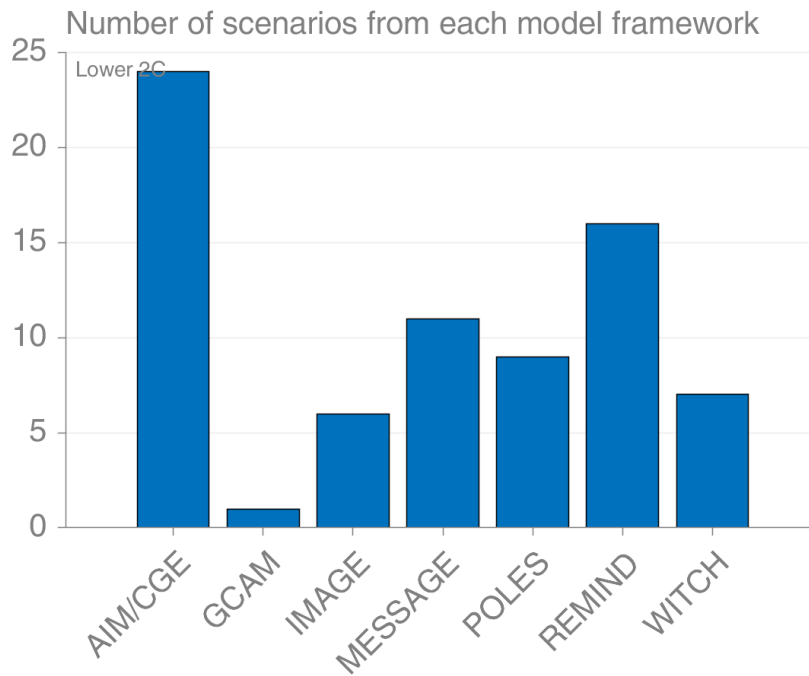
Lower 2C

Data: IAMC 1.5°C Scenario Explorer (hosted by IIASA) • Figure: @Peters_Glen

Figure 4: The distribution of models in the lower 2°C category, see **Table 2** for definitions.

4.3   Selection criteria

After an initial scenario selection, it is further possible to refine the selection using additional criteria. As all mitigation pathways consistent with 1.5°C and 2°C global warming are very demanding, one can argue that some of the aspects of the scenarios are unrealistic, very difficult, or in conflict with other societal objectives (e.g., SDGs).

The amount of bioenergy with carbon capture and storage (BECCS) on mitigation scenarios has come under a lot of scrutiny: is realistic and is it sustainable? What is sustainable and not sustainable depends on the circumstances and what resources are used to produce this bioenergy. Hence, to give a clear constraint on the scenarios as a selection criterion is difficult. The special report on land (Arneth et al. 2019) show that pathways consistent with 1.5°C and 2°C indicate changes in forest area between 2010 and 2050 of between -2 and 12 million km^2. As much as 7 million km^2 of land might be needed to produce bioenergy crops in 2050, compared to 0.14 million km^2 today. Different sustainability concerns become a major issue around 1 to 4 million km^2 land used for BECCS. The risk is clear already at 0.1 to 1 million km^2 in scenarios with high population growth, low income and slow technological development. We cannot directly translate area used for BECCS to carbon captured by BECCS since that is dependent on the circumstances, but the large span shows that there is not a clear-cut definition of what is a reasonable selection criterion for scenarios. We explore this further, but our analysis will be based on criteria of $500GtCO_2$ cumulative BECCS and of $12GtCO_2/yr$ BECCS in 2100 as starting points.

Figure 5 shows how the number of scenarios from different model families changes as the scale of BECCS increases. As the scale of BECCS increases, the number of scenarios from each model family increases. As an example, the REMIND model framework has one scenario with a little over $100GtCO_2$ cumulative BECCS in 2100, and this increases gradually until a scenario with 1200 $GtCO_2$ cumulative BECCS. Similar findings are found for the amount of BECCS in 2100.

If criteria are taken, such as $500GtCO_2$ cumulative BECCS or $12GtCO_2/yr$ BECCS in 2100, several modelling frameworks will not be represented. GCAM and MERGE will no longer be in the scenario selections, and several scenarios from sensitivity analysis will be removed. In total, based on these criteria, for 1.5°C with no or low overshoot, only 23 scenarios will remain from the modelling groups AIM/CGE, C-ROADS, IMAGE, MESSAGE, POLES, REMIND, and WITCH. For lower 2°C, 53 scenarios remain, all from the same model frameworks.

It is also possible to constrain the level of BECCS in 2050, which links more closely to the IPCC special report on climate change and land (Arneth et al. 2019) (**Figure 6**), a value of $5GtCO_2/yr$ in 2050. A constraint of $5GtCO_2/yr$ in 2050 turns out to be not so different to the constraint of $12GtCO_2/yr$ in 2100, in that both constraints select out similar scenarios. It is possible to implement additional, different, or more strict criteria, which will further restrict the scenarios available for analysis and the model frameworks that are represented. At the end of the day, a balance (trade-off) is required between different criteria to avoid removing all scenarios.
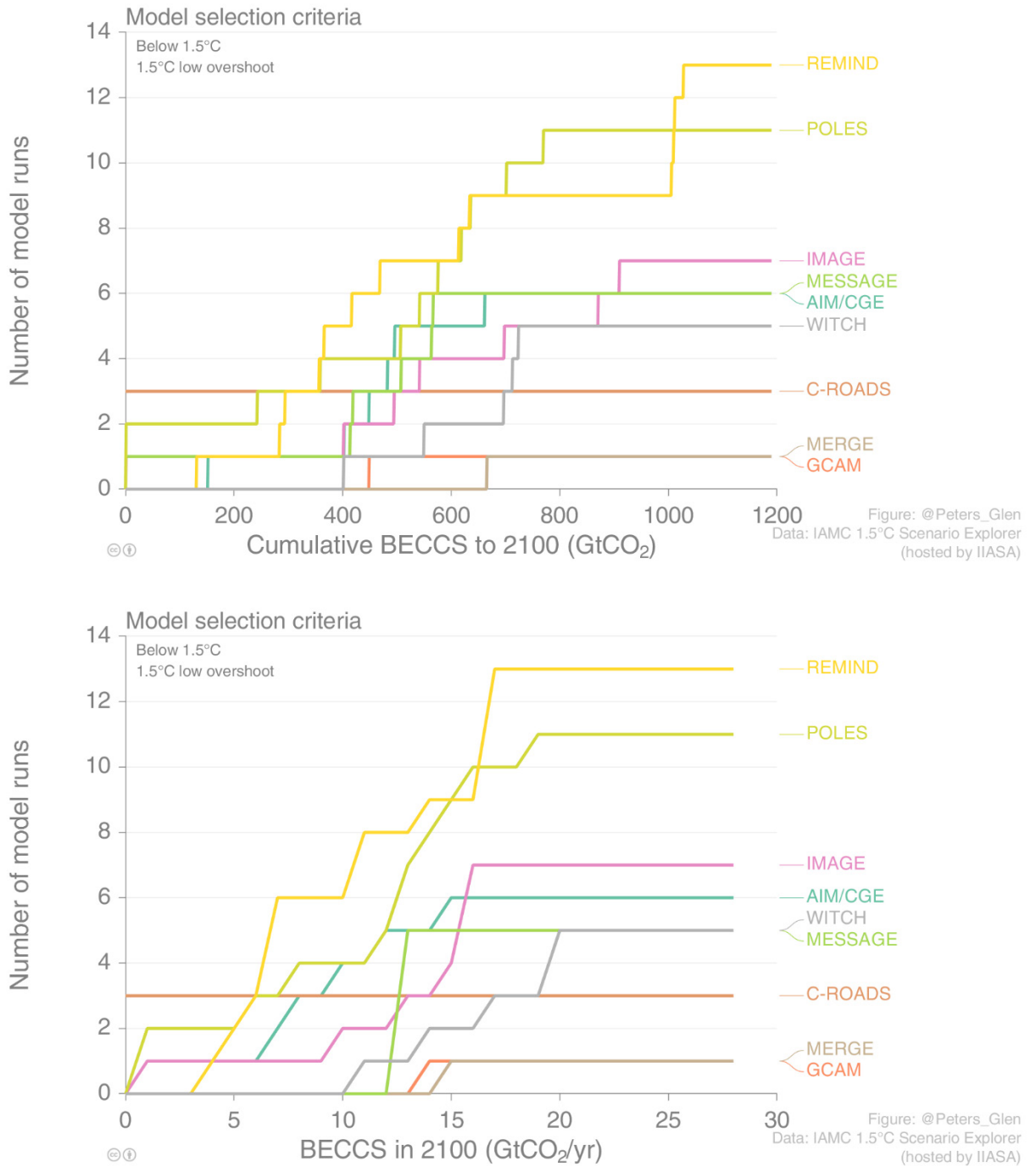
Figure 5: The number of scenarios from the main modelling frameworks as a function of BECCS, either cumulative (top) or in 2100 (bottom).

What relevant information do the integrated assessment models and scenarios from the 1.5 °C special report provide for Norway?
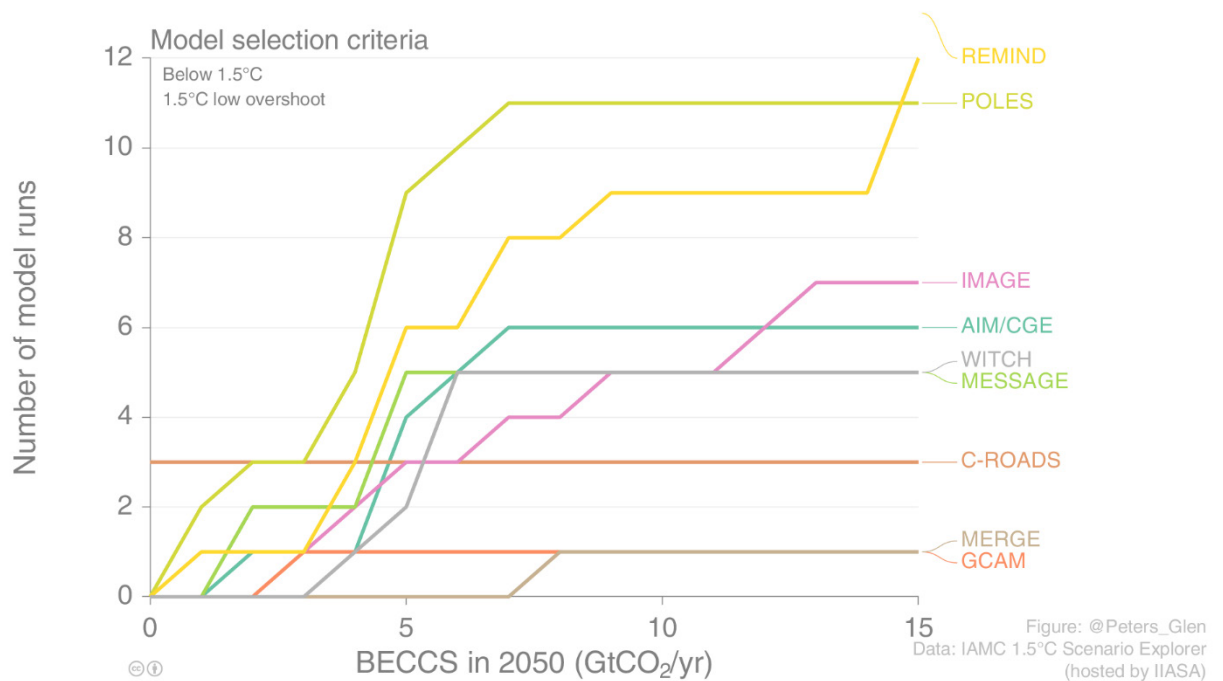
20

Figure 6: The number of scenarios from the main modelling frameworks as a function of BECCS to 2050.

It is important to note that filtering scenarios across one dimension, may lead to conflicts in another dimension (**Figure 7**). Even though attempts were made to minimise the use of BECCS, the land impacts are still significant, up to 400 million hectares for energy crops (supplying up to 250EJ of bioenergy) and 1500 million hectares additional forests. The fact remains that 1.5°C is extremely ambitious and restricting BECCS often means that bioenergy is still used as bioenergy (without CCS) and that afforestation increases to compensate for the lower BECCS. It is, of course, possible to implement other restrictions, such as on land-use or bioenergy, but ultimately, similar issues will arise, and ultimately, all scenarios will be filtered out. 1.5°C, as explained in SR15 and SRCCL, will require some level of trade-offs.
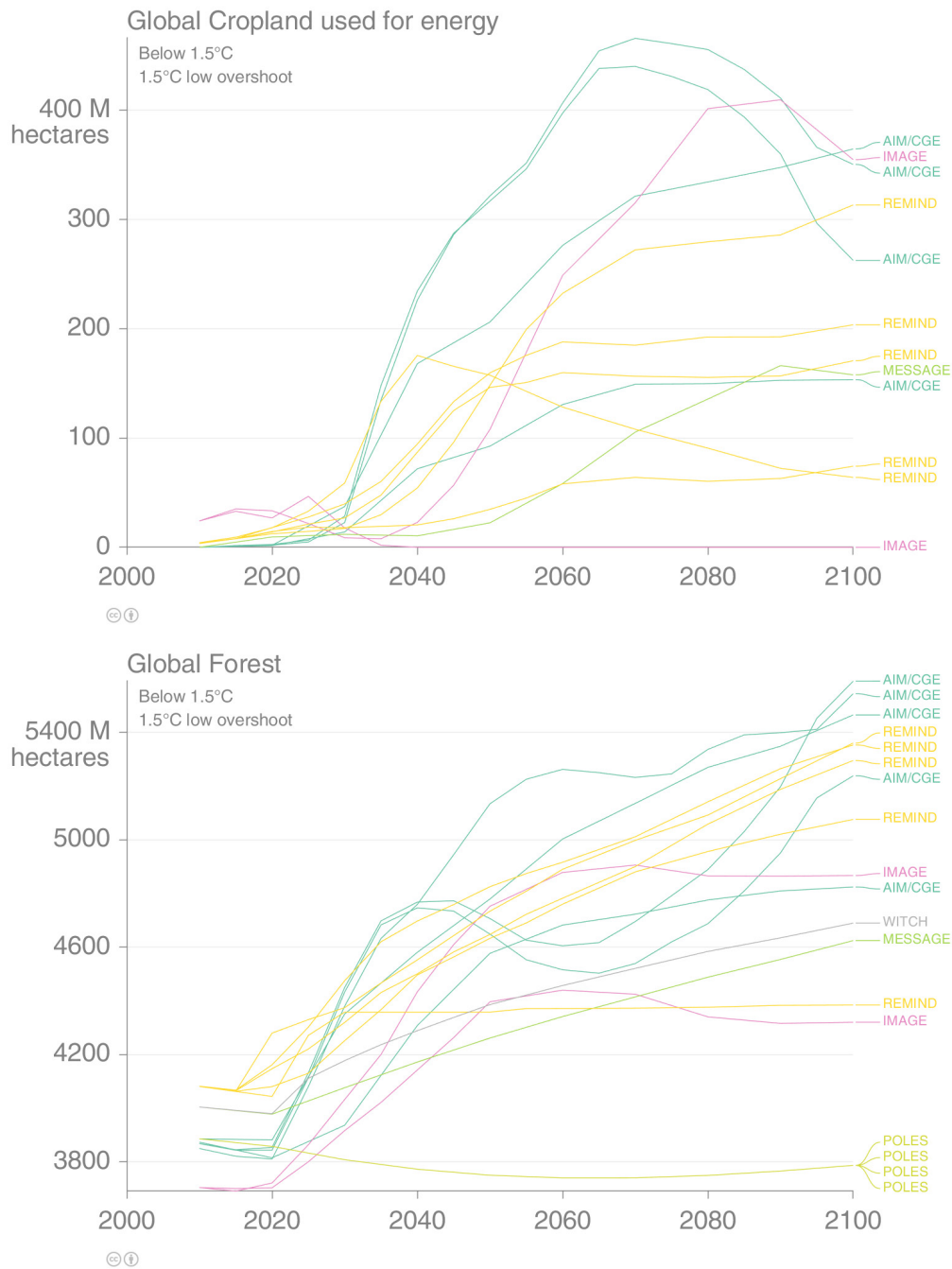
Figure 7: The land areas used for energy crops (top) and forests (bottom) in 1.5°C scenarios with low overshoot, filtered based on criteria on BECCS.

It is also possible to select scenarios based on land area. It is not necessarily BECCS that is the problem, but rather, the impacts caused by the land use. Similarly, or even worse, impacts could occur for large scale afforestation, which can sometimes cover significantly more land area. One challenge on using land areas is that not all models report detail land use data, and so some model frameworks would drop out because of lack of relevant data. Additionally, the extent of land use may not correlate to impacts. The use of land for BECCS might require more intensive use, while afforestation less intensive, with the resulting impacts from BECCS larger even though the land area is smaller. To select scenarios on land area would really require the land to somehow to be graded

by quality or impacts. Since that data does not exist, then there is limited option to do selections based on land area.

4.4 Comparison of selection criteria

Figure 8 shows a comparison of the different selection criteria as applied to BECCS, for both 1.5°C and 2°C scenarios. The constraint of 5GtCO$_2$/yr BECCS in 2050 is clearly weaker than the combined constraint of 12GtCO$_2$/yr in 2100 and cumulative BECCS of 500GtCO$_2$ through to 2100. These choices propagate down to the land used for cropland (**Figure 9**), but not so much forest area change (**Figure 10**). The changes are more significant for 1.5°C, less significant for 2°C.

The land area for bioenergy is reduced significantly for 1.5°C with the 12GtCO$_2$/yr in 2100 cut off, but the effect is less dramatic for 2°C. There are two factors that affect this. First, the constraint was applied to BECCS, but scenarios that have constrained BECCS generally do not have constrained bioenergy. Thus, some scenarios with a constraint on BECCS will have little impact on bioenergy use, as the model had preferentially used bioenergy in other parts of the energy system (e.g., biofuels in transportation). This is particularly evident in the lower 2°C (**Figure 9**, bottom-right), where scenarios are using bioenergy for reasons other than BECCS. Second, a more technical issue discussed earlier, is that the groupings of scenarios have different model coverage, and in particular AIM/CGE is far more representative in 2°C scenarios and uses a lot of bioenergy without CCS.

We additionally assessed using a selection based on bioenergy use, limiting bioenergy to 200EJ per year in 2100 (figures not shown). This gave a similar outcome for BECCS to the 12GtCO$_2$/yr limit, but still lead to some large land-use areas for bioenergy crops (over 400 million hectares) and lead to little change in the total increase in forest area (over 1500 million hectares).

Moving to afforestation in the constrained scenarios, **Figure 10** shows that the forest area change is significantly larger for afforestation compared to cropland. The cropland areas change up to 800 million hectares in the most extreme cases, and up to 1500 million hectares in the case of afforestation. The underlying reason is that BECCS is more productive at removing carbon per unit of land area (discussed in detail later). Again, the sample distribution is heavily affected by one model, AIM/CGE. Whilst the vast majority of IAMs have considerable afforestation, some have deforestation and this is particularly evident in POLES.

It is possible to have constraints on land areas, but the scenario data is not of sufficient quality to do this consistently. Each model has submitted different variables for land-use and some models don't include any land-use data. The use of land-use data as a constraint would probably require new primary data collection from the modelling groups, plus additional efforts to ensure they report data with the same land-use definitions.

Hopefully these figures illustrate the challenges with selecting scenarios. It is very difficult with the scenario information available to select scenarios that meet several criteria. Placing limits on BECCS is justified, but this may come at the expense of greatly increased use of other types of bioenergy use, forest areas, etc. Ultimately, it is the quality of the land use that is of interest (SRCCL). However, scenarios do not in any way differentiate the land use by quality, or its water use, fertilizer use, or degradation. Almost by definition, the land use in scenarios will be sustainable according to the modelling groups. What matters is how this land is then used in practice, in the real world.

It is possible to go through a range of different scenario groupings, but they will all ultimately lead to the same challenges. Addressing one criterion, may lead to problems in other criteria. And putting constraints on all possible criteria, may only leave behind a small sample of scenarios. This partly indicates the challenges to keep temperatures below 1.5°C or 2°C, in that there are very few options available that do not lead to major trade-offs.

Figure 8: A comparison of BECCS deployment in 1.5°C scenarios with no or low overshoot (left) and lower 2°C (right) with all scenarios include (top), maximum of 5GtCO$_2$/yr BECCS in 2050 (middle), and maximum of 12GtCO$_2$/yr BECCS in 2100 combined with cumulative maximum of 500GtCO$_2$ through to 2100 (bottom).
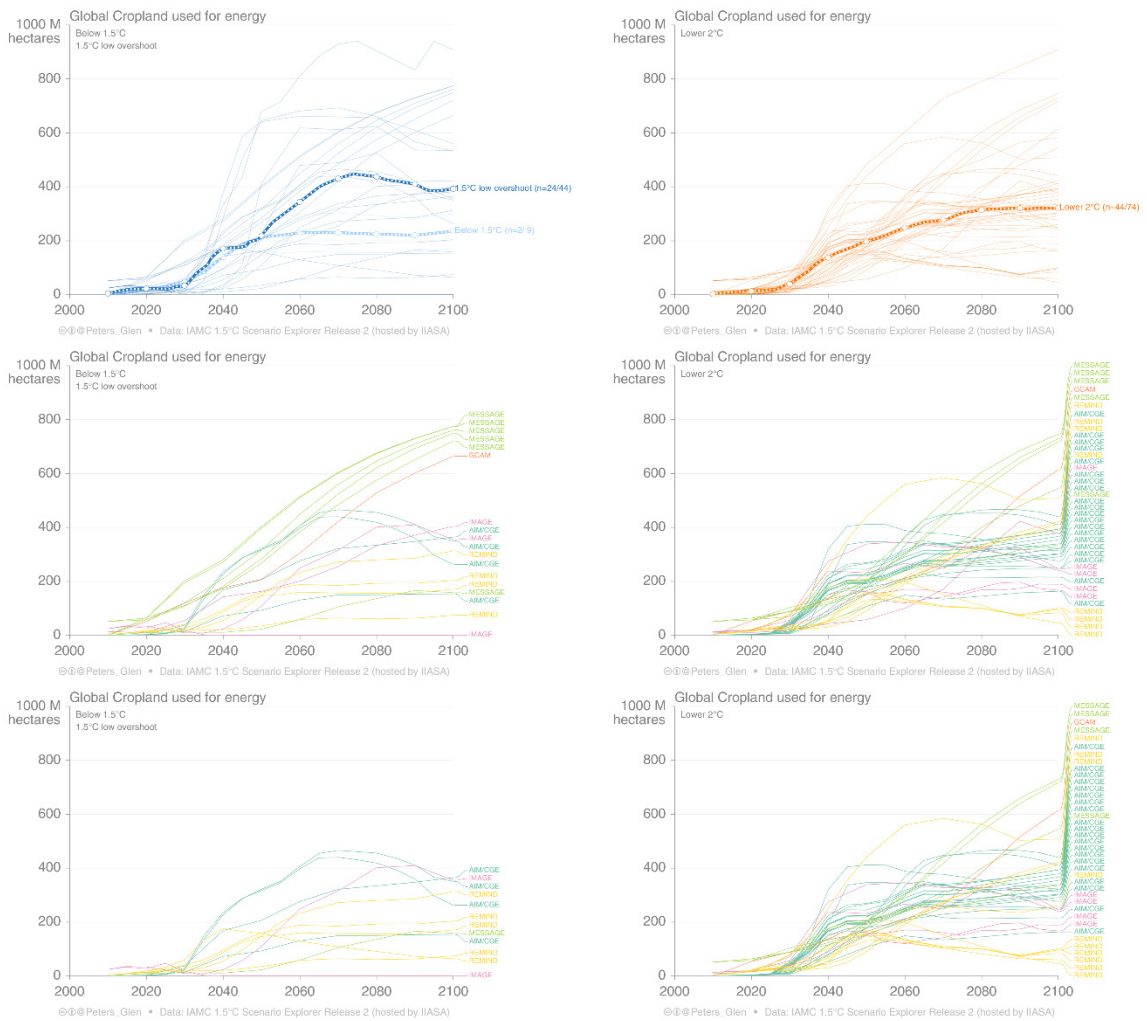
Figure 9: A comparison of bioenergy cropland use for 1.5°C scenarios with no or low overshoot (left) and lower 2°C (right) with all scenarios include (top), maximum of 5GtCO$_2$/yr BECCS in 2050 (middle), and maximum of 12GtCO$_2$/yr BECCS in 2100 combined with cumulative maximum of 500GtCO$_2$ through to 2100 (bottom).

Figure 10: A comparison of forest area change for 1.5°C scenarios with no or low overshoot (left) and lower 2°C (right) with all scenarios include (top), maximum of 5GtCO$_2$/yr BECCS in 2050 (middle), and maximum of 12GtCO$_2$/yr BECCS in 2100 combined with cumulative maximum of 500GtCO$_2$ through to 2100 (bottom).

4.5 Selection criteria used

After considering a range of options for classifying scenarios, and discussed in the previous sections, we have decided to retain the original choice by the Environment Agency: maximum of 12GtCO$_2$/yr BECCS in 2100 combined with cumulative maximum of 500GtCO$_2$ through to 2100. While not ideal on every dimension, the choice does seem to limit the overall land impacts, without removing all scenarios. The choice appears to be practical, but it is not perfect.

5 Emission pathways by region and sector (a)

Topics discussed: *a) Global and regional emission pathways, both for all GHGs and CO_2 only, and emission pathways for different sectors.*

5.1 Characteristics of emission pathways

While it should be seemingly straightforward to present CO_2 or GHG emission pathways associated with different scenarios, the presence of negative emissions gives rise to some ambiguities. Most scenario studies only report and present the variable "total carbon dioxide emissions from fossil fuel combustion and industrial processes", which represents "net" CO_2 emissions. This variable includes the negative emissions from Bioenergy with Carbon Capture and Storage (BECCS), meaning that the net emissions can be negative (**Figure 11**). If BECCS were not included in the "fossil fuel combustion and industrial process" emissions, then it would not be possible to get negative emissions. This is not well understood and often leads to the perception that negative emissions start decades into the future, when emissions become net negative (Anderson and Peters 2016). As shown in **Figure 11**, gross positive emissions (from the burning of fossil fuels, industry, and net deforestation) do not go to zero, and indeed, there exists virtually no scenario that has zero gross positive emissions, while negative emissions start to scale up already today. The negative emissions become much greater than the positive emissions in the latter half of the century, leading to net negative emissions (discussed further in the section on negative emissions).

In the following sections, CO_2 and GHG emissions are discussed at the global level and by region. The figures represent "net" emissions. The section on negative emissions discusses gross negative emissions. In all results where relevant, medians are used instead of averages.
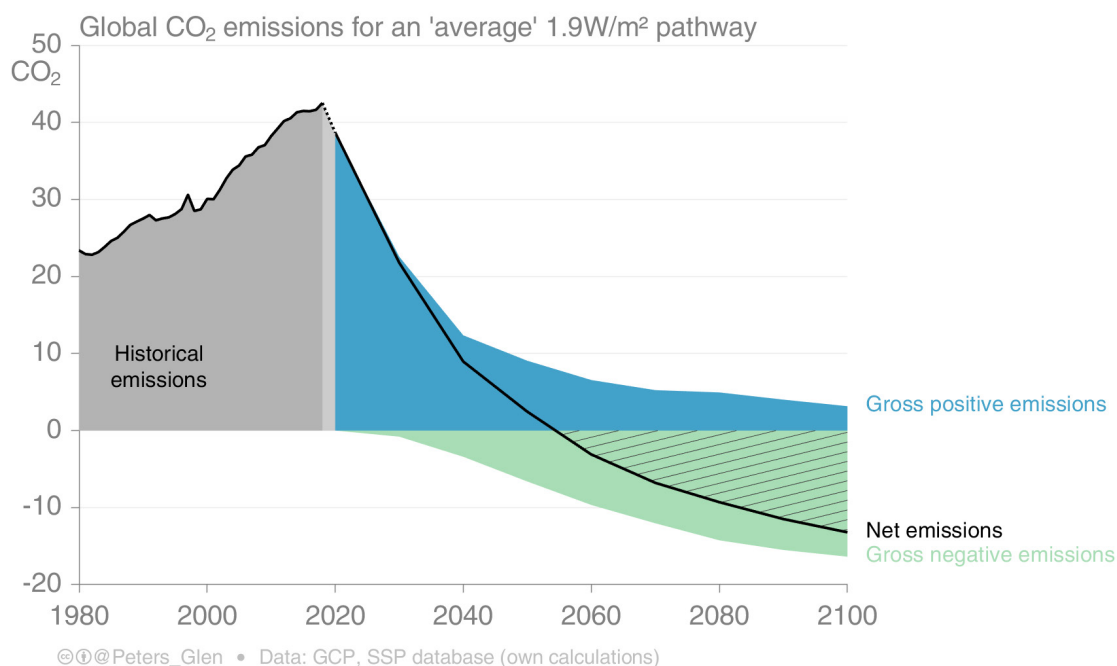
Figure 11: A stylised figure showing the gross positive (blue), negative (green), and net (black line) emissions in a below 1.5°C pathway (based on the median of the SSPs for RCP1.9). The net emissions reported in most scenarios databases includes BECCS.

5.2 CO2 emission pathways

Figure 12 show the global net CO_2 emissions for the 1.5°C scenarios selected in this study, highlighting the model framework in each case, while **Figure 13** shows the four main regions used in the IPCC (the Economies in Transition are not shown). At the global level, net zero CO_2 emissions are reached around 2050, depending on the scenario, and then emissions become negative. Net-zero CO_2 emissions also occur at the regional level, and often around 2050 depending on regional circumstances.

It is perhaps more instructive to compare the scenarios globally and by region using the year that net emissions become zero (**Table 3**). For the median of 1.5°C scenarios that meet the criteria for inclusion in the analysis, global CO_2 emissions reach zero in 2051, but only Latin America reaches net-zero before that year (2042) and OECD reaches zero well after (2058). This indicates that most of the negative emissions occur in Latin America, either through afforestation or BECCS. This result is also somewhat driven by REMIND, which finds greater negative emissions in Latin America than other scenarios.

Moving to 2°C pathways, the years for reaching net-zero emissions are shifted back about 10 to 20 years depending on the region. There is only a small shift back for Latin America (to 2046 instead of 2042), but the world shifts back 23 years (zero in 2074 instead of 2051) and OECD back 20 years (2078 instead of 2058). For both 1.5°C and 2°C pathways, there is a substantial number of scenarios that do not reach zero before 2100.
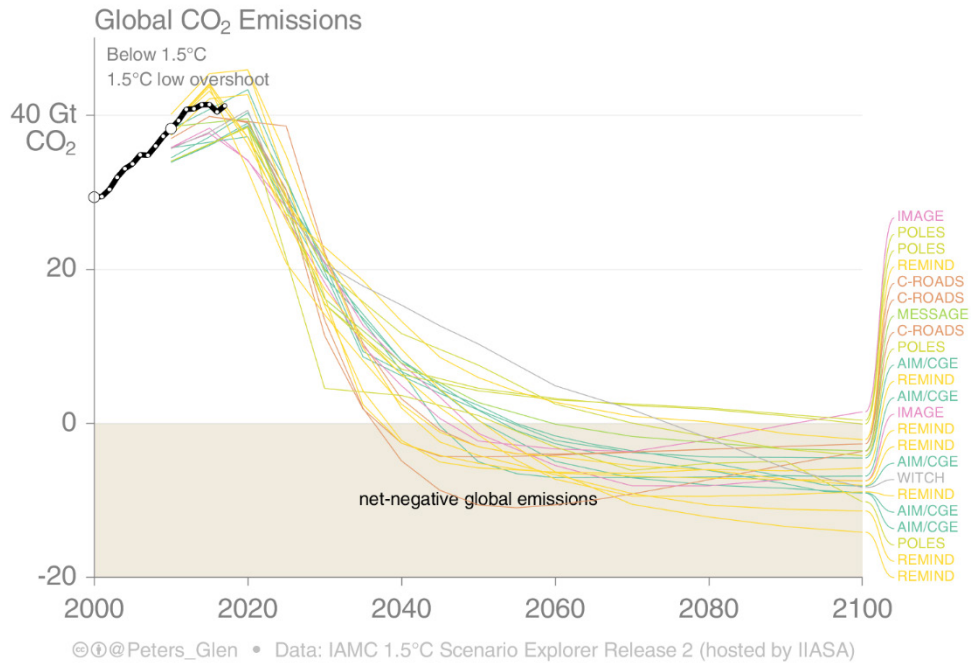
Figure 12: Global CO$_2$ emissions for the 1.5°C pathways selected using the selection criteria in this study.
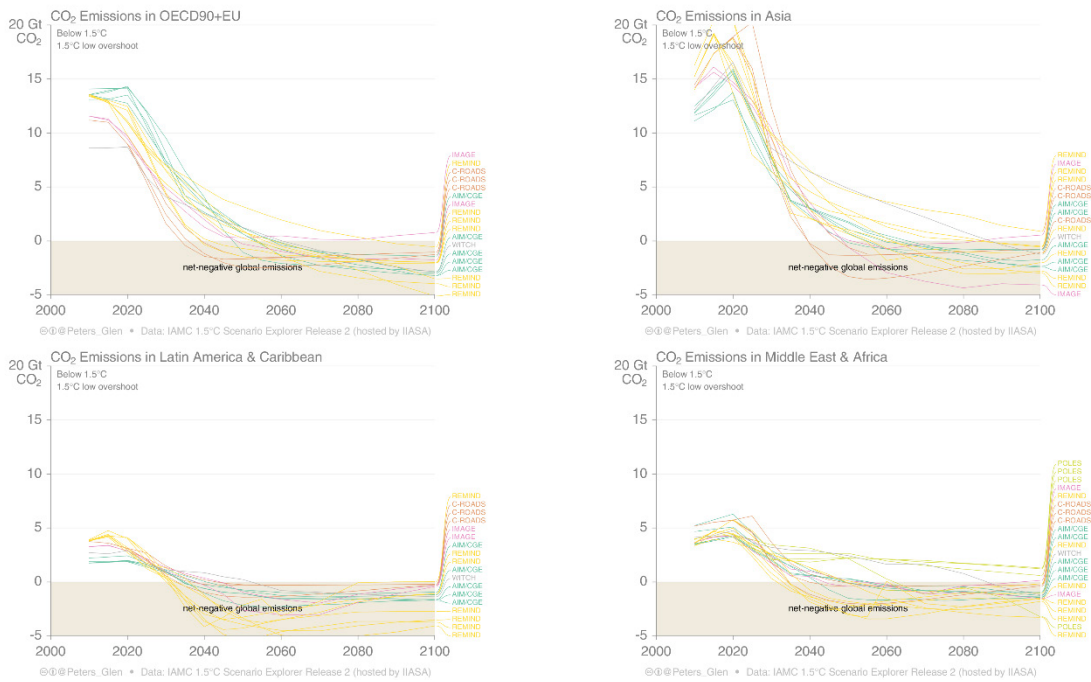

Figure 13: Regional CO$_2$ emissions for the 1.5°C pathways selected using the selection criteria in this study.

Table 3: Table showing when net emissions become zero for CO_2 and GHG in the selected 1.5°C and 2°C scenarios.

			Percentiles				
			0	25	50	75	100
CO_2	1.5°C	**Global**	**2037**	**2048**	**2051**	**2059**	**>2100**
		OECD	2034	2049	2058	>2100	>2100
		Asia	2040	2051	2066	>2100	>2100
		Latin America	2027	2037	2042	>2100	>2100
		Middle-East & Africa	2028	2050	2057	2075	>2100
	2°C	**Global**	**2050**	**2065**	**2074**	**>2100**	**>2100**
		OECD	2046	2064	2078	>2100	>2100
		Asia	2054	2074	2089	>2100	>2100
		Latin America	2032	2041	2046	2062	>2100
		Middle-East & Africa	2047	2063	2099	>2100	>2100
GHG	1.5°C	**Global**	**2045**	**2061**	**2071**	**>2100**	**>2100**
		OECD	2040	2061	2070	>2100	>2100
		Asia	2049	2081	>2100	>2100	>2100
		Latin America	2032	2045	2063	>2100	>2100
		Middle-East & Africa	2042	2066	2098	>2100	>2100
	2°C	**Global**	**2065**	**2089**	**>2100**	**>2100**	**>2100**
		OECD	2060	2078	>2100	>2100	>2100
		Asia	2080	>2100	>2100	>2100	>2100
		Latin America	2041	2049	2092	>2100	>2100
		Middle-East & Africa	2055	>2100	>2100	>2100	>2100

5.3   GHG emission pathways

Figure 14 shows the global net GHG emissions for the 1.5°C scenarios selected in this study, highlighting the model framework in each case, while **Figure 15** shows the four main regions used in the IPCC (the Economies in Transition are not shown). The median year for reaching zero GHG emissions is around 2070 before becoming negative, and this is around 20 years later than the net-zero year for emissions of CO_2 alone. Despite the Paris Agreement calling for net-zero GHG emissions between 2050 and 2100, only about half of the scenarios need to reach net-zero in that period to meet the 1.5°C target. This suggests that Article 4 of the Paris Agreement may be too strong on requiring net-zero GHG emissions, though net-zero CO_2 emissions are probably more important.

Table 3 allows comparison of the CO_2 and GHG net-zero years for 1.5°C and 2°C pathways. For 1.5°C scenarios, globally GHG emission reach zero in 2071, 20 years later than for CO_2 only. Latin America reaches net-zero GHG emissions in 2063, and OECD reaches zero GHG emissions in 2070 both more similar to the global level compared to CO_2 emissions. Moving to 2°C pathways, the zero years are shifted back even further. Many 2°C scenarios do not require zero GHG emissions before 2100. Latin America is the only region where more than half the scenarios reach net zero GHG emissions before 2100.
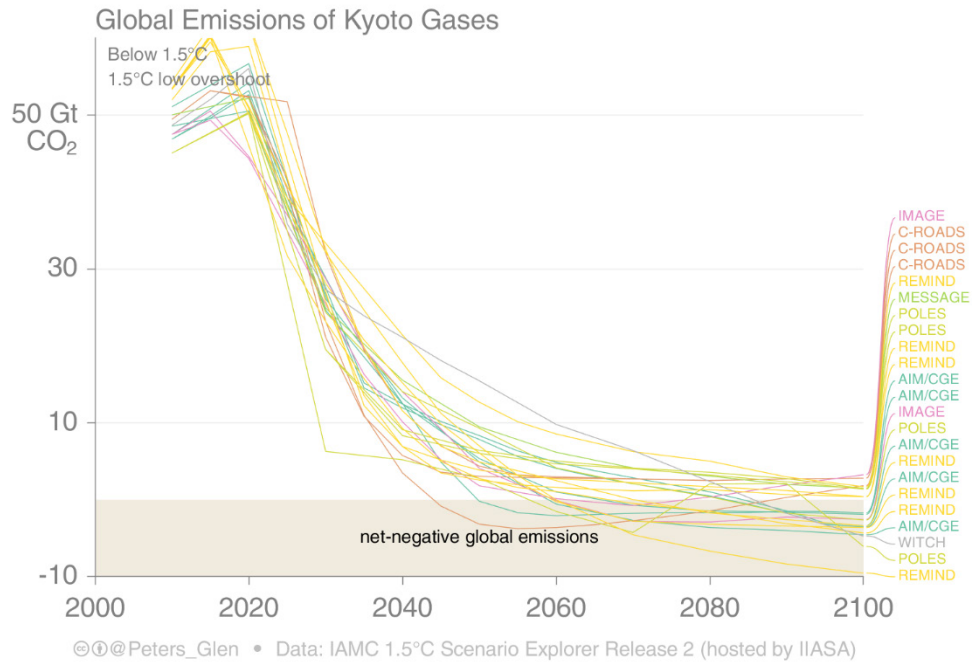
Figure 14: Global GHG emissions for the 1.5°C pathways selected using the selection criteria in this study.
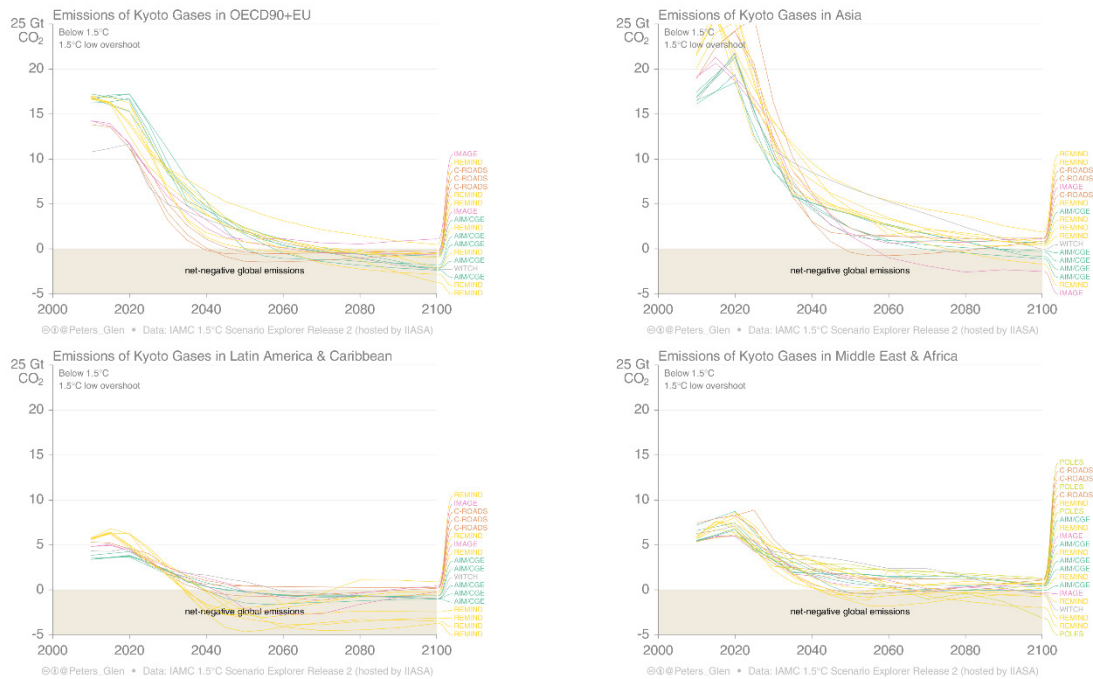

Figure 15: Regional GHG emissions for the 1.5°C pathways selected using the selection criteria in this study.

5.4   Non-CO₂ emission pathways

Total GHG emissions are dominated by CO_2 emissions (from fossil sources and land-use change), with non-CO_2 emissions covering around 20-25% of the total (depending on the choice of Global Warming Potential). The non-CO_2 emissions are dominated by CH_4, with N_2O and fluorinated gases making smaller contributions. The reduction in GHG emissions (Figure 14) are dominated by the reductions in CO_2 emissions (Figure 12), but non-CO_2 reductions are important and should not be downplayed. **Figure 16** shows steep reductions in non-CO_2 emissions, with 1.5°C scenarios showing an average reduction across scenarios of 35% by 2030 and 53% by 2050 while 2°C scenarios show slightly lower reductions of 31% for 2030 and 49% for 2050 (not shown). Unlike CO_2 emissions, the non-CO_2 emissions do not reach zero (or go negative) as there are currently no removal options for these species and agricultural sources are hard to mitigate (CH_4 from agriculture and N_2O from fertiliser).
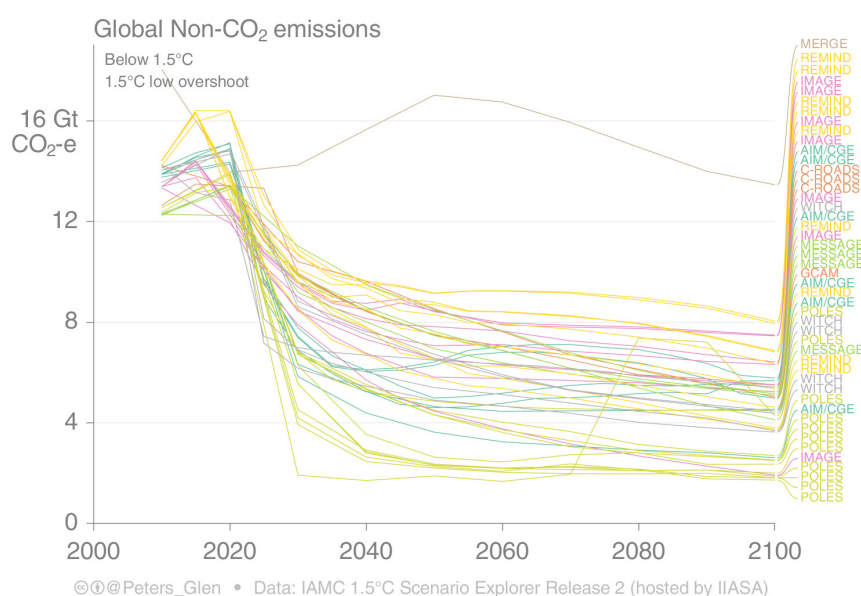

Figure 16: Global non-CO₂ emissions for the 1.5°C pathways selected using the selection criteria in this study using the Global Warming Potentials from IPCC AR5 with a 100 year time horizon.

Figure 17 shows the emission pathways for CH_4 and N_2O in both 1.5°C and 2°C scenarios. Rapid short-term reductions occur for CH_4 in both 1.5°C and 2°C scenarios, due to reductions in CH_4 from energy production (leaks, mining, etc). Reductions in the agricultural sector are limited, as most scenarios do not incorporate technologies to remove CH_4 from the atmosphere, reduce emissions from agricultural source (e.g., CH_4 from ruminants or rice production), or reduce consumption of food products with CH_4 in the supply chain (e.g., meat from ruminants). Scenarios show limited or no reduction in N_2O emissions which stem mainly from fertilisations. Particularly since scenarios depend heavily on yield improvements and large-scale bioenergy, fertiliser use continues at high levels in most scenarios. Emissions from fluorinated GHGs (PFC, SF6, HFC) rapidly decline across nearly all scenarios.

There are a range of other non-GHG emissions sources that lead to a radiative imbalance, both warming and cooling. Most notable are some air pollutants such as sulphur dioxide and black and organic carbon. Most scenarios have strong reductions in air pollutants with sulphur dioxide emissions dropping around 50% by 2030 and 75% by 2050 when averaged across 1.5°C scenarios. The reductions in black carbon are a little weaker, with 25% by 2030 and 52% by 2050, and organic carbon weaker again with 12% by 2030 and 25% by 2050.
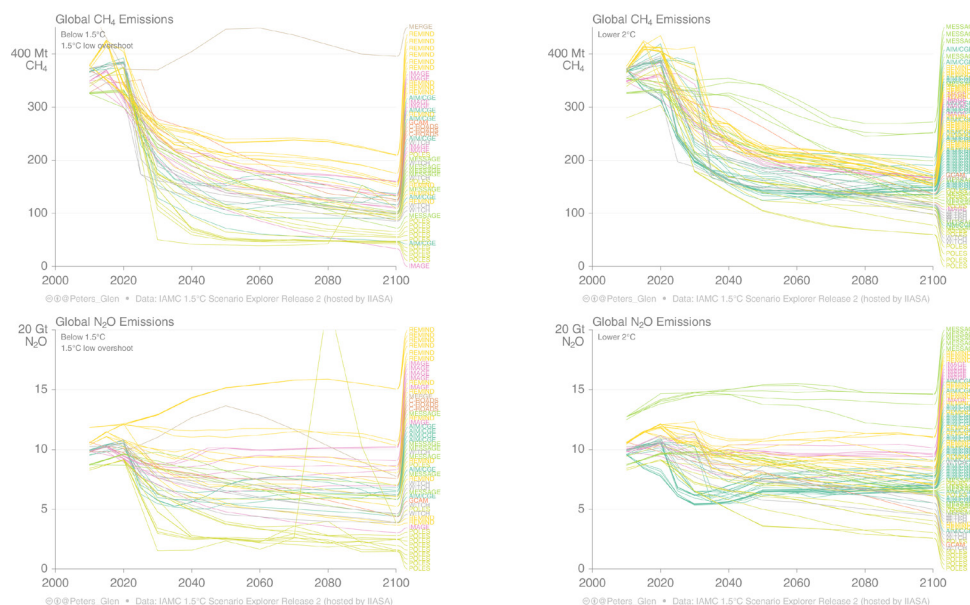
Figure 17: CH$_4$ (top) and N$_2$O (bottom) emission pathways in 1.5°C (left) and 2°C (right) scenarios used in this study.

5.5 Net-zero years

The Paris Agreement calls for a balance in the sources and sink of GHG between 2050 and 2100 (Article 4), but **Table 3** shows that not all 1.5°C or 2°C scenarios meet that requirement. Recent scientific studies confirm that zero GHG emissions are not necessary for 1.5°C or 2°C, though a target of net-zero CO$_2$ emissions is probably more relevant (Tanaka and O'Neill 2018). As expected, 1.5°C scenarios reach net-zero emissions before 2°C scenarios. When interpreting the Paris Agreement Article 2 – "well below 2°C…pursuing…1.5°C" – the additional net-zero constraint (Article 4) would at least indicate a pathway closer to 1.5°C versus 2°C based on the scenarios presented in the previous section.

As background, there are several reasons why net-zero CO$_2$ emissions are necessary, but not necessarily GHG emissions. Science has clearly shown that the CO$_2$ induced warming is roughly proportional to cumulative CO$_2$ emissions. This was highlighted in IPCC AR5, and particularly WG1 Figure SPM10. This implies that to stop temperature change, then CO$_2$ emissions must go to zero. This result, often counterintuitive, is since zero CO$_2$ emissions will lead to a decline in CO$_2$ concentrations, but this is offset by the slow warming of the ocean system – in short, the warming that is already in the 'pipeline' when CO$_2$ emissions reach net-zero is offset by the declining CO$_2$ concentration.

Most non-CO$_2$ greenhouse gases have a simple half-life (exponential) decay after they have been emitted. A consequence of this is that constant emissions of non-CO$_2$ GHGs lead to a constant temperature change (Aamaas et al. 2013), consequently, declining non-CO$_2$ emissions leads to a declining temperature contribution. Thus, zero CO$_2$ emissions are necessary to stop temperatures rising further, while non-CO$_2$ emissions only need to decline sufficiently to lead to a declining temperature. In this way, zero CO$_2$ emissions combined with declining non-CO$_2$ emissions could be enough to stabilize (and even reduce) the temperature contribution. The lower the total non-CO$_2$ emissions get, the lower will be their warming effect, and so deep mitigation of non-CO$_2$ emissions is also essential.

5.6 Equity considerations

Another counterintuitive finding is that OECD countries, who have larger responsibility for historical contributions to climate change and greater capacity for mitigation, do not reach net-zero earlier and do not mitigate faster than other regions. This is really a consequence of model set up. Equity considerations are not included. A typical model, which goes quickly to a global carbon price, will mitigate where it is cheapest. If mitigation is cheaper in India, for example, it would happen there first rather than in the OECD. In addition, some developing countries, particularly Latin America, have much greater resources for negative emissions (either afforestation or bioenergy), and this will cause them to reach net-zero earlier.

Since models implicitly allocate mitigation to where it is cheapest, it becomes dependent on emissions trading or financial transfers to balance out equity issues. Even so, in a political context, this may still be problematic. If models suggest Latin America should have large-scale afforestation and BECCS, then even with financial transfers, Latin American countries might prioritise mitigation and land use differently to cost-optimising models. Or a country might find it politically unacceptable for a third country, via emission trading or financial transfers, to cover the costs of all their new infrastructure. This reemphasises that models given an extremely idealised view of the world, which may not be possible to replicate in practice. It is probably necessary for models to more explicitly include equity considerations. Therefore, care is needed not to overinterpret the regional variation in mitigation pathways, as they are heavily influenced by model set up.

6 Carbon Prices (b)

Topics discussed: *b) Global and regional carbon price trajectories (calculated in 2019-USD), preferably with some extra information on the regional split most closely covering EU/EEA in individual models. Also if possible, a CO₂-price for the energy and industry sectors in the EU/EEA for the purpose of comparison with EUA-price trajectories. If this is not possible, information should be provided to serve this purpose, such as marginal abatement cost over time for relevant sectors. The same should be done to asses CO₂-price trajectories for other sectors as a group, for the purpose of comparison with current non-ETS climate policy.*

6.1 Carbon prices in Integrated Assessment Models

Most IAMs are driven by carbon prices, and there is a tendency to want to use those carbon prices directly for policy. While carbon prices from IAMs can certainly feed into a policy discussion, care needs to be taken in how those carbon prices are interpreted. The carbon price in an IAM, is from one perspective, an outcome of the model structure and assumptions, and thus, may not directly correlate to a carbon price in practice. A model may use perfect foresight over 100 years, or it might be myopic, leading to very different carbon prices – which carbon price is relevant for policy?

Further, models generally apply very stylised climate policies, such as all countries and sectors with the same carbon price, a condition that is unlikely to be ever met. In practice, climate policy is likely to be a mix of policy instruments. Even if a carbon price was preferably implemented in countries, it is likely to vary across countries and sectors, something not common in IAMs. To reach a given climate target, with regional and sectoral variations in carbon pricing, is likely to lead to much higher prices in some regions to reach the same climate target.

The carbon prices are essentially implemented in IAMs in a highly stylised way. This is since the models are essentially run in a back-cast mode, asking the question of what it would take for the world to transition to 1.5°C or 2°C. The concept of the scenarios is not to run a simulation with differential and realistic carbon pricing, staged implementation across sectors and countries, and mixed in with a range of supporting regulations. Generally, the carbon prices start globally, and rise over time, with some scenarios assuming advanced countries implemented carbon prices earlier. The carbon price is set at a level, or derived, to ensure that temperatures are stabilised at the desired level. Essentially, IAMs are shaping the major contours of the required mitigation to reach given climate targets, alternative approaches are necessarily to design and implement policies at the national level.

The vast majority of IAMs meet a given climate target using carbon pricing, as opposed to regulation or emission caps. In theory, the carbon price increases over time exponentially with the discount rate given an exhaustible resource (Hotelling's Rule). While each model has different characteristics, model structure and assumptions, as a guiding rule the Hotelling Rule is a useful benchmark (Emmerling et al. 2019). In principle, models will have a carbon price that will rise over time, with the rate of increase similar to the discount rate depending on model structure (Guivarch and Rogelj 2017). In general, intertemporal optimisation frameworks (perfect foresight) will have exponentially increasing carbon prices, while recursive dynamic frameworks (limited foresight) may have higher carbon prices in the short term and lower in the longer term.

The discount rate is a key parameter in the carbon price but is rarely analysed as a key parameter. Most IAMs have discount rates at around 5%, and all else equal, that has an effect of pushing mitigation further into the future. A recent analysis has shown that reducing the discount rate from 5% to 2% would double the carbon price but reduce the amount of negative emissions requiring more short-term action (Emmerling et al. 2019). Thus, it is difficult to separate the role of carbon prices and the scale of negative emissions (hence the scenario selection criteria). Unfortunately, there is very little literature on these points, even though they are rather fundamental in nature.

Carbon prices are generally applied to all greenhouse gases. The carbon price on CO_2 emissions is the same as the "carbon" price applied to non-CO_2 greenhouse gases, with the non-CO_2 emissions converted into CO_2-equivalent emissions using Global Warming Potentials with a 100-year time horizon (GWP-100). The GWP-100 is often taken from earlier IPCC assessment reports, and depending on the scenario and model, could be from the second, fourth, or fifth assessment report. While this is important, it should only lead to a minor change in results as most of the mitigation is from reducing CO_2 emissions. In some scenarios, the carbon price may not be applied to land use change (deforestation) or may have a different price compared to fossil fuels.

Most models apply a uniform carbon price that does not vary by sector. The new SSP framework, accommodates staged implementation of scenarios, where some countries act faster than others. In a SSP1 world (sustainability) all countries will uniformly apply a carbon price, while in a SSP5 world (fragmentation) rich countries will act first but carbon prices will eventually converge to a global level at a later year (e.g., 2050). This means that in most models, there is a limited variation of carbon prices across regions. When additional scenario selection criteria are used, such as in this study, the models with fragmented carbon prices will not be included (either they are not 1.5°C or 2°C scenarios, or they are depended on high levels of BECCS).

We are not aware of the literature of IAM studies that systematically consider fragmentation of carbon prices across sectors. There is one study that looks at implementing a carbon price alongside a restricted set of regulations (Bertram et al. 2015). They find that they can apply a lower economy-wide carbon price if that carbon price is complemented with regulations to support low-carbon energy technologies and a moratorium on new coal-fired power plants. There are perhaps other studies in this vain, but they are likely to be similarly stylised. More specific analysis on policy implementation is usually found in national-level modelling.

6.2 Regional variation in carbon prices

In this section, we explore how carbon prices vary by region with different policy assumptions. Unfortunately, an error was identified in the regional carbon prices in the SR15 scenario database[6], however, and conveniently, it is more appropriate to use the Shared Socioeconomic Pathway (SSP) scenario database to compare regional carbon prices (Riahi et al. 2017). The SSPs are five hypothetical worlds comparing the challenges of mitigation and adaptation, and are labelled:

- SSP1   Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)
- SSP2   Middle of the Road (Medium challenges to mitigation and adaptation)
- SSP3   Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)
- SSP4   Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)
- SSP5   Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)

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[6] https://github.com/iiasa/ipcc_sr15_scenario_analysis/issues/19

The SSPs are quantified using six different IAMs for different forcing (temperature) levels. The SSPs are run in a baseline configuration (without climate policy), and then with different levels of carbon pricing (climate policy) to reach different radiative forcing levels in 2100. These radiative forcing levels often link to the Representative Concentration Pathways (RCPs). **Figure 18** shows an SSP/RCP matrix, where different models (six in the table) run different SSP and RCP combinations. The SSP/RCP framework is a nice system for scenario and model comparison, and will be drawn on extensively in this section. There was a particular SSP intercomparison project (Riahi et al. 2017) where only a limited set of models run different SSP/RCP combinations. This SSP intercomparison is included in the SR15 scenario database, but other scenarios in the SR15 database did not repeat the same experiments making comparisons more difficult.

The advantage of using SSPs for carbon pricing is that it is easy to control assumptions on socioeconomics, model, and forcing level. The SSP database also contains data for five world regions, and this allows the regional variations in carbon pricing to be highlighted. By contrast, the SR15 database does not have the same structure, and it is difficult to determine if carbon prices vary because of model structure, socioeconomics, or forcing target.

In this section, the carbon prices are first shown for RCP1.9 (66% below 1.5°C in 2100) and RCP2.6 (66% below 2°C in 2100) for four of the SSPs (SSP3 is dropped as it is not possible to obtain RCP1.9 or RCP2.6). The carbon prices are shown first to 2100, and then to 2040 for RCP2.6 to highlight the regional differences. The discussion will constantly refer to the model structure (**Table 1**) and whether scenarios were run in the SSP intercomparison or not (Figure 16, Rogelj et al. 2018).
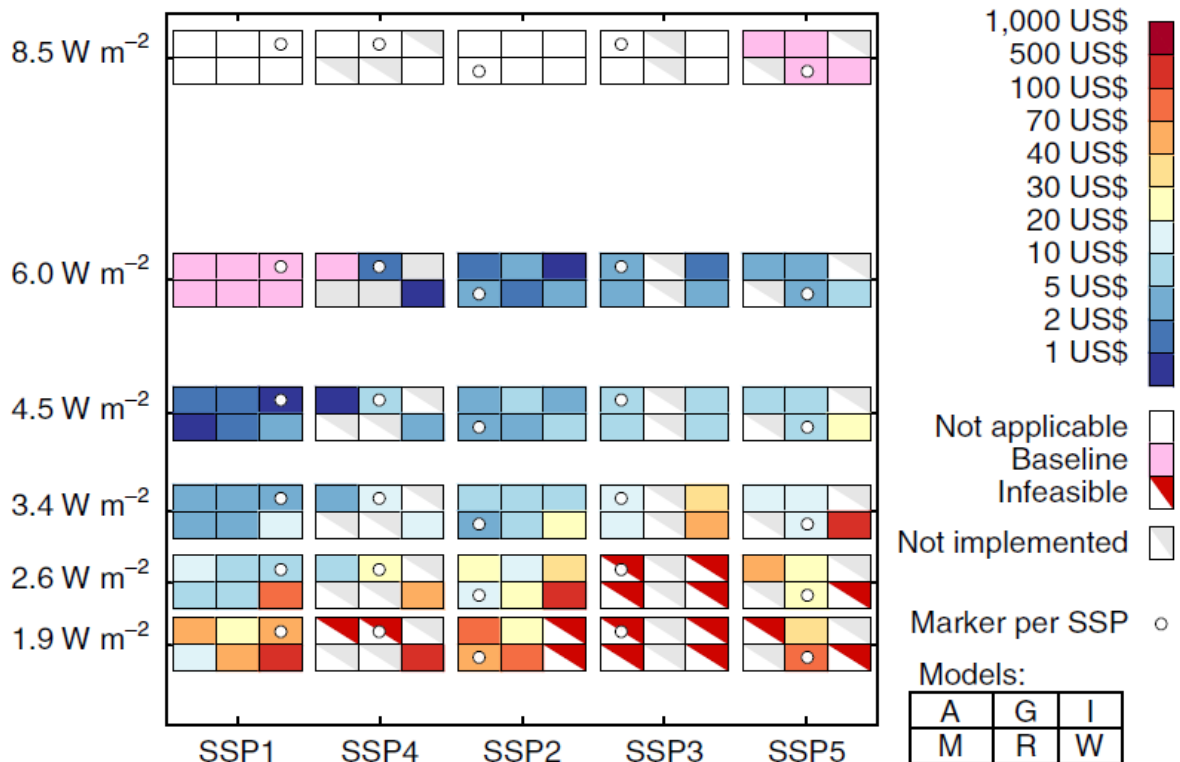

Figure 18: Figure 5 from Rogelj et al. (2018) showing which scenarios were run in different model frameworks (boxes with full colours), were implemented but were not feasible (red half full boxes), or were not even attempted meaning feasibility is unknown (grey half full boxes).

Figure 19 shows the carbon prices for RCP1.9 and SSP1, SSP2, SSP4, and SSP5 for various models and regions. It is difficult to see the regional variations, as the models at this scale of carbon price, have very little regional variation in carbon price. The regional variations will be discussed further below. The carbon prices, by 2100 are remarkably high, over 30,000$/tCO$_2$ for some models, but this varies heavily by model. WITCH has a much higher carbon price than the other models, and it is only shown for SSP1 and SSP4. This gives the impression that SSP1 and SSP4 might lead to higher carbon prices, but this is generally not the pattern. All other models show a lower carbon price for SSP1. It is also clear that all the models have an approximately exponential increasing carbon price, except AIM/CGE based on a different model structure (**Table 1**).
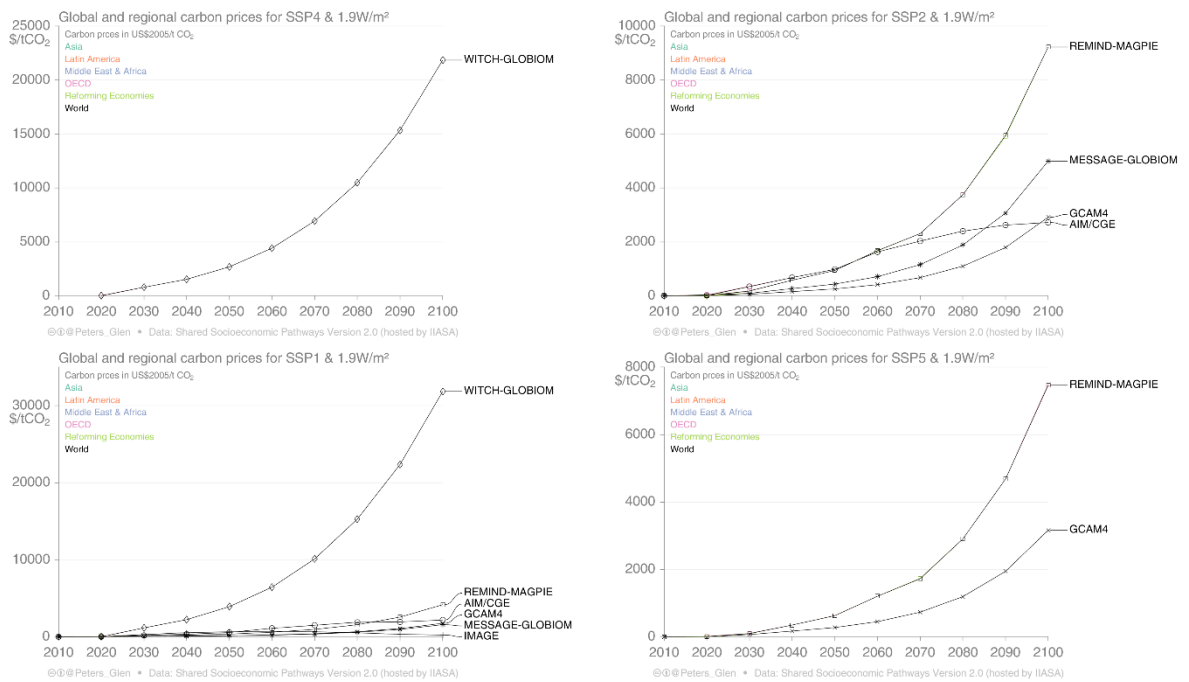

Figure 19: The carbon prices for RCP1.9 and SSP1, SSP2, SSP4, and SSP5 for various models and regions. If the regional colour coded is not clearly shown, it is because they sit behind the black line (global price).

Figure 20: The carbon prices for RCP2.6 and SSP1, SSP2, SSP4, and SSP5 for various models and regions. If the regional colour coded is not clearly shown, it is because they sit behind the black line (global price).
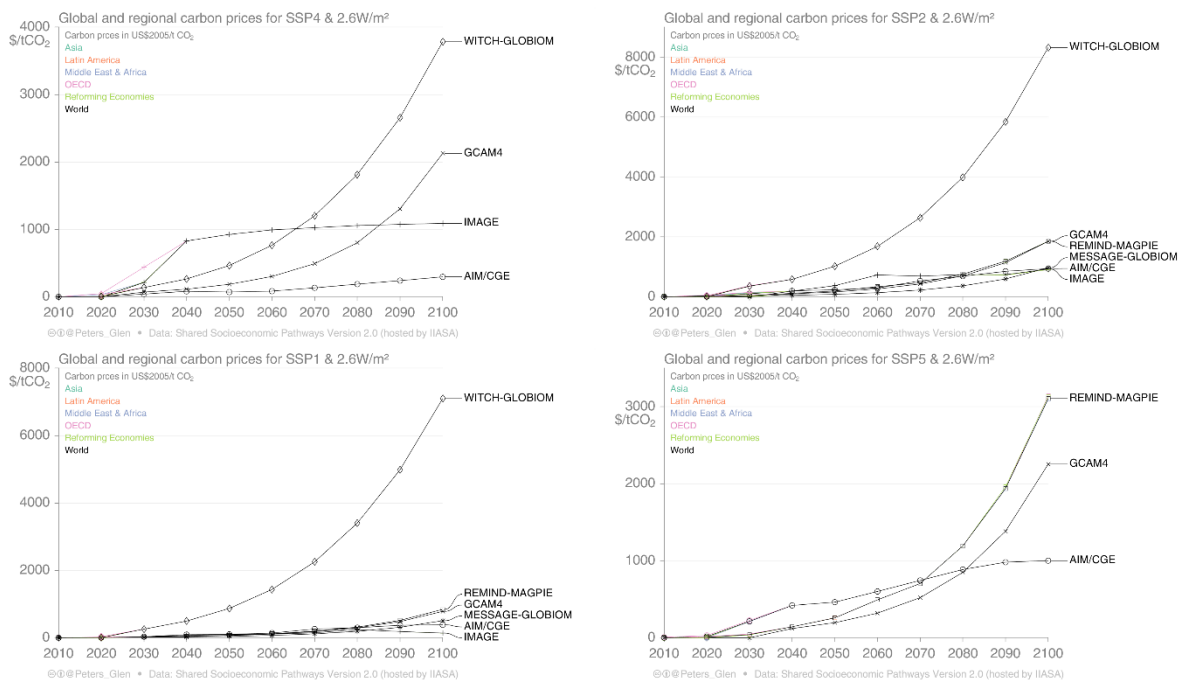
The results are repeated for RCP2.6 in **Figure 20**. The carbon prices are significantly lower for 2°C compared to 1.5°C. Again, care needs to be taken when comparing across SSPs, as the same model should really be compared, not the SSPs. Regional variations are also hard to detect in these figures.

To highlight the regional differences in carbon prices, the RCP2.6 version of the figure is plotted to 2040 only (**Figure 22**). Now it is clear that there are regional variations in the carbon prices. The different SSPs have different Shared Policy Assumptions (**Figure 21**). SSP1 and SSP4 have an earlier transition into a global cooperation of carbon prices, while SSP2 and SSP5 have some delay reaching a global carbon price in 2040. Carbon pricing on land-use change also varies across the SSPs. **Figure 22** shows how these different policy assumptions propagate into the regional carbon prices. As expected, OECD has a higher carbon price, but these carbon prices quickly converge to a globally harmonized price (in 2020, 2030 or 2040). After the uniform carbon price is obtained, all regions have the same carbon price. In many cases, the difference between the regional carbon prices before 2040 is much smaller than the rate of change in the carbon price. For example, in 2030, WITCH SSP1 RCP2.6 has a carbon price of around 5$/tCO$_2$ globally, but about 35$/tCO$_2$ for the OECD. While this differential seems large, but by 2030 the carbon price has grown to around 250$/tCO$_2$ globally.

While the SSP/RCP framework does allow for regional variation in carbon prices, these variations are much smaller than the rate of change of the carbon price over time. The climate targets 1.5°C and 2°C are so stringent, that the world must quickly move to a globally uniform carbon price, so any regional variations can only be short-lived.

Policy stringency in the near term and the timing of regional participation	Coverage of land use emissions
SSP1, SSP4 Early accession with global collaboration as of 2020	*SSP1, SSP5* Effective coverage (at the level of emissions control in the energy and industrial sectors)
SSP2, SSP5 Some delays in establishing global action with regions transitioning to global cooperation between 2020–2040	*SSP2, SSP4* Intermediately effective coverage (limited REDD[*], but effective coverage of agricultural emissions)
SSP3 Late accession – higher income regions join global regime between 2020–2040, while lower income regions follow between 2030 and 2050	*SSP3* Very limited coverage (implementation failures and high transaction costs)

Figure 21: Table 3 from Riahi et al. (2017) showing the Shared Policy Assumptions for the different SSPs.
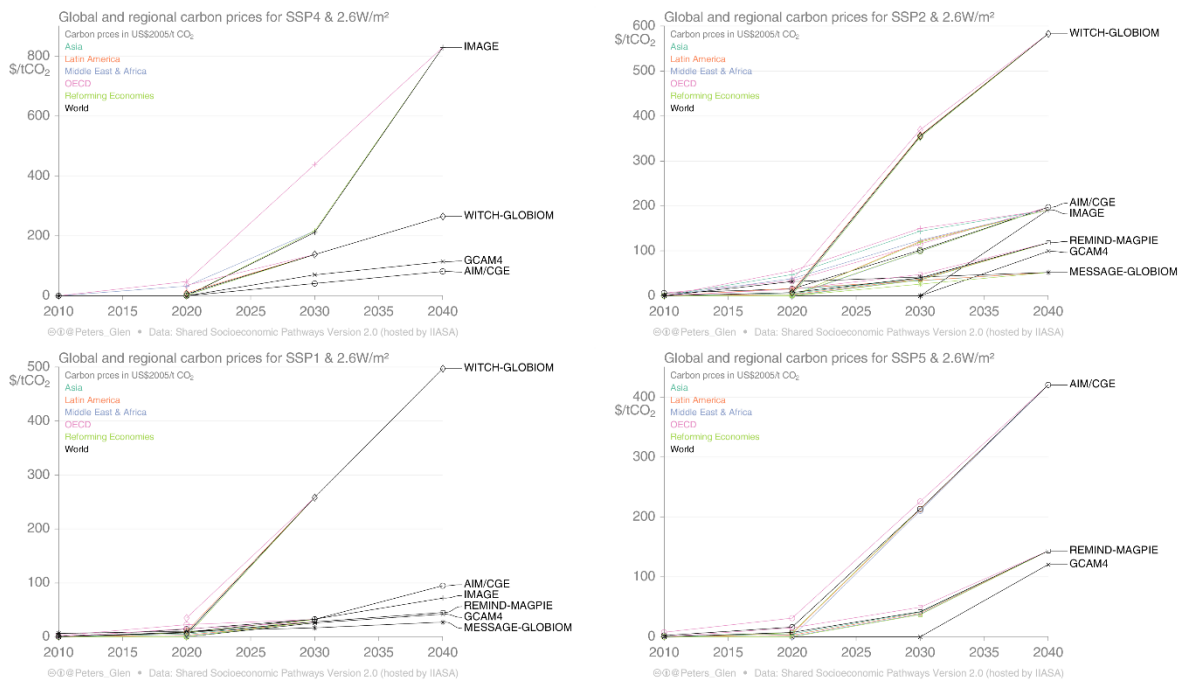

Figure 22: The carbon prices for RCP2.6 and SSP1, SSP2, SSP4, and SSP5 for various models and regions, with results shown only to 2040. If the regional colour coded is not clearly shown, it is because they sit behind the black line (global price).

Carbon prices also vary significantly by model and scenario. While this information is captured in the previous figures, it is worth presenting a few variations of these figures to highlight model and scenario variations more clearly. **Figure 23** shows the carbon price by SSP for 1.5°C scenarios with each panel representing a different model. First, it becomes clear that models only ran, or were able to solve, certain SSPs (**Figure 18**). IMAGE, for example, could only obtain 1.5°C with SSP1, could not solve for SSP2 or SSP3, and did not try for SSP4 or SSP5 (**Figure 18**). Second, different models have very different carbon prices, based on their model characteristics (**Table 1**). IMAGE stays below 1.5°C with less than a $800/tCO$_2$ carbon price, while WITCH has carbon prices reaching over $30,000/tCO$_2$ towards the end of the century. Third, carbon prices are generally lower for SSP1. And finally, not all models have exponentially increasing carbon prices due to different model structure, models with limited foresight have less than exponential increases.
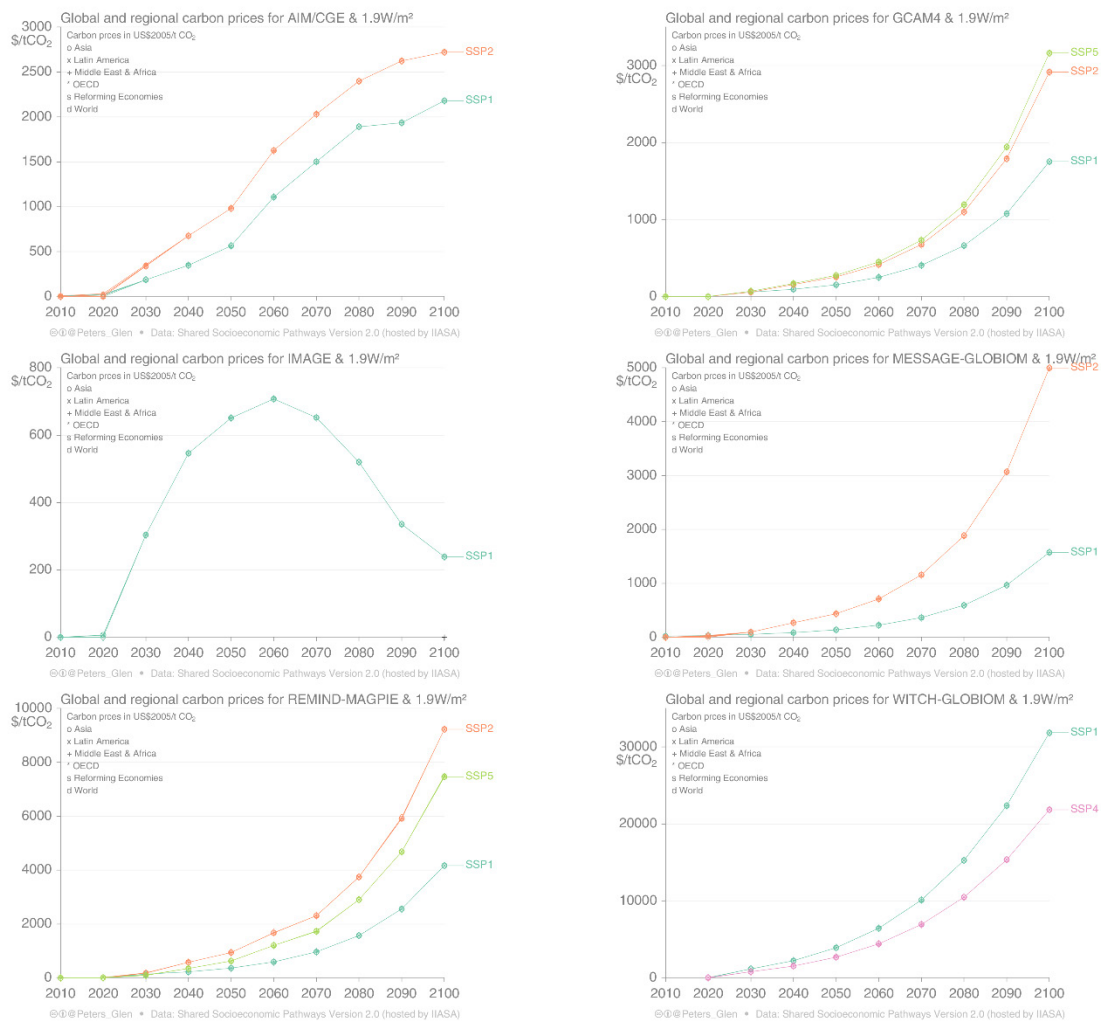
Figure 23: The carbon prices for 1.5°C scenarios with each panel representing a different model.

Figure 24 shows how carbon prices vary for SSP2 (the most common of the SSPs) across model (panels) and radiative forcing level (colours). As expected, the carbon price increases as the radiative forcing level decreases, but the changes between radiative forcing levels are not uniform. IMAGE and WITCH could not get to 1.5°C using the socioeconomics in SSP2 (**Figure 18**), and the other models generally show a large step change from 2°C pathways to 1.5°C pathways. These outcomes highlight the difficulty in staying below 1.5°C. Not all models can keep below 1.5°C, and those that can, often depend on very specific socioeconomic conditions.

Figure 24: Carbon prices for SSP2 (the most common of the SSPs) showing how prices vary by model (panels) and radiative forcing level (colours).

6.3 Sectoral variations in carbon prices

The previous section, particularly **Figure 21**, highlights that these IAMs do not really vary carbon prices at the sector level, at most variations occur between land use and fossil fuel use. Even when there are regional variations, they must quickly converge to a global carbon price to reach ambitious climate targets. Variations in sector carbon prices is more the domain for national level models.

The IEA does allow some variation across sectors in carbon prices in its World Energy Outlook (2018), but these are rather course, and more specific to the Current Policy Scenario and New Policy Scenarios. The carbon price captures the power, industry and aviation sectors, while other transport is covered by regulations. This would mean that the carbon price is lower than what would be the case if all transport was regulated with a carbon price.

Table 4: The carbon prices in the IEA World Energy Outlook (2018) for the European Union (Advanced Economies in the Sustainable Development Scenario)

Scenario	Sector	2025 ($/tCO₂)	2040 ($/tCO₂)
Current Policy	Power, Industry, Aviation	22	38
New Policy	Power, Industry, Aviation	25	43
Sustainable Development	Power, Industry, Aviation	63	140

At the EU level, the PRIMES model has one option to allow for variation of carbon prices by sector[7]. In the EU modelling of a net-zero target in 2050[8] the carbon prices were stylised and assumed to increase, but not via sector:

The stylised carbon price assumed increases significantly under all scenarios, reaching 28 EUR/tCO₂ in 2030 and then increasing to 250 EUR/tCO₂ in 2050 under the 80% reduction scenarios and 350 EUR/tCO₂ under the scenarios that achieve net zero GHG emissions by 2050. Real carbon price developments will be different and depend on numerous factors, including the deployment of other policies and how they impact technology costs and deployment. For this assessment with the PRIMES model suite it was not chosen to vary for instance other policy levers and see how carbon prices would be impacted.

It is beyond the scope of this work to survey what sectoral level carbon prices could be relevant for Europe (or Norway). This would necessarily involve much more detailed bottom up modelling that considered nationally relevant circumstances (and be based on national models).

6.4 Overview of carbon prices from the selected scenarios

In this section, the carbon prices from the selected scenarios are shown. It is important to note that each scenario here is based on a mix of models and socioeconomics, and so far, care needs to be taken with comparison. The earlier sections gave a better overview of variations across SSPs and models.

Confirming the results in previous sections, **Figure 25** shows that extremely high carbon prices are needed to stay below 1.5°C with no or low overshoot. By 2030, prices range from 69.5$/tCO₂ up to 6,050$/tCO₂, with a median of 245$/tCO₂ and interquartile range of 128$/tCO₂ to 502$/tCO₂. In the OECD, these ranges are 278$/tCO₂ up to 4710$/tCO₂, with a median of 1431$/tCO₂ and interquartile range of 547$/tCO₂ to 1891$/tCO₂. The lower 2°C scenarios have significantly lower, but still high carbon prices (**Figure 26**). The global average values are from 0$/tCO₂ (delayed mitigation) up to 416$/tCO₂, with a median of 131$/tCO₂ and interquartile range of 51$/tCO₂ to 263$/tCO₂.

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[7] https://ec.europa.eu/energy/en/data-analysis/energy-modelling
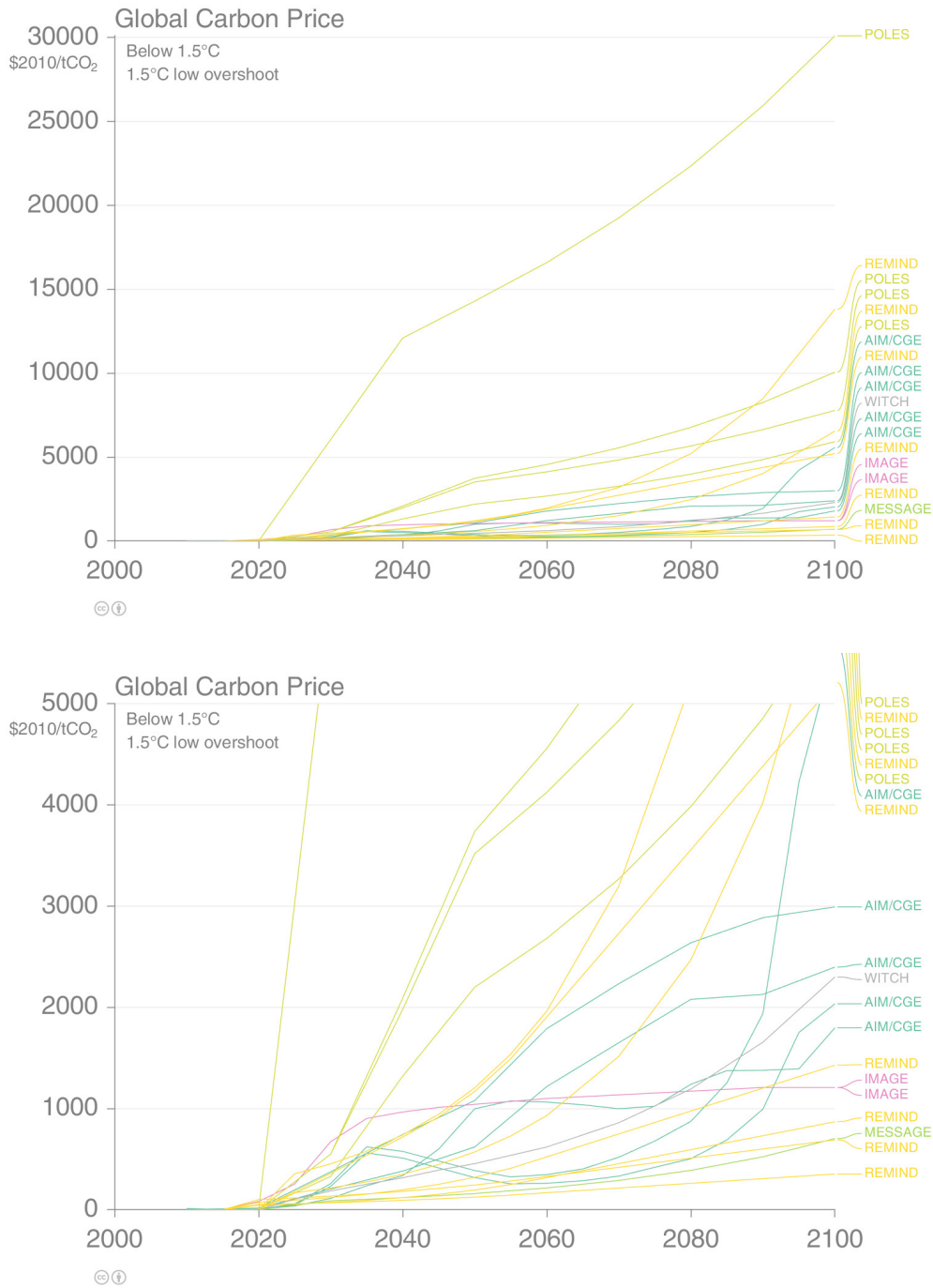[8] https://ec.europa.eu/clima/policies/strategies/2050_en

Figure 25: Carbon price for the selected 1.5°C scenarios with no and low overshoot, showing the full range (top) and a truncated version (bottom).
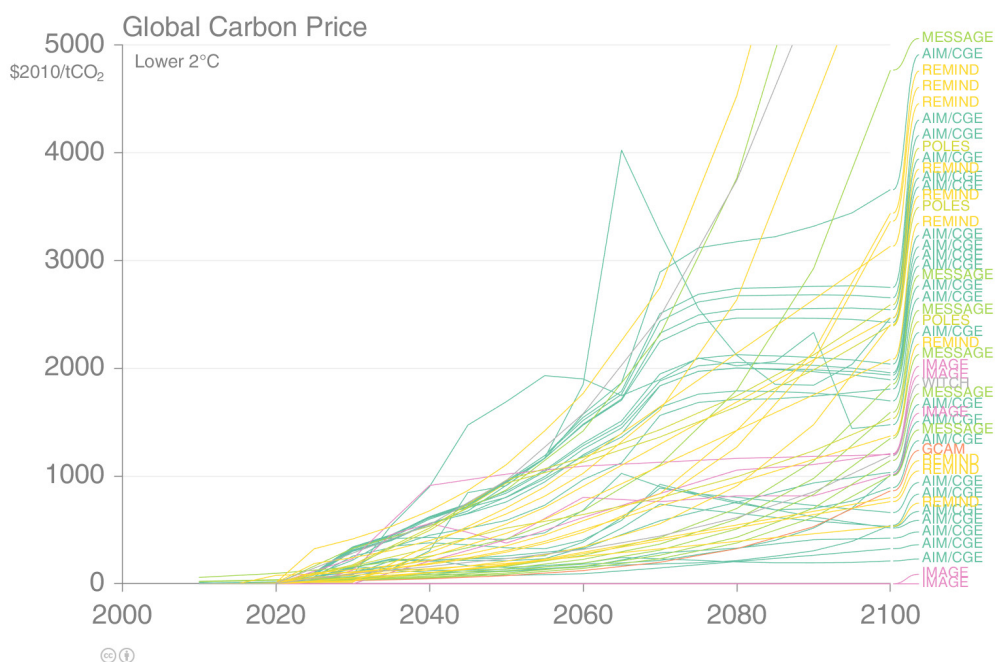
Figure 26: Carbon prices for the selected lower 2°C scenarios.

6.5   Using carbon prices from models in policy

The carbon prices from models are remarkably high, certainly above what is in any carbon pricing system today globally. The carbon prices also vary considerably across models. Caution should be therefore applied to how these carbon prices are applied. In a model, carbon prices can be considered as the outcome of an optimisation process, and the carbon price, therefore is reflective of how difficult it is to reach a given climate target. Different models are also known to be more flexible than others in meeting targets, therefore have different carbon prices (Kriegler et al. 2015). There is no single carbon price trajectory that is unique to 1.5°C or 2°C: the pricing depends on socioeconomics, policy implementation, model, and forcing target. An early study found that 90% of the variations in carbon price, for a given forcing level, is due to model structure (Guivarch and Rogelj 2017). We could potentially compare the carbon prices in the scenarios with other parameters, such as the demand for oil and gas. As the variations in carbon prices are large, such relationships are likely to be noisy and without clear correlations.

The carbon prices from IAMs may not reflect what carbon prices should be implemented in a different country. A more detailed, bottom-up, cost analysis within specific countries is probably necessary to correct or calibrate a carbon price. Or indeed, implementing an emission trading system and allowing the market to find the price. The current EU carbon price, of the order 25€/tCO$_2$, is sufficient to meet the current constraint for the emissions trading system, but a more stringent cap consistent with 1.5°C or 2°C pathways will lead to a higher carbon price, and potentially across more sectors.

Models are only depictions of the real world, and do not necessarily include all technologies or behavioural changes. It could be that if the carbon price rose to 50-100€/tCO$_2$, then mitigation could happen far faster and in different ways to what was modelled. New technologies and behaviours may quickly be discovered. Of course, the opposite could also occur.

IAMs also have limited representation of innovation, and more broadly, the processes around which new technologies and behaviours may be discovered. An IAM will represent a technology (say

BECCS) with a given price, that will then change over time either endogenously or exogenously. The model will strictly follow those prices, with no variations. IAMs do not represent first of a kind technologies. As an example, BECCS may take decades to become a mature technology (Nemet et al. 2018), but IAMs implement BECCS with known prices. Thus, carbon prices from IAMs are not useful tools for deciding whether investments should be made in a new technology, that would require additional analysis. IAMs can indicate what technologies may be needed in the future, but not the best way to get those technologies to maturity.

7   Deployment of negative emission technologies (c)

Topics discussed: *c) Deployment of negative emission technologies on a global and regional level*

7.1   Negative emissions in IAMs

Figure 11 highlighted the difference between gross and net emissions. As that figure showed, the gross negative emissions exceeded the gross positive emissions, leading to net-negative emissions. Scenarios therefore indicate that net negative emissions are necessary, zero emissions are insufficient. **Figure 27** splits the gross negative emissions into two parts (Geden et al. 2019):

1. A residual (or limited) component which is to offset the gross positive emissions that cannot be mitigated at appropriate cost, the hard-to-mitigate sectors (Davis et al. 2018); and

2. An overshoot (or comprehensive) component which offsets earlier emissions and therefore brings the temperature down to a lower level.
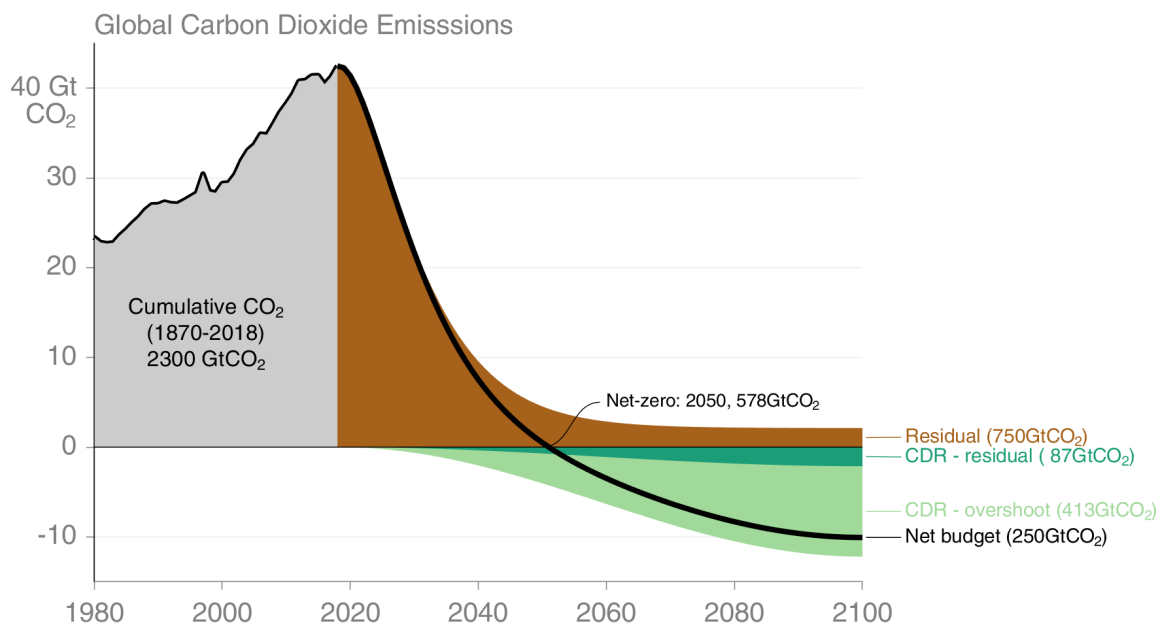
Figure 27: The gross negative emissions can be split into two parts, one to offset the gross positive (residual emissions) and the other to reduce the temperature.

As shown in the figure, and common in nearly all 1.5°C emission scenarios, the overshoot components of negative emissions dominate. There are several reasons for this. Scenarios are generally constructed with a target (whether cumulative emissions, radiative forcing, temperature) in the year 2100, because most models cannot reach the targets without an overshoot before 2100.

Consequently, scenarios nearly always overshoot the temperature target before 2100, before lowering to the temperature target in 2100 (**Figure 28**). The temperature peaks in the scenarios around about the same time that CO_2 emissions reach net-zero, and this principle was used as the definition for the carbon budgets in SR15. Most scenarios have declining temperatures in 2100, and that will continue on assuming that the negative emissions continue after 2100. Given that scenarios have a target in 2100, other modelling factors tend to exacerbate the peak and decline, and therefore the use of negative emissions. In particular, the discount rate is around 5% in most IAMs, and this leads to greater negative emissions (Emmerling et al. 2019). Lowering the discount rate will reduce the negative emissions, push mitigation to earlier times, and therefore raise the carbon price necessary for a given target.
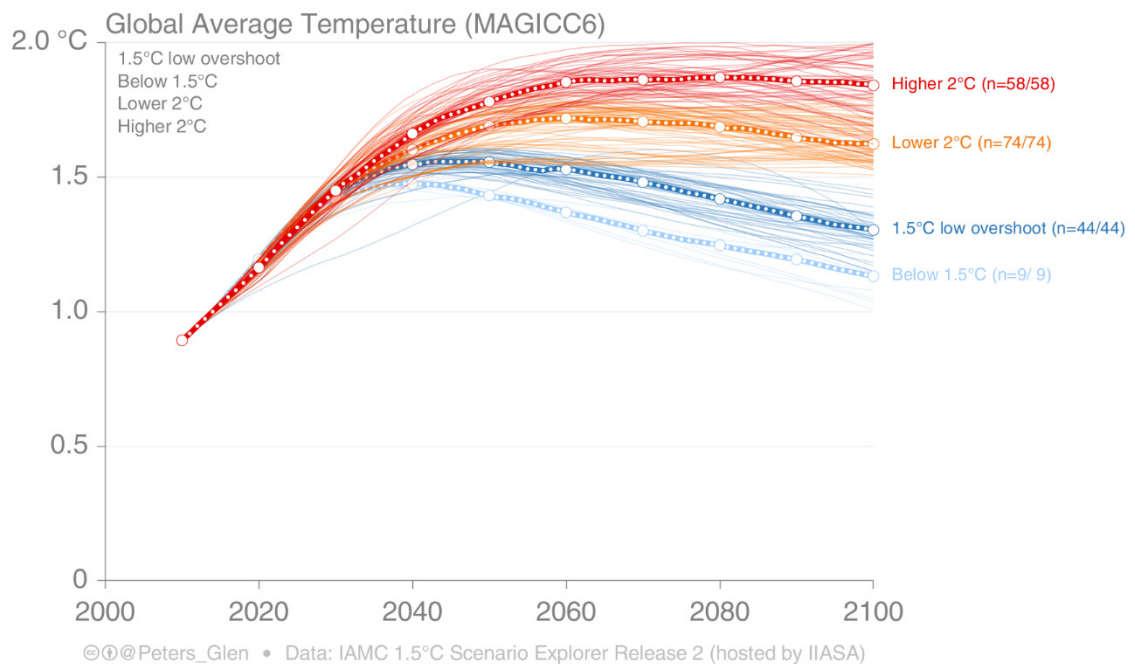

Figure 28: The temperature profile of the 1.5°C and 2°C scenarios from SR15, showing the peak and decline in nearly all 1.5°C scenarios.

Therefore, for a variety of structural reasons and mitigation reasons, negative emissions are needed and unavoidable in almost all deep mitigation scenarios. There are very few scenarios that do not have negative emissions, but this is often misunderstood. Nearly all IAMs have some sort of negative emissions: the most prominent are afforestation (AF) and Bio-Energy with CCS (BECCS) (Henri et al. 2019):

- Afforestation is the planting of *new* forests on lands that historically have not contained forests. In some models, afforestation could also include reforestation of previously forested areas.
- Bioenergy is energy derived from biomass, which could originate from waste products, forestry activities, or most commonly in scenarios, bioenergy crops.

In SR15 there are two models that include Direct Air Capture (DAC) (MERGE and REMIND), no models report enhanced weathering, biochar, or soil carbon in the selected scenarios. Thus, the emission scenarios are dominated by AF and BECCS, even though there is potential for other types of negative emissions. Hence, the large-scale use of AF and BECCS illustrated in the following sections can be considered as a proxy for other types of negative emission technologies.

In the following section we outline the negative emissions used in the selected scenarios. A full list of the negative emissions technologies is listed together with other mitigation technologies in the table in section "f) For each sector a description of the deployment of key abatement options."

7.2 BECCS

Figure 29 and **Figure 30** show the global deployment of BECCS for 1.5°C and 2°C in the selected emission scenarios. Several scenarios do not use BECCS at all, but the ones that do have at least $3GtCO_2/yr$ BECCS by 2100 and reaching $12GtCO_2/yr$ (the scenario selection threshold). Since the BECCS level in 2100 was used as a criterion for selection of scenarios, these global figures are perhaps not so instructive by themselves. **Figure 8** provides more context on the variation of BECCS across scenarios, and the selection criteria used here.

At the regional level for the selected 1.5°C emission scenarios interesting differences start to emerge (Figure 31). The OECD and Asia dominate the use of BECCS, with approximately equal shares each. Latin America, the Middle East and Africa, and Economies in Transition (not shown, but up to $1.5GtCO_2/yr$ in 2100) make modest contributions. While data is not provided on the regions where biomass is grown in the scenario database, nor the resulting trade flows, it is likely that there is a significant amount of trade flows on bioenergy resources (Muratori et al. 2016). The section on land use change contrasts with the land use associated with bioenergy. The regional differences cannot be discussed in isolation of the carbon dioxide removal from afforestation, which somewhat mirrors the regional distribution. The follow section discusses BECCS in addition to afforestation.
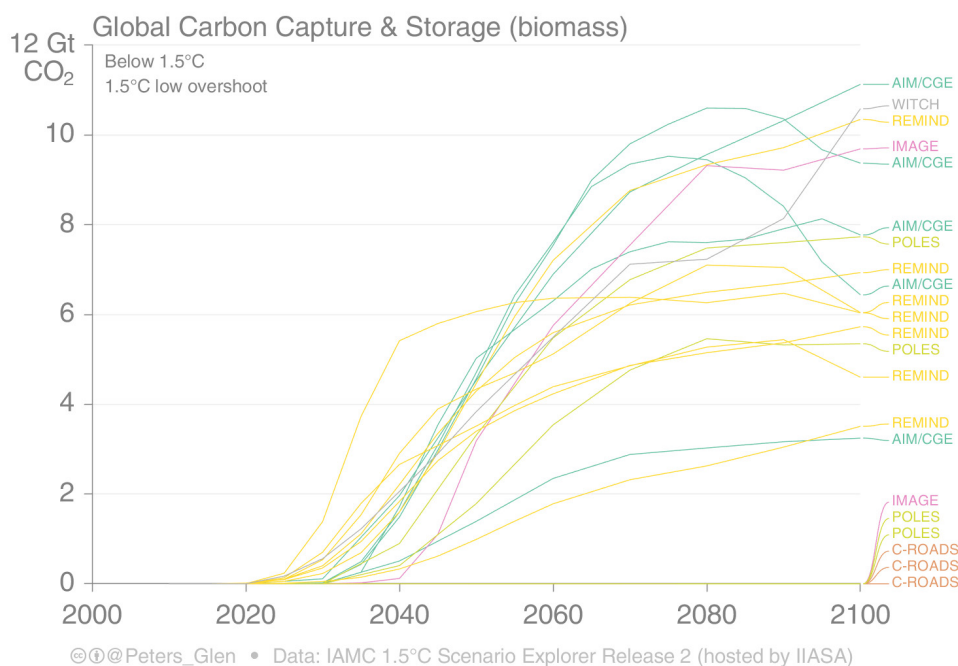
Figure 29: BECCS deployment at the global level in the selected 1.5°C emission scenarios.
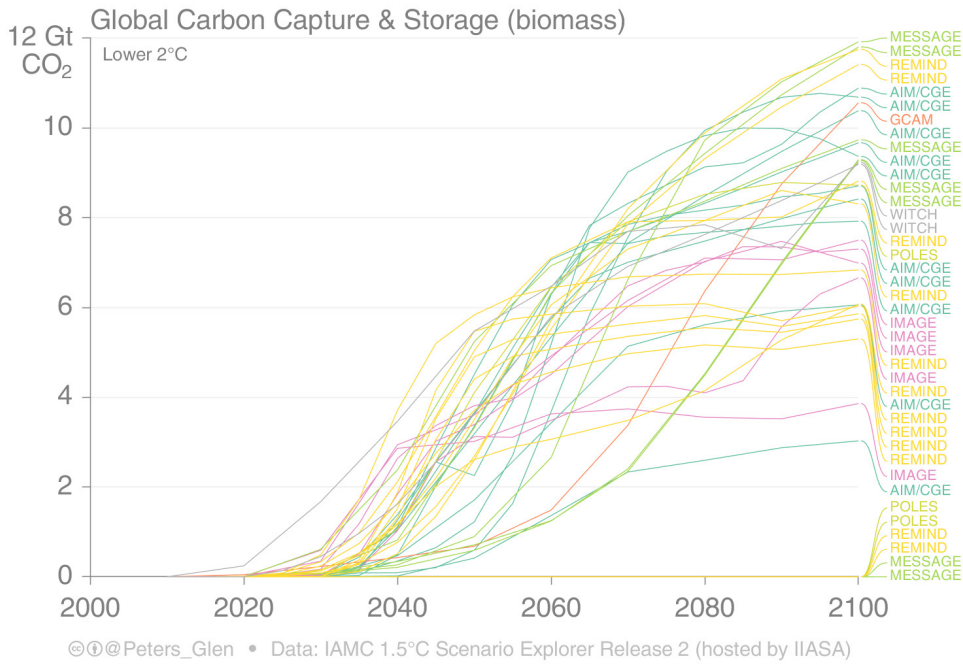
Figure 30: BECCS deployment at the global level in the selected 2°C emission scenarios.
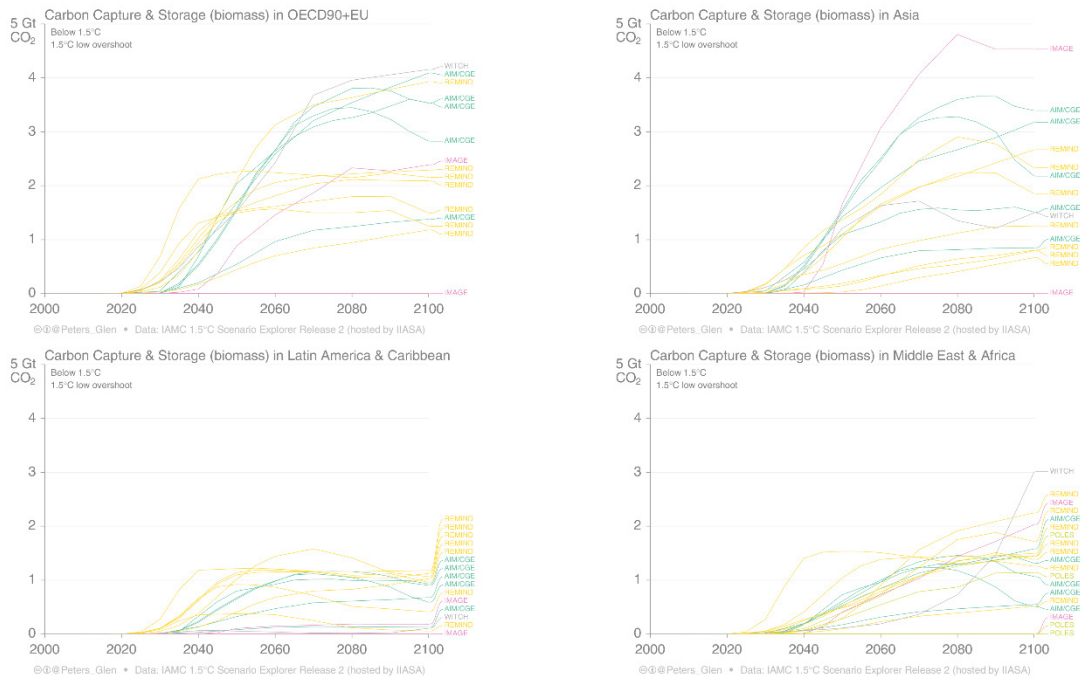
Figure 31: BECCS deployment by main IPCC regions in the selected 1.5°C emission scenarios, all figures with the same y-axis.

7.3 Afforestation

Figure 32 and **Figure 33** show the global carbon uptake from afforestation for the selected 1.5°C and 2°C scenarios. It is important to note that when selecting the scenarios to be included in our analyses, a constraint was placed on BECCS only, and not on afforestation. While in the previous

section BECCS deployment was similar for 1.5°C and 2°C, because the BECCS was constrained, the same is not true for afforestation, for which less is used in 2°C scenarios compared to 1.5°C. Further, compared to BECCS, the profile of afforestation over time is very different. For BECCS, the carbon update continues to grow over time as the same land is used (and expanded) to continually withdraw carbon for a given area and yields are assumed to constantly improve over time. In the case of afforestation, the forest grows fast initially, and then update slows down as the forest matures, and the forest does not exhibit yield improvements over time. Thus, the afforestation shows a distinct inverted U profile, particularly in some models, while BECCS generally has continuous growth over time.

Figure 34 shows the regional distribution of carbon update by afforestation. While BECCS was dominated by OECD and Asia, afforestation is dominated by Latin America and the Middle East and Africa. The Economies in Transition are not shown but have very low afforestation. It is likely that within each model there is competition for land between afforestation and BECCS, as well as food, and this competition seems to place afforestation in the tropics and BECCS outside of the tropics. These issues are touched on further below. It is also clear that different models lead to significant variations in how carbon is taken up in different regions, though model diversity is low, with nearly all scenarios with data from REMIND and AIM/CGE.
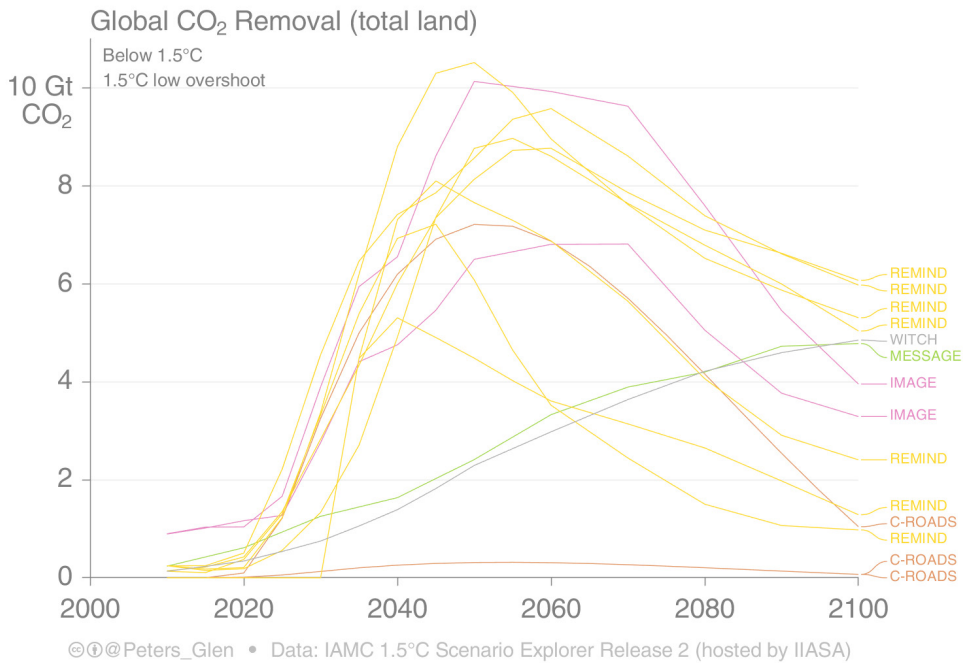
Figure 32: Afforestation at the global level in 1.5°C emission scenarios for the selected scenarios.
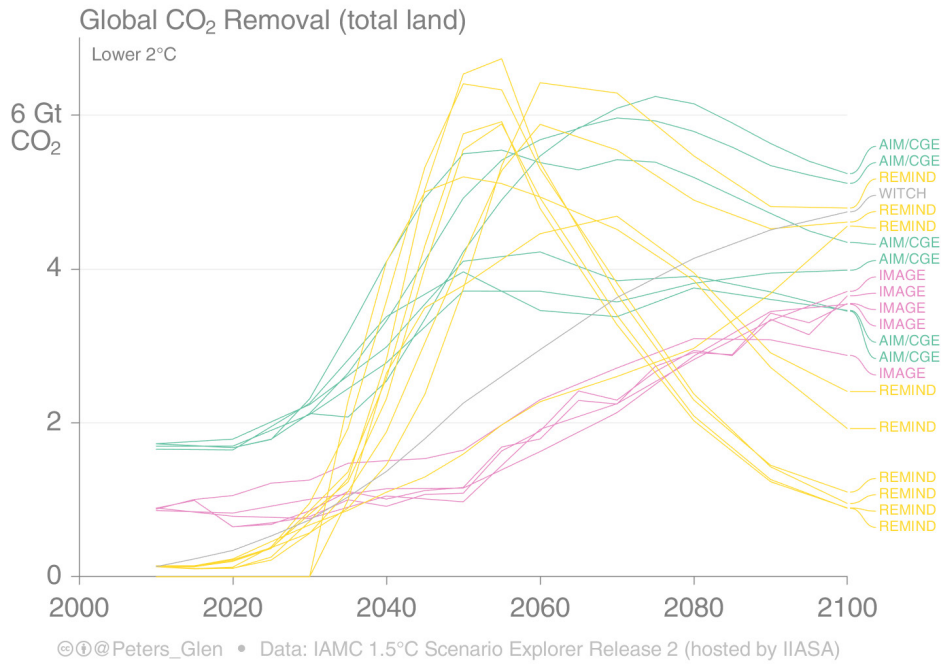
Figure 33: Afforestation at the global level in 2°C emission scenarios for the selected scenarios.
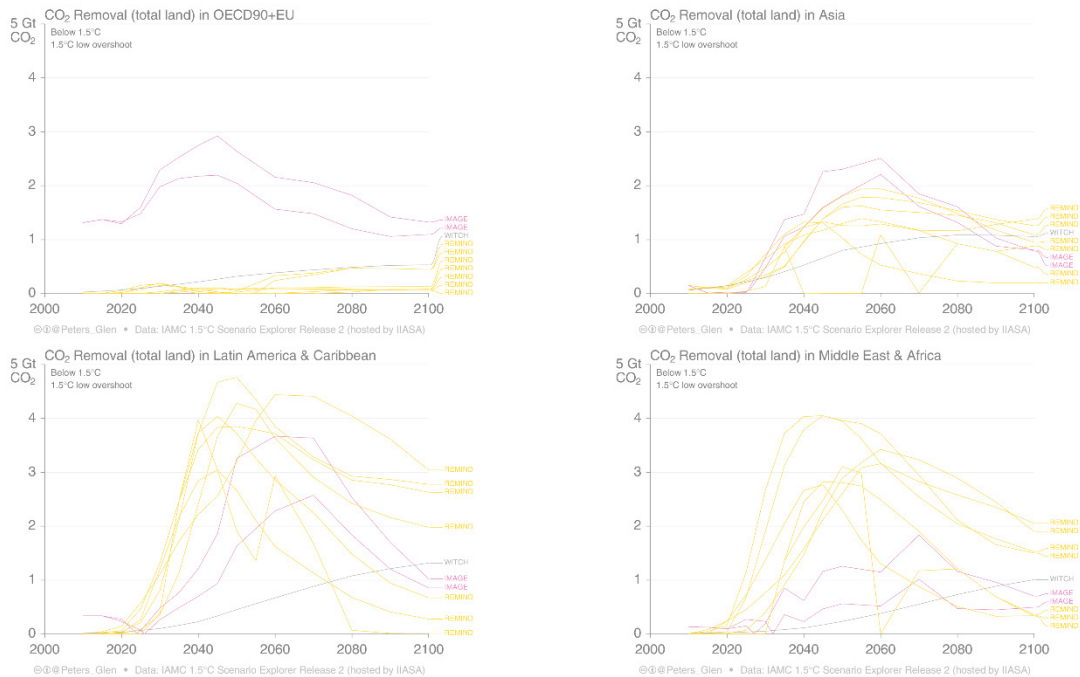
Figure 34: Afforestation deployment by main IPCC regions used in emission scenarios, all figures with the same vertical extent.

7.4 Direct Air Capture

Direct Air Capture (DAC) has not been implemented in many models to date, and for the 1.5°C (**Figure 35**) and 2°C scenarios considered here, only the REMIND model has DAC. **Figure 35** shows that REMIND has between 2 and 4GtCO$_2$/yr DAC in 2100 for 1.5°C scenarios and around

2GtCO$_2$/yr for 2°C (not shown), building up from 2060. Nearly all the DAC is implemented in OECD countries.

There exist a few recent modelling studies on DAC, the most recent being a model comparison (Realmonte et al. 2019). DAC also has several advantages over BECCS, despite its infancy and current high costs (Creutzig et al. 2019). Perhaps a reason that DAC has been implemented in so few models is that it is likely to be a cheap and attractive alternative to short-term mitigation. In other words, DAC will be used prolifically in models and may get strong critiques.
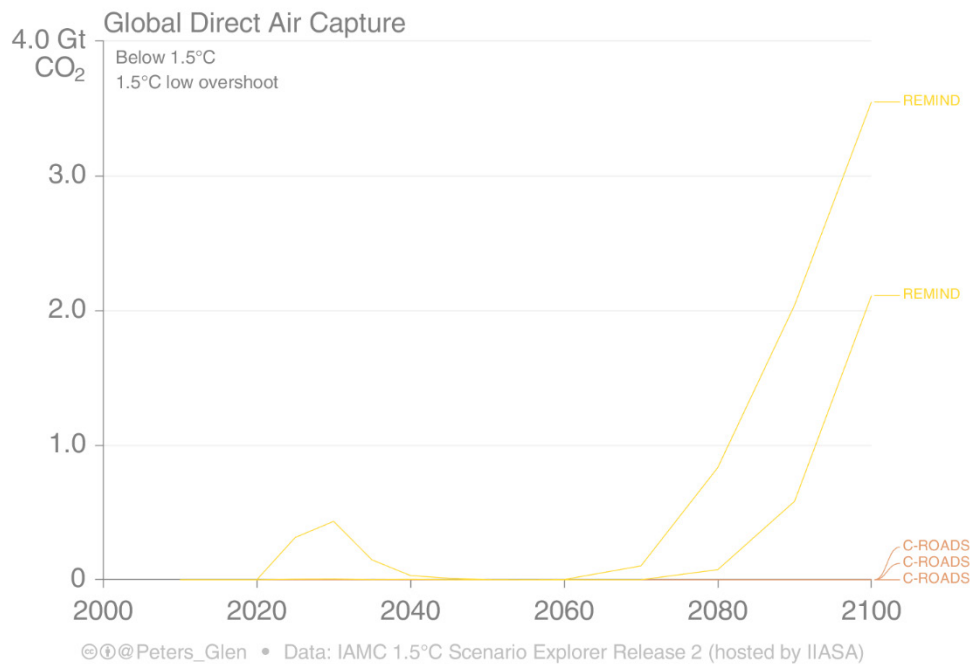
Figure 35: Direct Air Capture for 1.5°C scenarios come from only one model (REMIND).

8   Land use change (d)

Topics discussed: *d) Land use change on a global level and regional level*

Land use data are available only for some of the IAMs from the scenarios selected. In the scenario database, land is classified as cropland (including irrigated, cereals, bioenergy), pastures, forests (including manged, natural forest, afforestation and reforestation), and other (natural land, other land, other arable land, and built-up land). Many scenarios only include a subset of all these variables. C-ROADS does not report any land-use data. POLES only includes data on forests. REMIND only includes land-use data when coupled with MAgPIE. WITCH does not include bioenergy crop areas. Thus, while the selected scenarios already exist some biases, these biases are further exacerbated when showing land use data. For the comparisons in this section, we aggregate the land to cropland – energy, cropland – other, pastures, forests, and other. This is also a standard aggregation used in many papers.

The different definitions of land-use (as defined in the 1.5°C scenario database) are:

- **Cropland**: total arable land, i.e. land in non-forest bioenergy crop, food, and feed/fodder crops, as well as other arable land
- *Cropland – Energy Crops*: land dedicated to 2nd generation energy crops. (e.g., switchgrass, miscanthus, fast-growing wood species)
- **Forest**: managed and unmanaged forest area
- **Pastures**: All categories of pastureland (based on FAO definition of "permanent meadows and pastures"
- **Other arable land**: Unmanaged land (e.g., grassland, savannah, shrubland), excluding unmanaged forests that are arable

8.1   General land use dynamics

Figure 36 shows the land-use changes from 2010 for a selected set of scenarios with the necessary data, from the 1.5°C scenarios with no or limited overshoot and BECCS constrained to 12GtCO$_2$/yr in 2100 and 500GtCO$_2$ cumulatively to 2100. The figure demonstrates the general land-use dynamics across models: land use for afforestation and bioenergy increases across scenarios, but it decreases for pastures, cropland, and other land. Pastures are currently inefficiently used, and by yield improvements plenty of land becomes available for bioenergy and afforestation. To a degree, and depending on definitions, the same is true for other land. Very few scenarios require deforestation to meet increased bioenergy demand, certainly not at the aggregated global level. The yield improvements in most models are extremely high and is an area where the models could be critiqued on feasibility grounds (Creutzig 2016; Harper et al. 2018; Krause et al. 2018).

Figure 36 shows how behaviour varies across models. The top row is from one model, AIM. Interestingly, AIM has a bigger land-use change in the SSP1 compared to SSP2 pathway, but SSP1 does have less bioenergy crops and more forests compared to SSP2. The land-use changes are considerable, with forests expanding 1500 million hectares, with forests replacing other land, pastures and cropland. The second row shows model results from IMAGE, with the two selected scenario variations of the base case (sensitivity analysis). One scenario does not use bioenergy crops, but greatly expands forests and other land, while the other scenario uses bioenergy. To make the new land available for bioenergy and afforestation, there is a large decrease in pastures and

cropland. The bottom row shows a scenario from REMIND and the Low Energy Demand (LED) scenario based on the MESSAGE framework. Numerous REMIND scenarios were submitted, but this scenario is characteristic of the others. It shows a significant increase in forests, grown mainly on pastures. The LED scenario has the most tempered land use change, achieved by more rapid short-term emission reductions compared to other scenarios. While the land-use changes in LED are less than other scenarios, there is still a 600 million hectare increase in forest area, primarily based on pastures.

While the scale of the land-use changes varies across model and scenario, all models and scenarios exhibit similar characteristics. Most of the land-use change is associated with expanded forests (afforestation). While forests may reduce the risk of impacts (SRCCL), the scale of the forest expansion will likely cause some impacts and some additional land-use pressures. Some scenarios increase other land, which is likely also an expansion of forests (unmanaged). After forests, the next biggest increase in land use is from bioenergy crops. While the areas are generally smaller, they can still be several hundred million hectares, which is a significant change in land use likely to require land-use trade-offs. The underlying drivers of this difference is that BECCS is much more productive at removing carbon per unit land area (partly driven by yield improvements), so afforestation generally requires significantly bigger areas to remove the same amount of carbon.

Given a fixed land area, an expansion of forests or bioenergy must come at the expense of other land uses. Most models and scenarios assume significant yield improvements in pastures and cropland, and additionally some also use other land areas. It is generally thought that extensive cattle production uses land ineffectively, so large yield improvements are possible. Crop yields through technology and behavioural change can also greatly increase the amount of food that can be produced per unit area. Though, the yield gap (between current yields and potential yields) remains wide, despite advances, suggesting that incentives, political, and technology do not always align. Further, future climate impacts may limit the yield improvements.
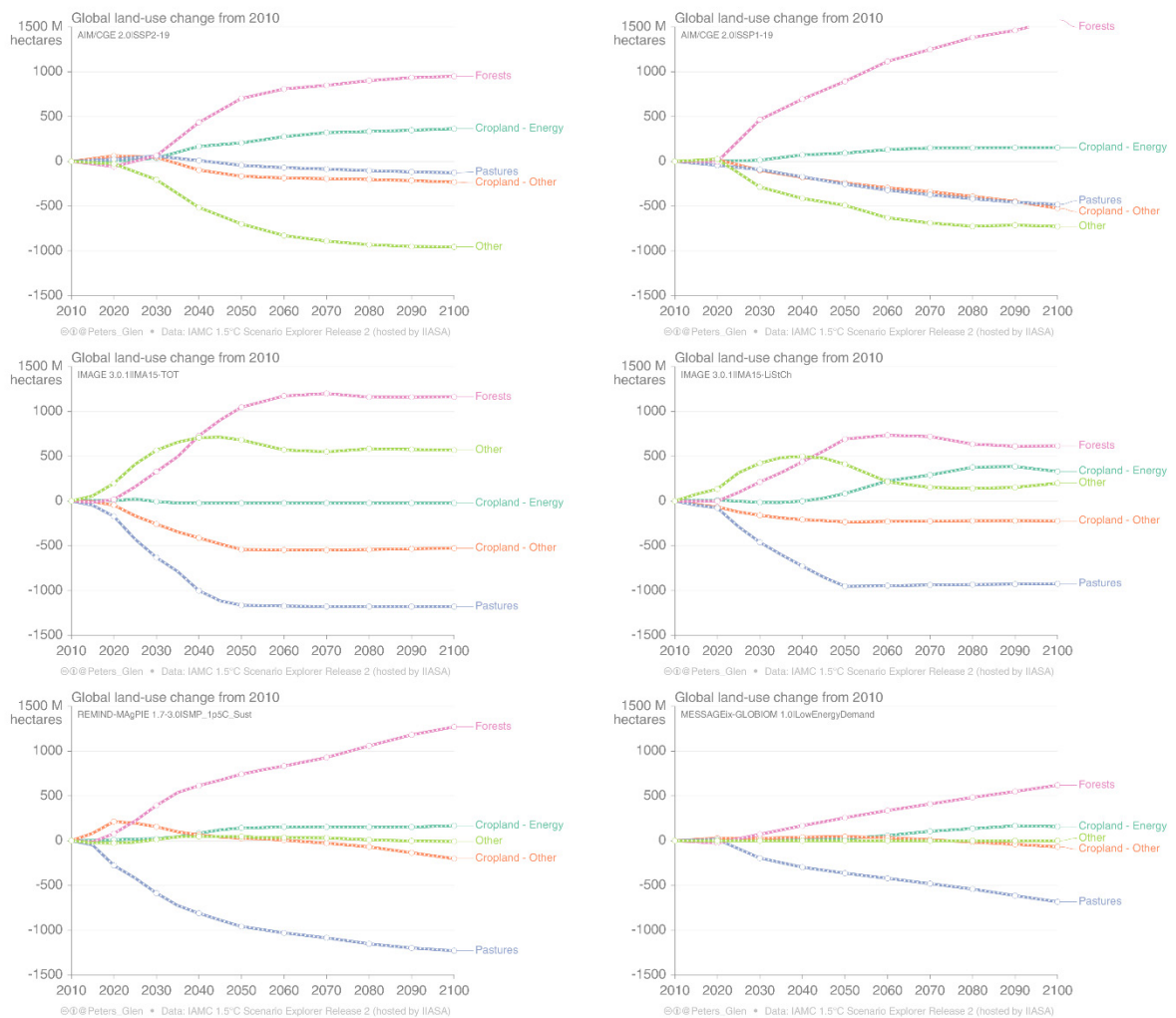
Figure 36: The land-use change in selected scenarios with sufficient data for the 1.5°C grouping of scenarios, to highlight the general land-use dynamics used in IAMs.

8.2   Regional land-use dynamics

Figure 37 shows the land use dynamics in the selected scenarios, with sufficient data, for both 1.5°C and 2°C, for both afforestation and bioenergy. The scale of the figure is to 1,750 million hectares, which is more than five times the area of India. The top row is bioenergy and the bottom row is afforestation, and the first column is 1.5°C and the second 2°C. Several features are prominent:

- Models use much more land for afforestation than for bioenergy. This is primarily because bioenergy has higher yields, particularly over time (see section below).
- There is no clear difference between 1.5°C and 2°C. This is primarily because many models are at or close to land constraints already in 2°C scenarios, so 1.5°C scenarios often require faster short-term emission reductions as opposed to greater CO_2 removal (or land use).
- Certain models dominate the outcomes. AIM clearly has higher land-use than other models and is overrepresented in 2°C scenarios.

Figure 37: The land use for afforestation (increased forest area) and bioenergy in the selected 1.5°C and 2°C scenarios with data.

The land use dynamics change at the regional level, with the results shown for bioenergy (Figure 38) and afforestation (Figure 39) in the selected 1.5°C scenarios. For bioenergy, the land use is greater in OECD compared to other regions, while all regions have large increases in land use for afforestation. The results can vary significantly depending on the model. It is worth comparing these figures to the carbon uptake in Figure 31 and Figure 34. For bioenergy, carbon uptake is about the same in OECD and Asia (Figure 31), while the Asia uses much less land (Figure 38). This indicates that the yields are higher in Asia than in the OECD. For afforestation, the carbon uptake is much greater in Latin America and Middle East and Africa (Figure 34), while the land use is similar across all regions (Figure 39), indicating higher yields in Latin America and Middle East and Africa. This helps illustrate that yields are important parameters to consider for carbon uptake rates and land use impacts.
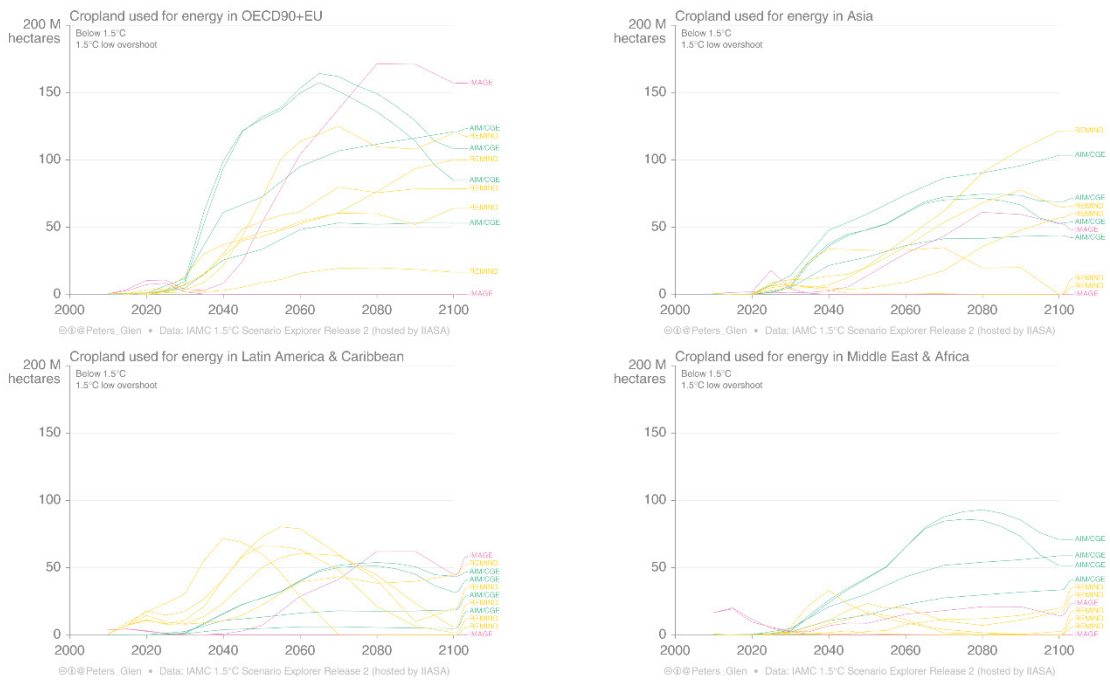
Figure 38: Land use for bioenergy in the selected 1.5°C scenarios by region.
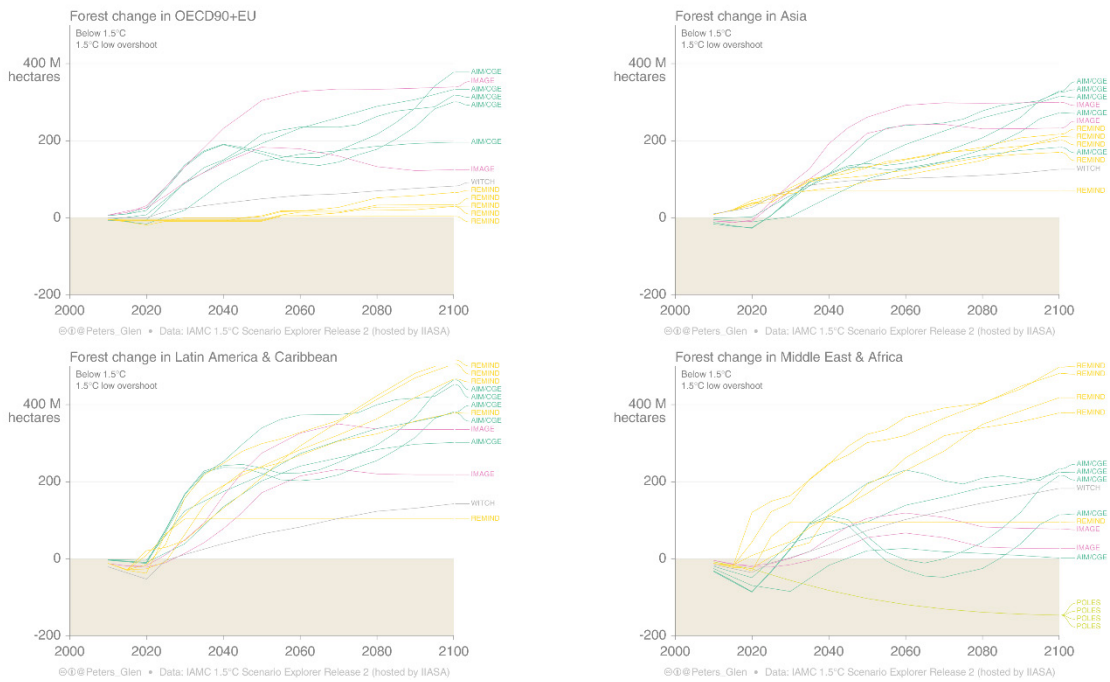

Figure 39: Land use for afforestation in the selected 1.5°C scenarios by region.

8.3 Yield and yield improvements

The scenario database does not provide information on yields. However, it is possible to crudely back-calculate yields to get an idea of the differences. A quick comparison of the earlier figures suggests that bioenergy crops sequester twice the carbon but with half the land area when compared to afforestation. This suggests that the yields for bioenergy would be about four times higher than afforestation.

Figure 40 and **Figure 41** show the approximate yields (CO_2 uptake per unit area) for the selected 1.5°C scenarios for BECCS and afforestation. These estimates are only indicative to show relative differences and changes. More specific information would require contacting individual modelling groups for more detailed data. The BECCS yields are estimated by taking the CO_2 removal from BECCS and comparing it to the land used for bioenergy. Note that some bioenergy is not used for BECCS, which means that yields will tend to be underestimated (for a given CO_2 removal, too much land is assumed). The afforestation yield is the carbon uptake from afforestation compared to the total forest change. The initial spike for afforestation in all scenarios is likely a mathematical issue that arises as the area change goes from zero to non-zero values.

The figures confirm that afforestation has, broadly speaking, lower yields than BECCS, and according to our rule of thumb from earlier figures, yields are approximately a factor of four difference. The afforestation yield is also roughly constant over time, while the bioenergy yield improves over time. This is also confirmed in other studies (Humpenöder et al. 2014).

A study using the REMIND framework (Humpenöder et al. 2014), found that in the base period (1995), afforestation had higher yield than BECCS in all regions, but over time the bioenergy yield improves so that by 2100, BECCS has much higher yield than afforestation. The study also found that despite higher BECCS yields in the tropics, BECCS was not utilised as afforestation had even higher yields in the tropics (relative to other regions). Thus, bioenergy happened in OECD and Asia, while afforestation happened in the tropics. While this study was for the REMIND framework, the results are broadly consistent with the figures shown here.

It is also important to understand the different ways forests (afforestation) and bioenergy crops (leading to BECCS) function.

Afforestation requires growing a new forest, and once this has been done on a given area, it cannot be repeated. The forest will initially take up carbon as it grows, and eventually it will reach a point in time where it will take up very little new carbon (and may even saturate). The resulting mature forest has built up its carbon stock, and all else equal, the carbon stock will remain constant as long as the forest is protected. The forest will interact with the carbon cycle (being a source and sink of emissions), but on balance, the forest will not take up additional carbon once it has matured. The time horizon of forests reaching close to full carbon stock will depend on the region (ranging from decades to centuries).

Bioenergy crops are grown on shorter time cycles and are optimised to get the maximum carbon in the minimum time. The bioenergy crop is then harvested, and a new crop is planted. This is more akin to large-scale agriculture, where fertilisers, crop selection, management, etc., is used to drive yield improvements. Bioenergy crop yields improve in the same way that agriculture yields improve. In contrast, afforestation requires planting a new forest once, and there are no real avenues to increase yields (though, fertiliser or management could be used in increasing the total carbon stock).
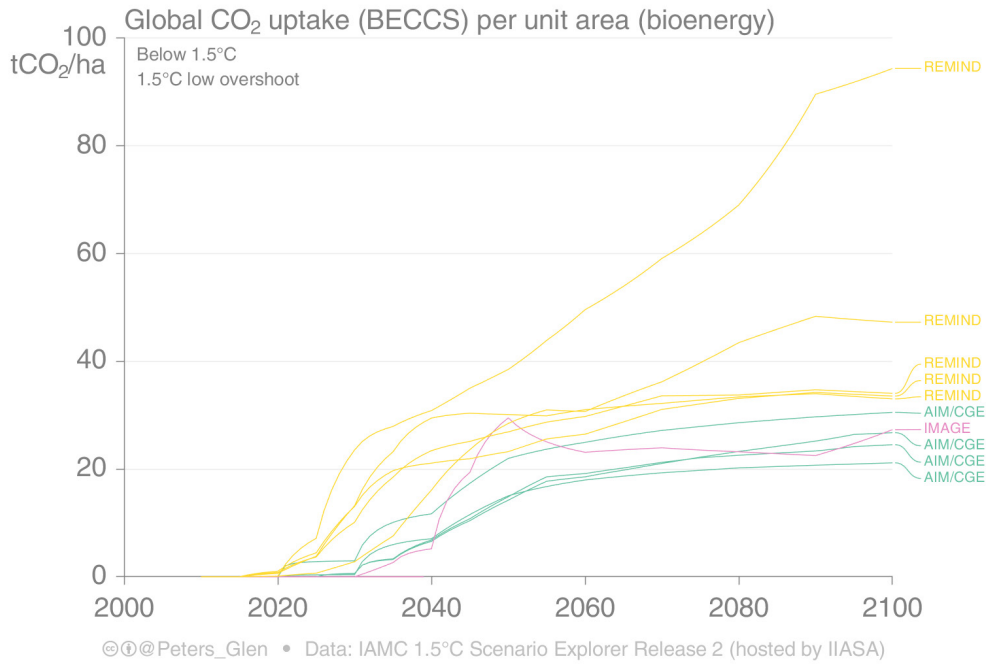
Figure 40: A crude estimate of the yield for BECCS for 1.5°C scenarios. This is a crude estimate and is only used to indicate changes, and compared carbon update from BECCS with all bioenergy land use suggesting these yields are underestimated.
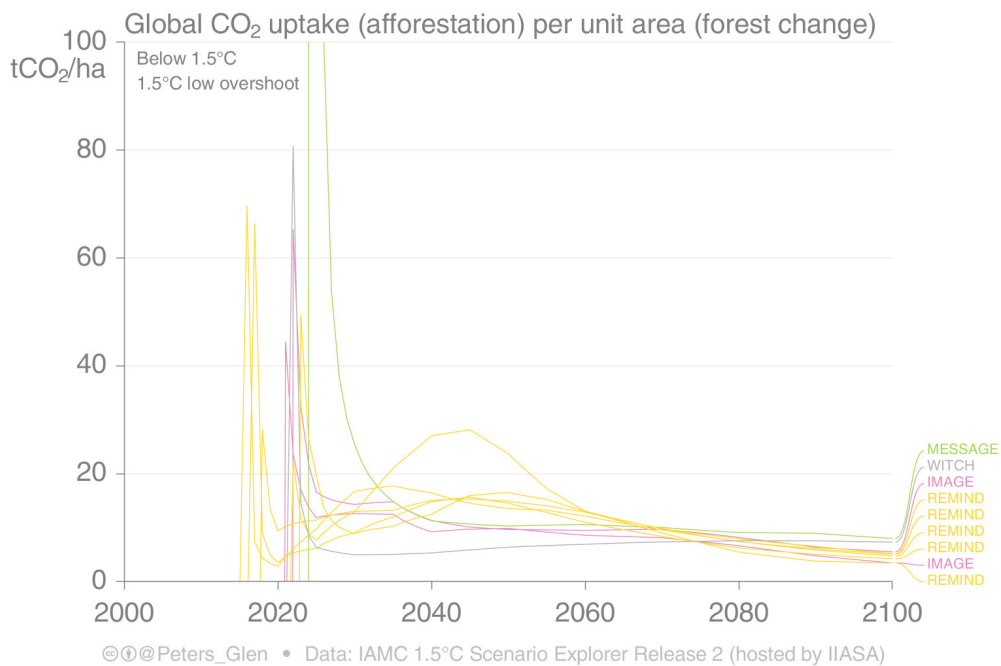
Figure 41: A crude estimate of the yield for afforestation for 1.5°C scenarios. This is a crude estimate and is only used to indicate changes.

9 Investment needs (e)

Topics discussed: *e) Investment needs on a global level and regional level*

In the scenario database, there is data on investment in energy supply and energy efficiency. For the investment in energy supply, it is further decomposed into the extraction of fossil fuels, electricity generation from different sources, transmission and distribution, CO_2 transport and storage, heat, liquids from different sources, and hydrogen. As usual, only some models provide the detailed data.

Figure 42 shows the investments in energy efficiency and energy supply (rows) for the selected 1.5°C and 2°C scenarios (columns). Only two scenarios provided data on energy efficiency, but these models are also represented in the energy supply investments, making a comparison possible. Overall, the two models with energy efficiency data, invest more (up to several times) on energy supply compared to energy efficiency. Though, this result should be taken with caution given the lack of data form other modelling frameworks.

In terms of energy supply, there is a large variation across models, and very little variation across climate targets. The REMIND framework has much higher investments compared to the other modelling frameworks. There is also relatively little difference from 1.5°C to 2°C. This result, while seemingly surprising, is expected. Energy infrastructure eventually retires and needs to be replaced, so the investment costs are not so different in a 1.5°C pathway compared to a pathway above 2°C. The main difference will be across energy sources. For example, investments in in 1.5°C and 2°C pathways are dominated by non-fossil sources, with the opposite in baselines. While it is possible to show figures of this, the data across different scenarios is rather noisy, with scenarios often reporting different variables, making the results more difficult to interpret.

Figure 42: Investment for energy efficiency (top) and energy supply (bottom) in the selected 1.5°C and 2°C scenarios.

10 Key abatement options (f)

Topics discussed: *f) For each sector a description of the deployment of key abatement options, including the cost of first-of-a-kind and cost-curves, and other important assumptions if relevant. Most importantly, we need information about CCS in the industry and energy sectors in EU/EEA, or the region most closely covering EU/EEA. Assumptions about CCS in different modelling frameworks must be described.*

The abatement (or mitigation) measures in these models are classified into demand-side measures, supply-side measures, agriculture forestry and other land-use (AFOLU) measures, and carbon dioxide removal (CDR) measures. Notice that a specific model is unlikely to consider all the measures. In the excel file submitted separately, we provide a list of the key abatement options considered in the relevant models, and whether the abatement options are represented, if represented, then whether they are endogenous and explicit or not in each model.

The demand-side measures can be roughly divided into two groups. One is energy-related measures including improvement of energy and other resource efficiency, electrification of energy demand, direct reduction in consumption of energy, and switch from traditional biomass and solid fuel to modern fuels. The other group is food-related measures including switch from livestock-based products to plant-based products, and reduction of meat consumption and food waste. All the models have considered certain demand-side measures either explicitly or implicitly. While some models explicitly include energy-related measures, almost no models explicitly include food-related measures.

The supply-side measures are all related to the energy sector. These measures include decarbonization of electricity (e.g. renewables, nuclear, and CCS at fossil power plants), decarbonization of non-electric fuels (e.g. hydrogen from biomass, biofuels, power-to-gas, methanization, and heating from solar and nuclear process) and other processing measures (e.g. fuel switch, substitution of halocarbons for refrigerants and insulation, electrical transmission efficiency improvement, electricity storage, and grid integration of intermittent renewables). Almost all the IAM models consider explicitly and endogenously all decarbonization measures of electricity and certain measures of both decarbonization of non-electric fuels and other processes.

AFOLU measures include better forest and agricultural management, reduction in deforestation and land degradation, agroforestry and silviculture, changing agricultural practices that enhance soil carbon, increasing productivity, methane reduction in rice paddies, nitrogen pollution reductions, and influence measures on land albedo of land-use change. Most of the models explicitly consider the measure of "reduced deforestation, forest protection, avoided forest conversion" while the other AFOLU measures are generally not represented or considered implicitly in the IAM models.

CDR measures include BECCS, direct air capture and sequestration (DACS), mineralization of atmospheric CO_2 through enhanced weathering of rocks, afforestation/Reforestation, restoration of wetlands, biochar, soil carbon enhancement, carbon capture and usage (CCU), bioplastics, carbon fibre, material substitution of fossil CO_2 with bio-CO_2 in industrial applications, ocean iron fertilization, ocean alkalinisation, and removing CH_4, N_2O and halocarbons via photocatalysis from the atmosphere. In most of the IAM models, BECCS is considered explicitly and endogenously while the other CDR measures are not represented or considered only implicitly.

It is natural that most mitigation measures are related to the energy sector since almost all the IAMs are developed from a detailed energy model. BECCS, which is also energy-related, is the only CDR measure explicitly considered by most of the IAMs. Generally, the IAMs describe poorly on the AFOLU measures although some IAMs (such as MESSAGE-GLOBIOM) consider some AFOLU measures explicitly.

Below we focus on the assumptions of CCS and capital costs in the electricity sector in the relevant models by looking into relevant model description documents and other studies.

10.1 CCS assumptions in the models

CCS captures the CO2 using chemical processes and stores the carbon underground or in the deep sea. It is mainly available for the large point CO_2 emission sources.

Most target scenarios are based on a baseline scenario corresponding to a SSP2 world. In general, SSP2 is taken a middle-of-the-road world, also relying on fossil-fuel based CCS technology to achieve its climate mitigation (Fricko et al. 2017). Hence, additional mitigation pressure consistent with 1.5 °C or 2 °C in the target scenarios would induce future adoption of fossil-fuel based CCS technology, particularly in the second half of the century (Figure 28). The assumptions of the CCS technology differ across the IAMs.
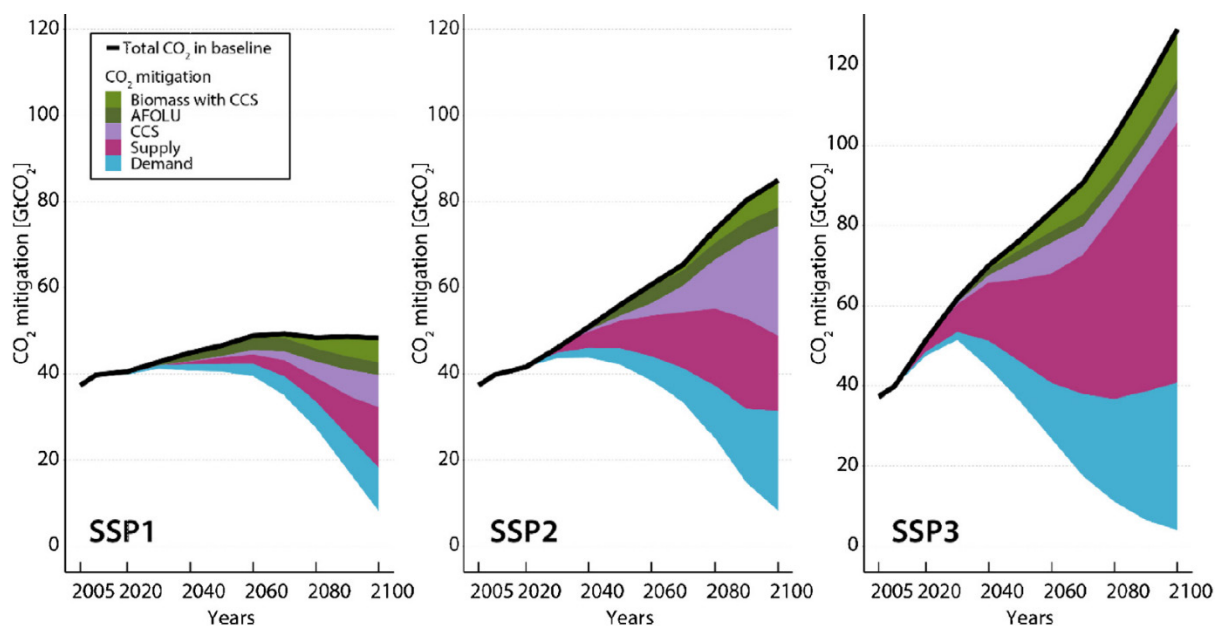
Figure 43: Mitigation of CO2 from baseline CO2 emission levels in SSP1, SSP2, and SSP3 for achieving a global radiative forcing target in 2100 of 4.5 W/m2, as modelled in the IIASA IAM framework. Mitigation contributions show the direct emission reduction contributions for each sector. Source: Fricko et al. (2017).

AIM/CGE 2.0

AIM/CGE 2.0 takes CCS technology as one of the key technologies for climate mitigation. The CCS technology is assumed available for fossil-fired power plants, biomass power plants, oil refineries and coal transformation plants, nonmetal and mineral, chemical, and paper and pulp industries in the model. These sectors need CCS services, which is provided by a CCS service sector with independent production activities. The costs of the technology are the medium values of

the cost estimates provided by IEA (2008) and differ among sectors (Table 13.6). In the model, CCS technology can be introduced after 2020 with a maximum yearly increase of 5% if the GHG emission price becomes higher than these costs.

The CCS service sector needs inputs of five factors including labor, capital, chemical products, transport, and other services with cost shares assumed as 0.1, 0.4, 0.1, 0.3, and 0.1, respectively, which are also based on IEA (2008).

Table 5: CCS technology cost. Source: Chapter 13.6, Fujimori et al. (2017b).

	Sectors	Price (US$/tCO$_2$)
Manufacturing	Petroleum refinery coal transformation	100
	Nonmetal and mineral	200
	Paper and pulp	150
	Chemical	150
Power	Coal fired	50
	Oil fired	70
	Gas fired	70
	Biomass fired	70

GCAM 4.2

GCAM 4.2 does not consider *oil refining technology* option with CO_2 CCS.

Biomass Liquids. The biomass liquids sector includes up to eight technologies in each region, with a global total of 11, as listed in Table 1. Among the technologies, up to two "first-generation" biofuels in each region, defined as biofuels produced agricultural crops that are also used as food, animal feed, or other modeled uses (described in the AgLU module). Second-generation technologies consume the "biomass" or "biomassOil" commodities, which include purpose-grown bioenergy crops, as well as residues from forestry and agriculture, and municipal and industrial wastes. Starting in 2020, second-generation biofuels (cellulosic ethanol and Fischer-Tropsch syn-fuels) are introduced, each with three levels of CCS: none, level 1, and level 2. The first CCS level generally consists of relatively pure and high-concentration CO2 sources (e.g., from gasifiers or fermenters), which have relatively low capture and compression costs. The second CCS level includes a broader set of sources (e.g., post-combustion emissions), and incurs higher costs but has a higher CO2 removal fraction.

Table 6: Biomass liquids production technologies in GCAM.

Technology	Inputs
biodiesel (soybean)	Oil Crop, natural gas
biodiesel (oil palm)	Palm Fruit
biodiesel (Jatropha)	BiomassOil
cellulosic ethanol	biomass
cellulosic ethanol CCS level 1	biomass

Technology	Inputs
cellulosic ethanol CCS level 2	biomass
corn ethanol	Corn, natural gas, electricity
sugar cane ethanol	Sugar Crop
FT biofuels	biomass
FT biofuels CCS level 1	biomass
FT biofuels CCS level 2	biomass

Coal to Liquids. As with biomass liquids, two different production technologies with CCS are represented, with costs and CO2 removal fractions based on Dooley and Dahowski (2009).

Table 7: Characteristics for each 0.5 MMB/D of Oil Shale Production Capacity: CO2 Streams and Estimated Cost of Employing Carbon Dioxide Capture and Storage Technologies (U.S. Dollars per ton of CO2). Source: P.4227, Dooley and Dahowski (2009).

	$MtCO_2$/yr	Cost of CO_2 Capture and Compression for Transport via Pipeline[2]	Cost of CO_2 Transport and Storage in a Deep Geologic Formation[3]	Total Cost of Employing CCS for Each Major CO_2 Stream
High-Purity CO_2 Stream Associated with Gas Cleanup	6.2	$6.00	$5.00	$11.00
High-Purity CO_2 Stream from IGCC Power Plants	42	$23.00	$5.00	$28.00
Uneconomic to Capture CO_2 from IGCC Power Plant	5.4	n/a	n/a	n/a
Low-Purity / Dispersed CO_2 Associated with Oil Upgrading Processes	1.6	$50.00	$5.00	$55.00
Uneconomic to Capture CO_2 from Oil Upgrading Processes	.17	n/a	n/a	n/a

Table 8: Characteristics of 0.5 MMB/D of Coal-to-Liquids Production Capacity: CO2 Streams and Estimated Cost of Employing CCS Technologies (U.S. Dollars per ton of CO2). Source: P. 4229, Dooley and Dahowski (2009).

	$MtCO_2$/yr	Cost of CO_2 Capture and Compression for Transport via Pipeline	Cost of CO_2 Transport and Storage in a Deep Geologic Formation	Total Cost of Employing CCS for Each Major CO_2 Stream
High-Purity CO_2 Stream	150	$6.00	$5.00	$11.00
Low-Purity CO_2 Stream from Combustion of Tail Gas to Generate Electric Power	30	$53.00	$5.00	$58.00
Uneconomic to Capture CO_2 from Tail Gas Combustion	3.4	n/a	n/a	n/a

Gas to Liquids. There is only one production technology represented in GCAM, with no CCS option available.

Hydrogen Production. The most common hydrogen production technology today is natural gas steam reforming, though coal chemical transformation is the dominant technology in China (IEA 2007b). In GCAM, all regions have access to all technologies when hydrogen as an energy carrier becomes available; as shown in Figure 10, hydrogen can be produced from up to 7 primary energy sources. Three of these sources (coal, gas, and biomass) include production technologies with CCS, characterized by higher costs and higher energy intensities, but lower CO2 emissions.

IMAGE 3.0.1

The CCS assumptions in IMAGE is based on CCS potential provided by Hendriks et al. (2004) and Metz et al. (2005).

Table 9: Costs and plant characteristics for power plants with capture of CO_2. Source: Hendriks et al. (2004).

Type of capture technology	Pre-comb.	Pre-comb.	Post-comb.	Post-comb.	Post-comb.
Type of plant	Natural gas	Coal	Natural gas	Natural gas	Coal
	(NGCC)	(IGCC)	(NGCC)	fired (steam)	(Pulverized)
Without capture					
Plant efficiency (%LHV)	58.0%	47.0%	58.0%	42.0%	42.0%
Emission factor ($kgCO_2$/kWh)	0.35	0.72	0.35	0.48	0.81
Power costs (€/kWh)	3.1	4.8	3.1	3.8	4.0
With capture					
Plant efficiency (%LHV)	51.5%	42.2%	52.0%	36.4%	33.7%
Emission factor ($kgCO_2$/kWh)	0.05	0.09	0.05	0.07	0.12
Loss of plant efficiency	6.5%	4.8%	6.0%	5.6%	8.3%
Power costs (€/kWh)	4.6	6.4	4.1	5.0	6.0
Power cost increase (%)					
CO_2 avoided (%)	85%	88%	85%	85%	85%
Costs (€/tCO_2)	43	26	37	30	29

Table 10: Typical costs of CO2 capture for industrial plants. Source: Hendriks et al. (2004).

Facility	€/tCO_2	Facility	€/tCO_2
Cement plants	28	Refineries	29-42
Iron and steel plants	29	Hydrogen (flue gas)	36
Ammonia plants (flue gas)	36	Hydrogen (pure CO_2)	3
Ammonia plants (pure CO_2)	3	Petrochemical plants	32-36

Table 11: Storage costs by depth (in €/tCO$_2$). Source: Hendriks et al. (2004).

	Depth of storage (m)		
	1000	2000	3000
Aquifer onshore	2	3	6
Aquifer offshore	5	7	11
Natural gas field onshore	1	2	4
Natural gas field offshore	4	6	8
Empty oil field onshore	1	2	4
Empty oil field offshore	4	6	8
	Low	**Medium**	**High**
EOR onshore	-10	0	10
EOR offshore	-10	3	20
ECBM	0	10	30
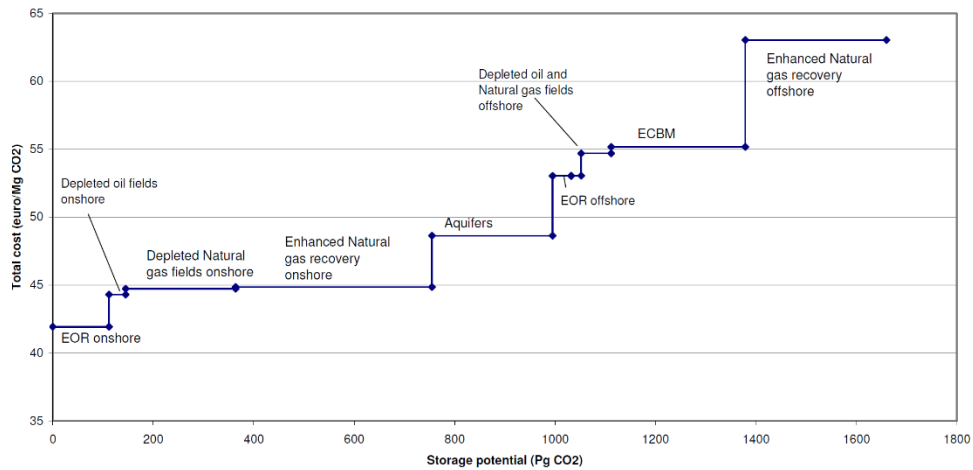
Figure 44: World cost curve CO2 storage. Costs are calculated by: (1) average capture and compression costs of 38.5 €/ tCO2, (2) weighted world average of transport distance per type of reservoir and (3) typical storage costs per type of reservoir. Source: Hendriks et al. (2004).

MESSAGE-GLOBIOM 1.0

Technological change in MESSAGE is generally treated exogenously. The current cost and performance parameters, including conversion efficiencies and emission coefficients is generally derived from the relevant engineering literature. The future alternative cost and performance projections are usually developed to cover a relatively wide range of uncertainties that influences model results to a good extent. As an example, Figure 45 below provide an overview of costs ranges for a set of key energy conversion technologies (Fricko et al. 2017).

Figure 45: Cost indicators for thermoelectric power-plant investment. Black ranges show historical cost ranges for 2005. Green, blue, and red ranges show cost ranges in 2100 for SSP1, SSP2, and SSP3, respectively. Global values are represented by solid ranges. Values in the global South are represented by dashed ranges. The diamonds show the costs in the "North America" region. CCS – Carbon Capture and Storage; IGCC – Integrated gasification combined cycles; ST – Steam turbine; CT – Combustion turbine; CCGT – Combined cycle gas turbine. Source: Fricko et al. (2017).

Figure 46: Cost indicators for non-thermoelectric power-plant investment. Black ranges show historical cost ranges for 2005. Green, blue, and red ranges show cost ranges in 2100 for SSP1, SSP2, and SSP3, respectively. Global values are represented by solid ranges. Values in the global South are represented by dashed ranges. The diamonds show the costs in the "North America" region. PV – Photovoltaic. Source: Fricko et al. (2017).
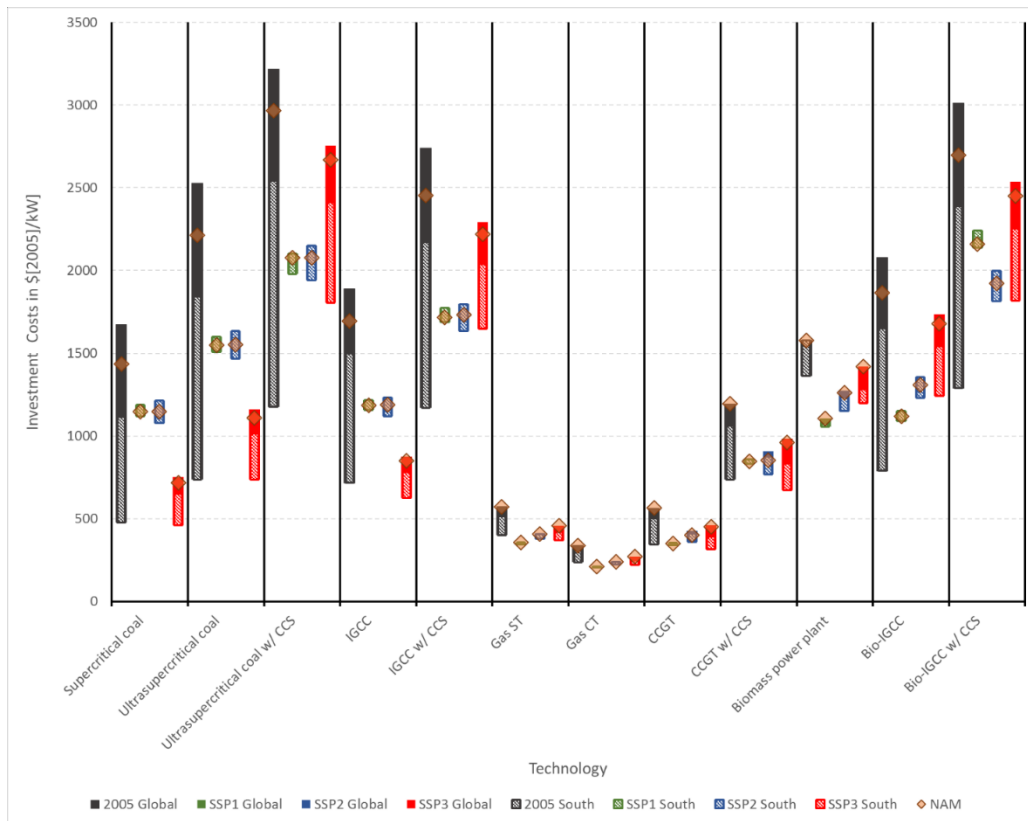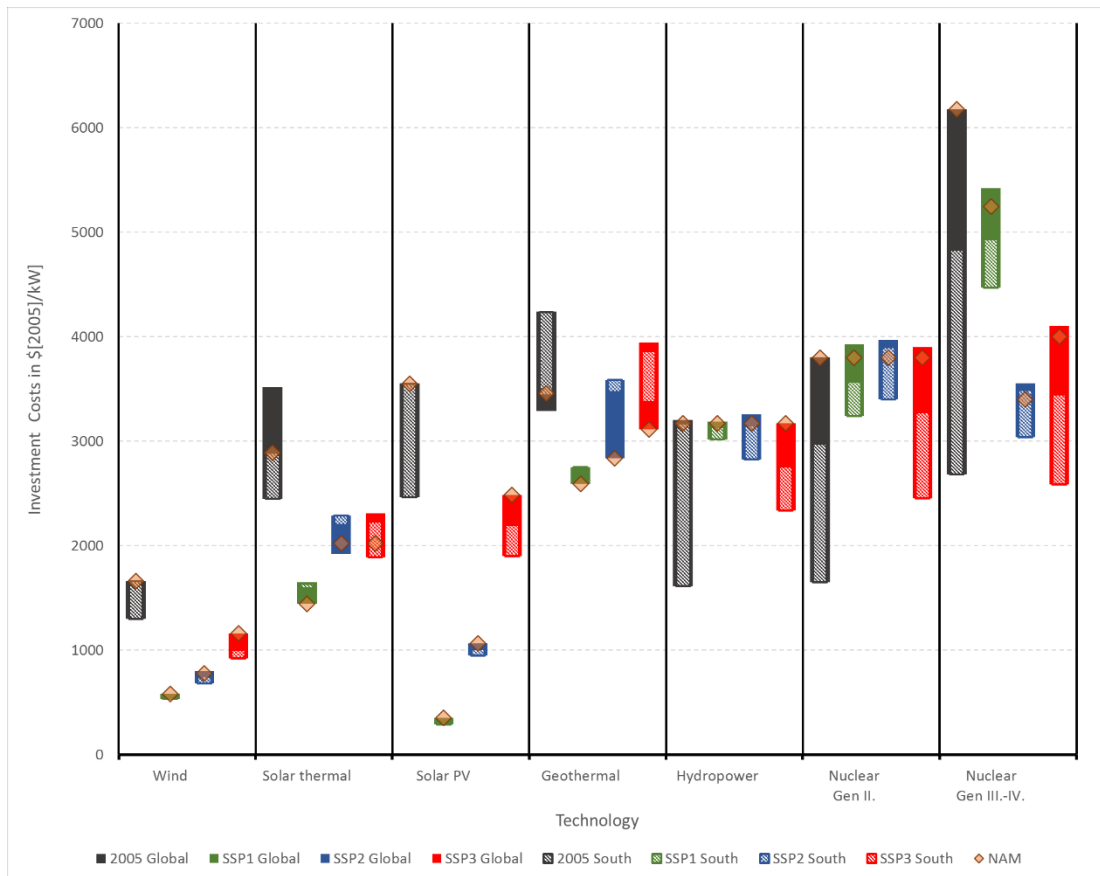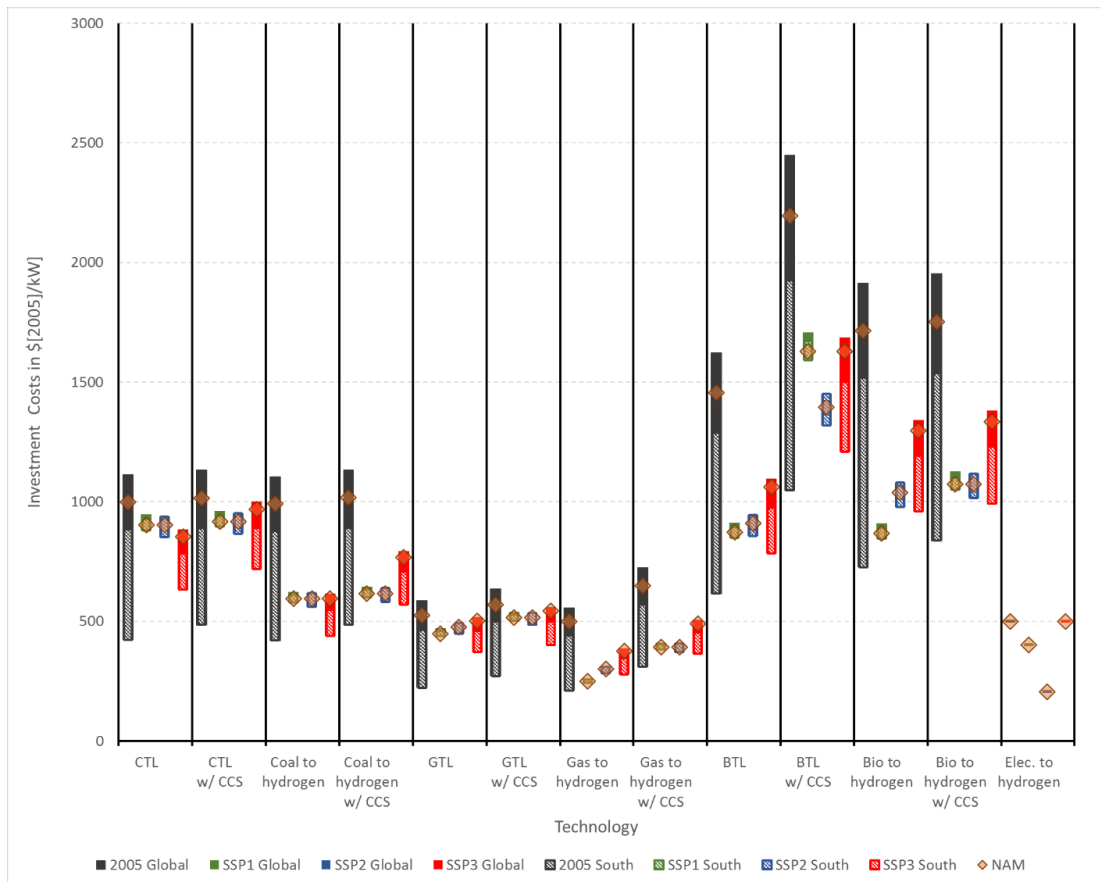
Figure 47: Cost indicators for other conversion technology investment. Black ranges show historical cost ranges for 2005. Green, blue, and red ranges show cost ranges in 2100 for SSP1, SSP2, and SSP3, respectively. Global values are represented by solid ranges. Values in the global South are represented by dashed ranges. The diamonds show the costs in the "North America" region. CCS – Carbon capture and storage; CTL – Coal to liquids; GTL – Gas to liquids; BTL – Biomass to liquids. Source: Fricko et al. (2017).

REMIND 1.7

REMIND considers several CCS applications. First, CCS technologies are options for electricity generation and the production of liquid fuels, gases, and hydrogen from coal and gas. Second, bioenergy CCS (BECCS) technologies are available for electricity generation, biofuels, hydrogen, and syngas production. Third, CCS can be used to reduce atmospheric CO_2 emissions from the industry sector.

REMIND explicitly consider the transportation and storage costs of CCS technologies (Bauer 2005). Regional constraints on CCS potentials are largely based on IEA (2008). The global CCS potential is around 1000 GtC, where for EU with 50 GtC, Japan with 20 GtC, and India with 50 GtC. The model assumes that the yearly injection rate of CO_2 is no more than 0.5% of total CCS capacity due to technical and geological constraints, which implies an upper limit of 5 GtC per year for global CCS. The tables below shows more details about the assumptions of the CCS technologies in REMIND.

Table 12: Techno-economic characteristics of technologies based on exhaustible energy sources and biomass. Abbreviations: PC - pulverized coal, IGCC - integrated coal gasification combined cycle, CHP - coal combined heat and power plant, C2H2 - coal to hydrogen, C2L - coal to liquids, C2G - coal gasification, NGT - natural gas turbine, NGCC - natural gas combined cycle, SMR - steam methane reforming, BIGCC – Biomass IGCC, BioCHP – biomass combined heat and power, B2H2 – biomass to hydrogen, B2L – biomass to liquids, B2G – biogas, TNR - thermo-nuclear reactor; * for joint production processes; § nuclear reactors with thermal efficiency of 33%; # technologies with exogenously improving efficiencies. 2005 values are represented by the lower end of the range. Long-term efficiencies (reached after 2045) are represented by high-end ranges. Source: https://www.iamcdocumentation.eu/index.php/Electricity_-_REMIND

		Life-time	Overnight investment costs		O&M costs (fix & variable)		Conversion efficiency		CCS capture rate	Capacity factor	
		Years	$US2015/kW		$US2015/GJ		%		%		
			No CCS	With CCS	No CCS	With CCS	No CCS	With CCS	With CCS	No CCS	With CCS
Coal	PC	40	1600		3		41-46#			0.75	
	IGCC	35	2200	2800	4.0	5.3	42-50#	33-43#	90	0.75	0.80
	C2H2*	35	1510	1720	1.9	2.1	59	57	90	0.8	0.8
	C2L*	35	1740	1820	4.2	5.0	40	40	70	0.85	0.85
	C2G	35	1440		1.4		60			0.9	
Gas	NGT	30	500		6.0		36-41#			0.09	
	NGCC	35	950	1350	2.1	2.9	56-63#	49-56	90	0.55	0.65
	SMR	35	600	660	0.6	0.7	73	70	90	0.9	0.9
Biomass	BIGCC*	40	2450	3150	5.1	6.9	37-46#	28-35#	90	0.75	0.75
	BioCHP	40	3000		6.0		35			0.75	
	B2H2*	35	1680	2040	5.7	6.8	61	55	90	0.9	0.9
	B2L*	35	3000	3600	4.2	5.4	40	41	50	0.9	0.9
	B2G	40	1200		1.9		55			0.9	
Nuclear	TNR	40	4700		6.7		33§			0.8	

Table 13: Techno-economic characteristics of technologies based on non-biomass renewable energy sources. Source: https://www.iamcdocumentation.eu/index.php/Electricity_-_REMIND

	Lifetime	Overnight Investment costs in 2005	Overnight Investment costs in 2015	Floor costs	Learn Rate 2003-2013	Cumulative capacity 2005	Yearly fix O&M costs	Capacity factor
	Years	$US2015/ kW	$US2015/ kW	$US2015/ kW		GW	% of Inv.Costs	Share of a year
Hydro	70	2300	2300	-	-	-	2%	0.15-0.55
Geo HDR	30	3000	3000	-	-	-	4%	1
Wind	25	2400	1850	1100	12%	60	2%	0.09-0.48
SPV	30	5900	1750	450	20%	5	1.5%	0.1-0.2
CSP	30	10300	6950	1550	10%	0.5	2.5%	0.15-0.67

WITCH-GLOBIOM

CCS supply costs of injections and sequestration are related to regional sites availability, energy penalties, and capture and leakage rates. CCS can be used with Gas, Coal, and Biomass power plants in WITCH and competes with traditional fuel power plants for a sufficiently high carbon price signal. The costs for CCS transportation and storage are increasing with the cumulative sequestrated emissions, where the parameters are calibrated to follow Rubin et al. (2015) and the available CCS capacity follows IEAGHG (2011). The main parameters related to the CCS technologies are summarized in Table 14 below.

Table 14: Main parameters related to the CCS technologies in WITCH. Source: https://www.witchmodel.org/documentation/

	Coal pre-comb	Coal post-comb.	Coal Oxyfuel	Natural gas	Biomass
Capacity factor [%]	81	83	83	84	80
CO2 Capture rate ratio [%]	89	90	95	89	90
Net efficiency [% on LHV basis]	33.88	33.7	33.15	47.99	28
Lifetime	40	40	40	25	25
Investment cost [$/kW]	3077.7	3063.4	3252.9	1508.4	3693.2
O&M costs [$/MWh]	10.15	13.44	9.54	6.41	10.33
Learning rate [%]	6.7	3.8	2.8	4.2	5
Floor cost [$/kW]	1472	1472	1472	750	2000
Capacity before learning [GW]	7	5	10	3	10

Retrofitting Coal plants operative in 2015 represents an alternative to CCS technologies. Retrofitting is defined as an investment cost for the retrofitting unit and differential effects for a subset of the existing coal capacity, namely efficiency drop of 10 percentages points and introduction of CO2 capture.

To sum up, the CCS costs assumed in the IAMs are mainly based on studies in around 2010 in the energy supply sector. Most of the IAMs typically include the BECCS and Afforestation and reforestation (AR) as the other technologies for net negative emissions (Henri et al. 2019). Since both BECCS and AR depends heavily on land use change, most models assume that both technologies are modeled explicitly and endogenously to compete with other land use purposes such as production of energy and food crops. Generally, it is assumed that the profitability of activities by land type determines how land moves from one type to another subject to boundary conditions. For other technologies to provide net negative emissions, almost no concrete costs data are provided for these models.

For the CCS technologies in the energy supply sector, while it is not comparable of the costs across the IAMs directly obtained from the model description, a recent study (Krey et al. 2019) has provided capital costs of electricity generation technologies with and without CCS of several IAMs, which will be summarized in the next subsection.

10.2 Capital costs in electricity sector

To compare the capital costs across the models, we use the capital cost data from 2010 to 2050 from (Krey et al. 2019). Krey et al. (2019) collected data for coal fueled power plants from models of GCAM, IEA, IMAGE, MESSAGEix-GLOBIOM, REMIND, and POLES_MILES. The capital costs are generally decreasing over time by assumption except REMIND and WITCH-GLOBIOM, where the capital costs are constant over time. Below we report capital costs in the EU region.

10.2.1 Coal-fueled power plants

The lifetime assumed in these models ranges from 30 to 60 years. Three technologies are assumed for the coal-fueled power generation: generic, Integrated coal gasification combined cycle (**IGCC**), and pulverized coal (PC). The capital costs in West EU is generally assumed a bit higher than CEU in IMAGE and EEU in GLOBIOM while other models assume the same for all the EU.

In the models, the technologies with CCS are assumed to have roughly double capital costs of that without CCS. If we assume a technology with CCS is built upon the same technology without CCS in an IAM, then the CCS costs can be derived from the data as shown in the last two columns "Cost of CCS" in the table below. In the calculation, if the capital cost for the whole EU is not available, then we simply average the data of the regions we have.

Table 15: Capital costs of coal-fueled power plants in IAMs. USD2010/Kw. Source: Summarized from Krey et al. (2019).

Technology	Without CCS		With CCS		Cost of CCS	
Year	2010	2050	2010	2050	2010	2050
Generic	1499-3371	1499-2950	3326-6200	2635-4782	1210	588
IGCC	1582-3999	1374-3215	2255-6600	2114-4945	275-2601	275-1730
PC	1041-2142	1053-2044	2640-3833	2640-2624	1100-2829	1100-1832

10.2.2 Gas-fueled power plants

The lifetime assumed in these models ranges from 25 to 45 years. Three technologies are assumed for the gas-fueled power generation: generic, combined cycle (CC), and Combustion turbine (CT). In the models, the technologies with CCS are assumed to have roughly triple the capital costs of that without CCS. If we assume the CT technology with CCS is the same as the generic technology with CCS, then the CCS costs can be derived from the data as shown in the last two columns "Cost of CCS" in the table below. In the calculation, if the capital cost for the whole EU is not available, then we simply average the data of the regions we have.

Table 16: Capital costs of gas-fueled power plants in IAMs. USD2010/Kw. Source: Summarized from Krey et al. (2019).

Technology	Without CCS		With CCS		Cost of CCS	
Year	2010	2050	2010	2050	2010	2050
Generic			1567-2101	1431-1672		
Combined cycle	465-1033	443-990	1210	1210	495-1068	391-824
Combustion turbine	302-498	268-694			1089-1617	642-978

10.2.3 Biomass-fueled power plants

The lifetime assumed in these models ranges from 20 to 60 years. Several technologies are assumed for the biomass-fueled power generation across models: generic, biomass steam turbine, Advanced biomass power plant- gasified biomass is burned in gas turbine plant, Biomass gasification, and Biomass combined cycle.

In the models, the cost of the technologies with CCS are assumed higher than the capital costs of that without CCS although the CCS costs are decreasing over time. If we assume the missing costs of all the technology with CCS is the same as the generic technology with CCS, then the CCS costs can be derived from the data as shown in the last two columns "Cost of CCS" in the table below. In the calculation, if the capital cost for the whole EU is not available, then we simply average the data of the regions we have.

Table 17: Capital costs of biomass-fueled power plants in IAMs. USD2010/Kw. Source: Summarized from Krey et al. (2019).

Technology	Without CCS		With CCS		Cost of CCS	
Year	2010	2050	2010	2050	2010	2050
Generic	1462-5000	1355-4260	2816-8276	2816-6444	770-3276	770-2183
Advanced biomass power plant - gasified biomass is burned in gas turbine plant	1740-1788	1511-1559		2427		892
Biomass steam turbine	2290-2454	2211-2279			1361-3415	592-1450
Biomass combined cycle	3023-2186	2435-2492			629	374
Biomass gasification	3028	2250			2784	1437

10.2.4 All other technologies for electricity generation

All the other technologies for electricity generation are non-fossil fueled and do not need CCS. Generally, in 2010, nuclear and CSP are the most expensive although some wind power is also very costly. Over time, the capital costs of hydropower are almost constant, the nuclear power is assumed increasing capital costs, while all the other renewables become less costly, particularly PV and CSP.

Table 18: Capital costs of non-fossil-fueled power plants in IAMs. USD2010/Kw. Source: Summarized from Krey et al. (2019).

Technology	2010	2050
Nuclear	3492-6325	3740-6121
Hydro	2090-3405	2090-3448
PV	1866-3619	951-1394
CSP	4688-10676	2892-5902
Wind Offshore	1285-6020	1054-2738
Wind Onshore	1183-2001	841-1607
Geothermal	2314-4819	2104-4083

10.3 Assumed costs differ considerably across models

The costs of electricity generation technologies are considerably different across these models, both for the base year and future years. This is not surprising since similar difference also exists in the literature other than the IAM studies. Notice that beyond the differences in the numerical costs data, the representation of technologies also differs among models, which needs to be considered when comparing numerical parameters.

Regarding BECCS, a bibliometric analysis based on academic BECCS studies between 2001 and 2017 (Laude 2019) shows that the BECCS research is largely conducted by the IAM research community. These models typically focus on long-term analysis and provide insufficient assessment of the implementation features of BECCS in the near future, e.g., techno-economic analyses, business models, local-scale assessments, and comparison with other negative emission technologies. Future research is suggested to provide better assessment of the near future of BECCS implementation features.

Since low energy demand 1.5C scenarios may be possible without negative emissions (Grubler et al. 2018) and a 100% renewable electricity system may be feasible (Diesendorf and Elliston 2018), we may possibly avoid the high costs associated with the negative emissions technologies. However, the worldwide CCS adoption would be critical if fossil fuels continue to be substantively consumed while still meeting climate targets (Budinis et al. 2018).

11 Demand for primary energy and base materials (g)

Topics discussed: *g) As far as possible, demand for primary energy and base materials (such as oil, gas, coal, different kinds of bioenergy, renewable electricity, cement, iron and steel, aluminum, and chemical products such as ammonia, ethylene, methanol). Most importantly, we need information about the demand for oil and gas globally and in Europe.*

The SR15 scenario database has demand for primary energy supply (coal, oil, gas, biomass, renewable electricity), but there is no data for base materials (cement, iron and steel, aluminum, and chemical products such as ammonia, ethylene, and methanol). It is likely many IAMs do not have sufficient detail to model specifically flows of base materials, this would require a sectoral model (Pauliuk et al. 2017).

The IPCC uses the *direct equivalent method* for primary energy accounting. This method counts one unit of secondary energy provided from non-combustible sources (e.g., nuclear, solar) as one unit of primary energy (1 kWh of electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy). This method differs somewhat from the approach used by IEA, which uses the heat produced in thermal power plants (i.e., fossil power plants, nuclear and geothermal) rather than the electricity generated, and is even more different from BP, which additionally uses a substitution method to scale up non-thermal electricity generation based on the average amount of heat energy needed to generate the same amount of electricity in a thermal power plant. The method is used in long-term scenarios, because it deals with fundamental transitions of energy systems that rely to a large extent on low-carbon, non-combustible energy sources such as wind and solar PV. We follow that convention in this section, as it is the convention used by the IPCC.

11.1 Global Primary Energy Use

Figure 48 and Figure 49 show the primary energy use in the selected 1.5°C and 2°C scenarios. The primary energy across 1.5°C and 2°C is relatively similar, and there are clear patterns across models. The REMIND framework uses more energy than the other modelling frameworks. Many scenarios have flat energy use across the century, though, the scenarios have a prominent drop until about 2030 before rising again (discussed further below). Based on the comparison of the 1.5°C and 2°C scenarios, the remainder of this section will focus on 1.5°C scenarios only.
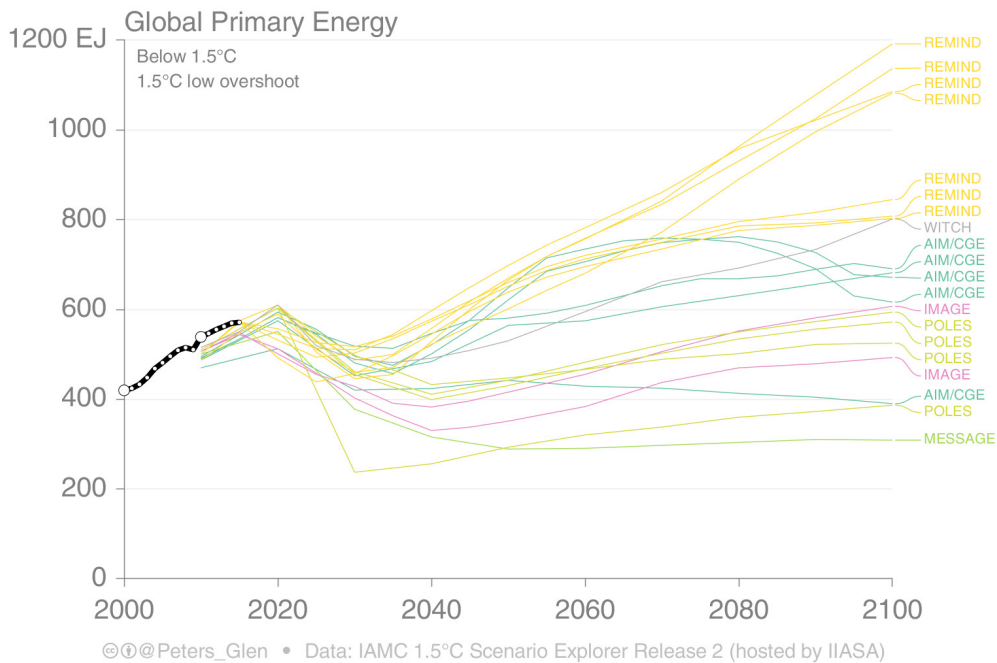
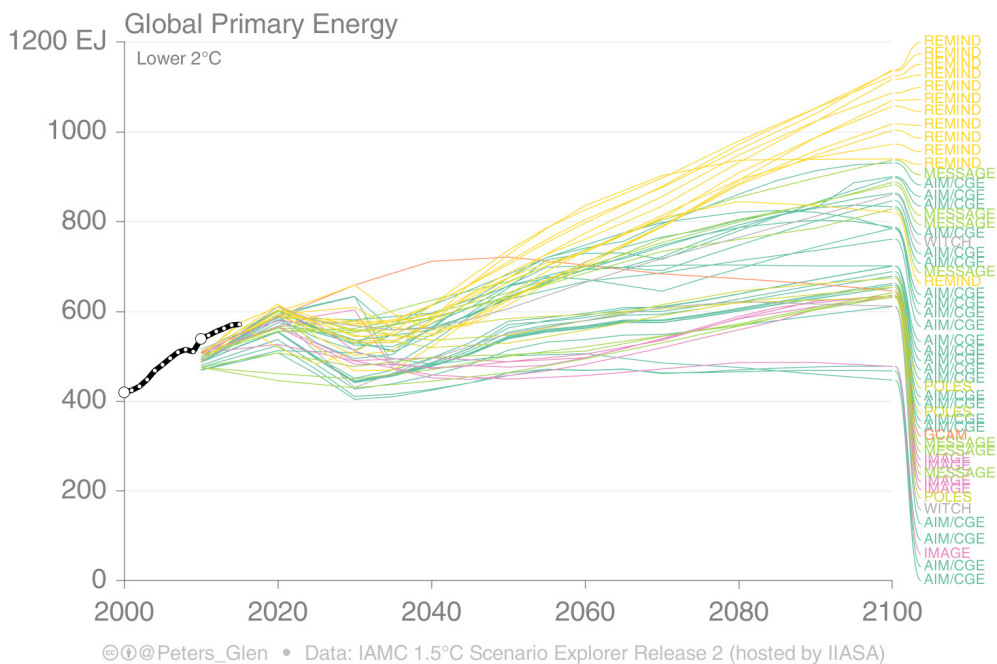**Figure 48**: Primary energy use in the selected 1.5°C scenarios.

Figure 49: Primary energy use in the selected 2°C scenarios.

Figure 50 shows the global primary energy use for the selected 1.5°C scenarios for fossil fuels, biomass, non-biomass renewables (mainly solar, wind, hydro), and nuclear. Fossil fuel use declines rapidly in 1.5°C scenarios, but they don't decline to zero. Fossil fuels are predominantly, and quickly, replaced by non-fossil sources, primarily solar, wind, and hydro. The growth of biomass is strong, though limited from the scenario selection. Nuclear remains small, though grows modestly in some scenarios depending on the modelling framework. Overall, the rapid decline in fossil fuels

in the first decades leads to a drop in global primary use, before it grows again with strong growth in renewables.
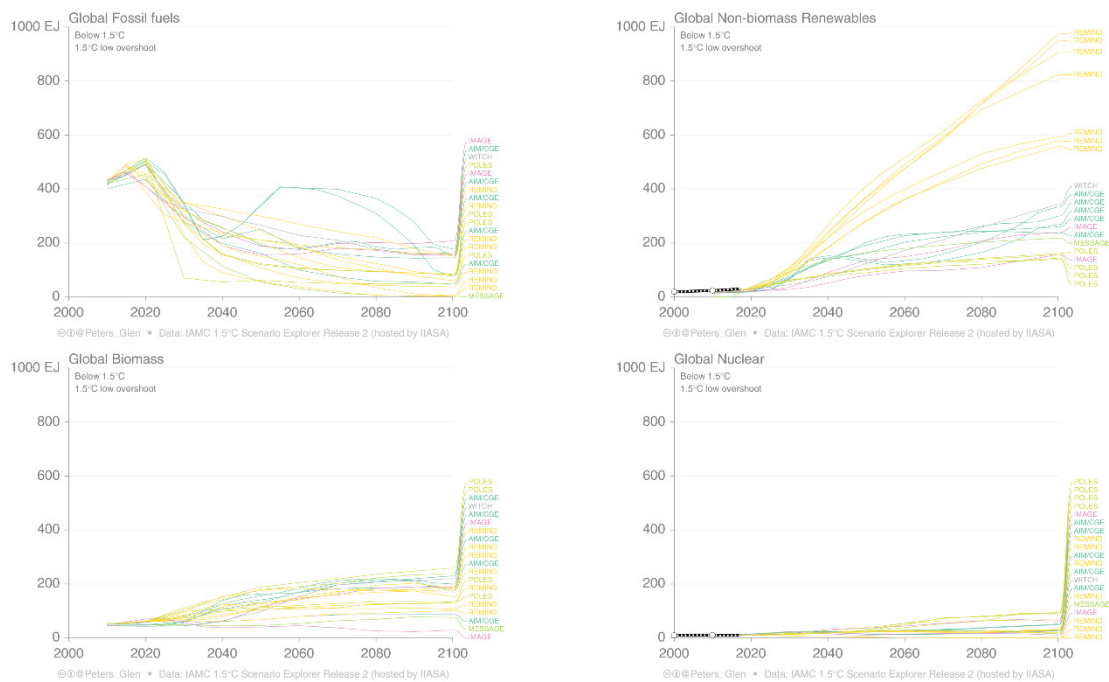

Figure 50: Primary energy use for the selected 1.5°C scenarios for fossil fuels, biomass, non-biomass renewables (mainly solar, wind, hydro), and nuclear.

Figure 51 shows fossil fuel use at the global level for the selected 1.5°C scenarios. There are a few characteristics worth noting.

- Coal: Drops strongly in most scenarios. Some scenarios have a renaissance of coal in the second half of the century, and this is due to the deployment of coal with CCS.
- Oil: Has a gradual decline in most scenarios, though the extent of the decline varies considerably by model, as does the value in 2100
- Gas: There is a large variation of natural gas use across scenarios, with some models showing declines and others showing rises. However, there are no scenarios where natural gas use grows in from today's levels.

In summary, in 1.5°C scenarios, coal declines quickly, oil declines moderately, and natural gas use is highly uncertain but does not rise. This is also a message from SR15.
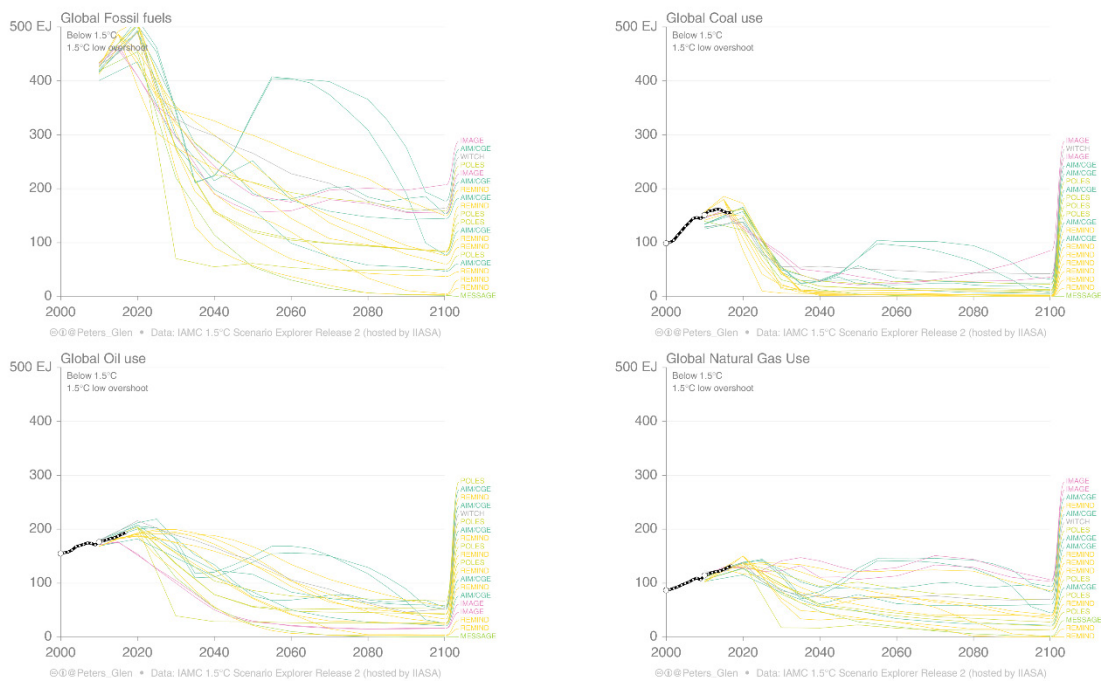
Figure 51: Fossil fuel use for the total, coal, oil, and gas in the selected 1.5°C scenarios, all with the same y-axis.

11.2 Regional oil and natural gas use

In this section, the focus is on regional oil and natural gas use, with coal not shown.

Figure 52 shows oil use in the four main IPCC regions for the selected 1.5°C regions, with the Economies in Transition not shown. Oil use drops sharply in the OECD in all scenarios, grows a little before declining in Asia, but has only slight declines in Latin America, the Middle East and Africa, and the Economies in Transition (not shown). In the OECD countries, oil use drops around 30% by 2030 and 80% by 2050. Asia has a decline of 8% by 2030, but a drop of 60% by 2050. There are variations across scenarios, but all exhibit similar trends over these periods, if only some changes in when the declines start. It is unclear why AIM has an increase in oil use from 2040 to 2060.
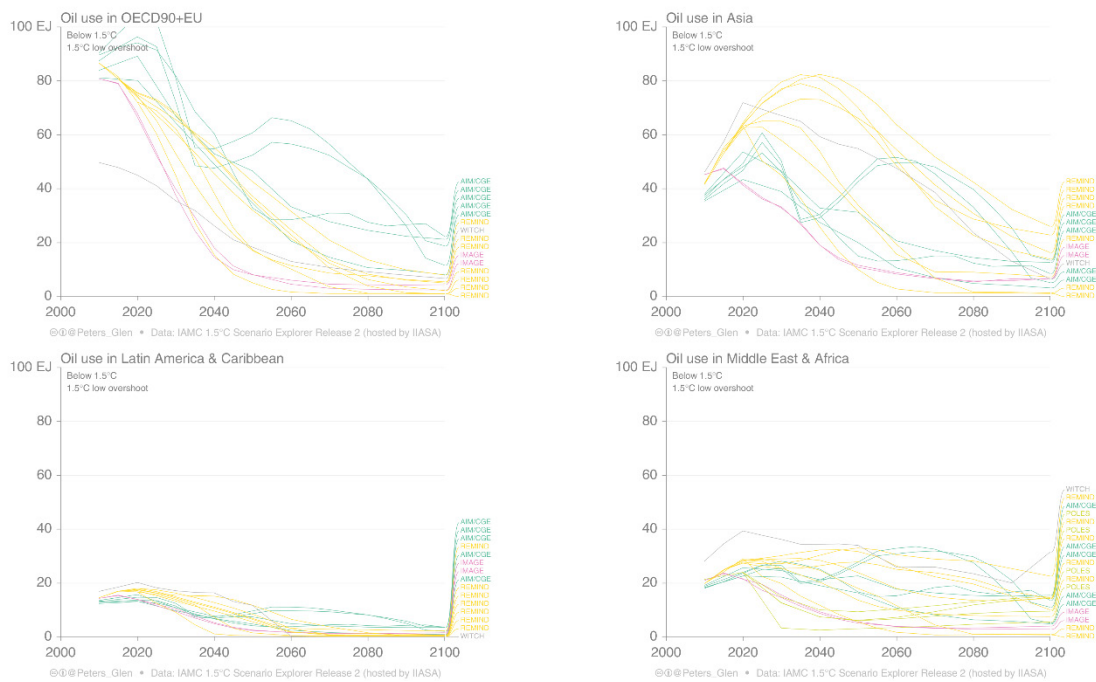
Figure 52: Oil use by region in the selected 1.5°C scenarios.

Figure 53 shows natural gas use in the four main IPCC regions for the selected 1.5°C regions, with the Economies in Transition not shown. Natural gas use is more nuanced in the future, with significant differences across scenarios. In the OECD, natural gas use on average declines 20% by 2030 and 50% by 2050, but AIM shows little change on average. AIM suggests there could be a slight rise, depending on which AIM scenario is selected. Asia also has considerable variation, with AIM suggesting natural gas use will remain flat, which others show an increase. Across these scenarios suggests natural gas use could rise 20% on average by 2030, or even 100% across some scenarios. However, the increases in natural gas are much lower than the increases in emission scenarios with weaker climate mitigation (policy). The different models and scenarios lead to very different outcomes for natural gas, particularly at the regional level, which suggests additional or more detailed modelling would be required.
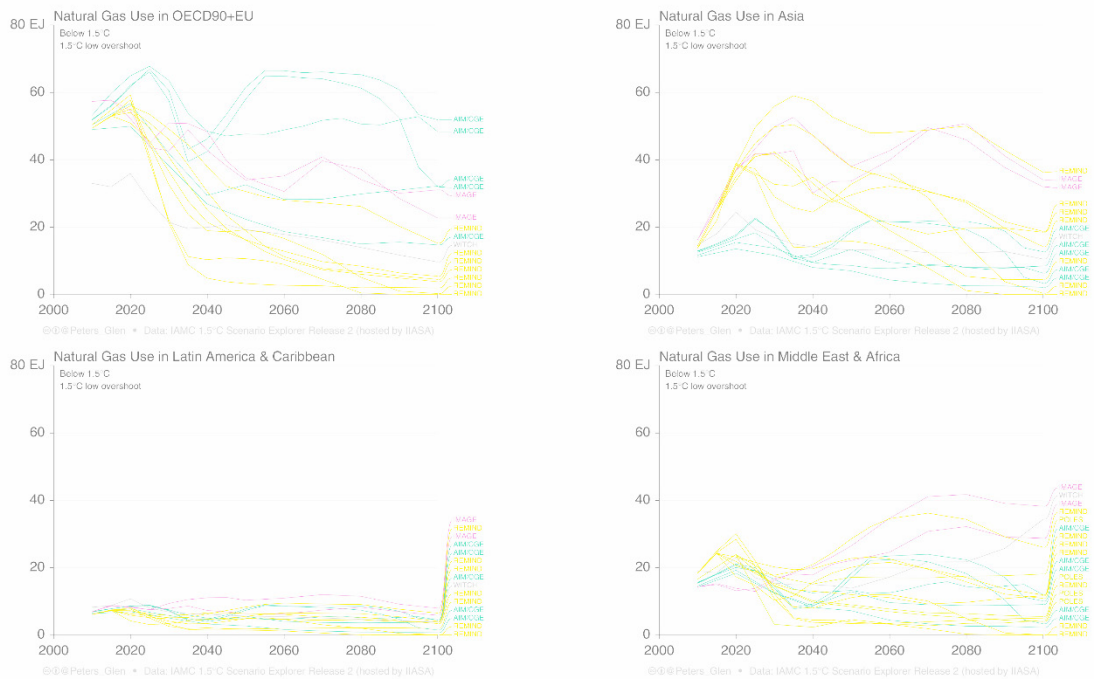
Figure 53: Natural gas use by region in the selected 1.5°C scenarios.

12 Abatement options in the industrial sector (h)

Topics discussed: *h) A detailed description of the portfolio of abatement options available in different models for different industrial sectors (such as iron and steel, chemicals, non-metallic minerals, pulp and paper, non-ferrous metals), and the most important assumptions about these options - such as cost and technological maturity.*

Most of the IAMs have modelled in details of the energy system while very aggregate of the economic activities. GDP per capital and population determines the output of the industrial sector, which is then treated as a consumer of energy services in the energy system. Hence, basically there are no mitigation measures specific for the industrial sector although CCS technologies are considered in industrial processes in some IAMs. One exception is a computable general equilibrium (CGE) model, i.e. the AIM/CGE model, where the industrial sectors are modelled as explicit production activities, with the potential to introduce specific mitigation measures other than that in the energy system.

In the IAMs, the mitigation measures explicitly modeled in the energy system related to the industrial sector include energy efficiency improvement, fossil fuels with CCS, CCS in industrial processes, and substitution of fossil fuels with non-fossil fuels. Below we present the assumptions in the main IAMs one by one.

AIM/CGE. The industrial sectors are divided into 'iron and steel', 'nonferrous products', 'chemical, plastic, and rubber products', 'paper, paper products, and pulp', and other sectors. Available abatement options include energy efficiency improvements, electrification of energy demand, CCS in industrial process application, and reduced energy demand in industry. How these options are adopted depends on requirements of different scenarios. For example, the energy efficiency is represented by the parameter 'autonomous energy efficiency improvement (AEEI)', which is given as a percentage change per year in a baseline scenario such as SSP2. In alternative scenarios such as SSP 1 and SSP3, high and low AEEI values are set as plus or minus a 1% annual change in the AEEI percentage (Fujimori et al. 2017a). To meet a climate target, the CCS adaptation is adjustment with an upper limit per year as presented in Section 10.

The 'Lower 2C' scenarios generated by AIM/CGE in a study (Liu et al. 2018) start from a baseline 'Ref' describing a SSP2 world (Fujimori et al. 2014). As shown in Table 19, the 'SupTech' scenario assumes 25% lower cost for solar and wind, and 25% higher rates of technology improvement for other renewables, CCS, and nuclear than SSP2. The Scenario 'EEEI' assumes 25% higher energy-end-use efficiency improvement than SSP2 in both industries and residential sectors. The other two scenarios in Table 19 assume lower preference for meat, industrial goods, and transportation ('Lifestyle') and lower bioenergy technology cost and higher social acceptance of modern biomass use ('Bio'). In this study, the other scenarios include one combined scenario ('combined') and five decomposition cases of the 'SupTech' scenario (ST_Solar, ST_Wind, ST_Nuclear, ST_CCS and ST_Biomass), where technological improvement in each individual technology was assumed independently. In these scenarios, all industrial sectors are assumed to adopt the same additional mitigation measures of energy efficiency improvement, lower costs for CCS, and technology improvement.

Table 19: Core assumptions of reference and alternative scenarios generated by AIM/CGE (Rogelj et al. 2015).

Case name	Socioeconomic factor description	Parameter assumptions
Ref	reference case: SSP2 parameters settings	SSP2
SupTech	lower cost for renewables, CCS, nuclear	Solar and wind is following SSP1, the rest assumes that the parameters representing the technology improvement are 25% higher than SSP2.
Lifestyle	lower preference for meat, industrial goods, transportation	Relevant parameters are set same as SSP1
EEEI	higher energy-end-use efficiency improvement	Relevant parameters are set same as SSP1
Bio	lower bioenergy tech cost and higher social acceptance of modern biomass use	The parameters representing social acceptance and technology improvement are 25% higher than SSP2

GCAM 4.2[9]. The regional economy is modeled at aggregate level. Regional income (GDP) is determined exogenously by population size, per capital GDP growth rate, and energy services. Cement is treated as a final demand driven by population and income, and the commodity is not an input to any further modeled processes. Mitigation measures for cement can be from the energy system and a CCS technology for cement production to capture the CO2 from limestone calcination with costs parameterized around values shown in Mahasenan et al. (2005).

Nitrogenous fertilizers ("N fertilizer") includes both the specific production technologies for transforming various feedstocks into N fertilizer, and the demands for the commodity in the agricultural sectors. Nitrogenous fertilizers for non-agricultural purposes are not modeled in GCAM. Input-output coefficients of fuel and feedstock sources are calibrated based on Table 4.15 of IEA (2007a). The hydrogen production stage of ammonia production emits a relatively pure stream of CO_2 that is often captured for commercial purposes. Technologies with CCS are optional and additional capture and compression costs and energy inputs are based on H2A Production Analysis (U.S. Department of Energy 2015).

The industrial sector except cement and fertilizer is represented as a consumer of generic energy services and feedstocks. Energy services are provided by a mix of fuels with the lowest cost with a low elasticity of substitution between fuels. Output of the industrial sector is represented in generic terms.

IMAGE 3.0. Production of cement and steel uses a mix of technologies. Each technology is characterized by costs and energy use per unit of production, both of which decline slowly over time. The actual mix of technologies used in the model are derived from a multinomial logit equation, resulting in a larger market share for the technologies with the lowest costs. The autonomous improvement of these technologies leads to an autonomous increase in energy efficiency. Fuel substitution is partly determined by price, but also depends on the type of technology because some technologies can only use specific energy carriers.

MESSAGE V.3. Energy service demands are provided exogenously to MESSAGE for the industry, including: Industrial thermal, Industrial specific, and Industrial feedstock (non-energy). These demands are determined by country-level historical relationship of GDP per capita (PPP) and final energy use as well as projections of GDP (PPP) and population in the future. There is no mitigation measures that is specific for the industry other than the measures in the energy supply and consumption.

REMIND. The production of the economy is modeled at the aggregate level, i.e., the aggregate GDP is produced by a combination of labor, capital and aggregate energy, where the aggregate energy is modeled by a detailed energy model, where the energy demand in the industry is

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[9] https://jgcri.github.io/gcam-doc/energy.html#industry

considered explicitly. Hence, any mitigation measures in the industrial sector must be through the simulated energy system.

<u>WITCH</u>. The production is very aggregated. Each region produces one single commodity that can be used for consumption or investments. Hence, like most of the IAMs, any mitigation measures in the industrial sector must be through the simulated energy system.

13 Scenarios used and literature (i)

Topics discussed: *i) A list showing which scenarios are included in each selection, and references to relevant studies and publications.*

The list of selected scenarios is shown in the Excel file. Below is an illustration of the list.

Table 20:Illustration of selected scenarios in the Excel file.

Model	Scenario	1.5C low overshoot Lower 1.5C low overshoot	1.5C low overshoot Higher 1.5C low overshoot	Lower 2C Lower 2C	1.5C high overshoot Higher 1.5C high overshoot	1.5C high overshoot Lower 1.5C high overshoot	Below 1.5C Below 1.5C (II)	Reference
AIM/CGE 2.0	ADVANCE_2020_WB2C			Y				Luderer et al., 2018; Vrontisi et al., 2018
AIM/CGE 2.0	ADVANCE_2030_Price1.5C			Y				Luderer et al., 2018; Vrontisi et al., 2018
AIM/CGE 2.0	ADVANCE_2030_WB2C			Y				Luderer et al., 2018; Vrontisi et al., 2018
AIM/CGE 2.0	SFCM_SSP2_Bio_1p5Degree			Y				Liu et al., 2018
AIM/CGE 2.0	SFCM_SSP2_EEEI_1p5Degree			Y				Liu et al., 2018
AIM/CGE 2.0	SFCM_SSP2_LifeStyle_1p5Degree			Y				Liu et al., 2018
AIM/CGE 2.0	SFCM_SSP2_Ref_1p5Degree			Y				Liu et al., 2018

The references to relevant studies and publications are shown in the Excel file in the format below.

Table 21: Illustration of references in the Excel file.

No.	Authors & Year	DOI	Title
1	Luderer et al. (2018);	10.1038/s41558-018-0198-6	Residual fossil CO2 determining carbon dioxide removal requirements in 1.5-2°C pathways. Nature Climate Change, 8:626–633, 2018
	Vrontisi et al. (2018)	10.1088/1748-9326/aab53e	Enhancing global climate policy ambition towards a 1.5-2°C stabilization: a short-term multi-model assessment. Environmental Research Letters 13(4):044039, 2018
2	Liu et al. (2018)	10.1080/17583004.2018.1477374	Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C. Carbon Management, 2018
..	..	..	…
14	Bertram et al. (2018)	10.1088/1748-9326/aac3ec	Targeted policies can compensate most of the increased mitigation risks in 1.5°C scenarios. Economic Research Letters 13(6):064038, 2018

14 Discussion: Limitations, relevance for Norway

The models have a crude representation of regions and no specific information about Norway. In the integrated assessment models, OECD is the most representative region for Norway. However, the models do not show large regional variations. Other studies are better at identifying conditions specific for Norway. This report is on relevant findings from the emission scenario database linked to the special report on global warming of 1.5 °C. We have not discussed Norwegian climate policies or how Norwegian policies should be framed to be in line with the pathways presented. Further, we have not discussed what of the topics addressed are more important for Norwegian policy.

One of the largest challenges with this project was data availability. On many of the tasks asked for by the Norwegian Environment Agency, data is not available or existing on the detailed level. The models are crude representations of the reality. Users of the emission scenarios should be aware of the limitations and that the perspective taken in the modeling are important for how they are framed.

15 Conclusion

We have analyzed the integrated assessment models and scenarios from the 1.5 °C special report to find relevant information provided for Norway. In most cases, OECD is the region most fitting with Norway. The scenarios show often small differences on a regional and sectoral scale, which is partly due to the models not focusing on these aspects, but rather how achieve 1.5 °C and 2 °C on the global level.

The selected scenarios from a database are not necessarily statistical samples as often some models or model structures are overrepresented or not all possible scenarios are explored. The REMIND and AIM/CGE models contribute with many of the scenarios in the SR15 database, while some other models provide only one or a few. Groupings of scenarios give an indication of the range of outcomes, but care is required not to over interpret the statistical samples.

Most 1.5°C scenarios require large-scale use of bioenergy with carbon capture and storage (BECCS), but this has become controversial as it may be infeasible or unsustainable. As a consequence, the Norwegian Environment Agency, wanted scenarios with unsustainable levels of BECCS removed. There is no clear-cut definition of what a sustainable level of BECCS is. The special report on land gives a wide range of BECCS deployment, but the nature for which it is deployed is important for sustainability concerns. After assessing several approaches, we decided to use the Norwegian Environment Agency criteria of 500GtCO$_2$ cumulative BECCS this century and 12GtCO$_2$/yr BECCS in 2100. After applying these criteria, there remain 23 scenarios consistent with 1.5 °C (with no or low overshoot) and 53 scenarios with 2°C (with a 66% chance). This selection of scenarios is discussed in detail throughout the report.

Emission pathways show that at the global level CO$_2$ emissions (not including other greenhouse gases) reach net-zero around 2050 for the selected 1.5 °C scenarios and 2075 for the selected 2°C scenarios. Different regions reach net-zero in different years, based on cost optimizing mitigation. Latin America is often the first region to reach net-zero (median 2042) due to its ability to provide CO$_2$ removal, while OECD is generally after the global average (median 2058). The modelled pathways do not consider equity. For 2 °C pathways, the net-zero year is about 15 years later than for 1.5 °C pathways at the global level, with some variation at the regional level. For all GHGs combined, net zero emissions (in CO$_2$-equivalent terms) is reached around 2070 for 1.5 °C pathways and after 2100 in 2°C pathways. The Paris Agreement calls for net-zero GHG emissions in the second half of the century (Article 4), but only about half of the assessed 2°C scenarios reach net-zero in that period. Consequently, the Paris net-zero constraint indicates a pathway more consistent with 1.5 °C than 2 °C. The year of net-zero in OECD for GHGs is very close to the global average. While the OECD has capacity for mitigation, this region does not mitigate faster or earlier than other regions, which is a consequence of the cost-optimizing model framework that does not introduce concepts of equity. Since models cut emissions where they are cheapest, regional variations should not be over interpreted given equity concerns.

There is a large variation in carbon prices across models, socioeconomics, and temperature outcomes. The carbon prices vary little between regions, and most scenario designs use global carbon prices which exclude regional variations. Depending on the model, socioeconomics, and climate target, carbon prices rise close to exponential over the century. Carbon prices are higher for 1.5°C and 2°C, with some models showing steep increases in carbon prices for 1.5°C scenarios indicating this pathway is close to the feasibility limit of the model. The carbon prices are outcomes of the model structure and are therefore very model dependent. Very high prices reflect the

difficulty of reaching targets, though care should be taken when comparing carbon prices across models as they may not always be comparable. Models rarely consider variations in carbon prices at the sector level and are weak on innovation. This means carbon prices from models may not be useful for guiding policy on innovation or first-of-the-kind technologies.

Most scenario databases and publications only report and present net emissions, but models distinguish gross positive emissions (from the burning of fossil fuels, industry, and net deforestation) and gross negative emissions (CO_2 removal like BECCS and afforestation). Negative emissions start being deployed in models almost immediately, even though net-negative emissions may not be reached until after 2050. Negative emissions can be separated into two, one part to cancel out residual emission and one part to reduce global temperatures after overshooting. In most 1.5 °C scenarios, the second dominates, which is partly due to the model set up where such a temperature overshooting is allowed. The discount rate also has a major impact on the amount of negative emissions. Models use a mix of BECCS and afforestation, but BECCS is more productive at removing carbon for a given area of land. In general, the considered scenarios remove twice as much CO_2 from BECCS than from afforestation. Models with less BECCS, often use more afforestation.

The land use impacts of BECCS and afforestation are immense, though it is not possible to characterize the quality of the land-use in scenarios. Some models have poor representation of land-use, and the analysis is therefore dominated by only a few different models. The land use impacts are generally greater for afforestation than BECCS in the assessed scenarios. Further, BECCS takes up about four times as much CO_2 per unit area than afforestation, since yield improvements generally apply to bioenergy but not afforestation. The additional land use for afforestation and BECCS comes from yield improvements in crops and pastures. The changes in land use are immense in both 1.5°C and 2°C scenarios and will potentially lead to trade-offs and conflicts. Regionally, the OECD generally uses more land for bioenergy, while most afforestation happens in the tropics.

Investment needs are provided in detail only in some models. Those few models indicate larger investments in energy supply compared to energy efficiency. The investment level is not very different between 1.5 °C and 2 °C as the energy infrastructure is to be replaced anyhow.

On key abatement options, many of the mitigation measures are related to the energy sector as most of the models are built from detailed energy models. Specific models are unlikely to consider all technologies and measures. The models are different, such as representing the technologies differently and with large differences in the costs of electricity generation technologies. The demand side measures can typically be divided into energy-related and food-related measures. The supply-side measures are linked to the energy sector. Costs on carbon capture and storage (CCS) are typically based on studies in the energy supply sector. Most of the models include BECCS and Afforestation and reforestation (AR) as negative emissions. Both depend heavily on land use change and in most models both technologies are modeled explicitly and endogenously to compete with other land use purposes such as production of energy and food crops. First-of-kind technologies and innovation processes are rarely modelled in these types of scenarios. Thus, these models are not useful tools to model initial investments required to scale up new technologies.

We present future demand for primary energy by source, but no data is available on the demand for base materials. Fossil fuel use declines rapidly in 1.5 °C scenarios but does not decline to zero. Fossil fuels are quickly replaced by non-fossil sources, such as solar, wind, and hydro. Coal drops strongly in all scenarios, oil has a more gradual decline, while natural gas has a large variation between scenarios with some indicating a decline and others indicating a rise before declining a few decades into the future. Relative to baseline scenarios, coal, oil, and gas use declines substantially. Oil use in the OECD drops by 30% by 2030 and 80% by 2050. For gas, the average indicates a decline of 20% by 2030 and 50% by 2050 in the OECD region.

Abatement options in the industrial sector are difficult to identify in the scenarios as most of the models have modelled the economic activities at an aggregate level. Basically, there are no mitigation measures specific for the industrial sector although CCS technologies are considered in industrial processes in some models.

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