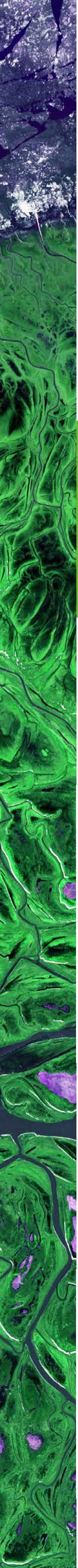


The Transition Institute 1.5

L'ambition d'une véritable transition

NOTE D'ÉCLAIRAGE

#5 - janvier 2023

Decoding the IPCC scenarios C1 to C8

Travail réalisé par les élèves du Master of Science in Climate Change and Sustainable Finance (EDHEC Business School & Mines Paris - PSL) et coordonné par Nadia MAÏZI, Professeure à Mines Paris - PSL et Auteure principale pour le 6ème rapport du GIEC, dans le cadre du cours " Designing feasible low-carbon transition".

MINES PARIS | PSL | TTI.5° The Transition Institute

SOMMAIRE

Introduction

AR6 (IPCC sixth assessment report) brings a complete overview of the causes (Working Group I), consequences (Working Group II) and solutions (Working Group III) to Earth's rising temperatures.

On 4 April 2022, the IPCC report on Mitigation of Climate Change was published by Working Group III (WG3) which contributes to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). WG3, thanks to the contribution of 278 authors and 354 contributing authors, paints a sobering picture of the state of responses to climate change, falling far short of what is needed in both scale and speed. Namely, **the group provided a database of 2,266 scenarios to draw future emissions pathways**, as long-term emissions scenarios are a key means to understanding solutions. These were generated by **Integrated Assessment Models (IAMs), which are simplified representations of the complex human interactions within society** in terms of economy and the environment and quantified in terms of energy, land use change, and emissions pathways. WG3 compiles emissions scenarios from the literature into a database that supports the assessment (since AR5, IPCC fifth assessment report) hosted by IIASA: https://data.ene.iiasa.ac.at/ar6

These scenarios are contributed by the wider research community – rather than being chosen by the IPCC – and are made publicly available.

The database contains both **global** and **regional** or **national** emissions scenarios:

- Global emission scenarios and underlying whole system transitions (**Chapter 3**)
- National transition scenarios (**Chapter 4**)
- Sector transition scenarios (**Chapters 6-11**)

Modeling teams were invited to submit their available emission scenarios using a common data reporting template with a defined variable structure, and all teams were required to submit detailed model and scenario metadata. Scenarios were required to come from a formal quantitative model. **The aim of the analysis of these scenarios**

is to obtain a significant overview of all of the different variables that can influence greenhouse gas (GHG) emissions. The scenarios were subject to an initial vetting based on historical trends criteria.

IPCC scenarios were not designed to be a single, coherent collection: they can be seen as ensembles of existing model runs that were not created to be an ensemble.

This collection of data represents in essence an arbitrary collection of pathways that researchers were able to model to answer questions they at some point cared to ask. This is why they do not encompass the full range of futures.

The global emission scenarios were vetted for historical trends (1686 scenarios remained) to ensure that key indicators relating to **emissions and the energy sector** were within reasonable ranges for the **baseline period (2019)**.

Then, those running to 2100 and with sufficient coverage of emissions sources (CO2 from fossil fuels and industry, and from land use, CH4, N2O; 1202 scenarios) were run through two climate model emulators (MAGICC, FAIR) calibrated to the Working Group I assessment of climate change to project associated climate outcome.

Emission scenarios in the AR6 database that passed the vettings were classified using the **global surface air temperature GSAT projections** from the emulator runs in **8 climate categories (from C1 to C8) based on potential 21st century warming outcomes with likelihoods computed with the 5th and 95th percentile values across all scenarios. The range of probabilities cover the extent of scenarios and climate model emulator uncertainties.**

The scenarios were also subject to Illustrative Pathway (IPs) vetting, involving historic trend and near-term plausibility criteria. **The scenarios were matched with 7 different IPs** (Illustrative Pathways), defined by the IPCC author team, and corresponding to a mitigation strategy.

IPCC scenario Category C1

Arthur FALINOWER, Chloé PAULIAT, Jung Wook SONG, Aliénor VIEU & Ziwei WAN

Scenario categories are defined by their likelihood of exceeding global warming levels (at peak and in 2100) and C1 category refers to the following:

- Category C1 comprises modeled scenarios that limit warming to 1.5°C in 2100 with a likelihood greater than 50%, and that reach or exceed warming of 1.5°C during the 21st century with a likelihood of 67% or less. These scenarios are referred to as scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C and for up to several decades.
- C1 scenarios also include sub-categories. These are subcategory C1a (all pathways achieve net zero GHG emissions) and subcategory C1b (no pathway achieves net zero GHG emissions).

Table 1: Classification of C1 emissions scenarios into warming levels using MAGICCv7.5.3

Description	Subset	WGI SSP	WGIII IP	Scenarios
C1	<1.5°C peak warming with 33% likelihood and < 1.5°C end of century warming with >50% likelihood	SSP1-1.9	SP, LD, Ren	97
C1a	identifies 1.5°C pathways that maintain warming "well below 2°C" and reduce greenhouse gas emissions to net zero in the second half of this century	SSP1-1.9	SP, LD	47
C1b	identifies 1.5°C pathways that maintain warming "well below 2°C" but do not achieve net zero GHG emissions	SSP1-1.9	Ren	50

Source: IPCC AR6 WGIII, chap 3-17

The IPCC AR6 report finds that the lowest class of emission scenarios that limit global warming to "1.5°C (with a probability greater than 50%) with no or limited overshoot" includes 97 scenarios for MAGICCv7.5.3.

For the MAGICCv7.5.3 results, "limited overshoot" typically implies exceedance of median temperature projections of up to about 0.1°C for up to a few decades, before returning to below 1.5°C by or before the year 2100. More than half of the scenarios in this category that comply with three "Paris- compatible" criteria, including net-zero or net-negative greenhouse gas (GHG) emissions, are projected to see median temperatures decline by about 0.3-0.4°C after peaking at 1.5-1.6°C in 2035-2055.

Table 2: Probabilities of mitigation pathways in C1 for each temperature range

Date at which specific temperature levels are reached			Likelihood of remaining below			Temperature changes 50% probability	
<1.5°C	<2°C	<3°C	<1.5°C	<2°C	<3°C	At peak warming	2100
2030-2035 (90%)	Never (0%)	Never (0%)	38 (33-73)	90 (86-98)	100 (99-100)	1.6 (1.3-1.6)	1.3 (0.8-1.5)

Source: IPCC AR6 WGIII, chap 3-44

Socio-economic development and climate change are closely linked, as economic and social activities are determining factors for emissions, land use and energy consumption, hence for climate change. Mitigation strategies are a response to global warming, to reduce the impact of climate change on humans. Illustrative Mitigation Pathways (IMPs) explore these strategies and are therefore based on several assumptions and projections.

Scenarios are characterized by a socioeconomic projections category, SSPs (Shared Socioeconomic Pathways). The C1 category can only be reached by models under SPP1-1.9 (low scenario at 1.9 W/m2), corresponding to a sustainable world in which the population's well-being is maintained. SSP1 explores low socio-economic challenges to adaptation and low challenges to mitigation and is defined by several projections:

- Population and education: the population grows until 2050 (peak at 8.5 billion) but declines to 7 billion in 2100 with a drop in fertility below replacement levels, rapid development, and investments in education

- Economic growth: growth is rapid (+2.3% per year GDP per capita) with a considerable convergence of income levels within and across countries and a relatively high income increase over the century
- Energy: lower energy demand compared to other SSPs (500 EJ in 2100) thanks to climate policies, less energy-intensive lifestyles and increased energy efficiency
- Food demand and amount of land used for agriculture: increase in food demand (+8.3% per capita caloric intake between 2050 and 2100) but the dietary composition shows a decrease in meat consumption, while agricultural land is projected to decline by 14.6% between 2000 and 2100 (depending on yield and population) thanks to regulations and respect for the environment

The models also assume different levels of climate policy. The models in the C1 category rely on globally coordinated climate policies (such as regulations, standards, subsidies) that are increasingly stringent and with immediate action thanks to strong, flexible global institutions. Their implementation leads to lower carbon pricing.

The set of pathways illustrating how selected choices may lead to a transformation that may limit warming to 1.5°C (C1 category) are the IMP-Ren model, the IMP-LD model, and the IMP-SP model. These models are part of the 97 scenarios contributing to the C1 category and cover GHG from all sectors, on a global scale.

The IMP-Ren model (REMIND- MAgPIE 2.1-4.3 model by Luderer et al., 2021) assumes the rapid deployment and technological development of renewable energies and electrification.

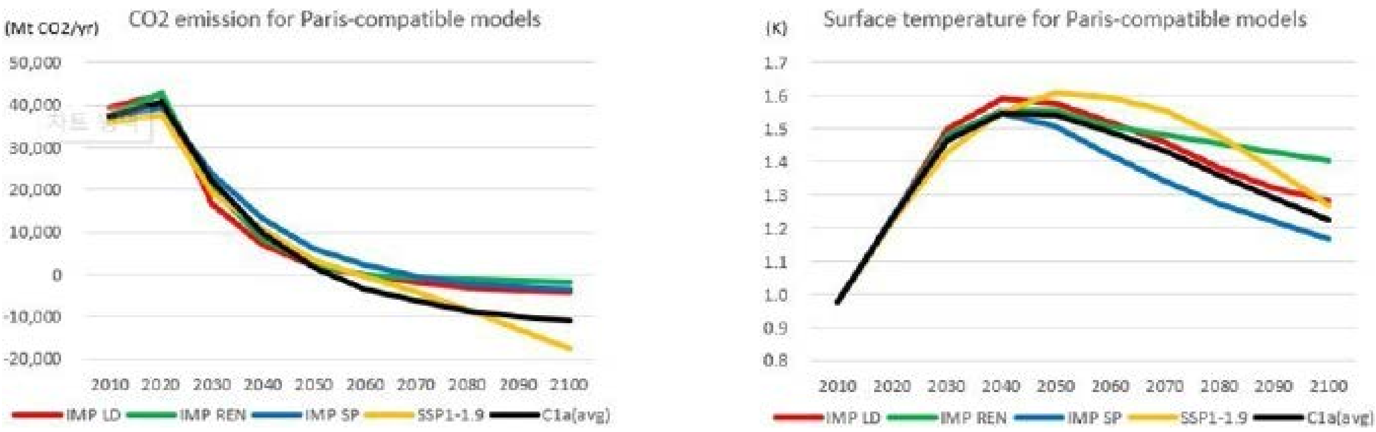
Successful international climate policies and financial incentives favoring the renewable energy sector enable this mitigation pathway. The rapid development of innovative electricity technology is assumed, along with changing demand as it adapts to a high renewable energy supply. The IMP-LD model (MESSAGEix-GLOBIOM 1.0 model by Grubler et al., 2018) corresponds to lower demand, leading to an early reduction of emissions. Indeed, social innovation and energy efficiency in all sectors reduce energy demand in this model, while techniques to reduce CO2 emissions in buildings and industries spread rapidly. Food and agricultural waste are reduced, contributing to mitigation, along with a less meat-intensive lifestyle. The IMP-SP model (REMIND- MAgPIE

2.1-4.2 model by Soergel et al., 2018) represents shifting pathways. Major transformations shift development towards sustainability and reduced inequalities, leading to a significant reduction of GHG emissions. Climate policies and policies relying on Sustainable Development Goals enable broader sustainable development, with a focus on poverty reduction and environmental protection. Regarding energy, demand is lower and renewable energy is well developed. Food and agricultural waste are reduced, contributing to mitigation, along with a less meat-intensive lifestyle for this model too.

An important part of the AR6 WGIII report was its evaluation of the Paris- compatible scenario.

First, the CO2 emission of Paris- compatible scenarios and the resulting surface temperature were examined. CO2 emissions will start to decrease from 2020 and will be reduced by 45% compared to the peak in 2030, and net zero can be achieved after 2055. Accordingly, the surface temperature decreases after a peak of 1.5 to 1.6 degrees between 2040 and 2050, and is projected to be 1.2 to 1.4 degrees in 2100. In conclusion, net zero emissions must be achieved in 2050-2060 to reach a temperature of 1.5°C or less in 2100.

Figure 1: CO2 emission and surface temperature of Paris-compatible models including C1a which is 47 scenarios averaged, IMP LD, SP, REN, and SSP1-1.9



Source: data from IIASA AR6 Scenario

Table 3: GHG, CO2 emissions, and warming characteristics of 97 mitigation pathways in C1

GHG Emissions			GHG emissions reductions			Emissions milestones	
2030	2040	2050	2030	2040	2050	Peak GHG Emission-swarming	Net zero GHGs
31 (21-36)	17 (6-23)	9 (1-15)	43 (34-60)	69 (58-60)	84 (73-98)	2020-2025	2095-2100 (52%)

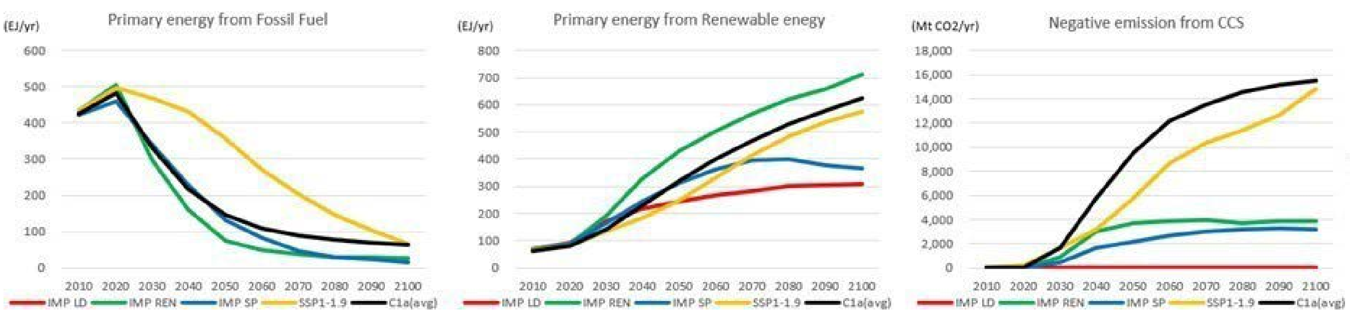
Source : IPCC AR6 WGIII, chap 3-44w

To this end, there are many changes in the composition of energy supply sources. Fossil fuels are shrinking fast, and at the same time, renewable energy generation must increase rapidly. Fossil fuels should be reduced by 30-80% in 2050 compared to 2020, and renewable energy in 2100 should be expanded by 200-700% compared to 2020. In the case of IMP-LP, the increase in renewable energy is the lowest without using fossil fuel.

Finally, many scenarios rely on CCS, a negative carbon emission technology that aims to reduce 15,000 CO2 per year in 2100 from almost insignificant levels by 2020. A strong reliance on technological advances increases the uncertainty of future scenarios. For reference, it is noteworthy that the IMP- LD scenario achieves net zero in 2060 without relying on CCS.

IMP-LD is a scenario that reduces demand through efficient use of energy. It is necessary to consider electricity consumption behavior rather than securing additional energy sources.

Figure 2: Primary energy from fossil fuel and renewable energy including biomass of Paris-compatible models including C1a, which is 47 scenario averaged, IMP LD, SP, REN, and SSP1-1.9 and negative emission from CCS of Paris-compatible models



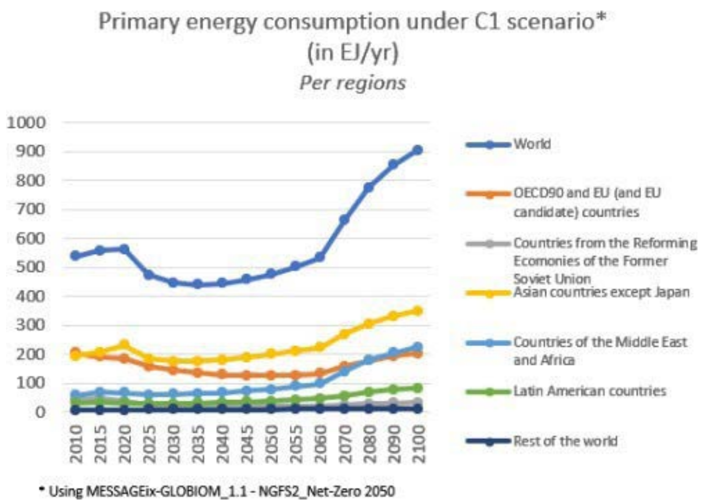
Source: data from IIASA AR6 Scenario

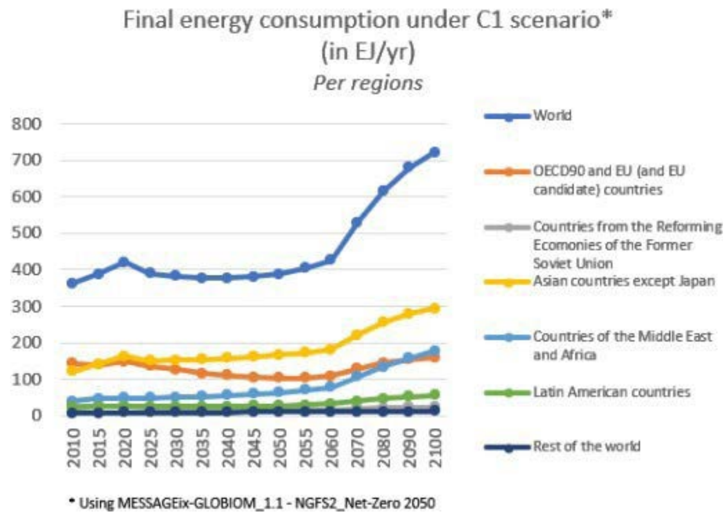
Overall, GHG emissions are expected to decrease by 49% between 2020 and 2030, by 83% between 2020 and 2050, and by 89% between 2020 and 2100.

In the same model, final energy consumption is expected to increase until 2020 and then decrease respectively by 9% between 2020 and 2030 and 8% between 2020 and 2050.

This decrease is highly heterogeneous among regions. For the reforming economies of the former Soviet Union, this decrease should be respectively 26% between 2020 and 2030 and 37% between 2020 and 2050. For countries in the Middle East and Africa, the final energy consumption should increase by 3% between 2020 and 2030 and by 30% between 2020 and 2050. However, overall, final energy consumption is expected to rise by 72% in 2100 compared with 2020 levels.

Figure 3: Primary and Final energy consumption under C1 scenario per region





The trend in primary energy consumption under the C1 scenario is also counter-intuitive. Overall, primary energy consumption should decrease by 20% between 2020 and 2030 and by 16% between 2020 and 2050. However, it should increase by 61% between 2020 and 2100.

The reforming economies of the former Soviet Union, the OECD90 and EU (and EU candidate) countries, and Asian countries except Japan are expected to lower their primary consumption between 2020 and 2050. However, countries in the Middle East, Africa and Latin America are expected to increase their primary energy consumption by 19% and 21% between 2020 and 2050 (and up to 240% and 154% between 2020 and 2100).

REFERENCES

- Summary for Policymaker: https://www.ipcc.ch/report/ar6/wg3/ downloads/report/IPCC_AR6_WGIII_SPM.pdf. Consultation date: Oct 20, 2022.
- IPCC report 2022, Working Group 3: https://www.ipcc.ch/report/ar6/ wg3/downloads/report/IPCC_AR6_WGIII_Full_Report.pdf. Consultation date: Oct 22, 2022.
- IPCC Annex III: Scenarios and Modelling Models: https://report.ipcc. ch/ar6wg3/pdf/IPCC_AR6_WGIII_AnnexIII.pdf. Consultation date: Oct 22, 2022.
- AR6 Scenario Explorer and Database hosted by IIASA: https://data. ece.iiasa.ac.at/ar6/. Consultation date: Oct 24, 2022.
- Carbon Brief, discussion on AR6: https://www.carbonbrief.org/ analysis-what-the-new-ipcc-report-says-about-how-to-limit-warming- to-1- 5c-or-2c/. Consultation date: Oct 22, 2022.
- Climate Analytics, discussion on AR6: https://climateanalytics.org/ blog/2022/new-pathways-to-15c-interpreting-the-ipccs-working-group-iii-scenarios-in-the-context-of-the-paris-agreement/. Consultation date: Oct 23, 2022.

CATEGORY C1

IPCC scenario Category C2

Emma ACCAD, Ithri BENAMARA, Paul CHAVES D'OLIVEIRA, Olivier COZ & Arthur PREVOSTEAU

Category C2 comprises 133 pathways featuring extensive use of net- negative emissions resulting in warming below 1.5°C in 2100, but with a high temperature overshoot during the 21st century. Indeed, it comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood greater than 50%, and exceed warming of 1.5°C during the 21st century with a likelihood greater than 67%. On the one hand, it therefore implies a high temperature overshoot, which consists of a temporary temperature increase exceeding

1.5°C global warming by 0.15°C–0.30°C for up to several decades. On the other hand, to achieve this 1.5° objective by 2100, category C2 relies heavily on biomass and bioenergy with carbon capture and storage (BECCS) for carbon dioxide removal from the temperature peak, and features a relatively slow phase-out of fossil fuels as well as high future energy demand.

1. Close look at models & scenarios of category C2

Out of the 2,295 scenarios used by the IPCC, 133 are considered to be part of the C2 category. These 133 scenarios were established from 9 different models: AIM, C-ROADS, Coffee, GCAM, GEM-E3, IMAGE, MESSAGE-GLOBIOM, POLES, an REMIND. Moreover, the scenario IMP-NEG, from the Illustrative Mitigation Pathways (IMPs), was selected as a representation of the key characteristics of the scenarios in the C2 pathway.

A. Models

The models used are called process-based Integrated Assessment Models (IAMs) which project long-term transformation pathways in energy and land- use systems based on "what-if" assumptions. They help us understand climate change and its effect on the planet. The models' input includes variables such as population growth, baseline economic growth, resources, and technological change. Using these variables, the model links together "modules" such as energy technologies, energy use choices, land-use changes, and societal trends to represent the global economy. As such, emissions are represented by modelling the underlying processes in energy and land use. This coupled energy-land- economy-climate system helps us explore the impact of different policies on output such as emissions, GDP, land and energy use (IPCC AR6 WGIII Annex III, 1-7, l.25-43).

IAMs rely on economic theory, which assumes markets and society are rational and make decisions using perfect information.

Moreover, the models are either in partial equilibrium, which means that individual markets are seen as independent units in isolation, or in general equilibrium, which takes into account the feedback effect of one market on another (IPCC AR6 WGIII Annex III, 1-6, l.15-20).

One weakness of most IAMs is the difficulty to take into account feedback effects such as economic damages and reduced growth due to climate change.

Models have specific features depending on how they were developed. Below is a summary of a selected number of IAMs used in C2 and their specificities:

- The Asia-Pacific Integrated Assessment/Computable General Equilibrium model (AIM/CGE), developed by a collaborative program of research institutes in several Asian countries. This is one of the more full-featured economic models, covering individual sectors from food products, to iron and steel, and construction.
- The Global Change Assessment Model (GCAM), developed by the Pacific Northwest National Laboratory in Washington state. GCAM is known for its open-source code and for its focus on exploring uncertainty.
- The COFFEE model was developed at COPPE/UFRJ, Brazil, and is the first IAM from an emerging country. As such, its technology and feedstock options, as well as CO2 storage logistics and costs, reflect some Brazilian specificities not present in other models.

Most models and scenarios were developed by researchers from OECD countries. AIM was developed in Japan, GCAM in the US, and MESSAGE in Austria. The only exception is the COFFEE model, which was developed in Brazil. This overrepresentation may lead to model assumptions specific to developed countries and thus to biased results. Using these IAMs, scenarios are made to explore plausible alternative futures.

B. Scenario linked to the IMP-NEG pathway

The IMP-NEG pathway might enable 1.5°C to be reached, but only after a significant overshoot, through the use of CDR. Its warming profile peaks around 2060 and declines to below 1.5°C shortly after 2100. While technically classified as a C3, it exhibits the characteristics of a C2 high overshoot pathway.

The IMP-NEG assumptions include mitigation in all sectors, however IMP- NEG also relies on extensive use of Carbon Direct Capture (CDR) measures in the energy and industry sectors to achieve net negative emissions, with further development of CDR options. Policy-wise, IMP-NEG assumes a successful international climate policy regime with a focus on long-term temperature goals. It also assumes H2/ electric transport based on negative emissions, afforestation/ reforestation, some BECCS, and increased competition for land, without any critical lifestyle changes but some price increases.

The scenario EN-NPi2020_400f_lowBECCS (Keywan Riahi et al. (2021) Cost and attainability of meeting stringent climate targets without overshoot) is the pathway selected for the IMP-NEG. NPi2020 means that the GHG emissions follow the national policies currently implemented and no additional new policies are assumed in the future. 400f means staying within an end-of-century budget of 400GtCO2. Finally, lowBECCS means that bioenergy with carbon capture and storage has a small role in this specific scenario.

C. Other scenarios

Keywan Riahi et Al have produced other similar scenarios that fall into the C2 category. These scenarios almost all employ an end-of-century CO2 budget. This explains the high temperature overshoot and global Net Negative CO2 Emmissions (NNCE) in the second half of the century, because when an end-of-century carbon budget is applied, the time it takes to reach net-zero CO2 emissions is delayed, and this delay, combined with the higher emissions over that period, results in an overshoot. They all have a carbon budget between 300GtCO2 and 800GtCO2.

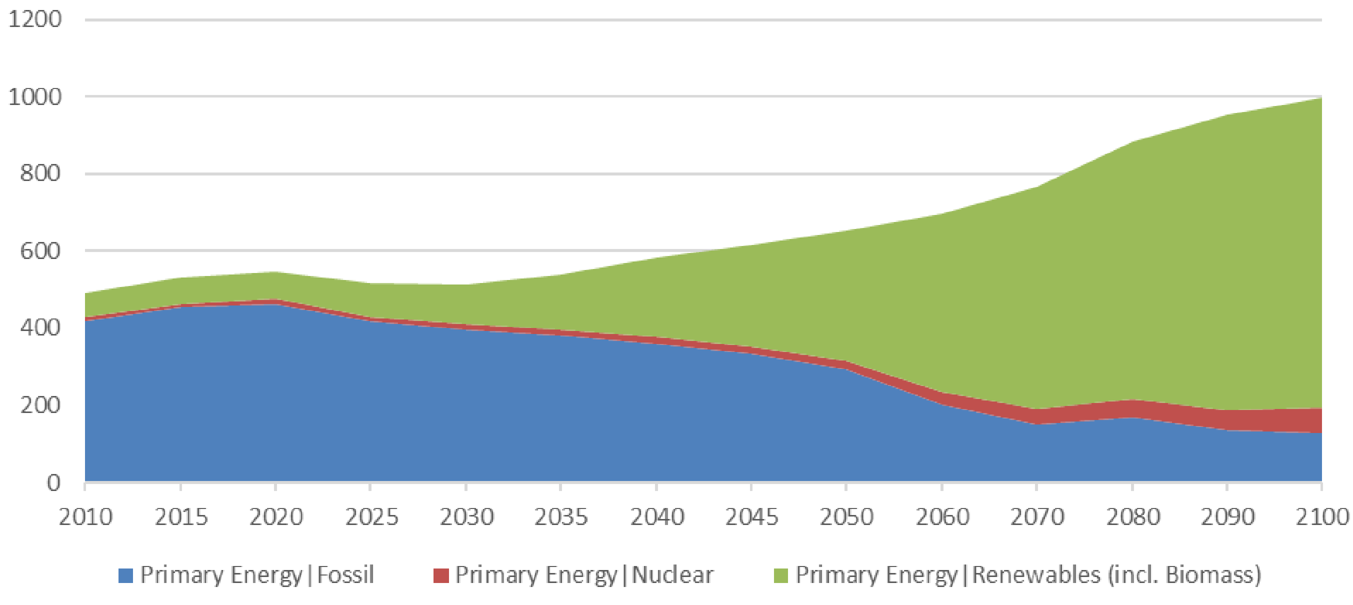
In the IMP-NEG scenario, non-CO2 emissions are priced at the same level as CO2 except non-CO2 emissions in the agricultural sector. As non-CO2 mitigation options can lead to a fairly large variation in the remaining carbon budget, some scenarios isolate the effect of non-CO2 emissions reductions (R-MAC scenarios, Yang Ou et al. (2021) Deep mitigation of CO2 and non- CO2 greenhouse gases toward 1.5 °C and 2 °C futures) by incorporating the updated marginal abatement cost curves for all major non-CO2 GHG across economic sectors and global regions.

2. Lessons and implications from these scenarios

A. Use of different energies and emissions

As in the pathways of the C1 category (where warming never exceeds 1.5°C), C2 pathways feature an immediate decrease in emissions from fossil fuels (peak in 2025), although the decrease is not as steep. This is due to the increased use of CCS and the increased share of low-carbon primary energy (from 16% in 2020, to 24% in 2030, 57% in 2050, and 86% in 2100 on average - IPCC AR6 WGIII, 3.3). Moreover, the energy intensity of the economy significantly decreases, with the final energy intensity of the GDP index shrinking on average from 100 in 2020 to 76 in 2030, 44 in 2050, and 23 in 2100. Figure 1, which shows the amount of primary energy from renewables, nuclear, and fossil fuels in the Neg scenario, clearly highlights the increased share of renewables in the energy mix.

Figure 1: Primary Energy from Different Sources – Scenario NEG



Source: IIASA database.

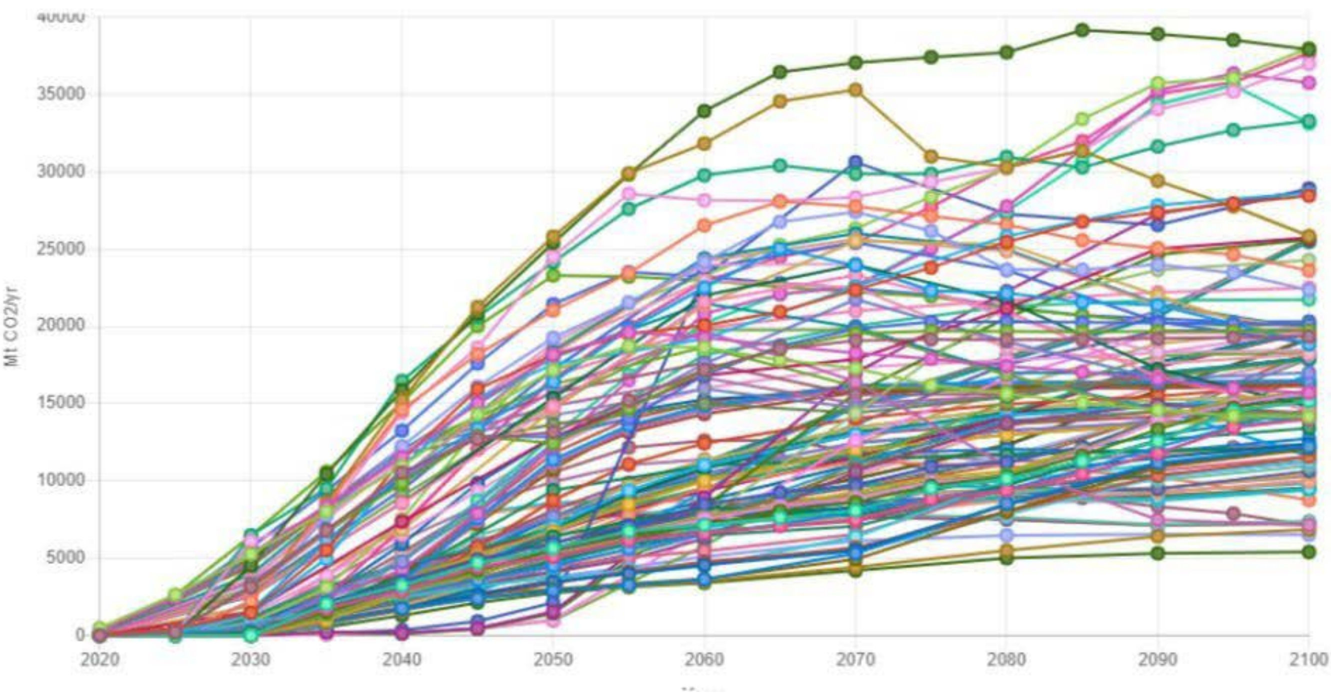
CATEGORY C2

The use of fossil fuels is not completely eliminated, even by 2100, but its impact is largely abated by the use of CCS. Primary energy from fossil fuels without CCS drops on average from 482 EJ in 2020 to 175.25 EJ in 2050, while their use with CCS goes from zero in 2020 to 57 EJ in 2050 (IIASA database). The use of coal, the fossil fuel with the highest CO_2 intensity, is virtually zero without CCS by 2050 (IPCC AR6 WGIII, 6.7.4)

B. Warming and use of technologies

In Category C2, 42 pathways show a temperature that peaks around 2060, with an overshoot of 0.15- 0.3°C, and declines to below 1.5°C (>50% likelihood) by 2100, as shown in Figure 5 in the Annexes (IPCC AR6 WGIII, SPM-17, B.6.4). To bring the temperature back to below 1.5°C by the end of the century, these scenarios have to strongly rely on CCS/CDR (as shown in Figure 2). Indeed, although positive CO_2 emissions from fossil fuels are significantly reduced, inertia and energy-consuming sectors still generate around 800-1000 $GtCO_2$ of net positive cumulative CO_2 emissions. Nevertheless, the current infrastructure is associated with 650 $GtCO_2$ if it is used until the end of its lifetime. Therefore, this tight carbon budget will have to be compensated with the extensive use of CCS/CDR (IPCC AR6 WGIII, 3-36, l.12-21).

Figure 2: Use of Carbon Sequestration/CCS in C2 Scenarios
The y variable shows the use of CCS in Mt CO2/year.



Source: IIASA database.

NOTE D'ÉCLAIRAGE #5

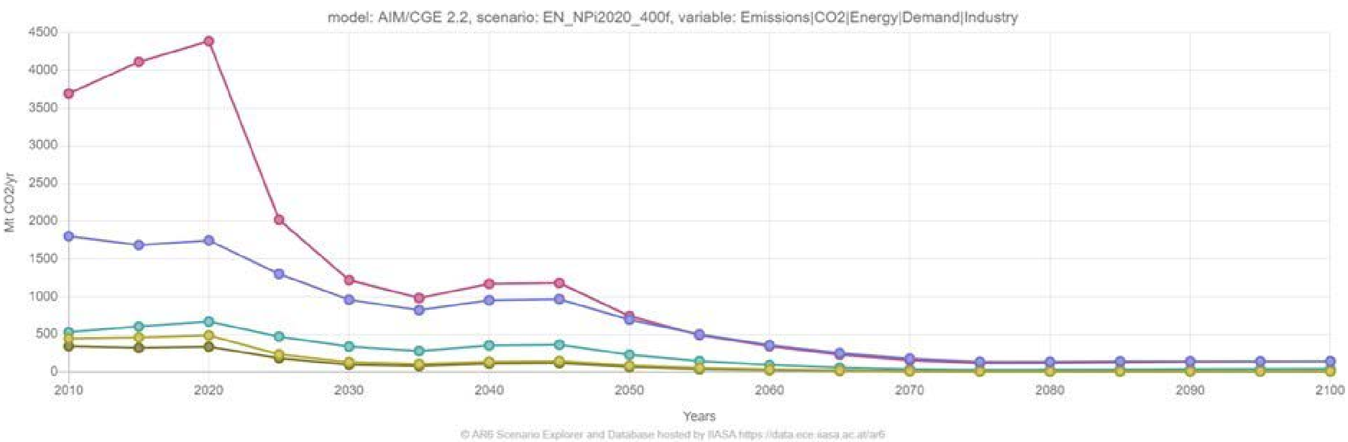
However, there is a high uncertainty regarding the scalability of these technologies as they are not being sufficiently developed today. Moreover, reliance on these technologies is also debatable given the possible consequences of land use related to biodiversity loss and food security as well as uncertain storage potential (IPCC AR6 WGIII, SPM-33, C.3.6).

Finally, this high overshoot pathway is also worrying as it implies increased climate-related risks but also greater social risks. Indeed, some scenarios entail losses in global consumption that correspond to an annualized reduction of consumption growth of 0.04% (median value) during the century (IPCC AR6 WGIII, 3-85, l.11-15).

C. Regional differences

The implied CO2 emissions from industrial energy demand peaked for every region in 2020: Asia (excl. Japan) peaked at 4.5 Mt CO2/year (i.e. more than double that of OECD 90/EU countries and more than 9 times that of Middle Eastern/ African, Latin American and ex-URSS countries). The next phase shows a strong decrease of these emissions in Asia between 2020 and 2030 (divided by >3) whereas the decrease is slower in the rest of the world (divided by <2). Global emissions increase again between 2035 and 2045 and decrease by 2050, when Asian countries are now aligned with OECD90/EU countries. Finally, global emissions will remain constant from 2075 (Figure 3).

Figure 3: Implied CO2 Emissions from Energy Demand in Industry – Scenario EN_NPi2020_400f

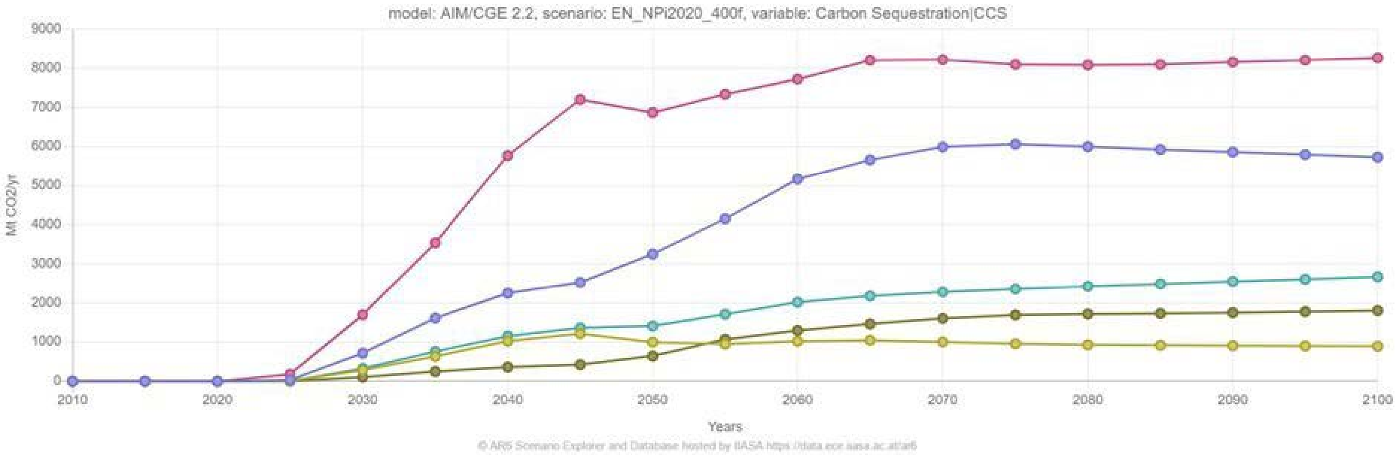


Source: IIASA database.

CATEGORY C2

When it comes to carbon sequestration, the hierarchy among global regions is almost the same as mentioned above. The rise of CCS starts in 2020 with Asia leading the way, closely followed by OECD 90/EU countries. From 2025, Asian countries stand out from other locations (twice as much CCS as OECD/EU countries). OECD and EU countries start closing the gap with Asia from 2050, but they are the only ones to peak in 2075 and then decrease, while the other countries keep increasing CCS. It is also worth noting that CCS decreases in ex-URSS countries from 2045 and that they are overtaken by Latin American countries in 2055 but remain behind Middle East/Africa and Latin America.

Figure 4: Use of Carbon Sequestration/CCS by Geography - Scenario EN_NPi2020_400f



Source: IIASA database.

Conclusion

What C2 scenarios highlight most is the three-way relationship between short-term emissions, medium-term transitional challenges, and long-term deployment of carbon capture technologies. The more we emit in the short- term, the more intense the transition will have to be, involving greater reliance on CCS and CDR. C2 scenarios are somewhat optimistic as they allow for less short-term changes than C1 scenarios, leading temperatures to peak above 1.5°C, but then to decrease in the latter part of the century to end up below 1.5°C. The credibility of these scenarios is highly dependent on the development of carbon capture technologies, which are still in their infancy.

REFERENCES

- Scenario Explorer develop by IIASA (n.d.). Retrieved October 31, 2022, from https:// data.ece.iiasa.ac.at/ar6/#/docs team, T.W.I.T.C.H. (2019) Witch documentation, WITCH documentation. Retrieved October 31, 2022, from https:// doc.witchmodel. org/index.htmlIPCC - Intergovernmental Panel on Climate Change, Assessment Report 6, Working Group 3. (n.d.). Retrieved October 23, 2022, from https://report.ipcc.ch/ar6wg3/pdfIPCC - Intergovernmental Panel on Climate Change, Assessment Report 6, Working Group 3. (n.d.) - Annex III: Scenarios and Modelling Methods. Retrieved October 23, 2022, from https:// report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_Annex-III.pdf
- Rochedo, R. (2016) Development of a global integrated energy model to evaluate the Brazilian role in climate change mitigation scenarios. UFRJ/ COPPE
- Keywan Riahi et al. (2021) Cost and attainability of meeting stringent climate targets without overshoot
- Yang Ou et al. (2021) Deep mitigation of CO_2 and non-CO_2 greenhouse gases toward 1.5 °C and 2 °C futures

IPCC scenario Category C3

Fantine DUTRONC, Emilie NING, Anna OLICARD, Marc FONTENEAU & Clément ROCHETTE

Category 3 encompasses 311 scenarios that aim at illustrating pathways likely to limit global warming below 2°C with a probability higher than 67%. The category also contains subcategories that regroup on the one hand scenarios with immediate action starting in 2020 (C3a) and on the other hand scenarios in line with current Nationally Determined Contributions (NDCs) (C3b). This category is therefore closely related to the Paris Agreement and to policy makers' goals, as NDCs are climate action plans communicated by countries following the 2015 Agreement.

1. The C3 scenarios

a. Description

To start with, scenarios were determined based on socio-economic assumptions that drive future greenhouse gas (GHG) emissions. For C3 scenarios, and based on the five exogenous assumptions of integrated assessment models, the following assumptions were made: 1/ stabilization of the population, 2/ increase of income per capita, 3/ rapid technological change, 4/ stringent policies striving to achieve the Paris Agreement goal, 5/ an increase in agricultural land and significant changes in resource management, i.e., an increase in renewable energies, Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture with Carbon Storage (DACCS) technologies and a decrease in fossil fuel energies (e.g., phasing-out of coal) [Figure 3.9].

Based on those assumptions, C3 scenarios project that peak cumulative GHG emissions will be reached in 2020-2025 followed by a decrease in annual GHG emissions, resulting in net CO2 emissions in 2060-2100 (more likely in 2070-2075). If the peak is reached during this period, a sharp decrease will be required right afterwards to remain in line with the Paris Agreement [Figure 3.29]. All GHG emissions will then decrease due to net negative CO2 emissions compensation.

For the latter, Agriculture, Forestry and Other Land Use (AFOLU), especially reforestation, will need to play a more important role than BECCS as a Carbon Dioxide Removal (CDR) component, as it is projected to be less costly (Rochedo et al., 2018).

b. Alignment with other scenarios

Working Group I, which works on the physical science of climate change, provided scenarios useful to derive different levels of greenhouse gas emissions under diverse climate policies, called Socio-economic Shared Pathways (SSPs).

The equivalent of C3 is the SSP2-2.6. SSP2 is considered as "middle of the road", suggesting medium-level socioeconomic challenges to mitigation and adaptation. Therefore, the economic, social and technological patterns will not abruptly shift from historical trends.

C3 is also in line with some Illustrative Mitigation Pathways (IMPs) aligned using MAGICC [Table 3.1], which are divided into five pathways targeting global warming below 2°C and highlighting the implications of different societal and policy choices. C3 relates to: 1/ IMP-GS, which illustrates the consequences of a gradual strengthening of current policies by 2030, 2/ IMP- Ren 2.0, which is based on accelerated deep renewable energy penetration and electrification, and 3/ IMP-Neg 2.0, which illustrates pathways with extensive use of net negative emissions.

Technically the IMP Neg is also classified under C3; nevertheless it relies on the fact that the temperature will peak but stay below 2°C and then slowly come back to 1.5°C. Therefore, the juxtaposition of this IMP with C3 is questionable as it exhibits strong characteristics of C2 [Table 2.3, Annex III, Working Group III].

2. Modelling

There are 311 C3 scenarios with most of the scenarios being designed for C3a, notably with the MESSAGEix-GLOBIUM models. 4 models stand out due to the quantity of scenarios provided, MESSAGEix-GLOBIUM, REMIND, WITCH and IMAGE.

Figure 1: Global scenarios that passed all vetting and checks for the C3 scenario

Number of Scenario	C3	C3a	C3b	
Model				TOTAL
AIM/CGE	1	13	3	17
GEM E3		5	7	12
IMAGE 3.0	3	27	4	34
MESSAGE GLOBIUM	1	38	21	60
POLES ADVANCE		1	1	2
POLES EMF33		6		6
POLES ENGAGE		9	7	16
POLES GECO		1	1	2
REMIND	2	25	1	28
REMIND MAgPIE	1	32	17	50
REMIND Transport		6		6
TIAM - ECN		10	10	20
WITCH	1	10	17	28
WITCH GLOBIOM		1	1	2
COFFEE 1.1	1	7	6	14
EPPA			1	1
GCAM 5.3		13		13
TOTAL	10	204	97	311

Source: Data from the Annex II of Working Group 3I, Scenarios and Modelling Methods

MESSAGEix-GLOBIUM was developed by the institute hosting the Scenario Explorer database (IIASA). More specifically, the energy model MESSAGE, the land use model GLOBIUM, the air pollution and GHG model GAINS and, the aggregated macro-economic model MACRO and the simple climate model MAGICC were used. Like the MESSAGEix-GLOBIUM models, models like WITCH and REMIND are also dependent on other models, rendering the large variety of models less relevant and their juxtaposition

questionable. Notably, numerous models rely on the land use model GLOBIUM.

The International Institute for Applied Systems Analysis is an international research institute with 24 member countries, notably the US, Russia, China, India, the UK and Germany.

It is financed by both member country contributions and grants. Grants come from the IEA, OECD, UNEP and FAO, in addition to the Rockefeller Philanthropy Fund, the Bill and Melinda Gates Foundation and other private trusts.

The IIASA seems independent considering the number of doners

(85) in addition to member country contributions; however, other models are financed by fewer parties, usually involving a particular country, which calls into question their independence. The REMIND model, for instance, is developed by the Postdam Institute for Climate Impact Research (PIK) and received €12.6 million from the Federal Republic of Germany and the Federal State of Brandenburg

(the German coal-mining state). Additional project funding from external sources amounted to around €19.2 million. Thus, the REMIND model might reasonably be considered to reflect Germany's interests.

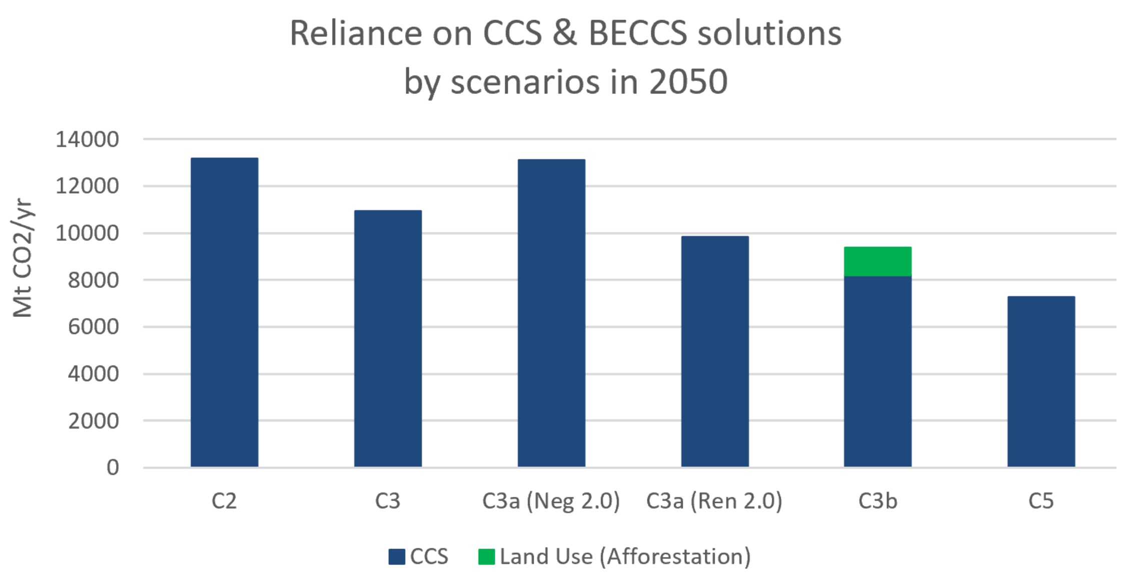
3. Implications

a. Evolution of emissions

To reach the C3 pathway, CO2 emissions will need to drop drastically until 2050, with a 97% reduction in energy supply, and become negative thanks to a reduction in emissions of 136% in AFOLU [Section 3.4.1.1]. More precisely, to stay under the 2°C threshold considering the Nationally Determined Contributions (NDCs), emissions will have to drop sharply by 2030, approximately 70% more than if we start stricter policies right now. Indeed, if we follow the C3a pathway (corresponding to immediate action), then CO2 emissions reductions will not have to diminish so drastically by mid-century and there will be less need for carbon capture and storage (85% less). The efforts will be more linear over time without the need to use a lot of CDR and therefore it will be less costly. On the contrary, emissions of non-CO2 greenhouse gases will not significantly decrease in the second half of the century.

Globally, while IMPs Neg and GS require BECCS and AFOLU sequestration, the C3 scenarios lead to a lower use of carbon dioxide removal techniques compared to

Figure 2: Comparison of the use of CCS and BECCS solutions according to different scenarios in 2050 computed thanks to the IIASA database



CATEGORY C3

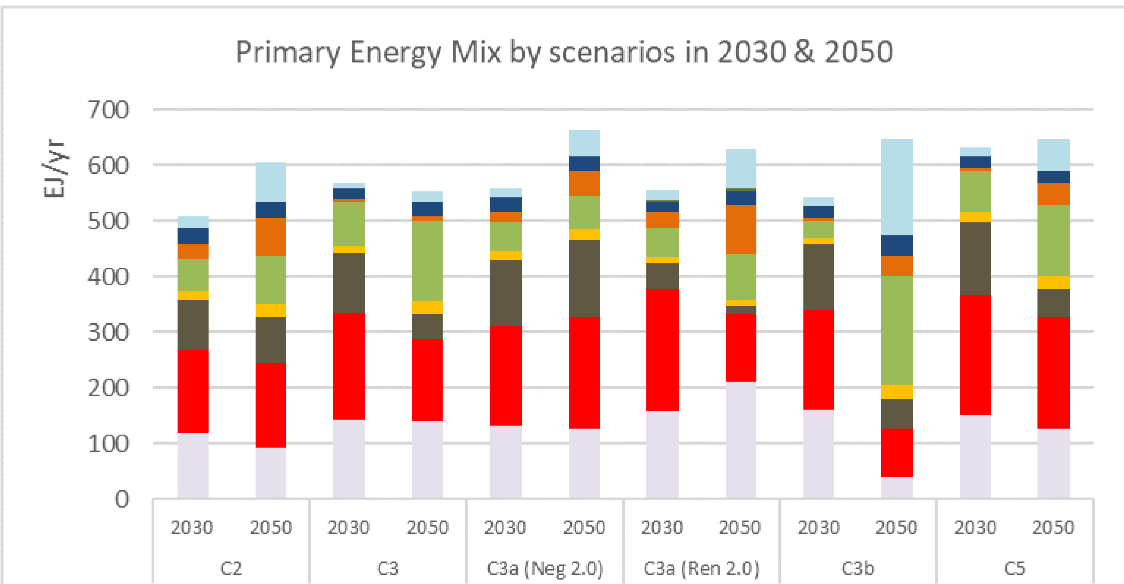
pathways with lower temperature targets (C1 and C2) [Table 3.5].

b. Transition costs

Limiting the temperature below 2°C will require considerable investment efforts to decarbonize the economy but also to support all economic actors in this transformation. First, it is highly likely that the global benefits of pathways likely to limit warming to 2°C outweigh global mitigation costs over the 21st century (even without accounting for co-benefits of mitigation on other sustainable development dimensions). Moreover, it is more cost-effective to start the transition quickly in order to reduce the costs of the transformation to limit warming to 2°C by 2100 (Moore and Diaz 2015; Ueckerdt et al. 2019; Brown and Saunders 2020; Glanemann et al. 2020).

To initiate change, the financial industry will have to play a considerable role. Ensuring this will inevitably involve a strong announcement on future climate policy seen as credible by investors, so that they realize the costs involved and thus reallocate capital towards green investments. For example, the investment needs in the electricity sector to initiate a major shift from fossil generation and extraction towards electricity are around USD 1.7 trillion over 2023-2050 on average for C3 scenarios (McCollum et al. 21 (2018a), Zhou et al. (2019) and Bertram et al. (2021)). Moreover, carbon pricing revenues in mitigation pathways consistent with limiting the temperature increase to 2°C could contribute to finance investment needs for basic infrastructure and for achieving the SDGs.

Figure 3: Primary energy mix according to different scenarios in 2030 and 2050 from the IIASA database



c. *Sectoral analysis*

Energy supply chain

In the C3 scenarios, all economic sectors will have to make structural changes to reduce their emissions, but some will be more affected. Firstly, the energy system must rapidly switch to low-carbon or zero-carbon types of energy (Rogelj et al. 2016, 2018b; Luderer et al. 2018; Grubler et al. 2018; Van Vuuren et al. 2018).

Therefore, there should be a reduction in the consumption of fossil fuel and a nearly total elimination of coal without carbon capture and storage (CCS) resulting to net zero energy supply around 2053. Conversely, low-carbon energy should reach 88% of primary energy in 2100, thus helping to decarbonize electricity. As for the IMP Neg, it reaches a peak around 2060 and declines afterwards due to carbon capture and storage. More precisely, fossil fuel infrastructures will need to be retired earlier to meet with the 2°C target, or at least be retrofitted with CDR. Coal-fired plants must be reduced to 42% of their capacity and retired three decades earlier to keep warming under 2°C.

Buildings, Transportation, and Industry

For the building and transportation sectors, demand will probably grow in the next few decades and therefore there is a need for electrification, which should be decarbonized. For example, 85% of building-sector emissions will need to be cut by 2100 to stay under 2°C, and the carbon intensity of these emissions will have to decrease sharply to give place to low- or zero-carbon electricity supply.

The same applies to the industry sector, and particularly steel, plastic, ammonia, and cement activities in which the median reductions in CO2 emissions between 2019 and 2050 is around 70% in scenarios likely to limit warming to 2°C and below, with a maximum reduction of 96% [Section 3.4.5]

AFOLU

Concerning the AFOLU sector, a big reduction in CO2 emissions is needed in contrast to other gases such as CH4 and N2O, which are still positive in a 2°C scenario (Popp et al. 2017; Roe et al. 2019; Reisinger et al. 21 2021). However, it should be noted that the 2°C pathway leads to structural changes in the land use and will therefore have an impact on biodiversity and sustainable development.

Robustness of the models

The models that describe the pathways according to sectors do, however, have some weaknesses. Indeed, the assumptions taken into account are sometimes too restrictive and do not include possible future changes. For example, for the transportation sector, it is said that the model does not account for changes in individual behavior or the recent trend of working from home that seems to be well established in society. Likewise, in the industrial sector, the models lack some information, such as the rise of the circular economy and the increased efficiency of some materials. It is therefore important to know what is behind the models to determine what can be considered as solutions to mitigate climate change.

d. Economic and social consequences

Economic cost of mitigation

If warming is limited to 2°C, the discounted economic impacts of stranded assets (evaluated at USD 1.8 trillion in the energy sector and USD 5-11 trillion in the building sector in 2050) could be as high as USD 1-4 trillion from 2015 through 2050 (Mercure et al. 2018). About 40% of these impacts correspond to unburned fossil reserves. Unfortunately, there are significant risks linked with carbon stranded assets, which depending on the assets, are risks for workers, asset owners, asset portfolio managers, financial institutions, and the financial system as a whole.

Mitigation pathways in the C3 scenarios result in an annualized reduction in consumption growth of 0.03% points relative to their mean baselines over the century. Compared to business-as-usual pathways, the global GDP that will be reached in 2050 is reduced by 1.3-2.7% in modelled pathways assuming coordinated global action starting between now and 2025 at the latest to limit warming to 2°C. It could be reduced by around 1.5% in 2100. Finally, the economic repercussions of mitigation policies will vary considerably across countries (Hof et al. 2017; Aldy et al. 12 2016).

The labor market will also be impacted by a temperature increase of 2°C. In C3 scenarios, job losses in the fossil fuel sector are found to be compensated by gains in wind and solar sectors, leading to a net increase in energy sector jobs in 2050 (Pai et al. 2021).

Food security, water access, health and biodiversity transformations

The 2°C pathway leads to structural changes in land and will therefore have an impact on food security, water access, health and biodiversity. Firstly, if mitigation policies aiming to achieve 2°C are not managed properly, 80 to 280 million people could be at risk of hunger compared to the baseline scenarios. In addition, bioenergy, BECCS, DACCS and CCS increase water withdrawals and water consumption, which will create conflicts between short-term needs for agriculture and long-term climate mitigation. Then, regarding public health in the USA, it is estimated that over the next 50 years, a 2°C pathway could prevent roughly 4.5 million premature deaths, about 3.5 million hospitalizations and emergency room visits, and approximately 300 million lost workdays. Finally, biodiversity will be deeply affected. At 2°C, 18% of insects, 16% of plants and 8% of vertebrates are projected to be at risk of extinction. (Warren et al. 2018)

Conclusion

In the light of this report, many changes need to take place to ensure that global warming stays below 2°C. Therefore, considering the C3 scenarios is essential, as current NDCs will not lead to achieving the Paris Agreement goal to stay under a 2°C global warming limit.

Nevertheless, the feasibility of C3 scenarios would be enhanced under favorable conditions, which are driven by socio-economic transitions. Indeed, C3 scenarios are more likely to occur in the presence of rapid technological change, socio-cultural change (i.e., moving away from an energy-intensive lifestyle), an economic shift and an increase in the use of geophysical and biomass energies (which both depend on policy implications).

REFERENCES

- Scenario Explorer develop by IIASA (n.d.). Retrieved October 28, 2022, from https://data.ece.iiasa.ac.at/ar6/#/login?redirect=%2Fworkspaces
- IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926, retrieved October 22 20226
- IPCC, 2022: Annex III: Scenarios and modelling methods [Guivarch, C., E. Kriegler, J. Portugal- Pereira, V. Bosetti, J. Edmonds, M. Fischedick, P. Havlík, P. Jaramillo, V. Krey, F. Lecocq, A. Lucena, M. Meinshausen, S. Mirasgedis, B. O'Neill, G.P. Peters, J. Rogelj, S. Rose, Y. Saheb, G. Strbac, A. Hammer Strømman, D.P. van Vuuren, N. Zhou (eds)]. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.022
- Aldy, J. et al., 2016: Economic tools to promote transparency and comparability in the Paris Agreement. Nat. Clim. Chang., 6(11), 1000–1004, doi:10.1038/nclimate3106
- Bertram, C. et al., 2021: Energy system developments and investments in the decisive decade for the Paris Agreement goals. Environ. Res. Lett., 16(7), 74020, doi:10.1088/1748-9326/ac09ae.
- Brown, P. T., and H. Saunders, 2020: Approximate calculations of the net economic impact of global warming mitigation targets under heightened damage estimates. PLoS One, 15(10), e0239520, 46 doi:10.1371/journal.pone.0239520.
- Glanemann, N., S. N. Willner, and A. Levermann, 2020: Paris {Climate} {Agreement} passes the cost-benefit test. Nat. Commun., 11(1), 110, doi:10.1038/

s41467-019-13961-1.

- Grubler, A. et al., 2018: A low energy demand scenario for meeting the 1.5 °c target and sustainable development goals without negative emission technologies. Nat. Energy, 3(6), 515–527, doi:10.1038/s41560-018-0172-6.
- Hof, A. F. et al., 2017: Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2 °C and 1.5 °C. Environ. Sci. Policy, 71, 30–40, doi:10.1016/j.envsci.2017.02.008.
- Luderer, G. et al., 2018: Residual fossil CO2 emissions in 1.5-2 °c pathways. Nat. Clim. Chang., 8(7), 626–633, doi:10.1038/s41558-018-0198-6.
- McCollum, D. L. et al., 2018a: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nat. Energy, 3(7), 589, doi:10.1038/s41560-018- 0179-z.
- Mercure, J. F. et al., 2018: Macroeconomic impact of stranded fossil fuel assets. Nat. Clim. Chang., 8(7), 588–593, doi:10.1038/s41558-018-0182-1.
- Moore, F. C., and D. B. Diaz, 2015: Temperature impacts on economic growth warrant stringent mitigation policy. Nat. Clim. Chang., 5(2), 127–131, doi:10.1038/nclimate2481.
- Pai, S., J. Emmerling, L. Drouet, H. Zerriffi, and J. Jewell, 2021: Meeting well-below 2°C target would increase energy sector jobs globally. One Earth, 4(7), 1026–1036, doi:https://doi.org/10.1016/j. oneear.2021.06.005
- Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. Glob. Environ. Chang., 42, 331–345, doi:10.1016/j.gloenvcha.2016.10.002.
- Reisinger, A. et al., 2021: How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals ? Philos. Trans. R. Soc. A, 379(20200452).
- Rochedo, P. R. R. et al., 2018: The threat of political bargaining to climate mitigation in Brazil. Nat. Clim. Chang., 8(8), 695–698, doi:10.1038/s41558- 018-0213-y
- Roe, S. et al., 2019: Contribution of the land sector to a 1.5 °C world. Nat. Clim. Chang., 9(11), 817-828, doi:10.1038/s41558-019-0591-9.
- Rogelj, J. et al., 2016: Paris Agreement climate proposals need a boost to keep warming well below 2°C. Nature, 534(7609), 631–639, doi:10.1038/nature18307.

- Rogelj, J. et al., 2018b: Scenarios towards limiting global mean temperature increase below 1.5 °c. Nat. Clim. Chang., 8(4), 325–332, doi:10.1038/s41558-018-0091-3.
- Ueckerdt, F. et al., 2019: The economically optimal warming limit of the planet. Earth Syst. Dyn., 10(4)
- van Vuuren, D. P. et al., 2018: Alternative pathways to the 1.5 °c target reduce the need for negative emission technologies. Nat. Clim. Chang., 8(5), 391–397, doi:10.1038/s41558-018-0119-8.
- Warren, R., J. Price, E. Graham, N. Forstenhaeusler, and J. VanDerWal, 2018: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. Science, 360(6390), 791 LP – 795, doi:10.1126/science.aar3646.
- Zhou, W. et al., 2019: A comparison of low carbon investment needs between China and Europe in stringent climate policy scenarios. Environ. Res. Lett., 14(5), 054017, doi:10.1088/1748-9326/ab0dd8.

IPCC scenario Category C4

Utsabh JAIN, Wencong TANG, Yuxin XIE,
Junyungbenedict GOH & Owen PUERINI

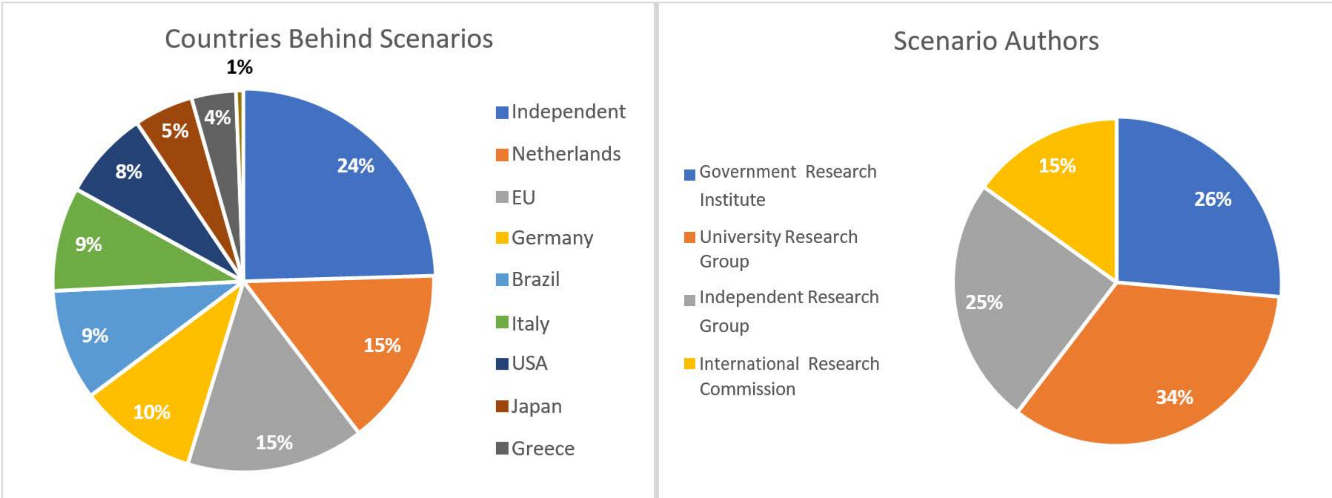
In its 6th Assessment Report (AR6), Working Group III (WG3) of the Intergovernmental Panel on Climate Change (IPCC) analyzed several scenarios and emission pathways which were submitted to the IPCC by various volunteers. In the context of the report, a scenario is defined as an integrated description of a possible trajectory of the human environment system, whereas an emission pathway is a modelled trajectory of man-made emissions and is a part of a scenario (Pathak et al., 2022). The scenarios submitted to the IPCC went through several rounds of vetting and emulation and, out of the 3,131 submitted, only 1,202 were eventually used in AR6 (Pathak et al., 2022). These 1,202 scenarios were further segmented into 8 categories – each with a defined probability of limiting global warming to a certain degree (Pathak et al., 2022). This report will focus on the scenarios within Category 4 – which were scenarios that limited warming to below 2°C with a > 50% likelihood (Pathak et al., 2022).

A total of 13 models were used to generate the 159 scenarios comprising the C4 group (Riahi et al., 2022). This review focuses on the top 6 models from which the most scenarios are derived, representing approximately 80% of total scenarios in the C4 group.

Models

Of the 159 models used in C4, the majority of the models were devised by university research groups and government research institutions. However, the two models that contributed the most scenarios to C4, MESSAGEix GLOBIOM and POLES, came from international research groups. The former was created by the International Institute for Applied Systems Analysis, and the latter by the Joint Research Centre European Commission.

Figure 1.1: Share of total scenarios by country and author (IPCC, 2022)



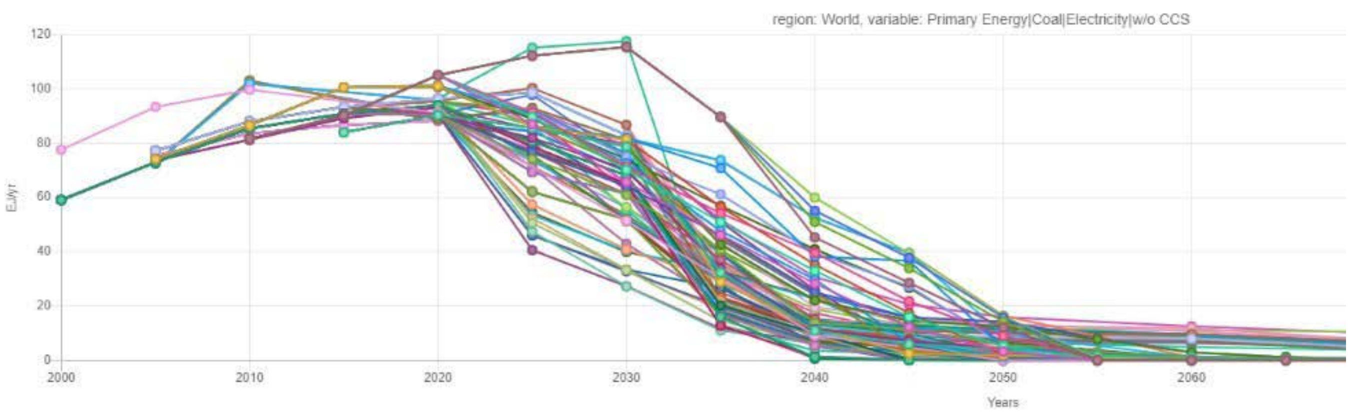
Scenario Implications by Sector

The trends of the various scenario variables in C4 over time have various implications on what is necessary to limit warming to below 2°C with a > 50% likelihood. These have been categorized according to the sectors most relevant to climate change and are discussed below.

Implications for Energy

In all C4 scenarios, the energy sector undergoes deep decarbonization by 2100 and final energy demand grows at a subdued rate, increasing by just 10% between 2020 and 2050. Electricity's share of final energy doubles, and primary energy reaches net zero CO2 emissions around 2070 in nearly all C4 scenarios.

Figure 1.2: Primary energy coal without CCS in all 159 C4 scenarios (Riahi et a.l, 2017)



In C4, as well as in virtually all scenarios in which warming is kept below 2°C, coal without carbon capture and sequestration (CCS) is reduced by 99% by 2100. These results imply that a radical shift is necessary in the way society produces and consumes energy. Renewable energy sources will have to be constructed at an unprecedented scale, and coal – which makes up nearly all primary energy in countries such as China – will need to be virtually eliminated. (IPCC, 2022)

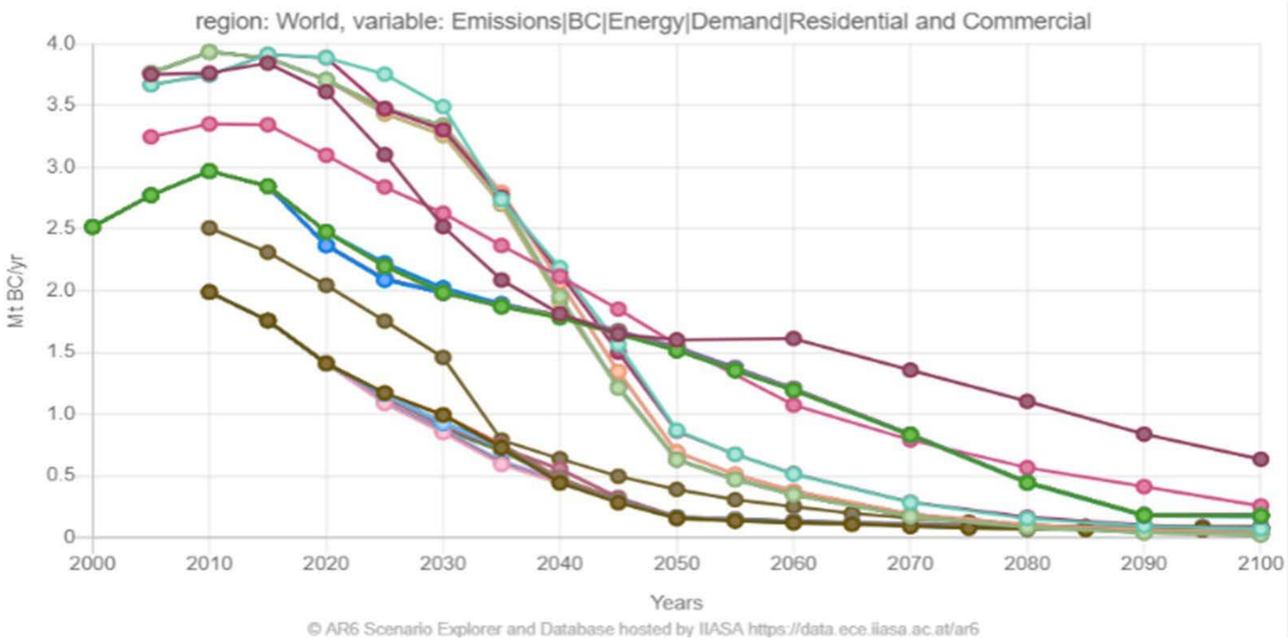
Implications for Buildings

Emissions from buildings account for 12GtCO2 in 2019, making up 21% of global GHG emissions. Emissions from buildings can be categorized as direct or indirect, with a 24% and 57% contribution respectively and 18% emissions accounting for embodied emissions. This sector mostly emits CO2 and the residential sector consumes over 70% of the global final energy demand within the buildings sector (Riahi et al., 2022).

To study the implications on this sector, the report will use 4 of the scenarios from the WITCH, IMAGE, POLES and COFFEE models, which incorporated and focused on the buildings sector and have also been defined in the report.

For final energy under the C4 scenario, there is a gradual increase in demand from now to 2100. The WITCH model incorporates an intertemporal economic growth model capturing long-term economic goals, which could explain the drastic rise in demand in both the residential and commercial sectors (IAMC, 2022).

Figure 1.3: Final Energy demand for Residential and Commercial sector under C4 mitigation scenarios (Riahi et al., 2017)



CATEGORY C4

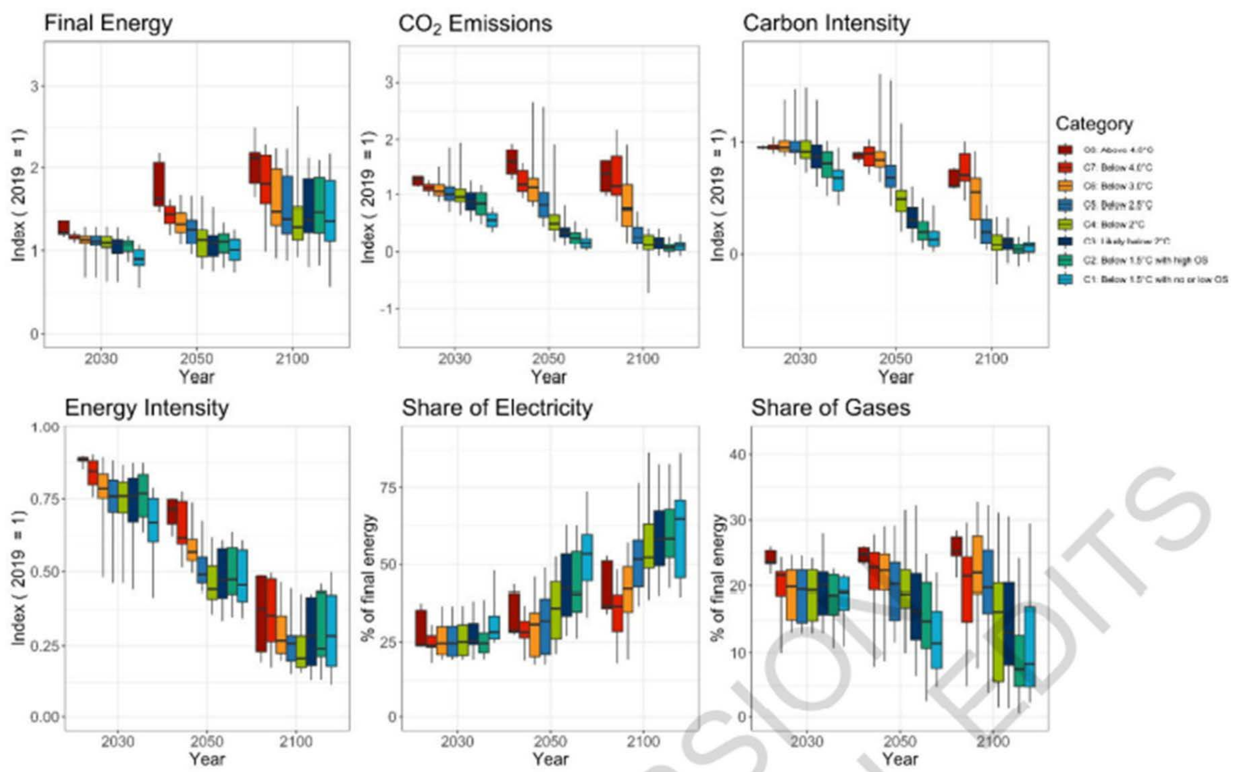
The C4 scenarios focus heavily on CO2 emissions, as GHG are presumed to be emitted in the highest amounts across industries and to be highly unlikely to go down to 0 . Although optimistic models like POLES and COFFEE (MESSAGE) do suggest that CO2 emissions will be closer to 0 by the end of the century, some models like the WITCH and IMAGE predict stagnant emission levels (see Appendix 2.2).

Lockdown policies as a measure to contain COVID 19 led to a global drop in CO2 emissions, but emissions from the residential buildings industry rose due to home schooling and teleworking (Riahi et al., 2022). A major increase in building retrofits is needed to achieve the C4 targets, involving the development of new innovations for a more sustainable building infrastructure and incorporating cleaner energy technologies (See Appendix fig 2.3).

Implications for Industry

Reference scenarios show declines in energy intensity but increases in final energy use in the industrial sector. These scenarios show increases in CO2 emissions both for the total industrial sector and individual subsectors like cement and iron and steel.

Figure 1.4: Industrial final energy, including feedstocks (top left), CO2 emissions (top middle), carbon intensity (top right), energy intensity (bottom left), share of final energy from electricity (bot- tom middle), and share of final energy from gas (bottom right).



Mitigation pathways show reductions in final energy for industry compared to the baseline and reductions in the carbon intensity of the industrial sector through both fuel switching and the use of CCS.

Many scenarios, including stringent mitigation scenarios, show continued growth in industrial final energy use; however, the carbon intensity of industrial energy use declines in all mitigation scenarios.

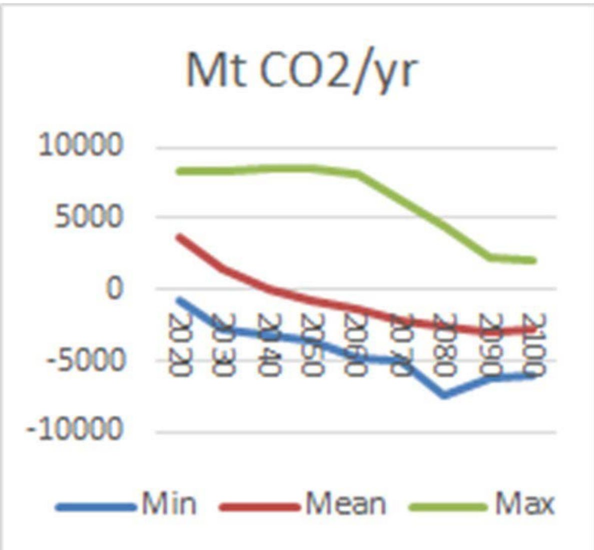
Sectoral studies indicate a large mitigation potential in the industrial sector by 2050, including the potential for net zero CO2 emissions for steel, plastics, ammonia, and cement. Detailed industry sector pathways show emissions reductions between 39% and 94% by mid-century compared to the present day and a substantial increase in direct electrification (IEA 11 2021a).

Implications for Agriculture, Forestry, and Other Land Use (AFOLU)

AFOLU accounted for approximately 22% of global emissions in 2019 and is the 2nd largest emitting sector after energy with its main emissions being CO2, CH4, and N2O. Some of the top contributors within AFOLU are land use change and forestry (deforestation), enteric fermentation (methane from livestock) and drained peat and peat fires (Riahi et al., 2022).

In all C4 scenarios the mean percentage reduction in CO2 emissions from 2019 is over 100% by 2050 and close to 200% by 2100 (Riahi et al., 2022). This indicates that to remain within C4, AFOLU needs to transform from a net emitter of CO2 into a net carbon sink. This is likely due to the afforestation trajectory under land use which would help to store carbon in forested areas.

Figure 1.5: Min, Mean, and Max of AFOLU CO2 emissions as projected by C4 mod- els.



Source: Data extracted from IIASA AR6 Scenario Explorer (https://data.ece.iiasa.ac.at/ar6/#/workspaces)

CATEGORY C4

The mean percentage reduction in CH4 and N2O emissions from 2019 levels under all C4 scenarios also increases from 2030 to 2100. However, the decrease is not as drastic as for CO2, with mean reductions by 2100 of around 50% and 20% respectively compared to 2019 levels (Riahi et al., 2022). Based on the mean trend, this implies a gradual decrease in the scale of agricultural activities, which are the main sources of these two emissions, across the majority of C4 scenarios, and this is supported by the trajectory of land use in the C4 scenarios.

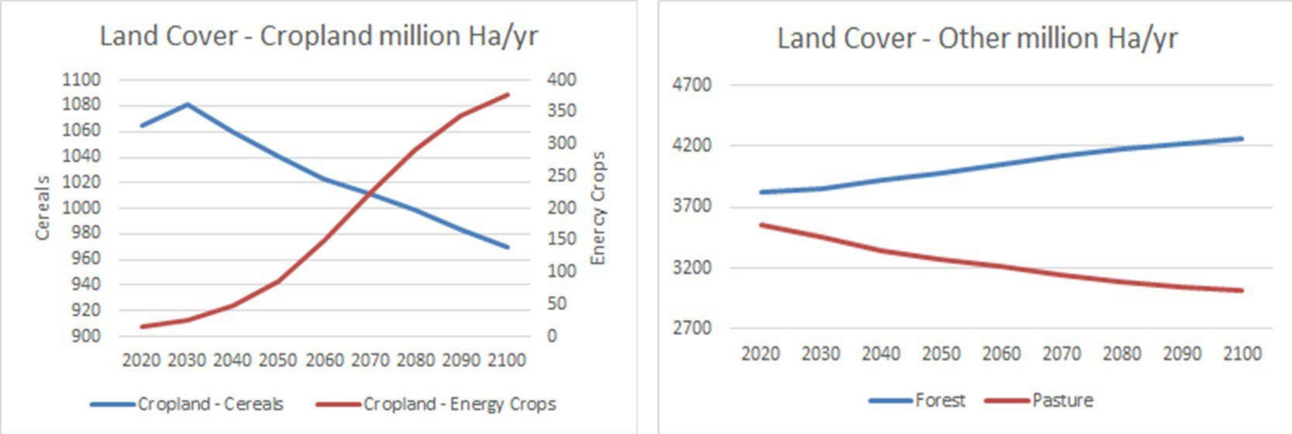
As for the overall land use relating to AFOLU, in all C4 scenarios, there is an increase in forested areas from 2019 with a mean increase of about 200 million hectares by 2050 and 400 million hectares by 2100 (Riahi et al., 2022). At the same time, in almost all scenarios within C4, there is a decrease in land use for both pastures and non-energy crops from 2019 levels (Riahi et al., 2022). The mean decrease in land use for pasture and non-energy crops respectively is about 250 million and 20 million hectares by 2050 and 550 million and 100 million hectares respectively by 2100. Lastly, as opposed to non-energy crops, the change in land use for energy crops increases greatly in all C4 scenarios with a mean increase of about 50 million hectares by 2050 and 250 million hectares by 2100 (Riahi et al., 2022).

Although the mean land coverage for crops and pastures decreases over time in the C4 models, the mean demand for crops and livestock increases slightly over the same period from 3,756 million and 261 million t DM/year respectively in 2020 to 4,964 million and 316 million t DM/year respectively in 2100 (Riahi et al., 2022). This implies that the efficiency of agriculture techniques is expected to increase in order to meet the projected demand with less land.

Implications for transport

In 2019, direct greenhouse gas emissions from the transport sector were 8.7 Gt CO2eq (from 5.0 Gt CO2eq in 1990) and accounted for 23% of global energy-related CO2 emissions. 70% of direct transport emissions came from road vehicles, while 1%, 11% and 12% came from rail, shipping, and aviation, respectively. (Riahi et al., 2022) The transport scenario literature's mean outcomes suggest that the transport sector may follow a less steep emissions reduction trajectory than the cross sectoral average and still be consistent with the 2°C goal, which is in line with perspectives in the literature suggesting that transport is one of the most difficult sectors to decarbonize. To meet temperature goals, global transport emissions would need to decrease by 17% below modeled 2020 levels in the C3-5 scenario group (Jaramillo et al., 2022).

Figure 1.6: Mean trajectories of land cover as projected by C4 models.



Source: Data extracted from IIASA AR6 Scenario Explorer (https://data.ece.iiasa.ac.at/ar6/#/workspaces)

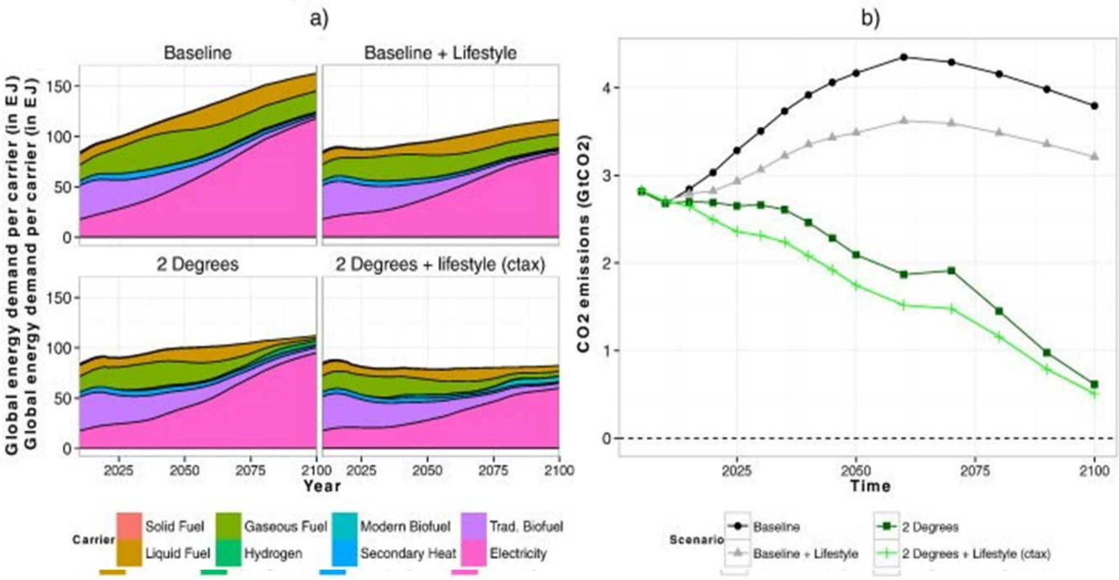
In terms of transport activity, the median transport demand from IAMs for all scenarios in line with warming levels below 2.5°C (C1- C5) suggests that global passenger transport demand could be multiplied by 1.14 - 1.3 in 2030 and by 1.5-1.8 in 2050 relative to the modeled 2020 level (Jaramillo et al., 2022)). Globally, over the last century, shares of faster transport modes have generally increased with rising passenger travel demand. Scenarios with higher warming generally lead to more freight by rail and less freight by international shipping. Common explored mitigation options related to transport mode change include a shift to public transit, shared mobility, and demand reductions through various means, including improved urban form, teleconferences that replace passenger travel, improved logistics efficiency, green logistics, and streamlined supply chains for the freight sector. Passenger transport's energy intensity drops to between 10%-23% in 2030 for the scenarios in line with warming levels below 2°C. In 2050, the medians across the 2°C increase group suggest energy intensity reductions of 45%-46% (Jaramillo et al., 2022).

Using the right tools and strategies is crucial for the successful deployment of mitigation options. Current explored tools and strategies include travel demand reductions and fuel/vehicle efficiency, light vehicle electromobility systems and alternative fuel systems for shipping and aviation. Table 2.1 in the appendix summarizes how to apply these tools and strategies with respect to providing education and R&D, access and equity, financing economic incentives and partnerships, ensuring co-benefits and overcoming fragmentation, ensuring regulation and assessment, governance and institutional capacity, and enabling infrastructure (Jaramillo et al., 2022).

Further studies on C4

A study conducted by PBL (Problem-Based Learning) explores the implications that a lifestyle change can enforce on the C4 mitigation scenarios. The study deploys the IMAGE model (integrated assessment) to infer that lifestyle changes overlap with more technical measures in the end-use sectors. The paper uses a lifestyle change framework that infers the need for further emission reductions based on the C4 mitigation scenarios to accommodate for residential, transport and industry-related lifestyle changes (Martinez et al., 2016).

Figure 1.7: Effect of lifestyle changes in the residential sector on the use of secondary energy carriers (Ej) and CO2 emission trajectories (GtCO2)



Source: Martinez et al., 2016.

Another study undertaken by Yi- Meng claims that cumulative CO2 emissions need to be limited to 1,000 Gt between 2020-2100 to achieve C4 targets (Wei et al., 2021). The paper studies various pathways to achieve the target and finds that the low-carbon transformation of the energy system is a key solution. The paper supports the C4 scenario to promote reorganization of the power system whilst greatly reducing global carbon intensity.

REFERENCES

- Integrated Assessment Modeling Consortium (IAMC). Retrieved November 3, 2022 https:// www.iamcdocumentation.eu/index.php/ IAMC_wiki
- IPCC — intergovernmental panel on climate change. (n.d.). Retrieved November 4, 2022, from https://www.ipcc.ch/site/assets/ uploads/2018/02/ipcc_wg3_ar5_chapter9. pdf
- IPCC AR6 WGIII Chapter 10 https://www. ipcc.ch/report/ar6/wg3/downloads/ report/ IPCC_AR6_WGIII_Chapter_10.pdf
- IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum,
- M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926
- Jaramillo, P., S. Kahn Ribeiro, P. Newman, S. Dhar, O.E. Diemuodeke, T. Kajino, D.S. Lee, S.B. Nugroho, X. Ou, A. Hammer Strømman, J. Whitehead, 2022: Transport. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum,
- M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.012
- Keywan Riahi, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O'Neill, Shinichiro Fujimori, Nico Bauer, Katherine Calvin, Rob Dellink, Oliver Fricko, Wolfgang Lutz, Alexander Popp, Jesus Crespo Cuaresma, Samir KC, Marian Leimbach, Leiwen Jiang, Tom Kram, Shilpa Rao, Johannes Emmerling, Kristie Ebi, Tomoko Hasegawa, Petr Havlík, Florian Humpenöder, Lara Aleluia Da Silva, Steve Smith, Elke Stehfest, Valentina Bosetti, Jiyong Eom, David Gernaat, Toshihiko Masui, Joeri Rogelj, Jessica Strefler, Laurent Drouet, Volker Krey, Gunnar Luderer, Mathijs Harmsen, Kiyoshi Takahashi, Lavinia Baumstark,

Jonathan C. Doelman, Mikiko Kainuma, Zbigniew Klimont,Giacomo Marangoni, Hermann Lotze Campen, Michael Obersteiner, Andrzej Tabeau, Massimo Tavoni. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Global Environmental Change, Volume 42, Pages 153-168, 2017, ISSN 0959-3780, DOI:110.1016/j.gloenvcha.2016.05.009

- M. Pathak, R. Slade, P.R. Shukla, J. Skea, R. Pichs Madruga, D. Ürge Vorsatz,2022: Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.002 News. iamconsortium. (n.d.). Retrieved November 4, 2022, from https://www.iamconsortium.org/
- Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, D.P. van Vuuren, 2022: Mitigation pathways compatible with long term goals. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.005
- S. H. Martínez, V. Daioglou, and D. P. van Vuuren, 2016: Exploring the implications of lifestyle 44 change in 2°C mitigation scenarios using the IMAGE integrated assessment model. Technol. 45 Forecast. Soc. Change, 102, 309–319, https://doi. org/10.1016/j.techfore.2015.08.013.
- Wei, Y.M., and Coauthors, 2021: Pathway comparison of limiting global warming to 2°C. Energy 16 Clim. Chang., 2, 100063, https:// doi.org/10.1016/J.EGYCC.2021.100063.

APPENDIX

Figure 2.1 Relative evaluation of models by parameter robustness based on model assessment in the IPCC report (IPCC, 2022)

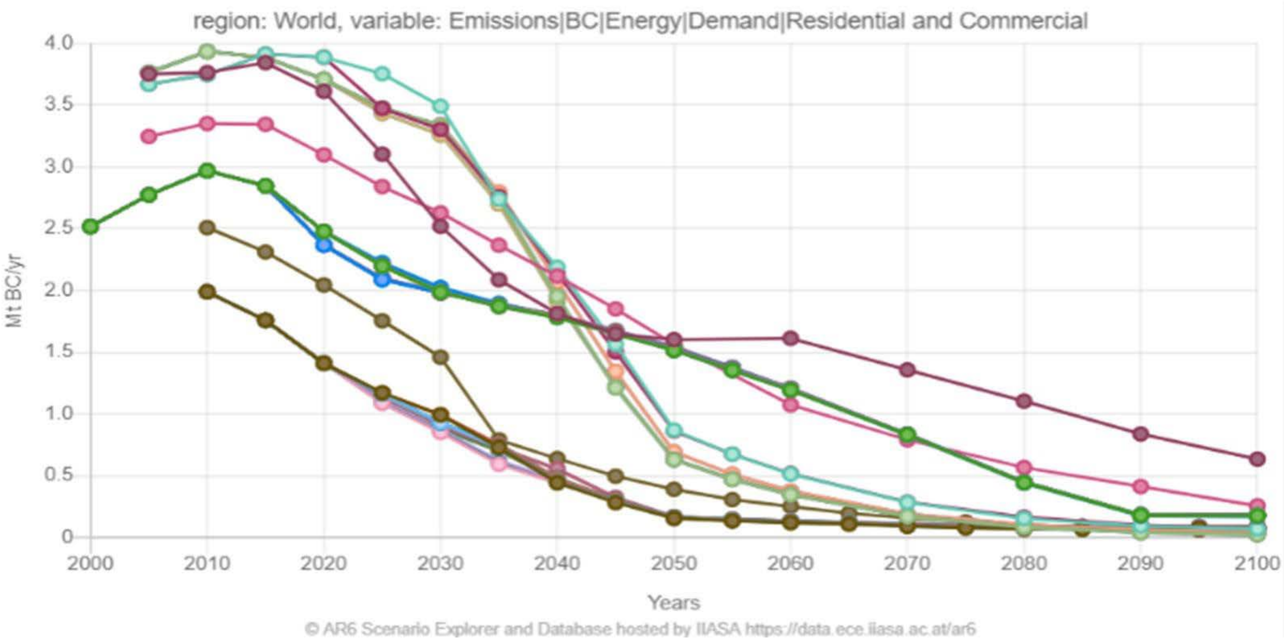


Table 2.1 Tools and Strategies for enabling mitigation options to achieve transformative scenarios (Jaramillo et al., 2022)

Tools and Strategies	Travel Demand Reductions and Fuel/Vehicle Efficiency	Light Vehicle Electromobility Systems	Alternative Fuel Systems for Shipping and Aviation
Education and R&D	TDR can be assisted with digitalization, connected autonomous vehicles, EVs and Mobility as a Service. Knowledge gaps on TDR exist for longer distances, non-mandatory trips and travel by older people. Travel demand foresight tools can be open source.	Behavior change programs help EV's become more mainstream. R&D helps for the socio- economic structures that impede adoption of EVs and the urban structures that enable reduced car dependence and how EVs can assist grids.	R&D is critical for new fuels and to test the full life cycle costs of various heavy vehicle options.
Access and Equity	TDR programs in cities can be inequitable. To avoid this, there is a need for better links to spatial and economic development, mindful of diverse local priorities, personal freedom and personal data.	Significant equity issues with EVs in the transition period can be overcome with programs that enable affordable electric mobility, especially transit.	Shipping is mostly freight and is less of a problem but aviation has significant equity issues.
Financing Economic Incentives and Partnerships	Carbon budget implications of different demand futures should be published and used to help incentivize net zero projects. Business and community pledges for net zero can be set up in partnership agreements.	Multiple opportunities for financing, economic incentives, and partnerships with clear economic benefits can be assured especially using the role of value capture in enabling such benefits. The nexus between EVs and the electricity grid needs opportunities to demonstrate positive partnership projects.	Involving R&D in demonstration projects is the main stage for heavy vehicle options and this is best done in the form of partnerships. Government assistance will greatly assist in such projects as well as an R&D levy. Abolishing fossil fuel subsidies and imposing carbon taxes are likely to help in the early stages of heavy vehicle transitions.

Regulation and Assessment	Implementing a flexible regulatory framework is needed for most TDR. Regulatory assessment can help with potential additional security risks due to digitalization, AVs, IoT, and big data. Assessment tools and methods need to take account of the greater diversity of populations and regions, the blurring of modes, and distinct spatial characteristics.	With zero carbon light vehicle systems rapidly growing the need for a regulated target and assessment of regulatory barriers can assist each city and region to transition more effectively. Regulating EVs for government fleets and ensuring a recharge infrastructure can establish incentives.	Zero carbon heavy vehicle systems need to have regulatory barrier assessments as evaluated in R&D demonstrations.
Governance and Institutional Capacity	TDR works better if adaptive decision-making approaches focus on more inclusive and whole- system benefit-cost ratios.	Governance and institutional capacity can now provide international exchanges and education programs based on successful cities and nations enabling light vehicle decarbonization to create more efficient and effective policy mechanisms towards self sustaining markets.	Governance and institutional capacity can foster significant progress if targets include levies for non-compliance. Carbon taxes would also affect these segments. A review of international transport governance is likely.
Enabling Infrastructure	Ensuring space for active transport and urban activities is taken from road space where necessary. Increasing the proportion of infrastructure that supports walking in urban areas will structurally enable reductions in car use. Creating transit activated corridors of TOD-based rail or mid-tier transit using value capture for financing will create inherently less car dependence.	Large-scale electrification of LDVs requires expansion of low-carbon power systems, while a charging or battery swapping infrastructure is needed for some segments.	In addition to increasing the capabilities to produce low- or zero-carbon fuels for shipping and aviation, there is a need to invest in supporting infrastructure including low carbon power generation. A new hydrogen delivery and refueling infrastructure may be needed. For zero-carbon synthetic fuels, infrastructure is needed to support carbon capital and CO2 transportation to fuel production facilities.

Figure 2.2: CO2 emissions for Residential and Commercial sectors under C4 mitigation scenarios

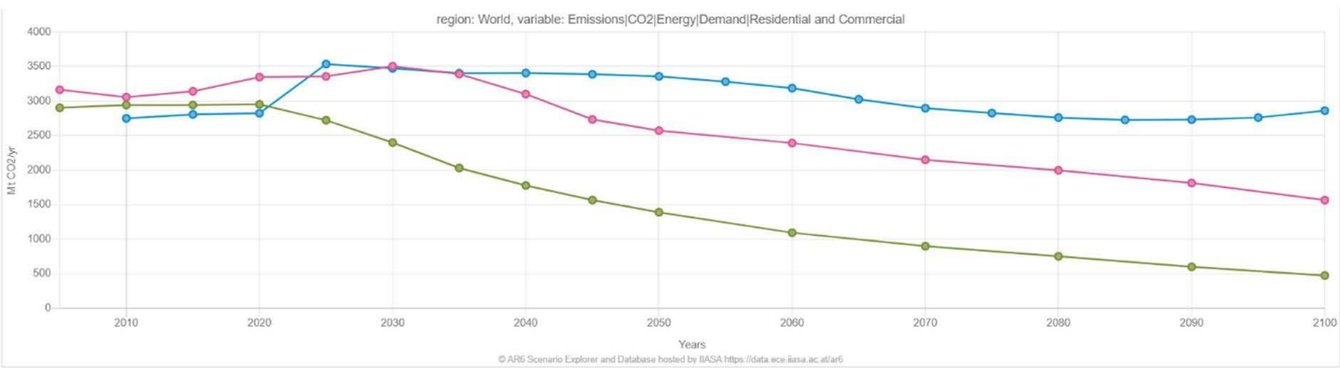
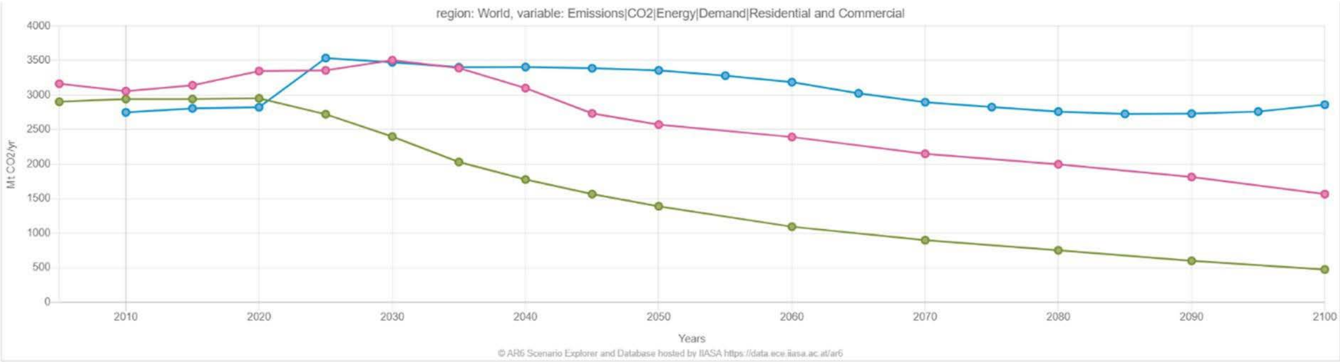
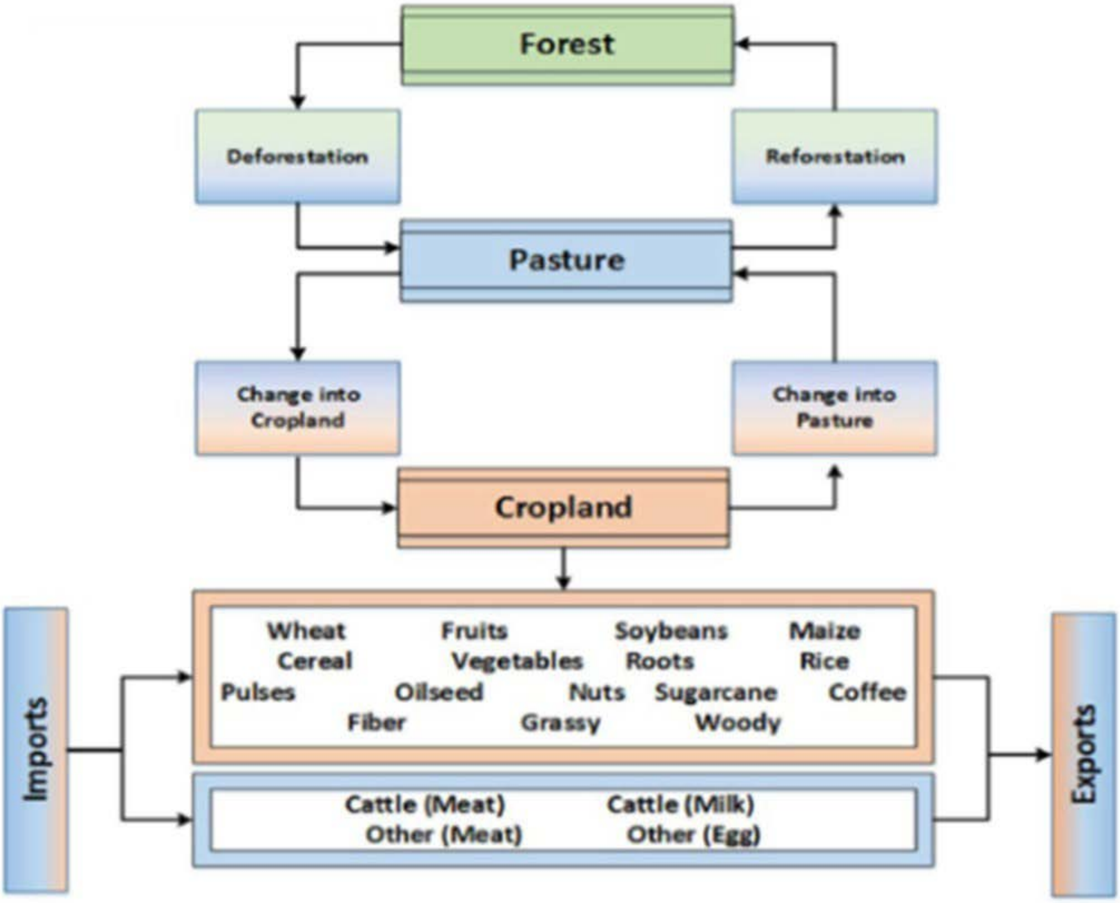


Figure 2.3: Investments needed for building retrofits under C4 mitigation scenarios



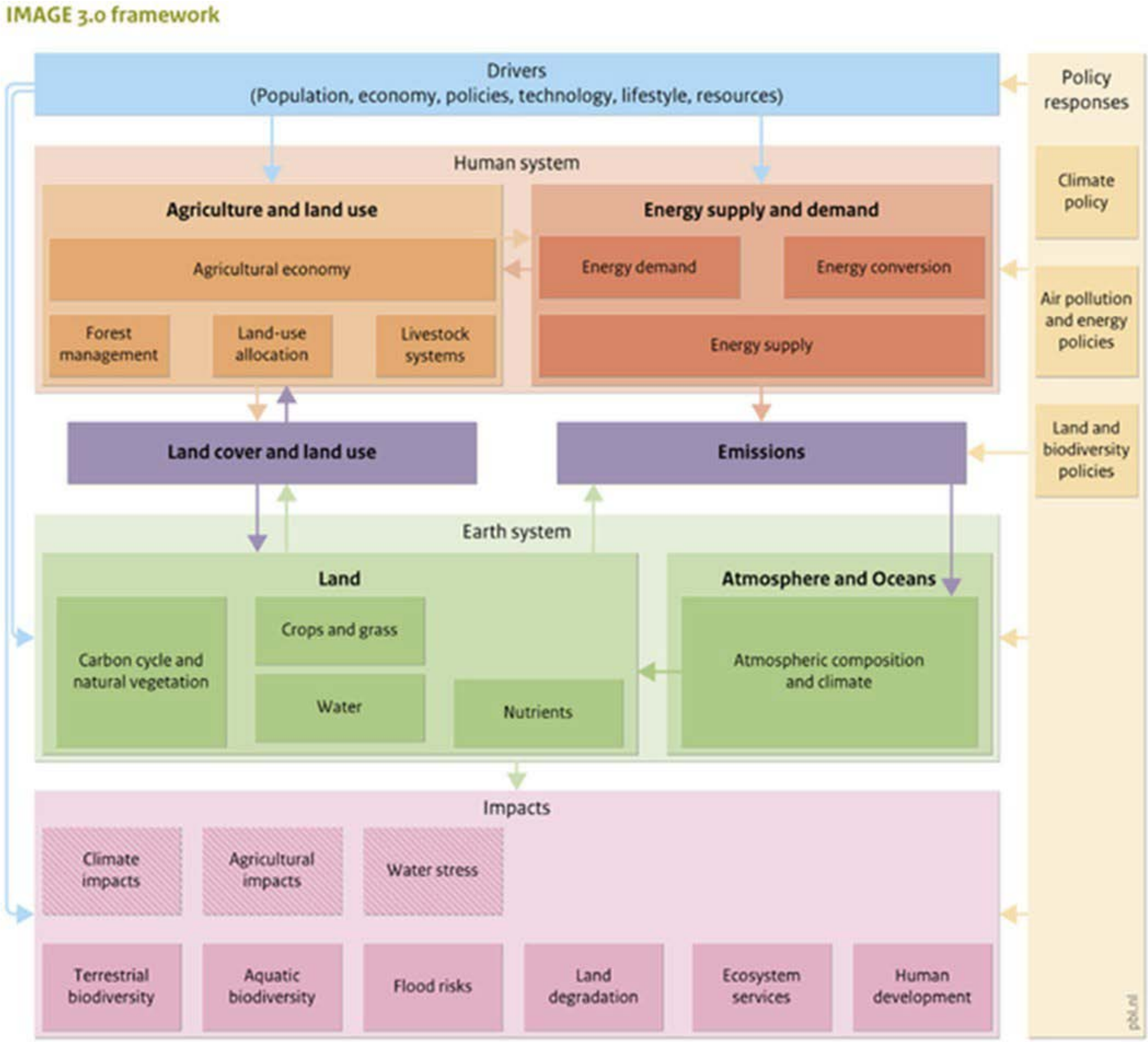
Investment in retrofitting amounts to less than USD 10 billion and needs to go up to almost 60 billion in the coming 10-15 years. This investment needs to be maintained at or about 40 billion up until 2100 in order to reach the target. The growing population and emergence of new technologies would require regular building retrofits.

Figure 2.4: The Land system for COFFEE model



CATEGORY C4

Figure 2.5: The IMAGE framework explained



Source: PBL 2014

NOTE D'ÉCLAIRAGE #5

IPCC scenario Category C5

Clara ANGIO, Ronan CHAMARD, Sara DAVO,
Hugues DURON & Hugo HAZON

This paper explains the global emissions pathway of the climate category C5 (grouping 212 scenarios) which projects global warming up to 2.5°C (with more than 50% probability).

Models and approaches

IPCC scenarios explore alternative climate trajectories or possible futures based on conditional assumptions and show different variables (within the group of energy, emissions, climate assessment, socioeconomic factors). They rely on a comprehensive modelling framework as they consider the interaction between the economy, society and the environment, and each model and scenario provides additional information to the assessment.

More specifically, scenario category C5 relies on 212 scenarios that have passed all quality controls, vetting and checks. They have received a temperature classification (trajectory with a 2.5°C peak global warming) categorized as C5. These 212 scenarios come from 11 different models. They all respect the condition to run until the end of century and as a minimum to report CO2 (total and for energy & industrial processes (EIP)), CH4 and N2O emissions to 2100. They all have common conditions and a temperature goal; however, each model varies in complexity and has a specific approach. For this C5 category, the models used are mainly global integrated assessment models, covering the whole world (and not national-focused) and are also full system, meaning they cover GHG in all sectors: energy, buildings, transport and industry. The scenarios submitted can come from the same model (for instance, MESSAGE-GLOBIUM includes 57 scenarios, REMIND PagPIE features 27, and WITCH has 24), but have different assumptions, inputs, and orientations. For instance, both the MESSAGE- GLOBIUM and REMIND models assess the energy system, but they have noticeably different representations, one focusing on macroeconomic, land-use and climate models, and second focusing on different assumptions regarding climate policies or targets.

Table 1 : First five models with the most scenarios selected in the C5 category as documented in the IIASA database and their specificities (number of scenarios selected within C5)

Models (number of scenarios)	Model objective and main characteristics
MESSAGE-GLOBIUM (57)	Energy-engineering optimization model used for energy planning, considering linkages to macro- economic, land-use and climate models.
REMIND PagPIE (27)	Global and full system model that focus on global energy-economy system, based on different assumptions on climate policies or targets.
WITCH (24)	Full system * and global integrated model that assesses climate change mitigation and adaption policies. It integrates an inter-temporal growth model, capturing long-term economic growth dynamics, energy sector, and land use mitigation linked with a land use and forestry model (Globium)
IMAGE (22)	Assesses the GHG effect and simulates the environmental consequences of human activities. It aims at exploring the long-term dynamics and impacts of global changes that result from interacting demographic, biosphere, technological, economic, social, cultural and political factors.
COFFEE (21)	Optimization model assessing climate, land, energy and environmental policies (full system). It provides information on possible development strategies and repercussions of long-term climate scenarios.

*The 6 remaining models also integrate a full system integrated assessment and mainly focus on energy system and policies, and climate change mitigation and adaptation policies.

Assumptions

Amongst the 212 scenarios comprised in the C5 category, all have adopted different assumptions on four main variables. Each of them is subdivided into different sections listed below. To provide an overview of the different assumptions, we identified the minimum and maximum of the variables listed for the 212 scenarios.

Firstly, socioeconomic drivers influence energy intensity (e.g., structural change, lifestyle, and efficiency) as well as economic growth (assumptions related to political stability, respect of current political pledges, technological progress, etc.) which in the long term have a direct impact on future CO2 emissions and thus climate change. Secondly, energy drivers are linked to the different sources of energy used globally. There is a wide variety amongst the 212 scenarios. Overall, we can see that the transition towards renewable energy is not fully achieved by 2100. In fact, in some scenarios, the world still relies heavily on coal and other carbon-intensive sources of energy. Lastly, the third variable is linked to Black Carbon (BC), CH4, CO, CO2, HFC, AFOLU, N2O, NH3, NOx, OC, PFC, Sulfur and VOC emissions.

The model gives us access to the different emissions in the world by 2100, which are impacted by the policies enacted.

To conclude on the assumptions, we understand the need to have versatile variables in the assumptions (socioeconomics, energy, emissions, and climate assessment) to give accurate metrics on the carbon emission and energy levels.

The relationship between climate change, their policies, and these variables involves a near-linear relationship between cumulative CO2 emissions and temperature.

Table 2: Assumptions table following the IIASA AR6 Explorer Database

Groups	Time-series variables
Socioeconomics	GDP: GDP PPP (Min: $288.8 T ; Max: $1,137.6 T) Population by 2100 (Min: 6.9 B ; Max: 12.8 B)
Energy	Final energy: final energy in the world by 2100 (Min: 282.5 EJ/yr ; Max: 874.6 EJ/yr), electricity in the world by 2100 (Min: 151.5 EJ/yr ; Max: 520.8 EJ/yr), gas (Min: 16.4 EJ/yr ; Max: 249.0 EJ/yr), industry, non-energy use, other sectors, residential and commercial sectors, solids, transportation of final energy (excl. feedstocks) Primary energy: primary energy in the world by 2100 (Min: 384.6 EJ/yr ; Max: 1,154.3 EJ/yr), biomass in the world by 2100 (Min: 23.6 EJ/yr; Max: 459.1 EJ/yr), coal in the world by 2100 (Min: 0.1 EJ/yr; Max: 271.7 EJ/yr), fossils, gas, non- biomass renewables, oil. Secondary energy: electricity, gas, heat, hydrogen, liquids, solids
Emissions	Black Carbon (BC), CH4, CO, CO2, HFC, AFOLU, N2O, NH3, NOx, OC, PFC, Sulfur, VOC
Climate assessments	Effective radiative forcing, exceedance probability 1.5°, 2.0°, 2.5°, 3.0°, infilled, native-with-infilled, surface temperature (GSAT)

CATEGORY C5

Teams

More than 60 experts (lead authors and contributing authors) who contributed to chapter 3 and annex 3 have extensive experience in applied research in energy, climate change and economy-climate modelling. They come from different countries in Europe, Latin America, North America, Asia, and Africa, therefore showing a global representativeness of regions and methods, and this diversity needs to be considered in their assessment. Indeed, a comprehensive methodology that integrates like-for-like comparisons between countries' approaches completes the global assessment. The majority come from research institutes (and affiliated universities related to research) specialized in systems analysis, climate impact, energy, agriculture, and the environment, with backgrounds in science, biology, economics and engineering.

None of them seem to be currently affiliated to private companies, at least as stipulated by the IPCC, thus reducing conflicts of interest between the private sector and IPCC-led research. Only one non-profit think tank (Council on Energy, Environment and Water) is represented.

Chapter 3, in which the scenarios were analyzed, was led mainly by research teams focused on energy and climate, and based on an academic and scientific approach, thus methodically explaining the consequences of climate change rather than prescribing policymaking or interaction with society (even though this is intended).

Interpretation

IPCC trajectory assessments aim at informing society about possible long-term trajectories and the effectiveness of possible mitigation strategies, and shedding light on key uncertainties about the future. As for the scenarios, they can be considered as tools for decision-making and international negotiations and represent a way to coordinate perceptions about possible and desirable futures between the different actors of society. Specifically, scenario C5 aims at exploring trajectories in a business-as-usual context with no new climate policies.

IPCC scenarios are usually goal-oriented or back testing: they are inherently normative and linked to human intervention. A scenario is a description of a possible future of the human–environment system. It can be a qualitative narrative, a quantitative projection or both and is not a prediction or a forecast. The experts behind the scenario manage to stay factual and to convey agreed and scientifically proven results. One of these results states that if humanity follows this trajectory (C5), the outcomes will be dramatic. Another conclusion is that various mechanisms are and will be needed to mitigate climate change.

As explained above, the aim of the scenarios is to explore pathways towards long-term climate goals. Additionally, goal- oriented scenarios often include the word pathway in their title, such as "climate change mitigation pathway", "climate change adaptation pathway", and "climate change transition pathway". They are sometimes called backcasting scenarios, or backcasts, especially when they are compared with forecasts.

Yet, the conclusions conveyed by the experts in the report are alarming enough to implicitly incentivize the different stakeholders (governments, companies, and individuals) to act, as they are explicitly identified as responsible for the current situation. Given the facts provided, the business-as-usual trajectory is not recommended and encourages all stakeholders to rapidly take another path.

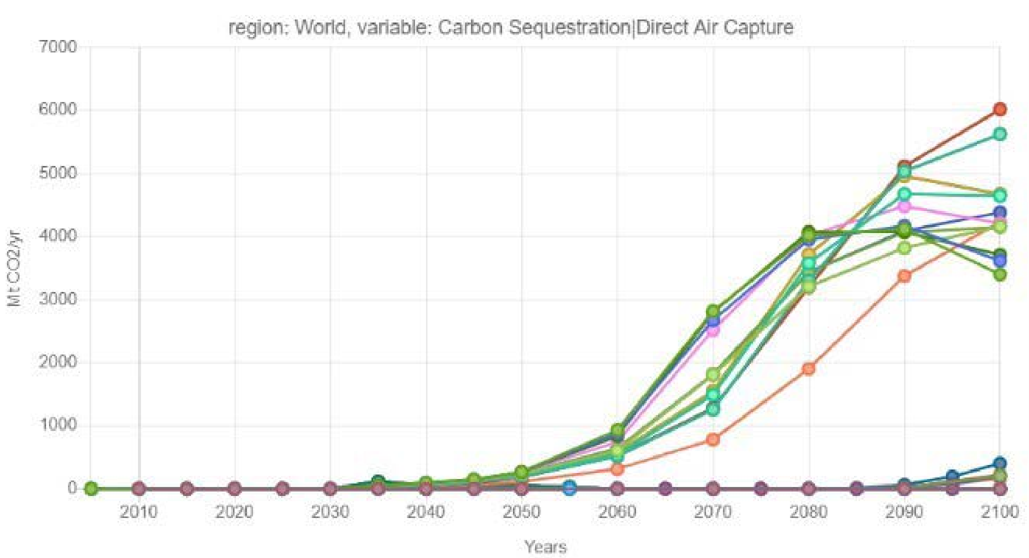
Scenarios are based on different assumed contexts; because one scenario is not a prediction of the future, it is fundamental to use them as a whole in order to compare and contrast different pathways, according to their specific assumptions. A policy-driven scenario is analyzed with a goal-trajectory (e.g. the 2.5°C goal).

Collection of scenarios

Because each model and scenario considers different simplified assumptions and variables, one scenario cannot capture all of the interactions and processes driving changes. The models employed are complementary and help to provide a comprehensive assessment of category C5. The assumptions also vary from one scenario to another. As shown before, they can feed into a global integrated assessment. Furthermore, by working on the IIASA database and combining different scenarios, the results highlight that there are several ways to reach a common goal. Some excess in energy consumption can be compensated by other variables, for example an increased amount of direct air capture.

Figure 1 shows a clear example of the disparities between the scenarios regarding carbon sequestration (direct air capture). The disparities which featured our category C5, which involves multiple scenarios, barely consider or do not consider carbon sequestration (e.g. Coffee 1.1 and Remind 2.1) to reduce carbon emissions, whereas other scenarios such as Poles Engage EN_ NPi2020_2000 and Poles Engage EN_INDCi2030 rely significantly on direct air capture (respectively 6,017 Mt CO2/year and 5,624 Mt CO2/year).

Figure 1: Scenarios modelizations from IIASA database.



Juxtaposition of categories also referred to as scenarios. This juxtaposition helps us understand which scenarios are in line with the current policies (C7) set by governments and companies, but also to what extent the reduction of CO2 emissions differs between close scenarios , for instance between C1 and C3 (a 0.5-degree difference), with a 43% difference in terms of emissions to reach net-zero.

It also shows us that if we abide by the first 4 scenarios, which involve limiting global warming to +2 degrees, the emissions peak should be reached by 2025 and steadily decrease afterwards, as a result of a rapid change in policies. That still leaves us with 2 years to radically change our consumption habits, and successfully adapt to a sustainable economy, which is not the case at the moment. On a more positive note, scenarios C3 to C5 still offer a chance to limit global warming by a peak of 1.5 degrees, hence it helps relativize regarding the outcome of each scenario, and this comparison gives us a more accurate idea of their potential outcomes depending on our global emissions.

Analysis of the results

Firstly, by looking at the figures given in this report we can tell there exists a near linear relationship between an increase in global mean temperature and cumulative CO2 emissions, which are critical from a climate's outcome standpoint (Figure 3.11, Chapter 3, Working Group 3). It seems that the global mean temperature is expected to increase in a C5 scenario context, throughout the century, and will be even worse in 2100, for the C6 and C7 categories. While expecting a warming ranging from 2.2-3.8 °C, a warming above 5° C cannot be excluded (Figure 3.13, Chapter 3, Working Group 3).

Figure 3.13: The near-linear relationship between cumulative CO2 emissions and temperature. The left panel shows cumulative emissions until net zero emission is reached. Source IPCC Report WG III

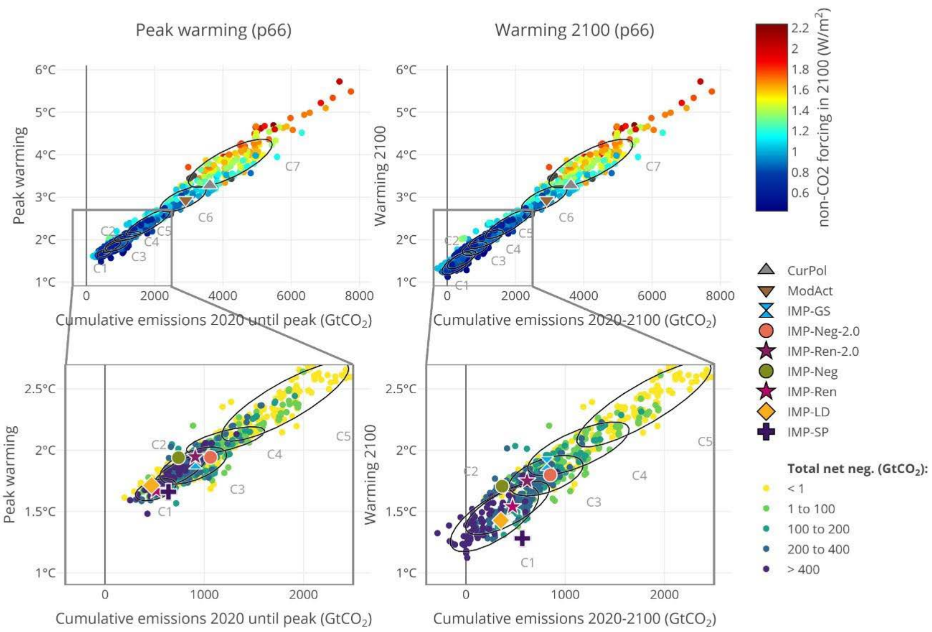
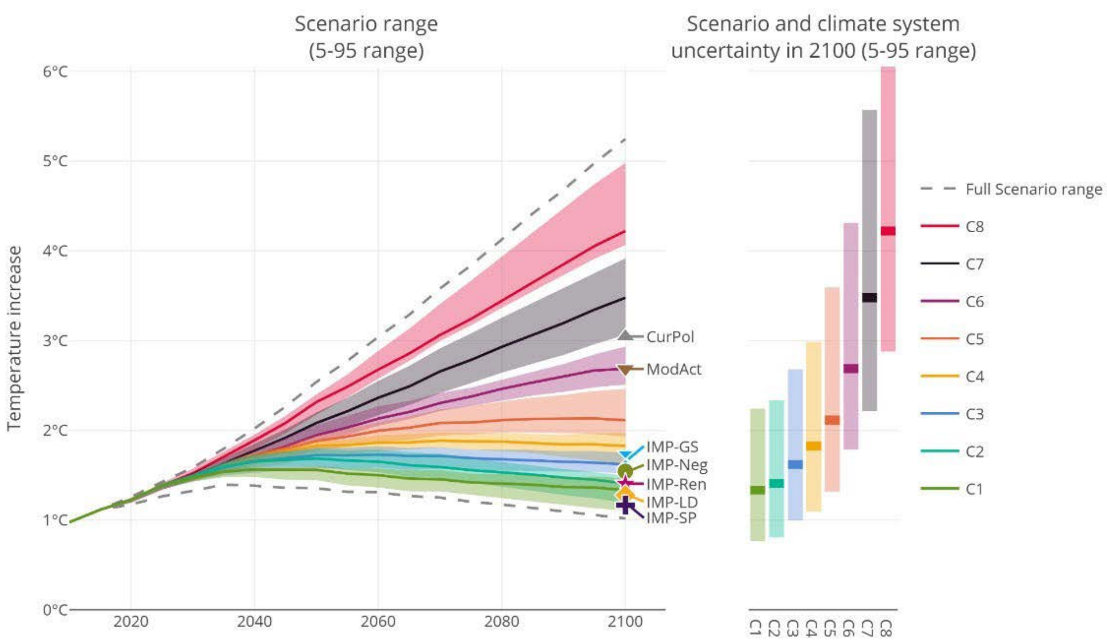


Figure 3.11: Global mean temperature outcome of the ensemble of scenarios included in the climate categories C1- C7 (based on RCM calibrated to the WGI assessment, both in terms of future and historic warming). The left panel shows the ranges of scenario. Source : IPCC Report WG III



CATEGORY C5

As for C5 and lower scenarios, there exists a negative contribution from both Agriculture, Forestry, and Other Land Use or (AFOLU) emissions and energy systems. Energy systems' negative emissions can be attributed to bioenergy, specifically bioenergy-and-carbon-capture-and- storage (BECCS). As for AFOLU, we can trace these negative emissions back to re- and afforestation initiatives. Again, for C3 and lower scenarios, cost-wise, reforestation initiatives have larger CDR contribution in comparison to BECCS. (Rochedo et al. 2018).

In Figures 3.36 & 3.37, it seems that there is an increased investment need in the energy sectors in lower temperature categories. This is accompanied by a major turnaround from fossil generation and extraction toward electricity including for system enhancements for electricity transmission, distribution and storage, and low-carbon technologies. For C5, C6 and C7, the investment needs would be USD 0.9-1.1 billion. Furthermore, there is also a need for investment flows to face climate change. In fact, a large amount of CO2 emissions can be saved based on innovation and the creation of new technologies. A great example is direct air carbon, but more will come which require capital. Thus, finance will play a huge role in fighting against climate change.

Figure 3.36: Global average yearly investments from 2023- 2052 for 9 electricity supply subcomponents. Source : IPCC Report WG III

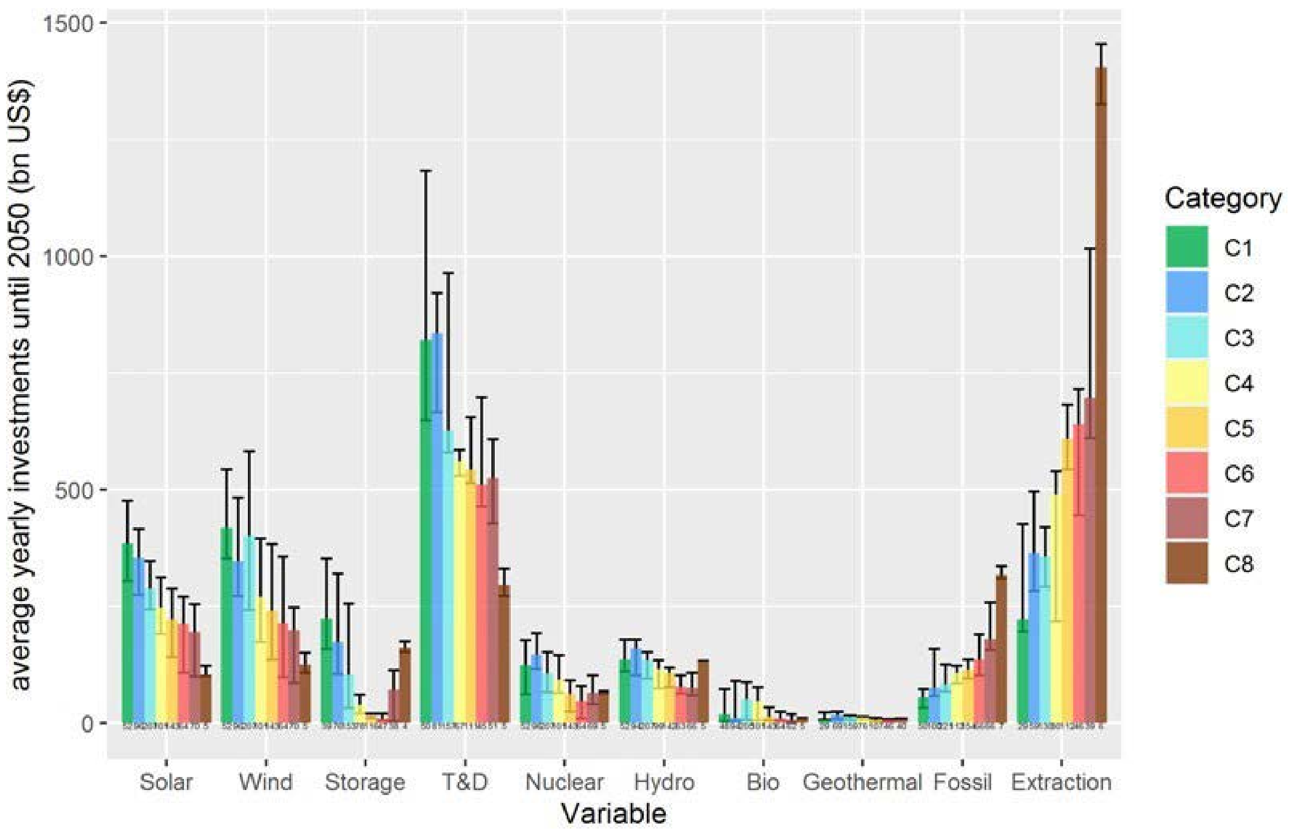
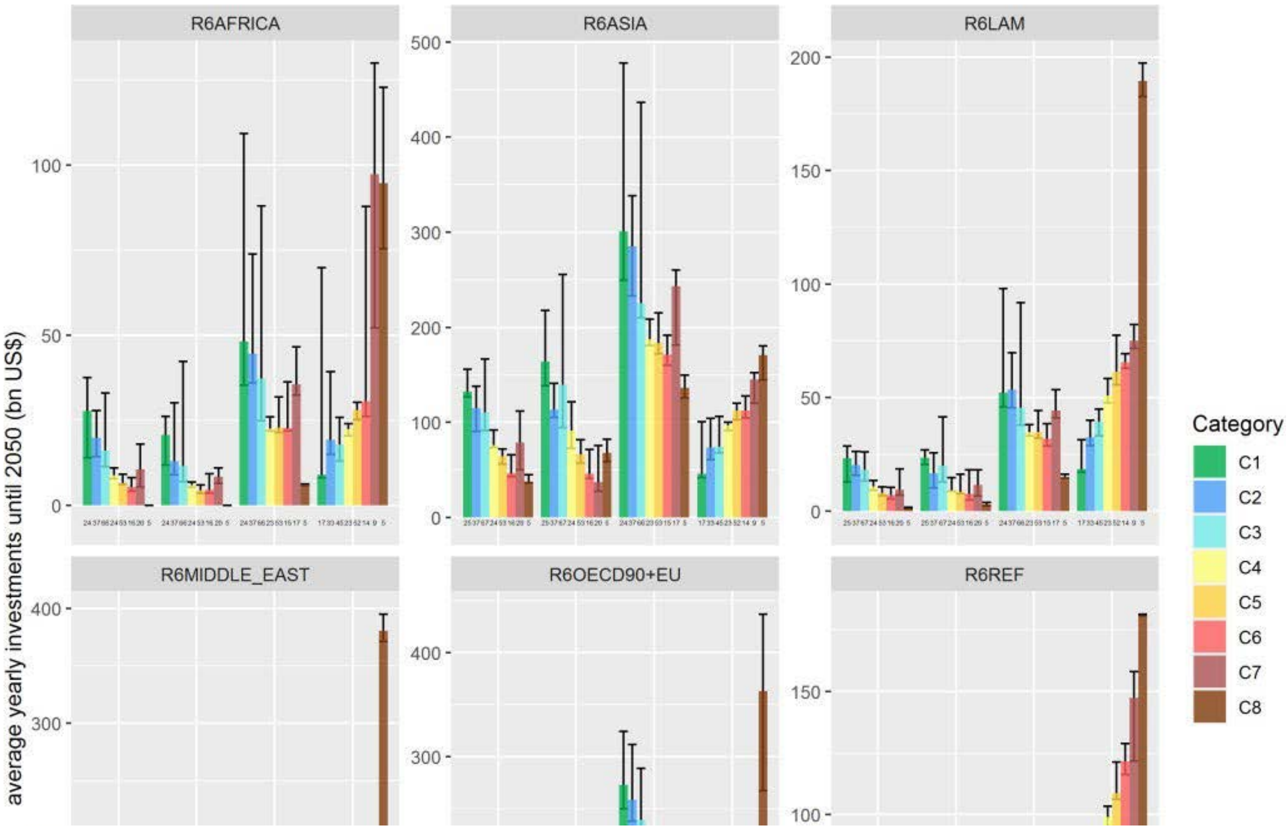


Figure 3.37: Average yearly investments from 2023-2052 for the four subcomponents of the energy system representing the larger amounts (in billion USD2015), by aggregate regions, in pathways by temperature categories. T&D: transmissions and distribution and distribution of electricity. Extr.: extraction of fossil. Source : IPCC Report WG III



Finally, we observe that CO_2 represents a constant amount of the total GHG emissions since 2010, what shows limited efforts and measures set in place by polluting countries.

Our scenario does not constitute a Shared Socioeconomic Pathways (SSPs), however, category C5 is likely to reflect a reference or baseline emission scenario, meaning that it assumes that current policies or pledged policies are implemented, but no further climate policy will be implemented.

CATEGORY C5

REFERENCES

- IPCC - Intergovernmental Panel on Climate Change. (n.d.). Retrieved October 23, 2022, from https://report.ipcc.ch/ar6wg3/pdf
- IPCC Authors (beta). (n.d.). Retrieved October 23, 2022, from https://apps.ipcc.ch/ report/authors/report.authors.php?q=37
- REMIND — Potsdam Institute for Climate Impact Research. (n.d.). Retrieved November 1, 2022, from https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind
- Riahi, K. [Pushpam K., & Schaeffer, R. (2022, April 4). Climate Change 2022: Mitigation of Climate Change: Chapter 3 : Mitigation pathways compatible with long-term goals. IPCC, Working Group III. https://www.ipcc.ch/report/ar6/wg3/
- Rochedo, P. R., Soares-Filho, B., Schaeffer, R., Viola, E., Szklo, A., Lucena, A. F., Koberle, A., Davis, J. L., Rajão, R., & Rathmann, R. (2018). The threat of political bargaining to climate mitigation in Brazil. Nature Climate Change, 8(8), 695–698. https://doi. org/10.1038/s41558-018-0213-y
- Scenario Explorer develop by IIASA (n.d.). Retrieved October 31, 2022, from https:// data.ece.iiasa.ac.at/ar6/#/docs team, T.W.I.T.C.H. (2019) Witch documentation, WITCH documentation. Retrieved October 31, 2022, from https://doc.witchmodel. org/index.html
- V. Krey, P. Havlik, P. N. Kishimoto, O. Fricko, J. Zilliacus, M. Gidden, M. Strubegger, G. Kartasasmita, T. Ermolieva, N. Forsell,
- M. Gusti, N. Johnson, J. Kikstra, G. Kindermann, P. Kolp, F. Lovat, D. L. McCollum, J. Min, S. Pachauri, Parkinson S. C., S. Rao, J. Rogelj, H. and Ünlü, G. Valin, P. Wagner,
- B. Zakeri, M. Obersteiner, and K. Riahi. MESSAGEix-GLOBIOM Documentation – 2020 release. Technical Report, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2020. URL: https://pure.iiasa.ac.at/id/eprint/17115, doi:10.22022/iacc/03-2021.17115.

IPCC scenario Category C6

Solène FENART, Emma DUCLOZ, Lucas ESPIRITO SANTO, Bastien BRUNHES & Adrien FRÈREJACQUE

Category 6 (C6) "Below 3.0°C (>50%)" of the IPCC sixth assessment is one of the higher emissions categories presented by WGIII. It includes scenarios that have >50% probability of reaching below 3.0°C warming by 2100. The illustrative pathway (IP) of C6 is the Moderate Action (ModAct) scenario.

C6 contains a total of 97 scenarios that, first, passed the vetting procedure of coherence with historical trends and, second, were assigned the "below 3.0°C" temperature classification using MAGICC7, a climate model emulator. The WGIII climate emulators are benchmarked using the temperature assessment of the five SSP scenarios of WGI, in order to ensure that this category classification reflects the climate assessment of WGI (SSPs).

For C6, the "below 3.0°C" pathway coincides with the SSP 2-4.5 scenario (Shared Socio-Economic Pathway). This scenario has a "middle of the road" approach (medium socio-economic challenges to mitigation and adaptation) and a nominal radiative forcing of 4.5 W/m^2 in 2100. The use of SSPs allows for a more systemic assessment of future GHG emissions and their uncertainties than was possible during the previous IPCC assessment (AR5). In the AR6 database, we can see that the majority of the C6 scenarios are consistent with SSP2.

The C6 scenarios come from 12 different models (see Table 1).

Table 1: Global Scenarios that passed the temperature classification for category 6 (organized by model)

Model Group	AIM/CGE +Hub	COFFEE	EPPA	GCAM-PR	GEM-E3	IMAGE	MESSAGE-GLOBIOM	POLES	REMIND	REMIND-MAgPIE	TIAM-ECN	WITCH	Total
C6	4	9	1	1	3	16	20	11	6	13	4	9	97

Source: IPCC AR6 Annex 3

CATEGORY C6

Among these 97 scenarios, one scenario (ModAct) has been specifically selected as an illustrative pathway (IP) to constitute a reference relative to the mitigation IPs of the lower emission categories. This scenario (selected from the model IMAGE3.0) is meant to illustrate the characteristics of the category C6, i.e. a pathway with higher emissions and some moderate action added to the current planned policies.

This ModAct scenario includes a mixed Covid recovery, the strengthening of policies to implement the 2030 Nationally Determined Contributions (NDCs) announced in 2020, and some further moderate action after 2030. For instance, in terms of energy, this mostly represents moving away from coal, the growth of renewables, and some lock-in fossil investments.

The 97 global scenarios comprised in C6 are based on 12 Model Groups. These models rely on several main sets of key assumptions: regional scope, sectoral coverage, benchmark setup, technology diffusion, capital vintaging, and discount rates. The models all implement a global scope and a full- system sector coverage (covering all GHGs from all sectors).

Table 2: Model groups for category 6, key assumptions (not exhaustive)

Model Group		AIM/CGE +Hub	COFFEE	EPPA	GCAM-PR	GEM-E3	IMAGE	MESSAGE-GLOBIOM	POLES	REMIND	REMIND-MAgPIE	TIAM-ECN	WITCH
C6		4	9	1	1	3	16	20	11	6	13	4	9
Baseline/Benchmark setup	Well-functionning markets in equilibrium	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Regulatory and/or pricing policies	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Socioeconomic costs & benefits of climate change impacts	No	No	No	No	No	No	No	No	Yes	Yes	No	No
	Physical impacts of climate change on key processes	Yes	No	No	No	No	No	No	No	Yes	No	No	No
Technology diffusion	Logit substitution	Yes	No	No	Yes	No	Yes	No	Yes	No	No	No	No
	Constant elasticity of substitution	No	No	No	No	No	No	No	No	No	No	No	Yes
	Lowest marginal cost without expanision constraints	No	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes
	Yechnology choice depends on agents' preferences	No	No	No	No	No	No	No	No	No	No	No	No
	Technologies without constraints or marginal cost without expansion constraints	No	No	No	No	No	No	No	No	No	No	No	No
Capital vintaging	Single Capital stock with fixed lifetime and load factor, early retirement via reduction in load	No	No	No	No	No	No	No	No	No	No	No	Yes
	Capital vintaging with fixed lifetime and load factors, early retirement of vintages or reduction	No	No	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	No
	Single Capital stock with fixed lifetime and load factor, without early retirement	No	No	No	No	No	No	No	Yes	No	No	No	No
	Mix of the above for different technologies	Yes	Yes	No	No	Yes	Yes	No	No	No	No	No	No
Discount rates	As a property of an intertemporal welfare function (social discount rate)	No	No	No	No	No	No	No	No	No	Yes	No	Yes
	In an objective function of an intertemporal optimization, to sum values at different times	No	Yes	No	No	Yes	Yes	Yes	No	Yes	No	Yes	No
	To compute lifecycle costs of investment decisions or returns on investments, in functions representing agents investment choices	No	No	Yes	Yes	Yes	Yes	No	Yes	No	No	No	No

In Table 2, we can see that the models employed in C6 make varying assumptions, with only two sub-section assumptions of technology diffusion remaining constant among all 12 models (the Technology choice depending on agents' preferences and Technologies without constraints, or marginal cost without expansion constraints).

Policy assumptions: The C6 scenarios have different policy assumptions. Just like for temperature, the scenarios have been classified in different policy categories. There are 32 scenarios in (P1): "No globally coordinated climate policy", 38 in (P2): "Globally coordinated climate policies with immediate (i.e. before 2030) action" and 26 scenarios in (P3): "Globally coordinated climate policies with delayed (after 2030) action". The ModAct scenario is in the (P3) category (source: IIASA database).

Socio-economic assumptions: Most socio-economic assumptions are based on population and economic activity. A wide range of these assumptions are covered in C6:

- Population is assumed to grow until the 2050s in all of the scenarios, then they diverge with some seeing a population increase and some a decrease. Population assumptions in 2100 range from under 7 billion at the lowest to 15 billion at the highest.
- Global GDP is assumed to grow throughout the century for all scenarios, the range in 2100 being from around $285 trillion at the lowest to around $633 trillion at the highest.

Technology assumptions: There are a wide range of technology assumptions among the scenarios. For example, carbon sequestration thanks to CCS technologies ranges from as low as 0 Mt CO_2/yr to 38 Gt CO_2/yr in 2100. Differences are also notable in investments, R&D, nuclear, renewables, etc. According to the IIASA database, 35 scenarios have standard technology assumptions (T0) while 62 have non-standard technology assumptions (T1).

Behind this production of scenarios

Most of the producers of the scenarios are research teams, including researchers from the MIT Joint Program on the science and policy of global change (two complementary MIT research centers, the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR)), the Potsdam Institute for Climate Research Impact (which advises the German government but is also a member of the European Scientific Advisory Board on Climate Change and the Mission Board on Adaptation to Climate Change), the European Institute on Economics and the Environment (EIEE), and The Netherlands Environmental Assessment Agency (PBL), which is part of the Ministry of Infrastructure and Water Management of the Dutch Government. The main role of these institutions is to inform and advise as neutrally as possible, and to provide explanations without political or social bias.

Of course, the construction of these scenarios respects the situation of each country, but the neutrality of the research teams is questionable, since they often advise their respective governments on national policy, especially regarding the energy transition. For example, the Potsdam Institute for Climate Research Impact has a major role in Germany's law on energy transformation and legislation to phase out coal-fired power.

Juxtaposition of scenarios

The scenarios in C6 were categorized using the MAGICC (v7) emulator that is calibrated against the behavior of complex climate models and runs observation data thousands of times. The MAGICC7 emulator is one of the most complex and comprehensive models: it includes representations of 43 greenhouse gas cycles, including aerosols, distinguishes between different hemispheres and land/ocean regions of the globe, has 50 ocean layers in each hemisphere, and runs on a monthly time step internally. MAGICC7 was preferred to the climate emulators FaIR and CICERO-SCM as it leads to higher temperature estimations - thus a lower and more restrictive probability for scenarios under a certain level of temperature.

Figure 1: Mt CO2 equivalent emissions per year for the 97 C6 scenarios.

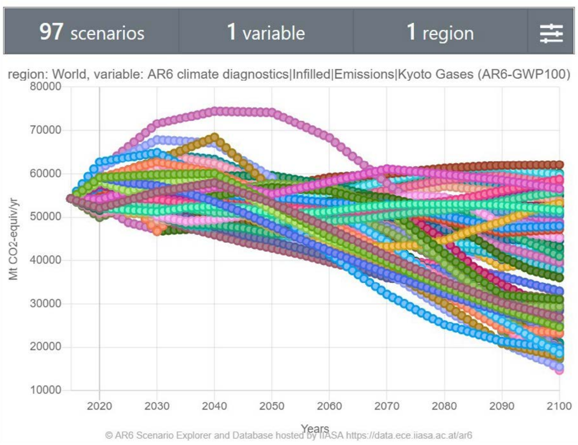
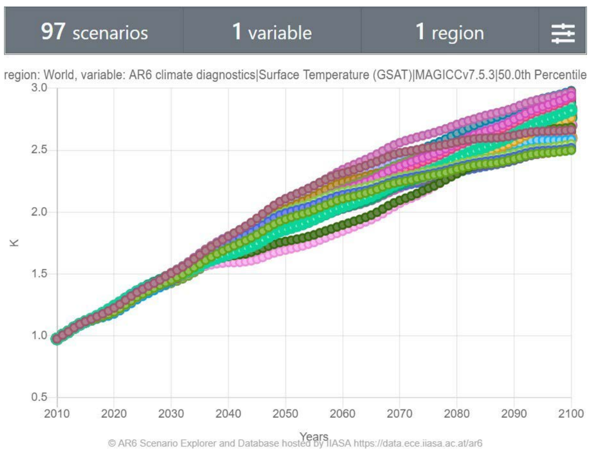


Figure 2: Surface temperature (GSAT) estimates (in K, 50th percentile).



Source: AR6 Scenario Explorer Database

The classification was also verified against the WGI temperature assessment of the five SSP scenarios, reinforcing the solidity of the classification of the scenarios.

Even though grouping relatively different scenarios may be a little confusing at first, it helps understand different pathways to a +3°C world, comparing and contrasting the effects of different metrics, policies and feedback effects. Each scenario is more or less probable, invoking different structural changes and variables (population, GDP, policy, etc.).

As we can observe in Figures 1 and 2, the 97 scenarios represent a wide range of outcomes corresponding to the category leading to a temperature increase below 3.0°C by 2100, both in terms of temperature increase and annual GHG emissions.

Nonetheless, although the process of harmonizing the scenarios using historical datasets can make it easier to compare the scenarios, it can also hinder their diversity.

What can we learn from the figures, knowing what is behind the trajectories

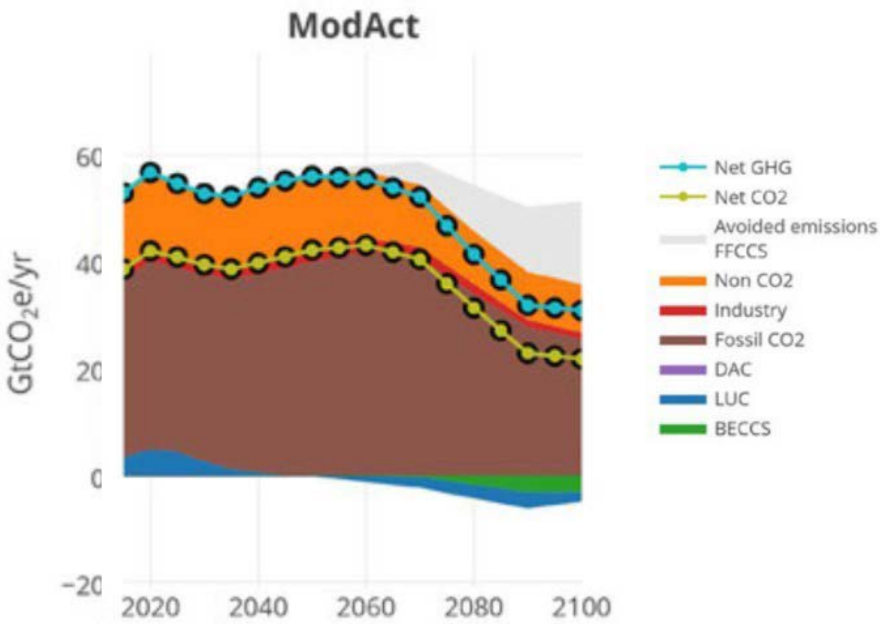
The ModAct (IP of C6) pathway shows a trajectory that would lead us to a rise in surface temperature of 2.69°C (50th percentile). In terms of emissions (see Figure 3), we see a strong decrease in CO2 emissions from land-use change (LUC) starting from 2030, mainly due to reduced deforestation, as well as moderately decreasing N2O and CH4 emissions from agricultural production due to improved agricultural management and dietary shifts away from emissions-intensive livestock products. However, in contrast to LUC CO2 emissions, which become net-negative around 2050 due to afforestation/ reforestation, CH4 and N2O emissions persist throughout the century due to difficulties of eliminating these residual emissions based on existing agricultural management methods.

Net GHG emissions do not start decreasing until the 2070s, with the deployment of carbon capture and storage technology. We can see that the effects of the moderate policies put in place in the 2030s and before do not materialize until the end of the century.

The primary energy system (see Figure 4) is seen to increase from around 587 EJ/yr in 2020 to around 833 EJ/yr in 2100 as a consequence of the rise of GDP and population. Fossil energy peaks in the 2070s and decreases slightly afterwards. From then on, the increase in primary energy is driven by renewables and biomass.

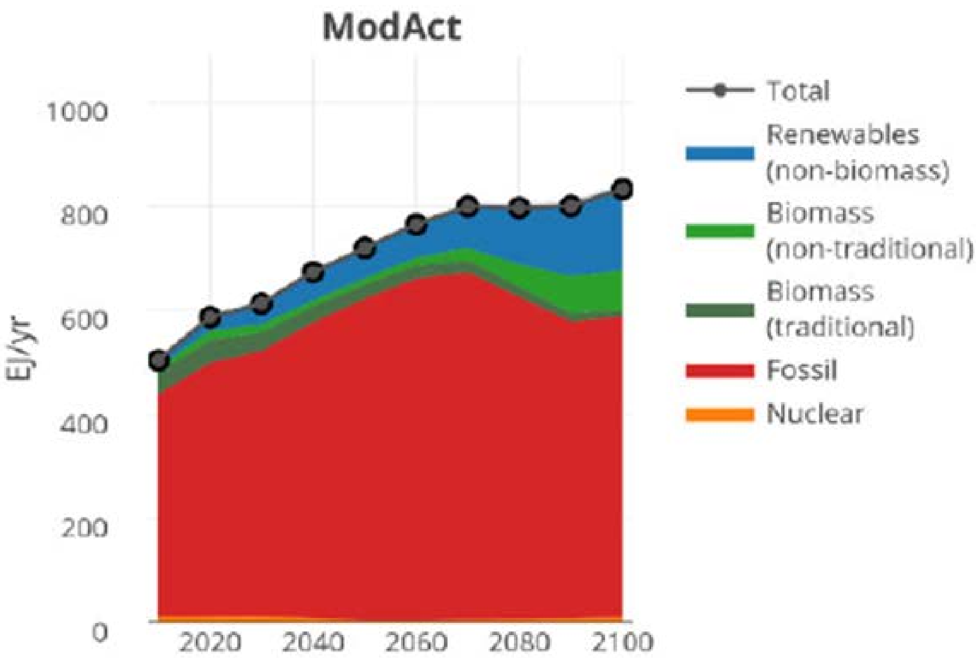
Overall, a study of the trajectories in the C6 category seems quite relevant as the latest United Nations report points out that current policies are leading us to a +2.8°C rise in global mean temperature in 2100 and that the implementation of current pledges would only have a 0.2-0.4°C impact. As such, the trajectory we are following today very closely coincides with the ModAct scenario in terms of policy assumptions and temperature rise.

Figure 3: Emissions in the ModAct scenario



Source: IPCC AR6 Chap3

Figure 4: Primary Energy system



Source: IPCC AR6 Chap3

NOTE D'ÉCLAIRAGE #5

REFERENCES

- IPCC AR6 WGIII: Mitigation of Climate Change 2022 - Chapter 3 https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter_03.pdf, consulted on the 20/10/2022
- IPCC AR6 WGIII: Mitigation of Climate Change 2022 - Annex III https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_Annex-III.pdf, consulted on the 18/10/2022
- IIASA: AR6 Scenario Explorer Database, 2022, https://data.ece.iiasa.ac.at/ar6/#/login?redirect=%2Fworkspaces, consulted on the 19/10/2022
- UN Emissions Gap report, 2022, https://www.unep.org/resources/ emissions-gap-report-2022, consulted on the 17/10/2022

IPCC scenario Category C7

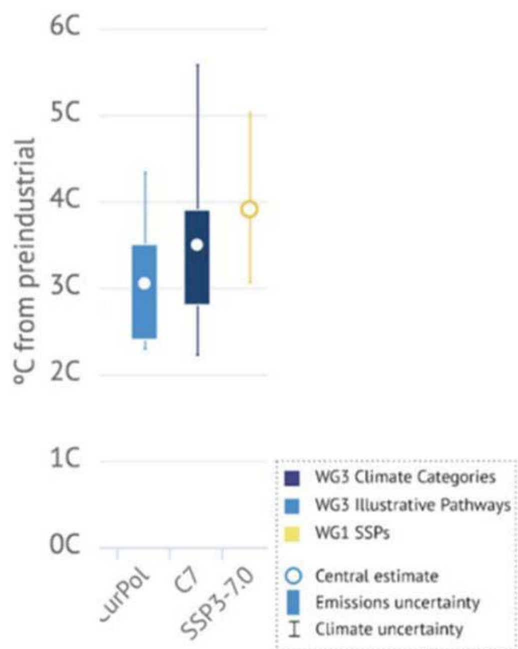
Alexanne HEURTIER, Neeti SHAH, Ekaterina SOKOLOVA & Theodora STEFANIDI

According to the IPCC, "without a strengthening of policies beyond those that are implemented by the end of 2020", meaning keeping the current track, "GHG emissions are projected to rise beyond 2025, leading to a median global warming of 3.2 [2.2 to 3.5] °C by 2100"[1].

This projection is consistent with several scenarios gathered by the IPCC under Category 7 in Chapter 3 of the Working Group III report[2]: limiting global warming to 4°C by 2100. The C7 is considered as "in line with the implemented policies as of 2020". It encompasses 167 IAM-based scenarios that were run using a climate emulator – also calibrated by Working Group I (WGI) – to determine possible temperature projections.

Scenarios are quantitative projections and are not predictions or forecasts: they are descriptions of alternative future developments and conditioned on assumptions

In what follows, we present Category 7, before exploring the SSP3-7.0, and the socio-economic assumptions developed by WGI in Chapter 4 and used for the calibration of Category 7. The scenarios resulting in this C7, provided by universities, research institutes and the Integrated Assessment Modeling Consortium (IAMC) among others, are



Source: Carbon Brief. Data from AR6 Database.

1. IPCC Summary for Policymakers (2022).
2. Chapter 3 was mandated by 16 leading authors from various backgrounds and regions across the world.

NOTE D'ÉCLAIRAGE #5

considered as reference scenarios: possible trajectories in the absence of new stringent climate policies. Alongside Category 7, below we describe and analyze the associated Illustrative Pathway, called the Cur-Pol, originally presented by the Network for Greening Financial System (NGFS 2021), and which provides an overview of a possible trajectory. Finally, we explain the implication of this reference category.

What is the C7?

The IPCC has provided a wide range of data regarding the C7: in this section, we present the median value for relevant characteristics:

Annual Emissions	As of 2019, the modeled GHG emissions were 55 GtCO2eq; the projected annual emissions could reach 62 GtCO2eq in 2030 (+12.7%), 67 GtCO2eq in 2040 (+21.8%), and 70 GtCO2eq in 2050 (+27.2%). These data imply that GHG emissions reduction is not considered in this category: emissions will keep increasing until they reach around 4,220 cumulative GtCO2eq in 2100 (calculated from the start of 2020).
Peak emission	The peak is projected for 2090-2095, with a probability of 56%. Emissions will plateau from the end of the century after growing over the coming few decades.
Transition	C7 implies no net-zero transition before the end of the century and no temperature peak, reaching 3.5°C in 2100 with only a 22% likelihood of remaining below 3°C. This means that warming will continue after the end of the 21st century.
Temperature range uncertainty	The range [2.2°; 3.5°] is one of the widest due to the difficult modeling of temperature regarding the implemented policies and 2030 pledges as reported in the Nationally Determined Contributions (NDCs). Uncertainty is also due to the high variability and uncertain development of sectors such as Land Use and Land Use Change and Forestry (LULUCF).
Other findings	The report also cites other studies on current policies with different outcomes: Sognnaes et al. (2021) finds that current policies would see warming reach a median level of between 2.2°C and 2.9°C; Höhne et al. (2021) finds a range of 2.2°C to 3.2°C based on the 2020 UNEP Emissions Gap Report, which has reevaluated its projection at a range of 2.1°C to 3°C.

Modeling pathways from a socio-economic narrative to temperature projection

The temperature projections produced by the IPCC are based on socioeconomic assumptions. But what are the steps involved in determining these projections?

The SSP 3-7.0 Narrative: a rocky road

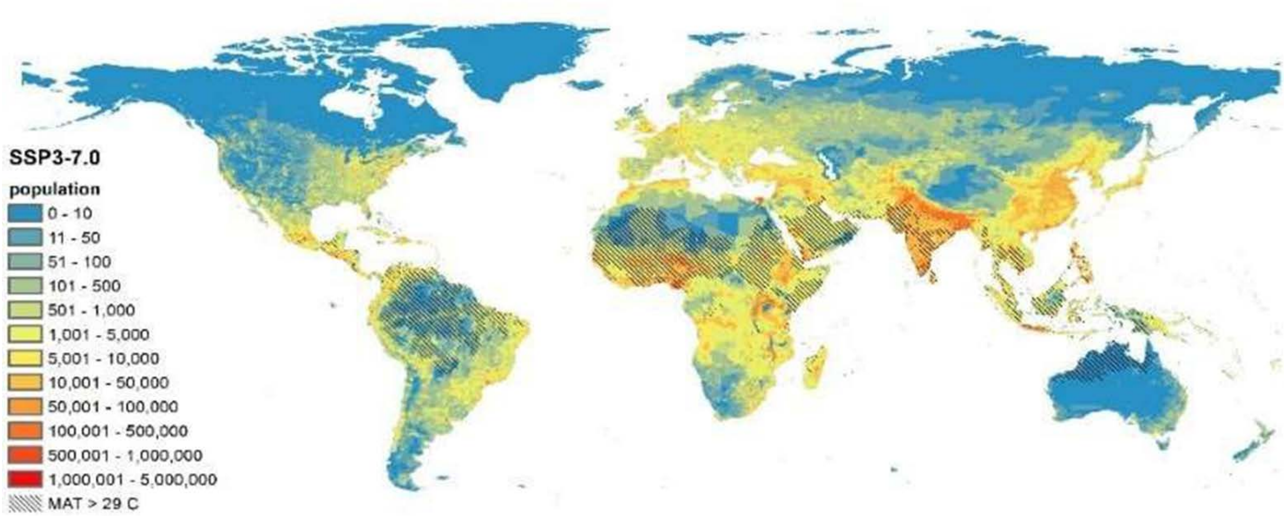
Shared Socioeconomic Pathways (SSPs) were developed by O'Neill et al. 2020b and presented by the WGI in the report published in August 2021: SSPs are "building blocks" that need to be combined with Integrated Assessment Modeling models (IAM) to construct scenarios or pathways.

These pathways include adaptation and mitigation challenges and take into account technologies, economic development, population, and institutions present within societies. SSPs are then combined with Representative Concentration Pathways (RCPs) representing radiative forcing pathways: each SSP can be combined with different levels of radiative forcing (from 1.9 to 8.5). The WGI decided to present the 5 most relevant SSP-RCP combinations.

The SSP3-7.0 combination is the most relevant to C7 and assumes a lack of cooperative action in the world. It corresponds to the scenario of regional rivalries. Assumptions as stated by O'Neill et al. 2020b are:

SSP Elements	SSP3 Assumptions
Population Growth	Low in OECD and high in other countries
Economic Growth	Slow
International Trade and Globalization	Strongly constrained, regional security and deglobalization
Consumption and Diet	Material-intensive consumption
International Cooperation	Weak, uneven
Environmental Policy	Low priority for environmental issues
Policy Orientation Institutions	Weak global institutions and national government dominate societal deci- sions
Technology Development	Slow
Environment	Serious degradation

Overlap between future population distribution and extreme heat in the SSP3-7.0



Source: Kemp et al. (2022)

The SSP3-7.0 does not make quantitative assumptions: in order to calculate output, this specific narrative has been associated with the AIM IAM model.

Which IAM models were used for the C7scenarios?

IAM model groups such as IMAGE, MESSAGE-GLOBIOM, REMIND and many others, were used to develop 167 vetted scenarios describing future trajectories for greenhouse gas emissions based on a wide set of assumptions regarding socio-economic development, technological changes, political development, and climate policy: these assumptions come from SSP-RCP narratives identified by the IPCC. They may be incomplete and lag some assumptions, but overall IAMs are "simplified, stylized numerical approaches to represent enormously

THE AIM MODEL

Cost-benefit IAMs based on aggregated costs such as the DICE model have long been used to quantify the "cost of carbon".

Complex IAMs (process- based on physical systems) use long- term historical data to provide trends regarding energy and land use, technology, or societal changes and show how future development and choices may affect the environment.

The AIM Model (Fujimori et al. 2014, 2017) is a process- based model that considers GHG emissions from every sector. Some of the characteristics are: logical substitution of technologies, complex physical and social systems"[3] focusing on the interaction between the economy, society, and the environment.

IAMs do not calculate temperatures, but help us to understand the feedbacks and tradeoffs amongst the economic and societal choices and the correlations between GHG emissions and these assumptions. Experts thus calibrate climate emulators depending on this framework and trends to provide climate projections.

regulatory and/or pricing policies or well-functioning markets at equilibrium. Supply and demand are mostly endogenous. Carbon capture usage is not considered nor is most carbon removal, except reforestation and BECCS (Bioenergy with Carbon Capture and Storage).

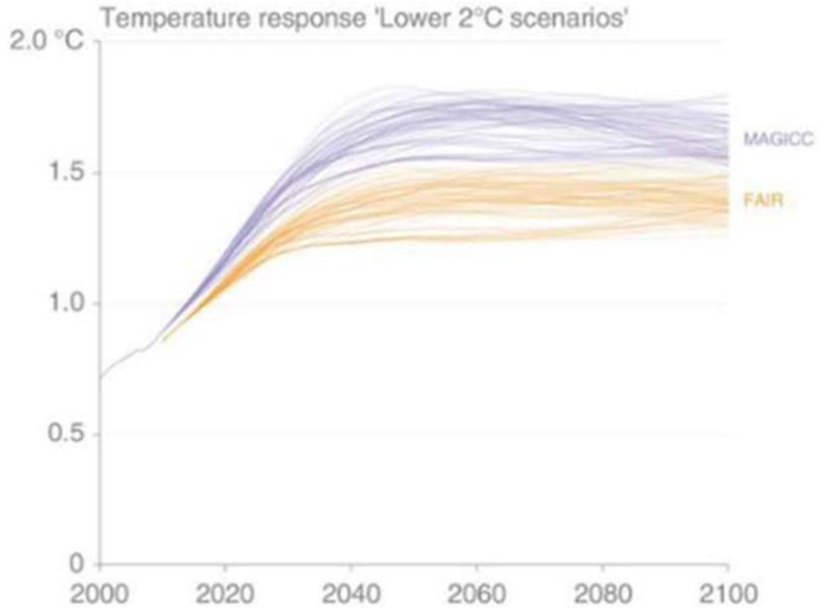
The climate emulator: from assumptions to projections

Climate emulators provide global average temperature changes and their key characteristics such as temperature and emissions peak year, GHG and aerosols concentrations, estimation of CO2 and non-CO2 contributions to temperature increase. The climate emulator used by the IPCC is MAGICC version 7 (Model for the Assessment of Greenhouse Gas Induced Climate Change, first developed by Meinshausen et al., 2009 from the University of Melbourne). It is a global emulator based on probabilistic distribution. MAGICC was selected by WGI and WGIII as it produces slightly warmer temperature predictions than the other two climate emulators considered. FaIR, CICERO- SCM and OSCAR were also used to provide additional uncertainty ranges on reported statistics to capture climate model uncertainty. WGIII has calibrated the emulator to closely match the global warming response to emissions as assessed in AR6 WGI.

The temperature projections from the emulator are used to classify those emissions scenarios in the AR6 database that passed the initial vetting and allowed a robust climate assessment. Let's take a close look at a specific C7 trajectory: the CurPol illustrative pathway.

3. IPPC, WG3, AR5, Chapter 6: Assessing Transformation Pathways

Comparison of MAGICC and FAIR using models from the IPCC Special Report 1.5°C

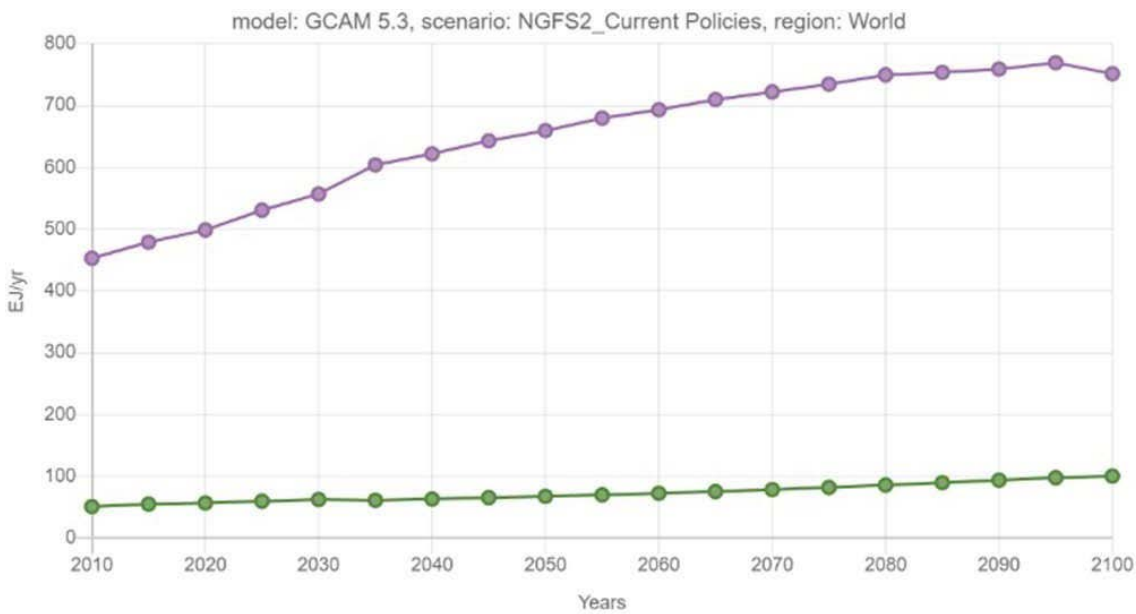


Source: Twitter - Glen Peters

CurPol scenario

Cur-Pol is an illustrative pathway of high emissions scenarios that was developed by the NGFS and selected as a reference pathway by the WG III as a comparison to the Illustrative Mitigation Pathways. The IAM model used is GCAM 5.3 and is listed as a NGFS2_Current Policies scenario in the IIASA Database. Other models such as REMIND and MESSAGE were used as output to run the NiGEM model for economic variables developed by the National Institute for Economic and Social Research (NIESR).

Primary energy under CurPol – Fossils (violet) vs Re- newables (green)

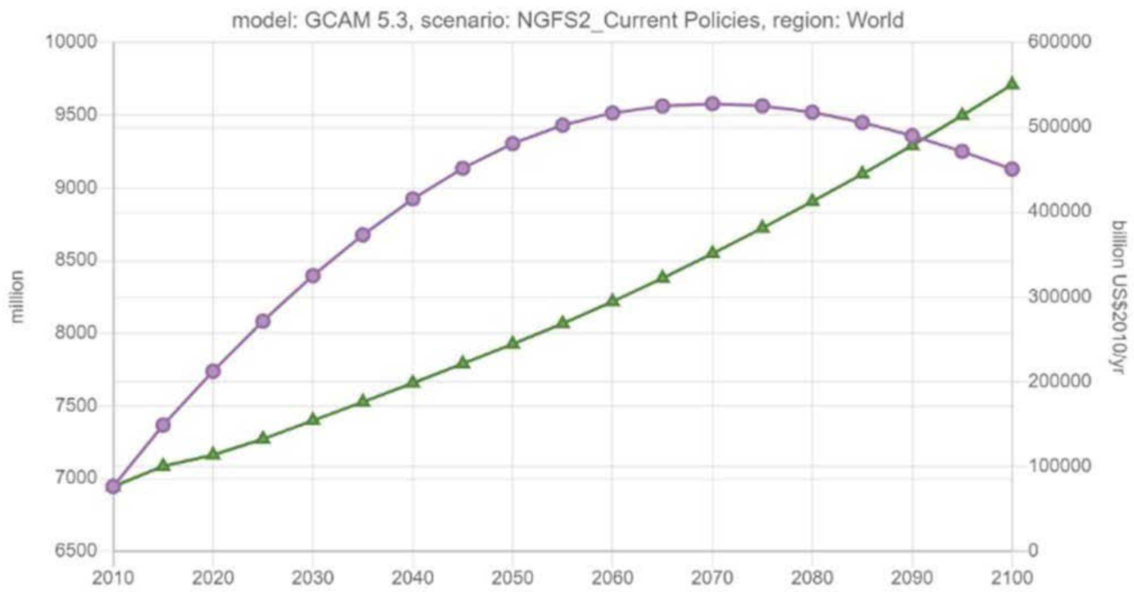


Source: AR6 Database (IIASA)

CATEGORY C7

The graph shows continued growth in the global population in line with the SSP3-7.0 assumptions mainly due to higher population growth in developing countries. Global emissions peak in 2090-2095, occurring later than the expected peak in population growth (2065-2070): this may be due to the primary use of fossil fuels in developing economies. The SSP3-7.0 assumes regional rivalries and political instability that translates into low per capita GDP growth with considerable divergence between OECD and developing economies. In line with this, the graph depicts a slow-down in global GDP growth rate (17% growth between 2025 to 2030, 10.4% growth between 2045 to 2050 and 7% growth between 2095 and 2100).

Population growth (violet) and GDP growth (green).



Source: AR6 Database (IIASA)

The graph shows the trajectories for use of primary energy sources: fossil fuels vs renewables (incl. bio- mass). There is a rapid increase in the use of fossil fuels under the CurPol pathway, while the share of renew- ables remains low in the primary energy mix. This is consistent with the SSP3-7.0 assumptions of lack of strong environmental action and coordina- tion amongst developed and developing regions.

This scenario lays in the “hot house world” quadrant meaning that “some climate policies are implemented in some jurisdictions, but globally efforts are insufficient to halt significant global warming”[4]. On the one hand, it leads to low transition

4. NGFS Climate Scenarios for central banks and supervisor, Networking for Greening the Financial Sys- tem (2021).

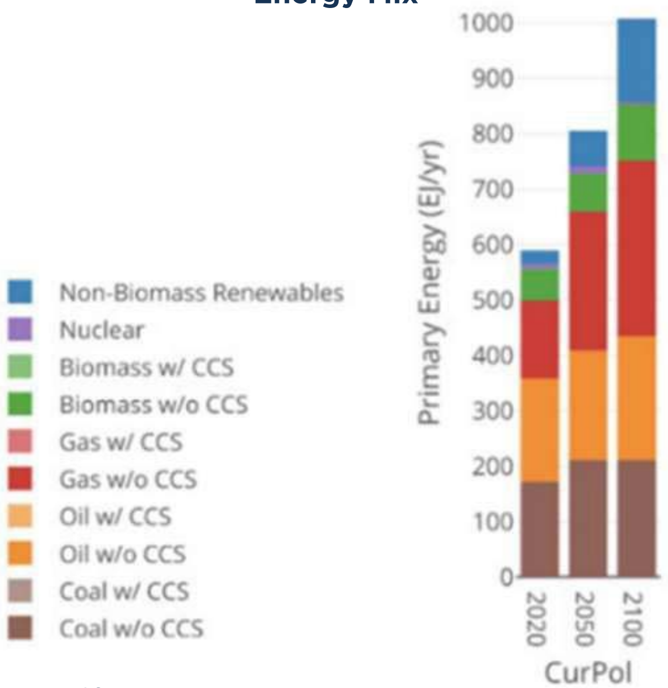
risks for the period 2020-2050. However, these scenarios are associated with severe physical risks, including irreversible chronic risks such as rising sea levels and biodiversity loss, and lead to a +3° trajectory with slow, moderate change in policies and use of technologies. The physical risk is assessed as moderate for 2020-2050 and very high for 2050-2100. Nevertheless, it is important to note that due to the differences between regions assumed in CurPol scenarios, the overall moderate risk assessment implies that damages may be negligible in some regions and hardly reversible in others. The scope of physical risk is not limited by the level achieved by 2100: these scenarios assume no stabilization of temperatures, meaning that global warming continues after 2100 with further growth of chronic and acute physical risks.

The implications of C7

Category 7 provides not only temperature projections but also a wide range of information on the evolution of sectors, especially their emissions contributions. The purpose of presenting such scenarios is to explore the consequences of climate change and act as a reference for mitigation scenarios.

The energy sector is at the core of the transition as it drives economies and societies while representing the first source of emissions. The low-carbon energy percentage, including renewables and fossil fuels with CCS and nuclear energy, is projected to represent 20% in 2030 and only 25% in 2050. Final energy demand will keep increasing: +17.4% in 2030 and +43% in 2050 compared to 2020.

Energy Mix

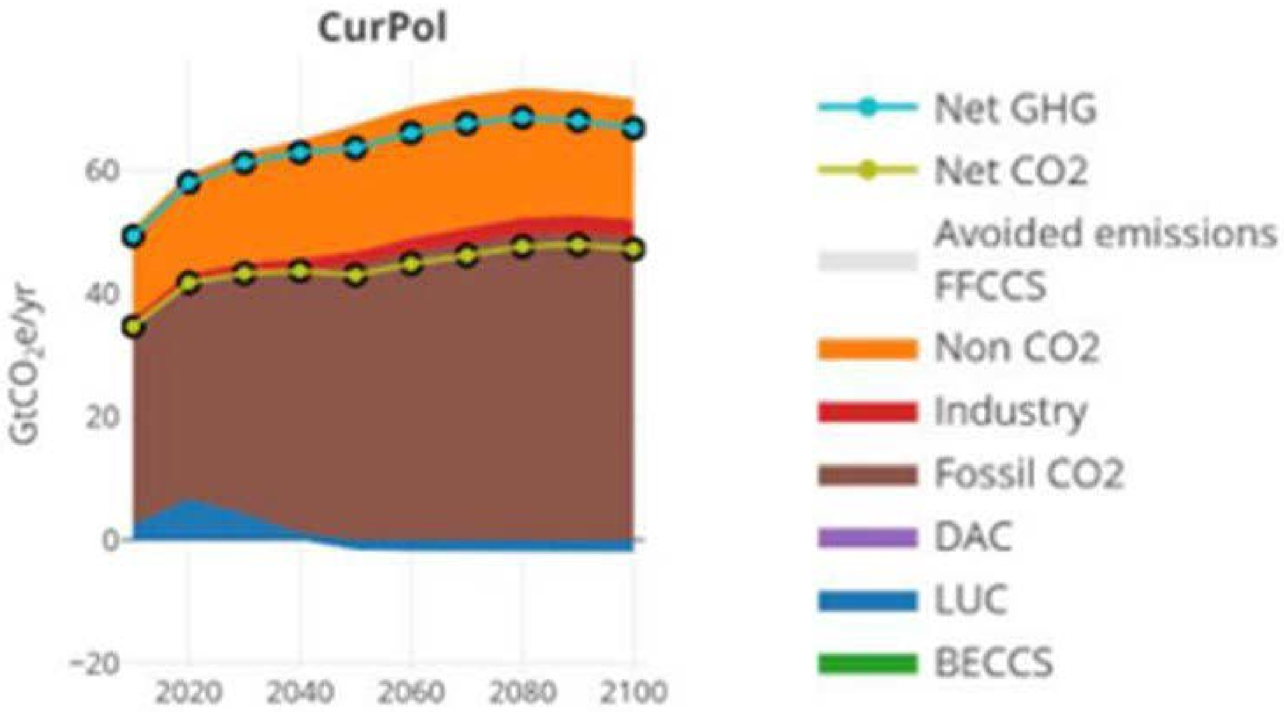


Source: IPCC (2022) Figure 3.16.

CATEGORY C7

Global average yearly investment from 2023-2052 will go up for fossil fuel extraction, and transmission and distribution (T&D) systems will represent the main investment in energy infrastructure at the expense of renewable and nuclear energy. Globally, the investment in electricity is projected to be between 0.9 to 1.1 billion USD in the 2023-2050 period: these figures are not at all in line with the IPCC conclusion, which implies that investment needs exceed current flows by 3-6 times across sectors and regions.

GHG emissions



Source: IPCC (2022) Figure 3.17.

Similarly, urban areas will face several transformations: urban mitigation is challenged by fossil fuel consumption associated with car-based and low-density urban growth. Progress in low- carbon urban development takes place at a relatively slower pace and there is limited policy learning within climate networks: in 2100, Buildings of around +29% compared to 2019.

Higher travel service demand per capita and increased freight activities drive the growth in emissions. Global transport emissions could grow up to [2 – 47]% by 2030 and [-6 – 130]% by 2050. Significant increases in emissions mainly come from Asia and the developing Pacific, the Middle East and Africa, whereas developed countries have lower transport emissions than the estimated 2020 level.

How plausible are high emissions scenarios and how are they references for action?

Category 7 and the reference pathways associated with it are projections of the path the world is currently taking considering the policies implemented: as these policies tend to be strengthened and improved, C7 scenarios, and more generally, high-emissions scenarios, are less likely to occur. However, the data and analysis clearly show that current policies are not enough to achieve the targets set in the Paris Agreement, and these scenarios provide significant tools for decision-makers choosing mitigation actions. The latest UN Climate Change Report in October 2022 showed that current policies and pledges put the world on track for a temperature rise of around 2.5°C, but that efforts remain insufficient for the 1.5°C trajectory.

The coming years are critical to redirect policies and take stronger measures as this kind of temperature increase constitutes considerable risks for humankind and the Earth's ecosystems.

REFERENCES:

- Summary for Policymaker: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf
- IPCC report 2022, Working Group 3: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Full_Report.pdf
- IPCC Annex III: Scenarios and Modelling Models https://report.ipcc.ch/ar6wg3/ pdf/IPCC_AR6_WGIII_Annex-III.pdf
- AR6 Scenario Explorer and Database hosted by IIASA https://data.ece.iiasa.ac.at/ar6/#/login?redirect=%2Fworkspaces
- Carbon Brief on AR6. Retrieved 12 October, 2022, from: https://www.carbonbrief.org/analysis-what-the-new-ipcc-report-says-about- how-to-limit- warming-to-1-5c-or-2c/
- Carbon Brief Q&A. Retrieved 12 October, 2022, from: https://www.carbonbrief.org/in-depth-qa-the-ipccs-sixth-assessment-on-how- to-tackle-climate- change/
- Carbon Brief (interview). Retrieved 15 October, 2022, from: https://www.carbonbrief.org/scientists-react-what-are-the-key-new-insights- from-the-ipccs- wg3-report/
- Carbon Brief on the emulators. Retrieved 17 October, 2022, from: https://www.carbonbrief.org/guest-post-the-role-emulator-models-play-in-climate-change- projections/
- EU Constrain (link between WGI and WGIII on emulators). Retrieved 12 October, 2022, from: https://constrain-eu. org/wp-content/uploads/2021/10/The_Role_of_Climate_Model_Emulators_in_IPCC_ AR6_D4.3.pdf
- UN Climate Change, October 2022 Report. Retrieved 28 October, 2022, from: https://unfccc.int/news/climate-plans-remain-insufficient-more-ambitious-action-needed-now

IPCC scenario Category C8

Anne-Océane BOUJU, Mayeul D'ANSELME, Coralie JAILLOT, Emma MICHEL & Marianne TOCANNE

The IPCC gathered more than two thousand prospective scenarios projecting possible futures and developments of climate change and greenhouse gases (GHG) emissions. They have been split into eight categories based on the temperature increase that each scenario projected by the end of this century (at horizon 2100). The eighth category (C8) reflects the consequences of the absence of emission reduction policies and an intensive use of fossil fuels to support the development of emerging countries. It comprises twenty-nine modelled scenarios that lead to a temperature increase above 4°C during the 21st century (with a likelihood of at least 50%) and which then continues to rise. The C8 trajectory, which is often compared to the seven other IPCC categories (C1-C7), can be interpreted as the projected global mean warming of all the modelled scenarios included in category C8. None of the scenarios associated with C8 integrate mitigation policies.

The 29 scenarios which make up category 8 are based on 6 types of model: the C-Roads, IMAGE, WITCH and MAgPIE models follow a pure top- down approach, while the REMIND and GCAM models follow a hybrid top-down/ bottom-up approach. All of the models explicitly target policymakers and aim at improving their understanding of climate change and the implication of the policies they implement; however, no rhetoric is explicitly promoted by the authors.

A close look at the models: Rhetoric & Assumptions

- The **GCAM** (Global Change Assessment Model) team that developed this model was composed of the University of Alberta, the Joint Global Change Research Institute, and researchers from the Canadian environment government agency. This model pictures interactions among five systems: energy, water, agriculture and land use, economy, and climate. The basic operating principle and key assumption of this model is market equilibrium. GCAM adjusts prices so that, in each market, the supply (from rice to solar power) matches demand. It considers conditional forecasts for the future and has an ever-growing scope (e.g., it incorporates new data, regulations, etc.). User outputs for this model are (i) prices and production quantities, (ii) the land use mix, (iii) water demand (by sector and to respond to scarcity), (iv) greenhouse gases and (iv) the economic cost of policies.

- The **C-ROADS** (Climate-Rapid Overview and Decision Support) model was developed by Ventana Systems (private company), Climate Interactive (non-profit) and the MIT. The model is calibrated with RCP (Representative Concentration Pathway) data from the IPCC, and sub-parts of the model are extracted from the FREE and DICE models. In addition, the model does not address the feedback effects between Climate and GDP, which undermines the effects of overall economic health on the climate and its role in the potential development of new technologies and infrastructure, which could mitigate climate change by the end of the century. User inputs for this model are GHG emissions and LULUCF1 and its outputs are carbon cycle, climate and forest state, and sea levels.
- **REMIND** (REgional Model of Investment and Development) was created by Potsdam University and aims at finding an intertemporal pareto optimal mix of investments in the economy and energy sectors for each modelled region, given a set of population, technology, policy, and climate constraints. The model uses population and GDP inputs from the Shared Socio-economic Pathway (SSP) scenarios. It also includes the MAGICC climate system and the MAgPIE land use system within its computations. As a potential limitation, renewable energy sources and secondary energy carriers[1] are non- tradable across regions, thus reducing the possibilities of building a globalized, interconnected system of renewable energies. The outputs of the model are water demand, air pollution and health impacts, among other environmental impacts.
- **MagPie** (Model of Agricultural Production and its Impact on the Environment) is a model built by Potsdam University used to assess the competition for land and water under future scenarios of rising food, energy and materials demand, climate change, and ambitious mitigation policies. Its objective it to minimize the global costs of production for a given amount of demand. Future trends

1. Land Use, Land Used Change and Forestry

in food demand are derived from scenarios on GDP and population growth. The variable inputs used are labor, chemicals, and other capital. Regions are initially characterized using 1995 data with full elasticity between cropland and rangeland. If additional land is required to fulfill demand, this can be taken from the pool of non-agricultural land at additional costs. The outputs given by the model are deforestation rate, water scarcity, and cropping patterns, all displayed across regions.

- **WITCH** (World Induced Technical Change Hybrid) and WITCH/ Globium (Global Biosphere Management Model) were developed by two Italian research foundations. They are global dynamic models integrating interactions between the economy, technological options, and climate change. WITCH represents the world as a set of regions; for each it generates optimal mitigation and adaptation strategies for the long term (from 2005 to 2100) as a response to climate damage. An open-loop Nash equilibrium is obtained through an iterative algorithm under a non-cooperative, simultaneous, and open membership game with full information to assess the climate policies with all degrees of cooperation. The model also uses DICE equations and SSP scenarios in its computation. The MAGICC climate model is used as a complement to compute the future climate. Economic outputs are impacted through a damage function, depending on the rate of investments in adaptation.
- The **IMAGE** (Integrated Model to Assess the Global Environment) model was created by PBL, a research institute that is part of a Dutch governmental organization, to analyze large-scale and long-term interactions between human development and the natural environment (energy, land, water and other natural resources, subject to resource availability and quality) in order to gain better insight into the processes of global environmental change. It aims at analyzing policy measures (climate policy, energy policy, and land and biodiversity policies) but also human development policies. It also improves the understanding of links between ecosystems and human development. Energy demand and supply are based on population and income. The IMAGE model relies on a lot of different models including an agroeconomic model called MAGNET and the GLOBIO model (biodiversity). The outputs of the model are various indicators concerning energy, agriculture, emissions, GHG and radiative forcing, temperature, water availability and sea level.

Focus on C8 Scenarios

This section focuses on two categories of scenario: Discrete scenarios and Shared Socio- economic Pathways (SSP) scenarios.

The Discrete category of scenarios is based on two major assumptions: the carbon budget and the consumption discrete rate. For many years, the consumption discount rate has been at the heart of the discussion on climate change economics due to its importance in the evaluation of climate change impacts in the future against today's costs of mitigating emissions. The choice of discount rate shapes the carbon emissions pathways constrained by carbon budgets. The WITCH model is run for different carbon budgets (from 400 to 1600 GtCO2 over the period 2010–2100) and varies the discount rate between 1% and 8% (global, averaged over the 21st century). The C8 Discrete scenarios incorporate the biggest carbon budget and the lowest discrete rate with no mitigation policies. The lower the discrete rate, the less people are willing to reduce their emissions to avoid future consequences.

SSPs (Shared Socio Economic Pathways) describe socio-economic trends and aim at evaluating how these trends will impact the climate in the long term (2100). SSPs picture five different narratives. We will only focus on three specific narratives (SSP2-Baseline, SSP3-Baseline and SSP5- Baseline) used in the C8 category and on key features. No climate policies are implemented in the baseline scenarios.

- The **SSP2-Baseline scenario**, also called the "Middle of the Road", describes a situation with intermediate challenges for both adaptation and mitigation but with the continuation of the current fossil-fuel dominated energy mix. Over the course of the century, C02 emissions double and the primary energy mix increases from 17% (2010) to 23% (2100). Despite a continued growth in renewables, moderate investments are made which limit their uses in the future.
- The **SSP3-Baseline scenario**, which describes a situation with regional rivalries, suggests a heavy reliance on fossils fuels and an increasing contribution of coal to the energy mix. Population growth, which is the highest among all SPP scenarios, is expected to reach 12.6 billion in 2100 and explains high future CH4 emissions through food demand. The capacity to adapt to climate change is weak due to the large, poor population and the lack of cooperation with slow technology development. The switch to clean fuels is difficult to achieve, as a large share of the population is not able to reach a decent income level and

relies on traditional fuels in their daily lives.

- The **SPP5-Baseline scenario** describes a fossil-fuel-reliant society with high challenges for mitigation and low challenges for adaptation. Rapid technological progress, increased investments in health, education and institutions, and strong growth of the global economy are coupled with significant use of fossil fuel resources. Energy demand triples during the century and the use of fossil fuel infrastructures generates a strong increase in CH4 emissions. The use of renewable energy starts to be deployed at a larger scale at the end of the century due to low policy support and acceptance.

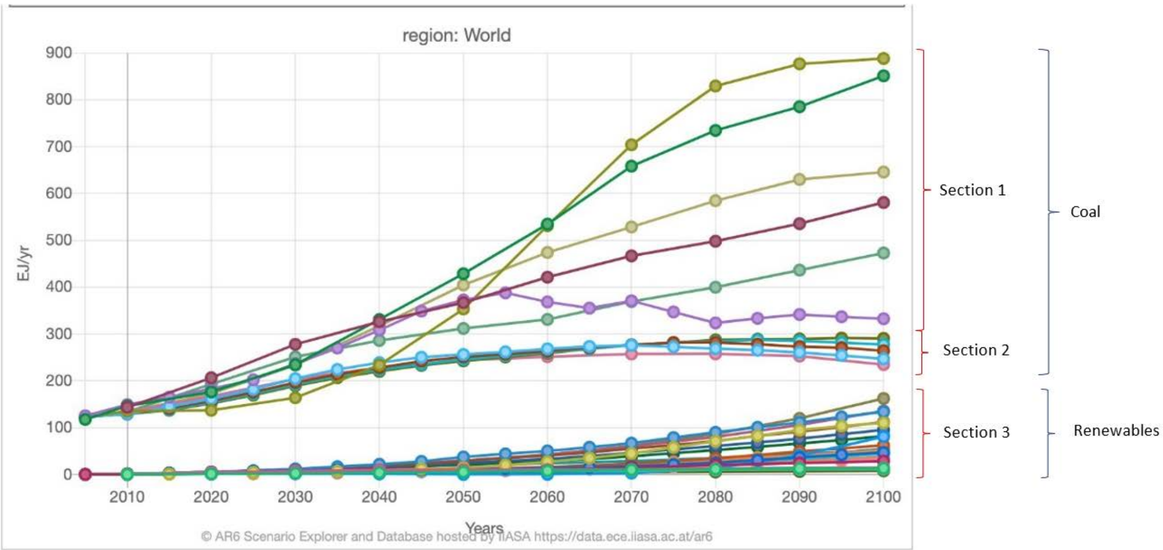
A look at the juxtaposition of scenarios

To analyze if a juxtaposition of the scenarios is relevant, we can take the example of the proportion of coal, wind and solar energy for the SSP and Discrete Scenarios. In Figure 1 [see Appendix] the proportion of renewable energy (wind and solar) across the two different scenarios Discrete and SSP is roughly the same for all C8 models (Section 3 – Figure 1). Moving to coal energy, only the SSP2 scenario has the same trajectory as the Discrete ones (Section 2 – Figure 1). Finally, the path followed by the SSP3 and SSP5 scenarios varies from one model to another (Section 1-Figure 1). The juxtaposition of these two scenarios is relevant as it allows us to understand the similarities and differences across different models used in the C8 category. In Figure 1, we can clearly see that the proportion of renewable energy is going to increase slightly in the coming years in comparison with coal. As each of these scenarios has its own path, the juxtaposition enables us to grasp the key features and dynamics of the C8 category and its models. However, since each scenario has its own assumptions and socio-economic inputs, the SSP and Discrete scenarios can have drastically different trends, for example in terms of world population. [See Appendix- Figure 2].

Learning from the figures: C8 take-aways

- Emissions: Category 8 anticipates that the levels of GHG emissions will rise, reaching 71 Gigatons of CO2 equivalent per year in 2030, 79 Gigatons in 2050 and 87 Gigatons in 2100, which, for comparison, is twice the amount that we currently emit per year (approx. 42 Gigatons of CO2 equivalent in 2021).

Figure 3: Projection of CO2 Emissions in Category 8



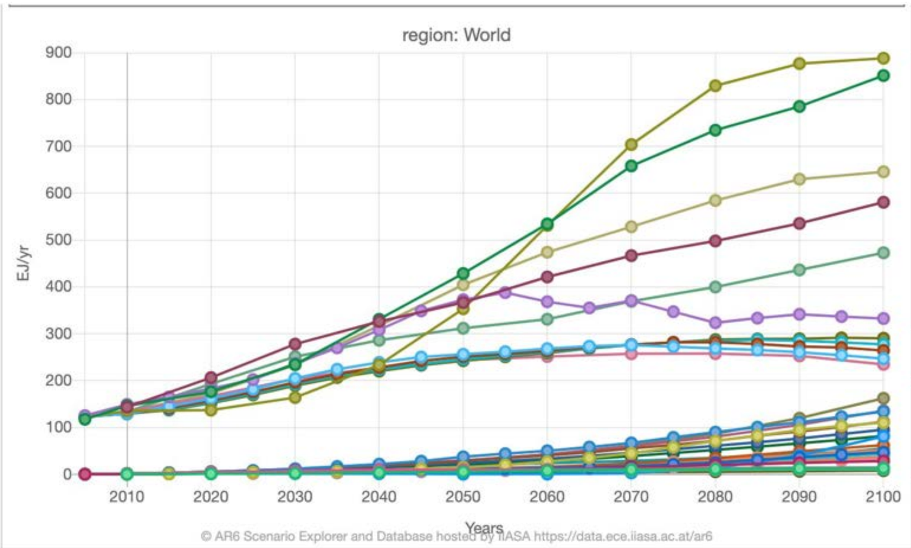
The IPCC considers two significant milestones regarding emissions: the approximate year when the peak in CO2 emissions will be reached before they decrease, and the year when net-zero CO2 emissions and greenhouse gas (GHGs) emissions will be achieved. For category C8, prospective scenarios anticipate a peak in CO2 emissions between 2080 and 2085. As for net-zero, it will not be achieved by 2100. Cumulative CO2 emissions will likely reach 5600 Gigatons over the horizon 2020-2100.

- Temperature: Under this category, it is projected that temperature levels will reach 1.5°C between 2030 and 2035, rise to 2.0°C between 2040 and 2045, and finally hit 3.0°C between 2065 and 2070. There is 50% probability that temperatures attain 4.2°C by 2100.
- Energy: Under the C8 Category, it is projected that the low-carbon share of primary energy will be reduced significantly from an estimation of 16% in 2020 to 13% until 2050, before increasing again to 29% by 2100. The CO2 intensity of primary energy will also rise above the 2020 estimated level but will fall to 91 by 2100. Final energy demand is projected to double at the very least in comparison to 2020 Demand (419 EJ/yr) and reach 941 EJ/yr) in 2100.
- Transport: global transport emissions could grow by 2030 and further by 2050 under the C8 scenarios without firm commitments to meet a long- term temperature goal.

Among drivers of the growth in emissions in these scenarios, we find population and GDP growth, a higher travel service demand per capita, and increased freight activities. Although transport efficiency is expected to continue to improve in line with historical trends, total transport emissions will likely grow due to roughly constant carbon intensity under the C8 scenarios. Significant increases in emissions come from Asia and the developing Pacific, the Middle East and Africa, whereas developed countries have lower transport emissions.

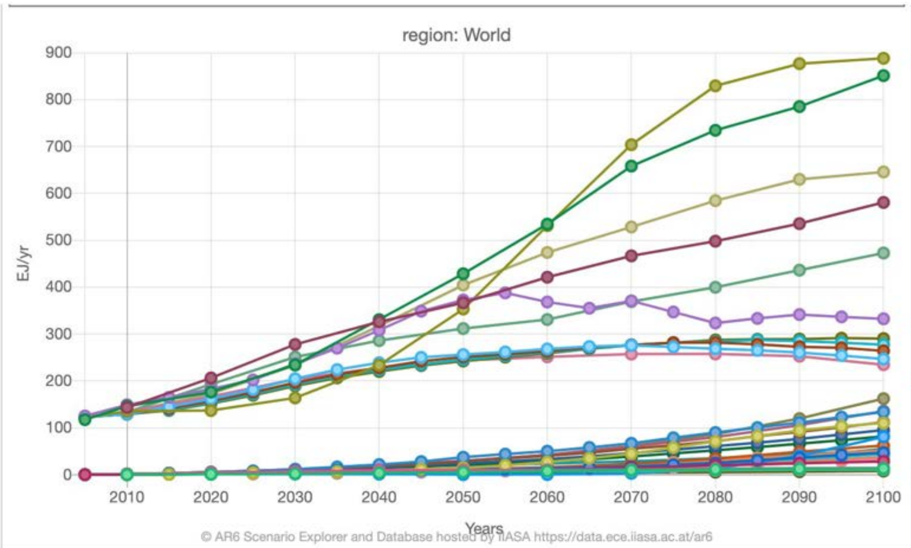
APPENDIX

Figure 1: Projection of coal and renewable energy uses in SSP2- SSP3- SSP5 and Discrete scenarios



All trends describing the SSP and Discrete scenarios above are based on different models used in the C8 category (GCAM, IMAGE, REMIND, WITCH, WITCH GLOBIUM). Section 1 represents the proportion of coal energy used in the SSP3 and SSP5 scenarios. Section 2 describes the proportion of coal energy for the Discrete scenarios as well as the SSP2 scenario. Section 3 shows the proportion of renewable energy (wind and solar) for all SSP and Discrete scenarios.

Figure 2: Projection of the world population in SSP2 - SSP3 - SSP5 and Discrate scenarios



All trends describing the SSP and Discrete scenarios above are based on different models used in the C8 category (GCAM, IMAGE, REMIND, WITCH, WITCH GLOBIUM). The population growth rate significantly varies from one scenario to another.

REFERENCES:

- IAMC wiki: https://www.iamcdocumentation.eu/index.php/IAMC_wiki (date: 15 October 2022)
- IPCC AR6, Mitigation of Climate Change, Full Report: https://report. ipcc.ch/ ar6/wg3/IPCC_AR6_WGIII_Full_Report.pdf (date: 15 October 2022)
- IPCC AR6, Mitigation of Climate Change, Summary for Policy makers: https:// www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_ WGIII_SPM.pdf (date: 15 October 2022)
- IPCC AR6, Mitigation of Climate Change, Technical support: https:// www. ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_ TS.pdf (date: 15 October 2022)
- The C-ROADS reference guide: https://img.climateinteractive.org/wp- content/ uploads/2020/01/C-ROADS_Reference_Guide_v87.pdf (date: 15 October 2022)
- The GCAM model: http://jgcri.github.io/gcam-doc/v4.3/overview.html (date: 15 October 2022)
- Scenario database: https://data.ece.iiasa.ac.at/ar6/#/docs (date: 15 October 2022)
- The IMAGE model: https://models.pbl.nl/image/index.php/Navigate_ the_ IMAGE_3.2_website (date: 15 October 2022)
- The REMIND model: https://www.pik-potsdam.de/en/institute/ departments/ transformation- pathways/models/remind (date: 15 October 2022)
- The REMIND-MAgPIE model: https://www.pik- potsdam.de/en/institute/ departments/activities/land-use-modelling/magpie (date: 15 October 2022)
- The REMIND-MAgPie model documentation: https://redmine. pik- potsdam.de/ projects/magpie/wiki/MAgPIE_Version_3_-_ Documentation (date: 15 October 2022)
- The role of the discount rate for emission pathways and negative emissions by Johannes Emmerling &co.: https://iopscience.iop.org/ article/10.1088/1748-9326/ab3cc9 (date: 15 October 2022)

- The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change. Keywan Riahi and al (2017). https://www. sciencedirect.com/science/article/pii/ S0959378016300681?via%3Dihub (date: 15 October 2022)
- The Shared Socioeconomic Pathways (SSPs) an Overview: https:// unfccc.int/ sites/default/files/part1_iiasa_rogelj_ssp_poster.pdf. (date: 15 October 2022)
- The WITCH model: https://www.witchmodel.org/ (date: 15 October 2022)
- The WITCH model: https://doc.witchmodel.org/ (date: 15 October 2022)

MINES PARIS | PSL | TTI.5° The Transition Institute

NOTE D'ÉCLAIRAGE #5

CONTACT

the-transition-institute.minesparis.psl.eu

tti.5@minesparis.psl.eu