Chapter 11
Climate Sensitivity Analysis: All Greenhouse Gases and Aerosols

Sven Teske

Abstract This section provides an overview of all greenhouse gases (GHGs) and aerosols, the sources, their contributions to overall emissions, and their likely cumulative effects on global temperature increases. The non-energy GHG modelling in this chapter is an update of the probabilistic assessment of the global mean temperature published in the first part of *Achieving the Paris Climate Agreements*, Chap. 12 (Meinshausen 2019). The 1.5 °C energy and non-energy pathways were assessed by Climate Resource—specialists in assessing the warming implications of emissions scenarios. The analysis focuses on the derivation of the trajectories of non-CO_2 emissions that match the trajectories of energy and industrial CO_2 emissions and evaluates the multi-gas pathways against various temperature thresholds and carbon budgets until 2100. (120).

Section 7.2 is based on the following: 'Documentation of 'UTS scenarios – Probabilistic assessment of global-mean temperatures' by Climate Resource Malte Meinshausen, Zebedee Nicholls, October 2021.

Keywords Non-energy GHG modelling · Agriculture, forestry, and other land use (AFOLU) emissions · N2O · CH4 · Global warming potential (GWP), Temperature projections and exceedance probabilities

11.1 Introduction

In previous chapters, we focused on the *energy* sector and the role of land use in certain industry sectors. This section provides an overview of all greenhouse gases (GHGs) and aerosols, the cause of their emission, their contribution to overall

S. Teske (✉)
University of Technology Sydney – Institute for Sustainable Futures (UTS-ISF), Sydney, NSW, Australia
e-mail: sven.teske@uts.edu.au

S. Teske (ed.), *Achieving the Paris Climate Agreement Goals*,
https://doi.org/10.1007/978-3-030-99177-7_11

emissions, and the likely cumulative effect of global temperature increases. The non-energy GHG modelling in this chapter is an update of Meinshausen (2019). The major sources of non-energy-related emissions—process emission from cement, steel, and aluminium production—have been quantified as part of the *industry* demand analysis (Chap. 5).

11.2 Overview: Greenhouse Gases and Aerosols (Substances, Origins, and Projected Development)

11.2.1 Energy-Related CO_2 Emissions

Energy-related CO_2 emissions all derive from oil, gas, or coal and are defined as '1A' emissions according to the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines (IPCC 2006) for the National Greenhouse Gas Inventory, shown in Fig. 11.1. These emissions are caused by combustion processes, such as those in power or heating plants, engines of cars, truck, planes, and ships, and any other use of fossil fuels that involves a combustion process. All the pre-2019 values are historical statistical data, whereas all the data points from 2020 onwards are the results of the 1.5 °C energy scenario documented in previous chapters.

11.2.1.1 Fugitive CO_2 Emissions

According to the IPCC (2019), fugitive CO_2 emissions can be broken down into energy- and industry-related emissions and are categorized as 'non-1A' emissions. Energy-related fugitive emissions are further subdivided into fugitive coal emissions from underground or surface mines, including the CO_2 from methane (CH_4) utilization or flaring from underground coal mines.

Fugitive emissions from oil and natural gas include the products of unconventional oil and gas exploration, such as tar sand and fracking gas, and emissions from abandoned wells. Fugitive emissions also arise from fuel transformation processes, such as in oil refineries, charcoal and coking coal production, or gasification processes. Fugitive emissions constitute only a fraction of the emissions from energy-related combustion processes. In our analysis of industry-specific emissions, they are included in the *Scope 1*, *2*, and *3* emissions.

11.2.1.2 Industrial Process Emissions

The second category according to the IPCC guidelines (IPCC 2019) is emissions from industrial processes and product use. The main emissions in this group are non-energy-related CO_2 from steel and cement manufacturing and include chemical

Main categories of emissions by source and removal by sinks		2006 IPCC Guidelines for National Greenhouse Gas Inventories		
National Greenhouse Gas Inventory	1 ENERGY	1A Fuel Combustion Activities	1A1 Energy Industries 1A2 Manufacturing Industries and Construction	
			1A3 Transport	1A3a Civil Aviation 1A3b Road Transportation 1A3c Railways 1A3d Water-borne Navigation 1A3e Other Transportation
			1A4 Other Sectors 1A5 Non-Specified	
		1B Fugitive Emissions from Fuels	1B1 Solid Fuels 1B2 Oil and Natural Gas 1B3 Other Emissions from Energy Production	
		1C Carbon Dioxide Transport and Storage	1C1 Transport of CO2 1C2 Injections and Storage 1C3Other	
	2 INDUSTRIAL PROCESSES AND PRODUCT USE	2A Mineral Industry 2B Chemical Industry 2C Metal Industry 2D Non-Energy Products from Fuels and Solvent Use 2E Electronics Industry 2F Product Uses as Substitutes for Ozone Depleting Substances 2G Other Product Manufacture and Use 2H Other		
	3 AGRICULTURE, FORESTRY, AND OTHER LAND USE	3A Livestock	3A1 Enteric Fermentation 3A2 Manure Management	
		3B Land	3B1 Forest Land 3B2 Cropland 3B3 Grassland 3B4 Wetlands 3B5 Settlements 3B6 Other Land	
		3C Aggregate Sources and Non-CO2 Emissions Sources on Land 3DOther		
	4 WASTE	4A Solid Waste Disposal 4B Biological Treatment of Solid Waste 4C Incineration and Open Burning of Waste 4D Wastewater Treatment ar Discharge 4E Other		
	5 OTHER	5AIndirect N2O Emissions from the Atmospheric Deposition of Nitrogen in NOx and NH3 5B Other		

Fig. 11.1 Main categories of emissions by source and their removal by sinks, as used by the IPCC. (Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, p. 6, (IPCC 2006))

substances used in the chemical industry, in aluminium production, or as technical gases for refrigeration. Although the volume of these chemical substances is small, their global warming effect is often significant. Details are provided in Sects. 11.2.5 and 11.2.6.

11.2.1.3 Black and Organic Carbon and Carbon Monoxide

There are three other forms of carbon:

- 'Black' and 'organic' carbon are particles from incomplete combustion processes that accumulate in the atmosphere. Whereas black carbon derives from fossil fuels, organic carbon derives from biofuels. These particles contribute to cloud formation and are hazardous to health, especially when inhaled. However, the quantities are relatively small, approximately 1% of the total energy-related CO_2 emissions.
- *Carbon monoxide* (CO) has a small direct global warming potential (GWP) but indirect radiative effects that are similar to those of CH_4 (IPCC 2001).

11.2.1.4 Responsible Industry Sectors: CO_2

Energy-related CO_2 emissions are obviously caused by all industry sectors that use fossil fuels. However, as reported in Chap. 4, the categorization of emissions into *Scopes 1*, *2*, and *3* helps define the levels of responsibility for emissions and the extent to which emission can be reduced. The primary energy industry is responsible for the exploitation and mining of fossil fuels and for fuel transformation from, for example, crude oil to kerosene. Therefore, the primary energy industry directly influences the potential reduction of fugitive emissions.

The conversion of fossil fuels into secondary energy, such as power and heat, and the transport of fuels to industrial, commercial, or private consumers are the responsibility of power, gas and energy utilities. Utilities only have a limited influence on the overall energy demand but can reduce conversion losses, including in coal or gas power plants. Although the amount of CO_2 released from burning a tonne of coal, a litre of oil, or a cubic metre of gas is constant and only varies across different qualities of fuel, the amount of secondary energy units (e.g. electricity) generated depends on the efficiency of the power plant. The GHGs emitted for each kilowatt-hour of electricity can be reduced, although the overall emissions can only be reduced by reducing the use of fossil fuel itself.

Finally, the end-use sector of fossil-fuel-based energy is responsible for the actual total demand for fossil fuels. End users are not responsible for fugitive emissions or conversion losses in power plants but can lower CO_2 emissions by using more-efficient end-use applications, such as energy-efficient cars, and by driving less. However, a total phase-out of energy-related CO_2 emission is possible with the use of carbon-free renewable energy sources.

11.2.2 *Agriculture, Forestry, and Other Land Use (AFOLU) Emissions*

In the climate science context, emissions from agriculture, forestry, and other land-uses are referred to as *AFOLU* emissions. The AFOLU sector contributes to the emission of multiple GHGs and aerosol species, including CO_2, CH_4, and nitrous oxide (N_2O). More details about AFOLU emissions and industry responsibilities are provided in Sect. 6.1 (Overview of the Global Agriculture and Food Sector) and Chap. 14. In the 1.5 °C pathway, the phase-out of AFOLU emissions by 2030—mainly by the cessation of deforestation and the introduction of negative emissions by the creation of carbon sinks with nature-based solutions, such as are-forestation and soil management—is vital. AFOLU emissions must decline sharply until 2030, in concert with the introduction of negative emissions and the absorption of CO_2, between 2035 and 2100 (Fig. 11.9).

11.2.3 *N_2O Emissions*

The long-lived GHG N_2O is emitted by human activities, such as fertilizer use, burning fossil and biofuels, and wastewater treatment (IPCC 2007 AR4). However, natural processes in soils and oceans also release N_2O. More than one-third of all N_2O emissions are anthropogenic and primarily derive from agriculture (IPCC 2007 AR4). In this analysis, we focus on human sources of N_2O.

11.2.3.1 Responsible Industry Sectors: N_2O

Of all GHG emissions, 6% are N_2O. About 71% of all N_2O emissions are caused by the use of synthetic and organic fertilizers in the agricultural sector. Of all N_2O emissions, 15% are related to the chemical production of fertilizers, fibres, and synthetic products; around 10% are the by-products of combustion processes; and 4% arise from wastewater treatment plants (IPCC AR4).

11.2.4 *CH_4 Emissions*

Methane is a GHG with an estimated lifetime of 12 years. About 17% of all GHG emissions are CH_4. Anthropogenic CH_4 is predominantly emitted from manure and as gastroenteric releases from livestock; from rice paddies; as fugitive emissions from the mining of coal, oil, and gas; and in gas transport leakages. There are also natural sources CH_4, such as gas hydrates, freshwater bodies, oceans, termites, and wetlands, and other sources such as wildfires. Globally, wetlands are the largest natural source of CH_4, with emissions estimated to be 102–200 Mt./year on average in 2008–2017, which constituted approximately one-quarter of global CH_4 emissions (UNEP 2021).

11.2.4.1 Responsible Industry Sectors: CH_4

Anthropogenic sources contribute to about 60% of total global CH_4 emissions, 90% of which come from only three sectors: 40% from the fossil-fuel industry, approximately 35% from the agriculture sector, and approximately 20% from waste and landfill utilities (UNEP 2021).

- *Primary energy sector*: CH_4 released during oil and gas extraction, or the pumping and transport of fossil fuels. About 23% of all CH_4 emissions are anthropogenic, of which 12% originate in coal mining.
- *Agriculture*: Methane emissions from enteric fermentation and manure management represent roughly 32% of global anthropogenic emissions. Rice cultivation adds another 8% to anthropogenic emissions. Agricultural waste burning contributes close to 1%.
- *Waste*: The third largest amount of anthropogenic CH_4 emissions are from landfills and waste management, which contribute 20% of global anthropogenic CH_4 emissions.

The remaining CH_4 emissions are mainly from wastewater treatment (UNEP 2021).

11.2.5 Other GHGs

Although CO_2, CH_4, and N_2O are the main GHG gases, representing approximately 90% of all GHG emissions, a large number of other GHGs and aerosol precursors are emitted, including substances used as feedstock for the chemical industry, such as ammonia, or chemical substances used for technical processes. The largest group of these chemical substances is controlled by the Montreal Protocol, which phases down the consumption and production of different ozone-depleting substances, including halons, chlorofluorocarbons (CFCs), and hydrofluorocarbons (HFCs) (UNEP MP 2021).

11.2.6 Global Warming Potential (GWP)

Greenhouse gases warm the earth by trapping energy and reducing the rate at which energy escapes the atmosphere. These gases differ in their ability to trap heat and have various radiative efficiencies. They also differ in their atmospheric residence

Table 11.1 Main greenhouse gases and their global warming potential (GWP)

Greenhouse gas	Formula	100-year GWP (AR4)
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
Sulphur hexafluoride	SF_6	22,800
Hydrofluorocarbon-23	CHF_3	14,800
Hydrofluorocarbon-32	CH_2F_2	675
Perfluoromethane	CF_4	7390
Perfluoroethane	C_2F_6	12,200
Perfluoropropane	C_3F_8	8830
Perfluorobutane	C_4F_{10}	8860
Perfluorocyclobutane	c-C_4F_8	10,300
Perfluoropentane	C_5F_{12}	13,300
Perfluorohexane	C_6F_{14}	9300

Source: IPCC AR4, compilation by the Climate Change Connection, Manitoba/Canada
Note: GWP values were changed in 2007. The values published in the 2007 IPCC Fourth Assessment Report (*AR4*) were refined from the IPCC Second Assessment Report (*SAR*) values. However, both values (AR2 and AR4) can be found throughout the literature

times. Each gas has a specific global warming potential (GWP), which allows comparisons of the amount of energy the emission of 1 tonne of a gas will absorb over a given time period, usually a 100-year average time, compared with the emissions of 1 tonne of CO_2 (Vallero 2019). Table 11.1 shows the main GHGs and their GWPs. Although the quantities of substances considered under the Montreal Protocol are small, their GWPs are significantly higher than those of the main GHGs.

11.3 Assessment of the 1.5 °C Energy and Non-Energy Pathways

This section is based on the analysis of *Climate Resource* under contract to the University of Technology Sydney (UTS) as part of the Net-Zero Sectorial Industry Pathways Project (UTS/ISF 2021). The study is an update of the previous OneEarth Climate Model (OECM) publication (Teske et al. 2019). However, the Generalized Quantile Walk (GQW) methodology used (Meinshausen & Dooley 2019) has been developed further.

The energy and industrial CO_2 emissions pathways are based on the OECM 1.5 °C energy scenario described in previous chapters, whereas the non-CO_2 GHG emission time series have been described with the advanced GQW methodology.

The probabilistic global mean temperature, radiative forcing, and concentration implications of the scenarios are also examined with the reduced complexity model MAGICC, in the same set-up used by the IPCC's Sixth Assessment Report (IPCC

AR6 2021). The emissions pathways developed are analysed in terms of their 1.5 °C, 2 °C, and 2.5 °C exceedance probabilities over time until 2050 and 2100. The climate projections are performed with a probabilistic modelling set-up that includes additional feedbacks, such as permafrost-related CH_4 and CO_2 emissions.

11.3.1 Accounting for Non-Energy Sectors

The IPCC Assessment Report 6 (IPCC AR 2021), published in August 2021, contains five scenarios, each of which represents a different emissions pathway. These scenarios are called the *Shared Socioeconomic Pathway* (*SSP*) scenarios. The most optimistic scenario, in which global CO_2 emissions are cut to net zero around 2050, is the SSP1-1.9 scenario. The number at the end (1.9) stands for the approximate end-of-century radiative forcing, a measure of how hard human activities are pushing the climate system away from its pre-industrial equilibrium. The most pessimistic is SSP5-8.5. The SSP1-1.9 scenario, described in detail by Rogelj et al. (2018), assumes that the global community takes strong mitigation action consistent with the sustainable development goals. As a result, this scenario sees strong reductions in GHG emissions.

In this analysis, the energy-related CO_2 emissions data are the results of the OECM 1.5 °C pathway documented in previous chapters. These sectorial energy scenarios include key fossil-fuel combustion activities, as defined under category 1A emissions of the IPCC 1996 guideline definitions (IPCC 2006), shown in Fig. 11.1.

Climate Resource has added CO_2 emissions that fall under other fossil fuel and industrial activities, such as fugitive emissions, cement production, and waste disposal and management, from the SSP1-1.9 scenario, a scenario in which there is strong mitigation action. The SSP1-1.9 scenario has been chosen, because it has similar reductions of CO_2 fossil-fuel emissions as the OECM 1.5 °C scenario. The combination of both time series creates an emission pathway that is likely to include all fossil-fuel and industrial uses.

Within the energy sector category, the non-1A category emissions are those that derive from fugitive emissions and fossil-fuel fires. In adding these emissions, we assume that they will remain constant into the future, and we derive their magnitude based on the detailed sectorial breakdown provided by Hoesly et al. (2018). The data categorization follows the latest scientific standards (Nicholls et al. 2021; Gidden et al. 2019).

The assumption that the non-1A emissions—industrial and fugitive emissions—will remain constant is an oversimplification, given the likelihood that changes (such as flaring during gas production) will vary into the future. With a complete fossil-fuel phase-out, there will be no further natural gas extraction and therefore no emissions from gas flaring. However, these emissions represent <1% of total CO_2 emissions, so the effect of this simplification will be of the order of hundredths of a degree, even in a baseline scenario. We chose not to assume that these emissions will continue to represent a fixed fraction of the total energy sector emissions, because the energy sector emissions will become negative in the twenty-first century under the SSP1-1.9 scenario and negative emissions from fossil-fuel fires seem highly unlikely.

In the industry sector, the non-1A category emissions mainly derive from cement and metal production. We assume that these emissions will represent a fixed fraction of the *industry* sector emissions, with the fixed fraction varying by region. We derive the fixed fraction from the ratio of non-1A category emissions in the *industry* sector to the total emissions in the *industry* sector in 2014 in the data of Hoesly et al. (2018). This assumption is once again a simplification. However, in the absence of other data sources, it is a simple and justifiable choice. Moreover, given that these emissions represent approximately 6% of the total emissions and that the fixed fraction assumption captures at least some of the underlying scenario dynamics, we expect the effect of this assumption to be limited to the order of a few hundredths of a degree centigrade.

We combined the 1A CO_2 emissions of the OECM with the estimate of non-1A emissions to create a complete time series of fossil CO_2 emissions (see Fig. 11.2). Whereas the 1A emissions from the OECM will reach zero in 2050, the non-1A sector emissions are generally considered harder to mitigate, so we assume that they will not reach zero in 2050.

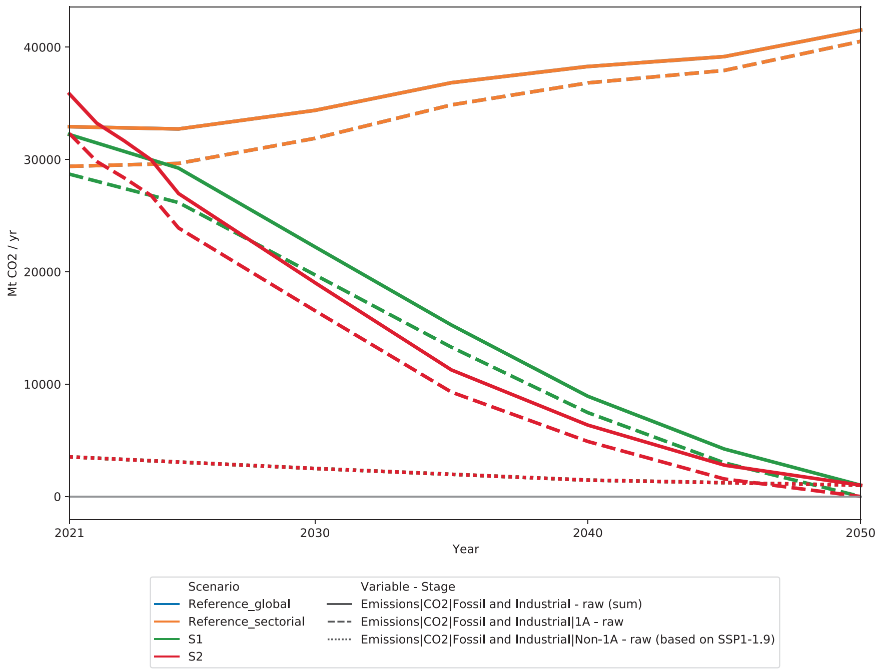

Fig. 11.2 Three non-1A fossil CO_2 emissions (Reference, 2.0 °C) and the OECM 1.5 °C pathway

The analysis performed above suggests there will be a small non-zero amount of emissions from these non-1A sectors in 2050, even under an ambitious mitigation scenario. As a result, the total fossil CO_2 emissions will generally follow the trajectory provided by the OECM but will be slightly higher, because the non-1A sector emissions are included, and in 2050, the total fossil CO_2 emissions will be close to, but not equal to, zero. Creating a scenario in which they reach exactly zero by 2050 would require further analysis of these non-1A sectors. Figure 11.2 shows the inclusion of non-1A fossil CO_2 emissions. The data for the additional scenario represent the reference case and the 2.0 °C scenario published by Teske et al. (2019).

11.3.2 Harmonization

In a second step, the projected emissions are harmonized to historical emissions estimates of the Global Carbon Project 2020 (GCP 2021a). To estimate the rebound after the COVID-related reduction in emissions in 2020, we assume that the 2021 emissions will rebound to their 2019 levels, within the same level estimated by the International Energy Agency (IEA PR 2021). This ensures a smooth transition between historical emissions and the three projections—a Reference case, a 2.0 °C scenario (see Teske et al. 2019) and the OECM 1.5 °C—as well as capturing the impact of COVID and the subsequent recovery efforts. The impact of harmonization on each of the OECM scenarios is illustrated in Fig. 11.3.

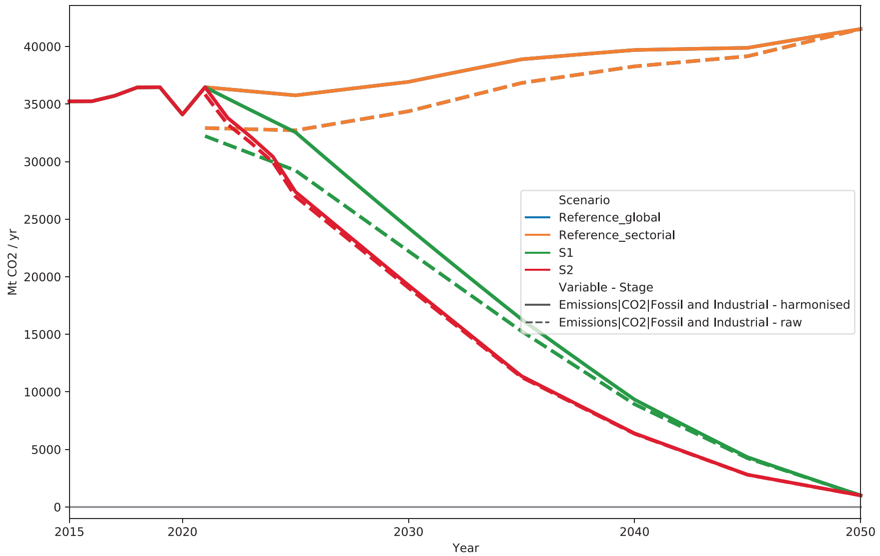

Fig. 11.3 Harmonization of fossil CO_2 emissions with historical emissions from the Global Carbon Project 2020 (GCP 2021b)

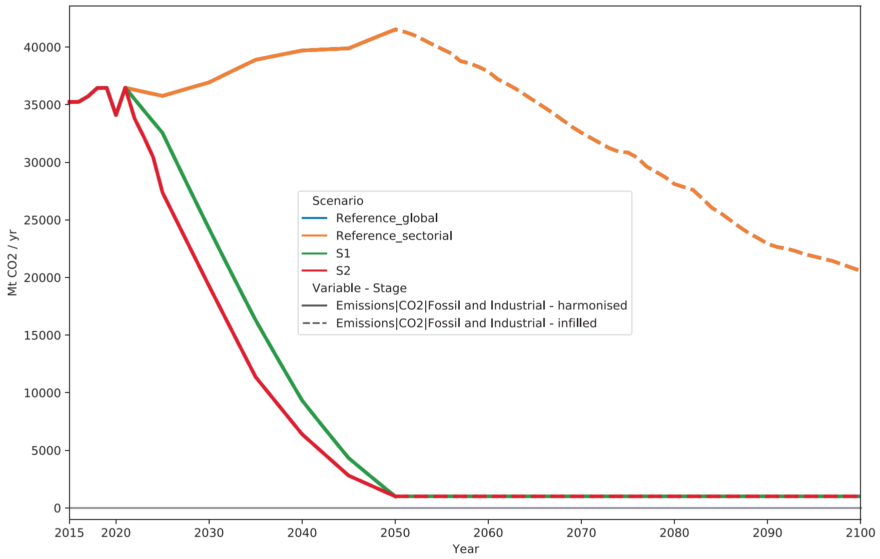

Fig. 11.4 Extending fossil CO_2 emissions from 2050 to 2100

11.3.3 Extending Emissions to 2100

A simple approach is taken to extending emissions to 2100. This process is also called ‘infilling’. For the mitigation scenarios OECM 2.0 °C and OECM 1.5 °C, fossil CO_2 emissions are simply held constant from 2050 to 2100. For the reference scenarios, fossil CO_2 emissions are extended forward by assuming that the emissions follow the evolution of other pathways at a similar level of emissions in 2050. This process has been undertaken with the Silicone Software (Lamboll et al. 2020). The other pathways are taken from the SR1.5 database, i.e. the scenarios that underpinned the IPCC’s Special Report on 1.5 °C (Huppmann 2018).

The SR1.5 scenarios are, at the time of writing, the most comprehensive set of strong mitigation scenarios available in the literature. Consequently, they provide the best basis for statistical inferences on how emissions will evolve over time (e.g. as we have done here by inferring the post-2050 emissions based on the emissions in 2050) and how the evolution of one set of emissions (e.g. fossil CO_2) is linked to changes in other sets of emissions (e.g. CH_4) (Fig. 11.4).

11.3.4 Infilling Emissions Other Than Fossil CO_2

11.3.4.1 Emissions in the SR1.5 Database

The OECM 1.5 °C fossil CO_2 time series is infilled with non-fossil-fuel CO_2 emissions from the SR1.5 database, whose targets are similar to the OECM 1.5 °C emissions trajectory (Fig. 11.5). This method examines the relationship between fossil

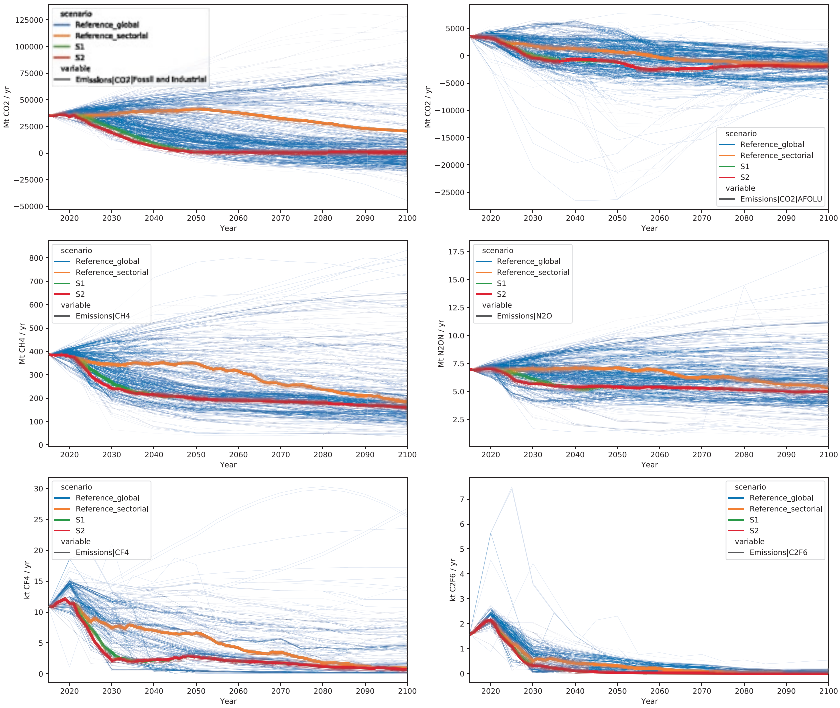

Fig. 11.5 Infilled emissions time series compared with the SR1.5 scenario database

CO_2 based on the OECM 1.5 °C pathways and other emissions of the SR1.5 database. This process requires the re-harmonization of the SR1.5 database to match the historical emissions inputs used by MAGICC v7.5.3 in the probabilistic AR6 set-up in 2015. This ensures that all-time series start from a consistent point, so there are no spurious jumps in the complete emissions time series, which are then passed to the climate model MAGICC (see Sect. 11.3.2 and Gidden et al. 2018).

In Fig. 11.9, the four scenarios analysed (thick lines) are shown in the context of the international integrated assessment model (IAM) scenarios, shown with blue thin lines, which represent 411 scenarios taken from the IPCC Special Report on the 1.5 °C warming scenario database. We show the OECM-modelled fossil and industrial CO_2 emissions (top left), the inferred CO_2 land-use (AFOLU)-related emissions (panel top right), inferred total CH_4 emissions (panel middle left), inferred total N_2O emissions (panel middle right), inferred total CF_4 emissions (panel bottom left), and inferred total C_2F_6 emissions (panel bottom right).

11.3.4.2 Emissions Not in the SR1.5 Database

In addition to the SR1.5 database emissions, as described in the previous section, emissions from the SSP scenarios—see definition in Sect. 11.3.1—are introduced into the analysis, as shown in Fig. 11.6.

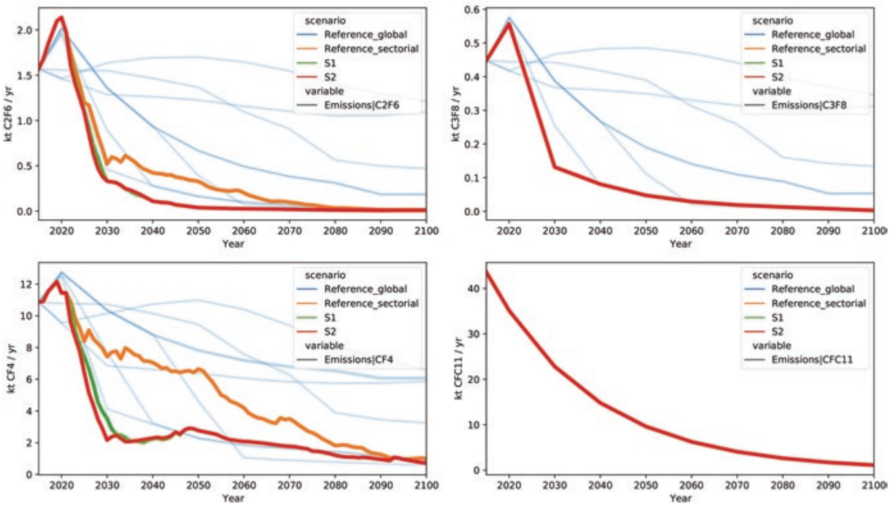

Fig. 11.6 Infilled emissions compared with the SSP scenarios

The SSP emissions pathways chosen for the analysis are those that are closest to the OECM 1.5 °C pathway. The SSP scenarios were selected using the root mean square (RMS) methodology, which measures closeness based on the difference in emissions for gases that have similar applications and uses.

A scenario for the extremely potent GHG octafluoropropane (C_3F_8) emissions, for example, was chosen based on its similarity to C_2F_6 emissions, which is a simplified way of inferring the appropriate emissions.

Hexafluoroethane (C_2F_6) is, like C_3F_8, a substance used in the semiconductor industry. However, this pragmatic technique is appropriate because the climate impact of these species is minor, representing <10% of the total GHG emissions.

In Fig. 11.10, the four scenarios analysed are shown in thick lines in the context of the SSP scenarios, which are marked in thin blue lines, and represent specific SSP scenarios (O'Neill et al. 2016). As examples, C_2F_6 emissions are shown (panel top left) as well as C_3F_8 emissions (panel top right), which follow from the C_2F_6 emissions, together with CF_4 emissions (panel bottom left) and CFC_{11} emissions (panel bottom right), which follow from the CF_4 emissions.

Carbon tetrafluoride (CF_4) and trichlorofluoromethane (CFC_{11}) are both substances used in refrigeration.

11.3.5 Temperature Projections and Exceedance Probabilities

Here, we provide the global mean probabilistic temperature projections, including their medians and 5%–95% ranges, for the OECM scenarios analysed (Fig. 11.7). These probabilistic ranges are sourced from the underlying 600 ensemble members, which are calibrated against the IPCC AR6 WG1 findings.

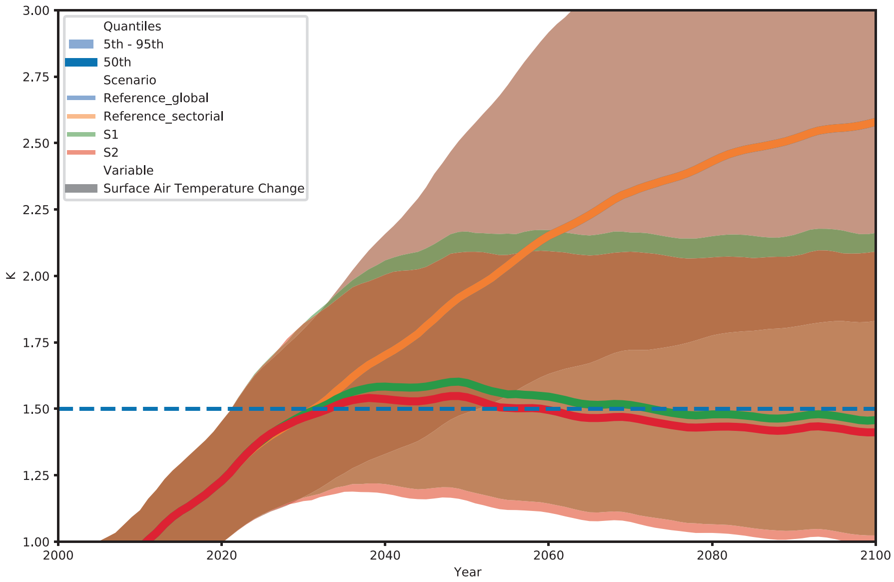

Fig. 11.7 Probabilistic global mean surface air temperature (GSAT) projections relative to 1850–1900

Similar to the SSP1-1.9 scenario in IPCC AR6 WG1, both the OECM 2.0 °C and OECM 1.5 °C pathways slightly overshoot the 1.5 °C pathway in their medians during the middle of the century, before dropping back to below 1.5 °C warming towards the end of the century. These probabilistic temperature projections can also be converted into exceedance probabilities (Fig. 11.8), i.e. the likelihood of exceeding a given temperature threshold at each point in time.

Both the OECM 2.0 °C and OECM 1.5 °C pathways are characterized as 1.5 °C low-overshoot pathways, i.e. pathways that end up below 1.5 °C (with a greater than 50% chance) at the end of century but slightly exceed a 50% chance of 1.5 °C over the course of the century. Both pathways are consistent with what is referred to in the SR1.5 report as '1.5 °C-compatible pathways'. However, the likelihood that the OECM 1.5 °C scenario will stay below 1.5 °C throughout the century, despite strong mitigation actions, does not exceed 67%. Figure 11.7 shows the probabilistic global mean surface air temperature (GSAT) projections relative to 1850–1900 for the scenarios analysed.

11.4 One Earth Summary Graph

The OECM 1.5 °C mitigation scenario limits the global average temperature rise to 1.5 °C using a carbon budget of 400 GtCO_2 in cumulative emissions, commencing in January 2020, as defined in the IPCC's Sixth Assessment Report, Working Group 1 (AR6 2021).

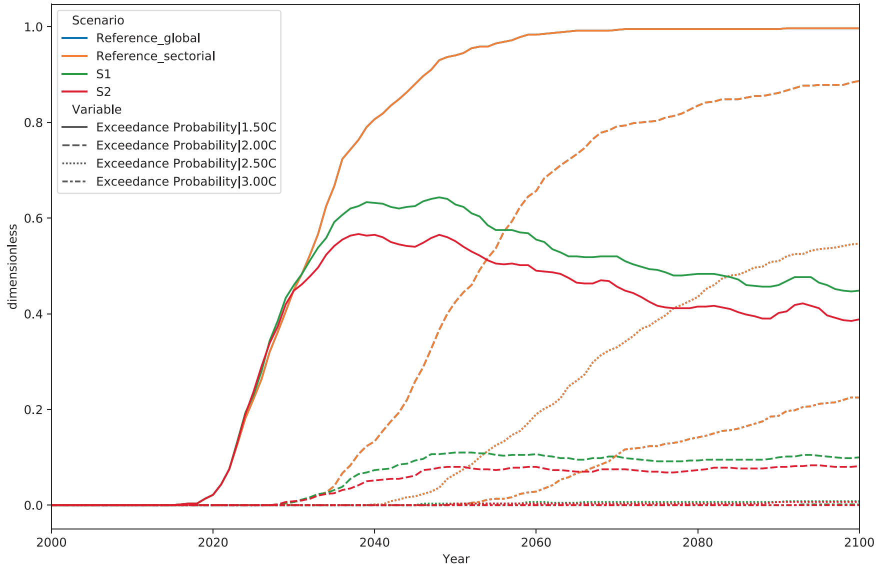

Fig. 11.8 Exceedance probabilities for the analysed scenarios relative to 1.5 °C, 2 °C, 2.5 °C, and 3 °C warming until 2100

The OECM calls for net-zero emissions by 2040, achieved by:

1. A rapid fossil-fuel phase-out for all uses by 2050 and a transition to 100% renewable energy.
2. Negative emission through nature-based solutions:

   (a) Approximately 400 $GtCO_2$ of additional carbon to be removed by reforestation and land restoration by 2100.
   (b) Natural land carbon sinks to absorb CO_2 but which will decline in the second half of the century.
   (c) Natural ocean carbon sinks, which will continue to absorb CO_2 throughout the century.

The IPCC AR6 presents the 400 $GtCO_2$ carbon budget as providing a 'good' (67%) chance of limiting warming to 1.5 °C, but it does not incorporate the anthropogenic emissions that occurred between the pre-industrial era (1750–1800) and the early industrial era (1850–1900).

If historical emissions between 1750 and 1900 are included, a 400 $GtCO_2$ carbon budget provides a 'fair' (50%) chance of an increase of 1.5 °C. In this case, a 'good' chance to achieve 1.5 °C warming would require an even steeper decline in emissions—net zero by 2040, instead of 2050—with the possibility of achieving 1.4 °C by 2100.

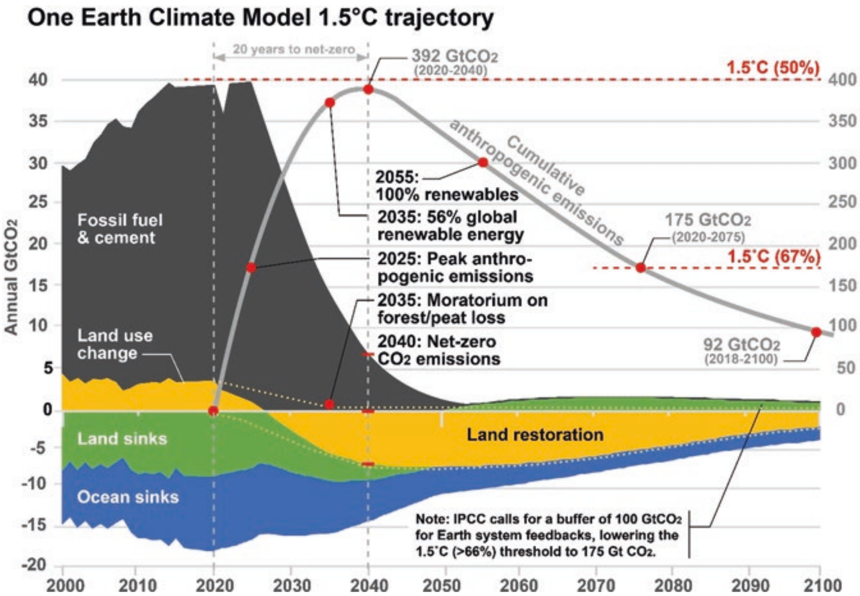

Fig. 11.9 Probability of remaining under 1.5 °C. (Source: Creative Commons: Karl Burkart, One Earth)

Figure 11.9 shows the reduction of energy-related CO_2 emissions (black), the removal of carbon by reforestation and land restoration (yellow), the natural land carbon sinks (green), and ocean carbon sinks (blue).

References

GCP. (2021a). *The global carbon project*. Online database.

GCP. (2021b). *The global carbon project*. Website, viewed December 2021. https://www.global-carbonproject.org/

Gidden, M. J., Fujimori, S., van den Berg, M., Klein, D., Smith, S. J., van Vuuren, D. P., & Riahi, K. (2018). A methodology and implementation of automated emissions harmonization for use in Integrated Assessment Models. *Environmental Modelling & Software, 105*, 187–200., ISSN 1364-8152. https://doi.org/10.1016/j.envsoft.2018.04.002

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., … Takahashi, K. (2019). Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. *Geoscientific Model Development, 12*, 1443–1475. https://doi.org/10.5194/gmd-12-1443-2019

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J.-I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., & Zhang, Q. (2018). Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community

Emissions Data System (CEDS). *Geoscientific Model Development, 11*, 369–408. https://doi.org/10.5194/gmd-11-369-2018

Huppmann, D., Rogelj, J., Kriegler, E., et al. (2018). A new scenario resource for integrated 1.5 °C research. Nature. *Climate Change, 8*, 1027–1030. https://doi.org/10.1038/s41558-018-0317-4

IEA PR. (2021). *Press release; global carbon dioxide emissions are set for their second-biggest increase in history, 20 April 2021*. https://www.iea.org/news/global-carbon-dioxide-emissions-are-set-for-their-second-biggest-increase-in-history

IPCC. (2001). *TAR climate change 2001: The scientific basis, Radiative Forcing of Climate Change, Ramaswamy et al.*. https://www.ipcc.ch/report/ar3/wg1/chapter-6-radiative-forcing-of-climate-change/.

IPCC. (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_1_Overview.pdf

IPCC, AR4, Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., & Van Dorland, R. (2007). Changes in atmospheric constituents and in radiative forcing. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. I. Miller (Eds.), *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IPCC. (2019). *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories*. https://www.ipcc.ch/site/assets/uploads/2019/12/19R_V0_01_Overview.pdf

IPCC AR 6. (2021). *Climate change 2021: The physical science basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press (see Cross-Chapter Box 7.1), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07.pdf).

Lamboll, R. D., Nicholls, Z. R., Kikstra, J. S., Meinshausen, M., & Rogelj, J. (2020). Silicone v1. 0.0: An open-source Python package for inferring missing emissions data for climate change research. *Geoscientific Model Development, 13*(11), 5259–5275.

Meinshausen, M. (2019). Implications of the developed scenarios for climate change. In S. Teske (Ed.), *Achieving the Paris climate agreement goals*. Springer. https://doi.org/10.1007/978-3-030-05843-2_12

Meinshausen, M., & Dooley, K. (2019). Mitigation scenarios for non-energy GHG. In S. Teske (Ed.), *Achieving the Paris climate agreement goals*. Springer. https://doi.org/10.1007/978-3-030-05843-2_4

Nicholls, Z., Meinshausen, M., Lewis, J., Corradi, M. R., Dorheim, K., Gasser, T., et al. (2021). Reduced complexity Model Intercomparison Project Phase 2: Synthesizing Earth system knowledge for probabilistic climate projections. *Earth's Future, 9*, e2020EF001900. https://doi.org/10.1029/2020EF001900

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development, 9*, 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Rogelj, J., Popp, A., Calvin, K. V., et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change, 8*, 325–332. https://doi.org/10.1038/s41558-018-0091-3

Teske, S., et al. (2019). Energy scenario results. In S. Teske (Ed.), *Achieving the Paris climate agreement goals*. Springer. https://doi.org/10.1007/978-3-030-05843-2_8

UNEP. (2021) *United Nations Environment Programme and Climate and Clean Air Coalition (2021). Global methane assessment: Benefits and costs of mitigating methane emissions*. Nairobi: United Nations Environment Programme. ISBN: 978-92-807-3854-4 Job No: DTI/2352/PA, https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions

UNEP MP. (2021). *UN Environment Programme; Implementing Agency of the Multilateral Fund for the Implementation of the Montreal Protocol/Ozon Action as part of UN Environment Programme's Law Division and serves 147 developing countries through the Compliance Assistance Programme*, website https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol

Vallero. (2019). *Air pollution calculations* (pp. 175–206., ISBN 9780128149348). Vallero, D. A. Elsevier. 10.1016/B978-0-12-814934-8.00008-9.