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2 °C AND 1.5 °C SCENARIOS AND POSSIBILITIES OF LIMITING THE USE OF BECCS AND BIO-ENERGY

Note

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Contents

Main findings

Model-based scenarios show pathways that limit global warming to well below 2 °C or further down to 1.5 °C. This report presents a range of scenarios that limit warming to well below 2 °C and to 1.5 °C, using IMAGE (PBL) and POLES (JRC) models. More specifically, the 2 °C and 1.5 °C scenarios are consistent with limiting global warming to below 2 °C in the 21st century, and to 1.5 °C by 2100, with a respective probability of at least 66% and 50%. The results show that these targets can be achieved, technically, under *Full technology* scenarios (i.e. using all available technologies). Such full technology scenarios rely on rapid and deep emission reductions through a mix of i) energy efficiency improvements, ii) rapid introduction of energy options without CO_2 emissions (e.g. renewable energy and CCS), iii) negative emission options (e.g. bio-energy with CCS (BECCS) and afforestation), and iv) reduction in non-CO_2 gases. Under the IMAGE scenarios, contributions of energy efficiency improvements and CCS are larger than under the POLES scenarios, whereas the latter include more renewable energy. According to both models, negative emissions play a substantial role in these cost-optimal, full technology scenarios. However, it should be noted that reliance on any large-scale future use of certain negative emission options is controversial, as these may require large amounts of land and suffer from a lack societal support.

In the literature, nearly all scenarios consistent with the 2 °C target achieve total greenhouse gas neutrality by the end of the century. Under the 1.5 °C Full technology scenarios, greenhouse gas neutrality is typically achieved in the 2050–2070 period. The scenario literature (i.e. the SSP database) shows a set of scenarios consistent with the targets of the Paris Agreement (Rogelj et al., 2018) (see Figure ES.1). The emission reduction pathways from IMAGE and POLES, as presented in this report, are broadly consistent with this literature. In the short term, the full range over all available scenarios under various socio-economic, technological and resource assumptions from five Shared Socio-economic Pathways (SSPs) is somewhat wider, but this is mostly due to a more diverse set of policy assumptions that also consider delayed participation scenarios (here we only consider the SSP scenarios that show a peak in emissions in 2020, or at the latest by 2030). After the peak in emissions, these scenarios typically show stronger reductions, in the long term.

Under the *Full technology* scenario range of IMAGE and POLES, by 2050, greenhouse gas emissions are projected to range from 16.8 to 17.9 $GtCO_2eq$ for the 2 °C target and from 9.0 to 10.7 $GtCO_2eq$ for the 1.5 °C target. The IMAGE and POLES scenarios achieve total greenhouse gas neutrality (net zero greenhouse gas emissions) by the end of this century (for the 2 °C target) and around 2060–2070 (for the 1.5 °C target). Under the IMAGE Full technology scenarios, by 2050, greenhouse gas emissions are reduced by 56% (for the 2 °C target) and 76% (for the 1.5 °C target), from 1990 levels. Under the POLES Full technology scenarios, by 2050, greenhouse gas emissions are reduced by 51% (for the 2 °C target) and 70% (for the 1.5 °C target), from 1990 levels.

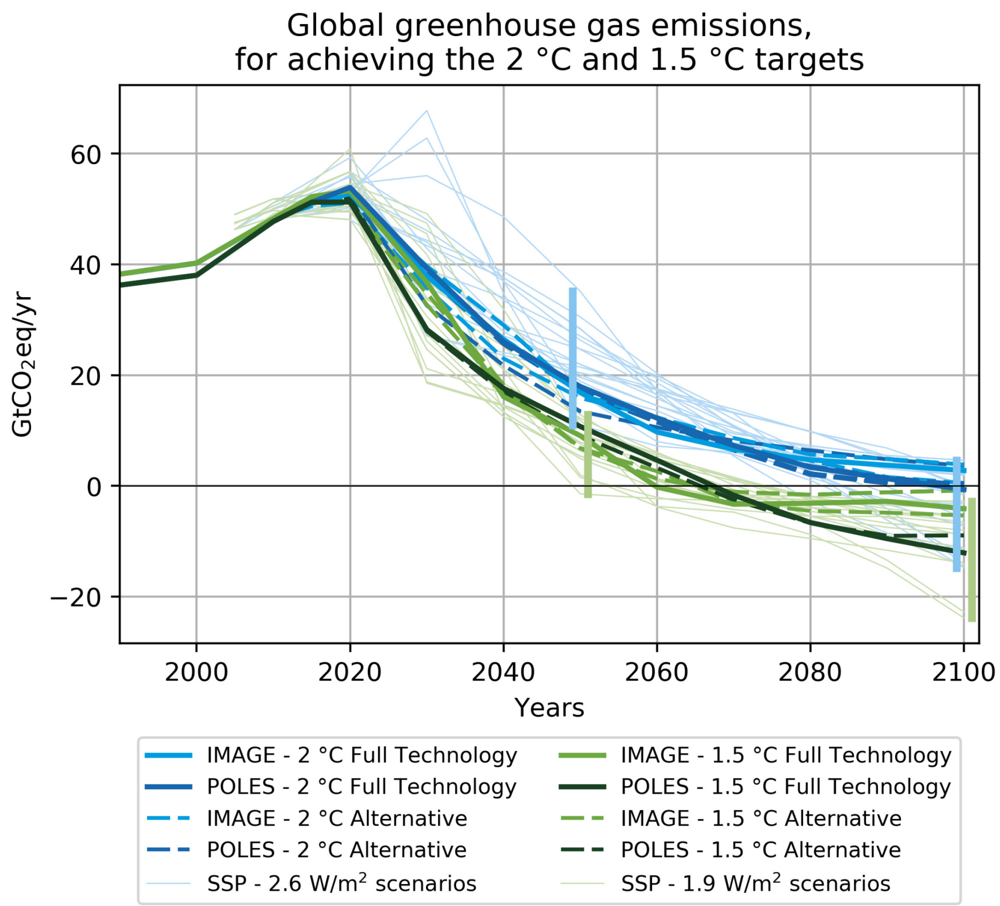

Figure ES.1. Global greenhouse gas emissions under the 2 °C and 1.5 °C Full technology and alternative scenarios of IMAGE and POLES, compared to the full set of cost-optimal SSP 2.6 W/m^2 and 1.9 W/m^2 scenarios (i.e. pathways leading to a radiative forcing level of 2.6 W/m^2 and 1.9 W/m^2 by 2100) (Rogelj et al., 2018). Vertical bars indicate the SSP scenario ranges for 2050 and 2100.

It is technically possible to rely less on negative emission technologies and bio-energy than is the case under the Full technology scenarios and still meet stringent climate goals. This report explores some *alternative* scenarios for achieving 2 °C and 1.5 °C targets that rely less on BECCS and bio-energy. These scenarios show that it is possible to decrease the dependence on bio-energy and BECCS, using alternative reduction options and timely efforts. Less reliance on BECCS can be achieved, for instance, through further penetration of renewable energy, rapid energy efficiency improvements, lifestyle changes, more reforestation and more rapid reduction in non-CO_2 gases. This report presents such scenarios, as explored using the IMAGE model. For instance, with respect to lifestyle changes, a scenario is presented that looks at a shift towards low-meat diets, which leads to fewer land-use-related CO_2 emissions and non-CO_2 greenhouse gas emissions. Several of the scenarios that use less BECCS assume that sequestration is achieved via other CDR options, such as reforestation and the application of CCS.

Nevertheless, under all scenarios presented here, in order to achieve the 1.5 °C target, net emissions still need to become negative during the second half of this century. Emission levels under most alternative scenarios are lower before mid century and higher at the end of the century, compared to their respective Full technology scenarios. The entire 2050 emission range, for the Full technology and alternative scenarios, results in a reduction of between 51% to 63% (for the 2 °C target) and between 70% and 82% (for the 1.5 °C target), below 1990 levels (Figure ES.1).

For the EU, emission reductions consistent with achieving the 2 °C and 1.5 °C targets are about 80% and 90%, respectively, below 1990 levels, by 2050, under the *Full technology* scenarios that assume reductions are implemented efficiently and on a global scale, beyond 2020. For the EU, the Full technology and alternative 2 °C scenarios show a reduction range of between 76% and 84% by 2050, below 1990 levels. The Full technology and alternative 1.5 °C scenarios show reductions of about 91% by 2050. For target setting, equity considerations can also be included. Scenarios based on equity principles other than cost efficiency lead to higher reductions, in high-income regions.

1 Introduction

Under the Paris Agreement (December 2015), nearly all countries in the world agreed to limit global temperature increase to well below 2 °C above pre-industrial levels, and to pursue efforts to limit this increase even further to 1.5 °C (UNFCCC, 2015). Mitigation scenarios in the literature that achieve the climate targets of 1.5 °C and 2 °C show deep reductions in greenhouse gas emissions and rely on net Carbon Dioxide Removal (CDR) from the atmosphere, mostly accomplished through large-scale use of bio-energy with carbon capture and storage (BECCS) and afforestation (Luderer et al., 2018; Riahi et al., 2017; Rogelj et al., 2017; Rogelj et al., 2018; van Soest et al., 2017; van Vuuren et al., 2017; Vrontisi et al., 2018). However, important challenges have been identified for large-scale application of negative emission technologies. This includes possible trade-offs between production of bio-energy, food and protection of biodiversity, all depending on limited land and water resources (Foley et al., 2005; Hasegawa et al., 2018). Given these limitations, CDR technologies cannot be applied without restriction, as there are limits to afforestation, bio-energy generation and carbon storage (Smith et al., 2016).

The question arises whether alternative deep mitigation pathways to limit warming to 1.5 °C and 2 °C above pre-industrial temperatures relying on less use of negative emissions from BECCS and afforestation exist. Van Vuuren et al. (2018) used the integrated assessment model IMAGE (Stehfest et al., 2014) to investigate BECCS specifically, and explored the impact of alternative pathways for meeting 1.5 °C that include lifestyle change, additional reduction in non-CO_2 greenhouse gases and more rapid electrification of energy demand based on renewable energy. Van Vuuren et al. concluded that these options significantly reduce the need for CDR, but not fully eliminate it. The role of bio-energy in these 1.5 °C pathways was investigated to a lesser extent, and 2 °C scenarios were beyond the scope of their work. Furthermore, the results were obtained through scenario calculations using one integrated assessment model.

This study builds upon earlier research, but specifically focuses on strategies to meet the Paris climate objective as well as scenarios that could limit the use of bio-energy and BECCS. Both the IMAGE and POLES suites aim for the same climate targets and both include Full-technology scenarios and scenarios that limit the deployment of BECCS. They do so however through different, but complementary, protocols. The IMAGE pathways present a world in which the additional use of renewables and lifestyle changes lower the need for BECCS deployment. The pathways calculated with the POLES model limit the availability of bio-energy overall which eventually leads to less use of BECCS, and consequently, more electrification and penetration of non-bio-energy renewables. We have structured the report to address the following two main research questions:

1) How do scenarios consistent with the Paris climate objective look like in terms of global energy use and production, land use, and emissions under full-technology assumptions, and what is the role of mitigation options BECCS and bio-energy in these scenarios?
2) Can we also develop emission pathways for meeting 2 °C and 1.5 °C that rely less on BECCS and bio-energy?

The scenarios were run by two different integrated assessment models, i.e. IMAGE and POLES. In addition to the overall results, we present the outcomes for the land-use system and some of the implications at the regional European scale.

This report is structured as follows: Chapter 2 describes the methodology and the scenarios. Chapter 3 analyses the Full technology scenarios that that limit warming to well below 2 °C or to 1.5 °C using the IMAGE and POLES models, and tries to address the first main research question. Chapter 4 explores alternative scenarios for meeting 2 °C and 1.5 °C, that rely less on BECCS and bio-energy, and thereby tries to address the second main research question of this report. Chapter 6 discusses the implications for the land-use sector. Finally, chapter 6 briefly discusses the changes in the energy use and production, and greenhouse gas emissions for the EU.

Box 1. Emission scenarios

The IPCC defines such scenarios as a plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols) based on a coherent and internally consistent set of assumptions about driving forces (e.g. demographic and socio-economic development, technological change) and their key relationships'. In other words, such scenarios are used to explore different possible trajectories for future emissions based on a set of key assumptions. Many scenarios, in fact, explore technically feasible and low-cost pathways towards achieving particular policy goals (e.g. the Paris climate objective). While scenarios normally depict pathways that are technically and economically feasible, the model outcomes say little about political or social feasibility. It should also be noted that scenarios are not meant to form a direct input for target setting. Targets are usually based on a much broader set of considerations than only technical and economic criteria.

2 Modelling set-up

2.1 Introduction

For the IMAGE analysis, the IMAGE 3.0 model was used. The IMAGE scenarios presented are either default (i.e. full technology, low-cost) pathways for reaching the Paris climate objective or the scenarios based on the recent work done on alternative 1.5 °C scenarios (lifestyle changes, more renewables & electrification) (van Vuuren et al., 2018), with the latest model updates on the electricity model. JRC used the POLES-JRC model starting from the GECO2017 model version (Kitous et al., 2017) with in addition recent model upgrades that will be used in the up-coming GECO2018 report: end uses in buildings, power system, oil and natural gas production module. The POLES scenarios presented here were finalised in July 2018. Both models are briefly described below.

2.2 Model description

2.2.1 IMAGE model

IMAGE 3.0 is a comprehensive ecological-environmental model framework that simulates the environmental consequences of human activities worldwide (Stehfest et al., 2014; van Vuuren et al., 2017; van Vuuren et al., 2018). It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The model is a simulation model, i.e. changes in model parameters are calculated on the basis of the information from the previous time step. The model includes a detailed description of the energy and land-use system and simulates most of the socio-economic parameters for 26 regions and most of the environmental parameters on the basis of a geographical grid of 30 x 30 minutes or 5 x 5 minutes (depending on the variable). Important inputs to the model are descriptions of the future development of so-called direct and indirect drivers of global environmental change. Exogenous assumptions on population, economic development, lifestyle, policies and technology change form a key input into the detailed energy system model TIMER and the food and agriculture system, including the agro-economic model MAGNET.

The IMage Energy Regional model, also referred to as TIMER, has been developed to explore scenarios for the energy system in the broader context of the IMAGE global environmental assessment framework (van Vuuren, 2007; van Vuuren et al., 2017). TIMER describes 12 primary energy carriers in 26 world regions and is used to analyse long-term trends in energy demand and supply in the context of the sustainable development challenges. The model simulates long-term trends in energy use, issues related to depletion, energy-related greenhouse gas and other air polluting emissions, together with land-use demand for energy crops. The focus is on dynamic relationships in the energy system, such as inertia and learning-by-doing in capital stocks, depletion of the resource base and trade between regions.

In IMAGE, the main interaction with the earth system is by changes in energy, food and biofuel production that induce land-use changes and emissions of carbon dioxide and other greenhouse gases. The calculated emissions of greenhouse gases and air pollutants are used in IMAGE to derive changes in concentrations of greenhouse gases, ozone precursors and species involved in aerosol formation on a global scale. Climatic change is calculated as global mean temperature change using a slightly adapted version of the MAGICC 6.0 climate model (Meinshausen et al., 2011a).

2.2.2 POLES model

The POLES-JRC (Prospective Outlook on Long-term Energy Systems) model is a global partial equilibrium simulation model of the energy sector, with complete modelling from upstream production through to final user demand (Keramidas et al., 2017; Vandyck et al., 2016). The POLES-JRC model follows a year-by-year recursive modelling, with endogenous international energy prices and lagged adjustments of supply and demand by world region, combining price-induced mechanisms with a detailed technological description and technological change in several sectors, in particular electricity generation. The model covers 39 regions around the world, including the EU. The model covers 15 fuel supply branches, 30 technologies in power production, 6 in transformation, 15 final demand sectors and corresponding greenhouse gas emissions. Population and GDP is an exogenous input into the model, while endogenous resource prices, endogenous global technological progress in electricity generation technologies and price-induced lagged adjustments of energy supply and demand are important features of the model. The power sector includes an explicit representation of hourly load curve for representative days and investment decisions for capacity planning, taking into account constraints of technical availability (not yet mature technology, base/peak load) and technology-relevant potential (hydropower, wind, solar, bio-energy, CCS geological storage). Electricity storage (including flexible demand) develops within the space defined by the load curve and the intermittent supply of renewables in each hourly step. Penetration of synthetic fuels is defined by their cost-competitiveness, with a representation of production costs and infrastructure costs (where relevant, e.g. hydrogen).

The mitigation policies discussed in the report are implemented by introducing carbon prices up to the level where emission reduction targets are met. Carbon prices affect the average energy prices, inducing energy efficiency responses on the demand side, and the relative prices of different fuels and technologies, leading to adjustments on both the demand side (e.g. fuel switch) and the supply side (e.g. investments in renewables).

The POLES-JRC model was specifically designed for the energy sector but also includes other greenhouse gas emitting activities. Non-CO_2 emissions in energy, industry and agriculture and CO_2 emissions from the land-use sector (land use, land-use change, and forestry (LULUCF) and agriculture) follow a cost curves approach. The land-use sector interact with the energy sector via the supply and demand of different forms of bio-energy; emission levels are determined by climate policies (marginal abatement cost curve, from GLOBIOM (Havlík et al., 2014) and bio-energy supply levels (marginal cost curve, also from GLOBIOM). GLOBIOM covers major greenhouse gas emissions from agricultural production, forestry, and other land use including CO_2 emissions from above- and below-ground biomass changes, N_2O from the application of synthetic fertiliser and manure to soils, N_2O from manure dropped on pastures, CH_4 from rice cultivation, N_2O and CH_4 from manure management, and CH_4 from enteric fermentation. More stringent climate policies result in increased competitiveness of bio-energy due to its low carbon content, and in a higher demand for bio-energy. This, in turn, leads to higher bio-energy prices, increased bio-energy supply to the energy sector in generally, and, in the absence of climate policies, to more land-use emissions. The bio-energy price and land-use emissions result from these interactions. A large part of the greenhouse gas mitigation potential in LULUCF and agriculture is accessible at low cost, and with relatively minor feedback due to an increased demand for bio-energy. Historical agriculture emissions are harmonised with the emissions from national statistics (FAO); historical LULUCF emissions are directly derived from GLOBIOM (which itself follows national inventory and FAO data). Forest management emissions consider that harvested wood results in emissions and removals upon production; in the rest of the model, combustion of solid bio-energy is considered carbon-neutral (and BECCS is considered carbon-negative to the amount of an average bio-energy carbon content) while liquid biofuels consider conversion efficiencies and transformation energy use in their carbon content.

Finally, the mitigation options for the agriculture sector (as estimated by GLOBIOM [1]), in more detail:

- Technical non-CO_2 mitigation options are included in the model based on the mitigation option database from EPA (Beach et al., 2015) and include: improved fertiliser management, nitrogen inhibitors, improved feed, conversion efficiency, feed supplements (i.e. propionate precursors, anti-methanogen), changes in herd management (i.e. intensive grazing), improved manure management (i.e. anaerobic digesters).
- Structural mitigation options (Havlík et al., 2014) are explicitly represented in the model via four different crop management systems ranging from subsistence farming to high input systems with irrigation technology. For the livestock sector, an extensive set of production systems from extensive to intensive management practises is available based on Herrero et al. (2013). This allows the model to switch between management practises in response to e.g. a carbon price and hence decrease emissions through greenhouse gas efficient intensification. The model may also reallocate production to more productive areas within a region or even across regions through international trade.
- The impact of changes in commodity prices on the demand side is explicitly considered and consumers' react to increasing prices by decreasing consumption depending on the region-specific price elasticities (Muhammad et al., 2011).

The mitigation options for the LULUCF sector (as estimated by GLOBIOM [2]):

- Reduction in deforestation activities.
- Increase in afforestation activities and afforested areas.
- Changes in rotation length of existing managed forests in different locations.
- Changes in the ratio of thinning versus final felling.
- Changes in harvest intensity (amount of biomass extracted in thinning and final felling activity).

[1] For further information about the mitigation options for the agriculture sector as considered within GLOBIOM, we refer to Frank et al. (2018).
[2] For further information about the about the mitigation options for the LULUCF sector as considered within GLOBIOM we refer to Havlík et al. (2014).

2.3 General scenario formulation

The IMAGE and POLES models can assess the implications of various mitigation strategies, in terms of changes in energy system, land use, emissions and associated costs. The IMAGE and POLES models can be used to design baseline scenarios (no climate policies), current policies scenarios and mitigation scenarios that can meet the climate targets of 1.5 °C and 2 °C, at certain probabilities, i.e.:

1. The 2 °C scenarios: keeping global warming below 2 °C in the 21st century, with a probability of at least 66%
2. The 1.5 °C scenarios: keeping global warming below 1.5 °C in 2100, with a probability of at least 50%

The baseline, current policies and mitigation scenarios are represented in the models IMAGE and POLES in different ways, as briefly described below. For the 1.5 °C and 2°C scenarios, we assume different assumptions around the use of BECCS, CCS and bio-energy, as will be described in Section 3.2.

2.3.1 IMAGE model

The IMAGE model is used for exploring mitigation scenarios for achieving the 1.5 °C and 2 °C climate targets, leading to a radiative forcing of 1.9 and 2.6 W/m^2 by 2100.

The IMAGE scenarios analysed here are all based on the IMAGE implementation of the SSP2 baseline scenario (van Vuuren et al., 2017), which is the IMAGE baseline (no policy) scenario in the analysis. The SSP2 scenario describes a middle-of-the-road scenario in terms of economic and population growth and other long-term trends, such as in technology development. The main drivers of this scenario for the energy and industrial sectors are population, gross domestic product (GDP), lifestyle and technology change.

The IMAGE current policies scenario was derived from the original SSP2 baseline by introducing explicit policy measures, and is reported in detail in Roelfsema et al. (2018), van Soest et al. (2017) and Kuramochi et al. (2017). This scenario assumes that current policies are implemented up to 2030. For the 2030–2100 period, the scenario assumes no new policies. Policies may have a long-term effect through the induced technology learning effects (e.g. by additionally installed renewable energy technologies compared to the SSP2 baseline). Mitigation efforts in the land-use sector assume an implementation of a low-carbon tax in the sector, to enhance REDD and to increase reforestation of half of the degraded forest, as described in more detail in Doelman et al. (2018).

In the standard set-up of the model for the mitigation scenarios, the mitigation scenarios are implemented by a universal global carbon tax in all regions and sectors, which is implemented from 2020 onwards, in order to reach the radiative forcing targets following a cost-optimal pathway. Before 2020, all mitigation scenarios assume the full implementation of the countries’ reduction proposals (conditional pledges) for 2020, as part of the Cancun Agreements (based on den Elzen et al. (2016) and the IMAGE implementation, as described in van Soest et al. (2017).

In terms of mitigation in the energy system TIMER covers a wide range of mitigation options, including a major shift from a system mostly based on fossil fuels to an increase in the use of nuclear power, renewable energy (different solar and wind technologies, hydropower), bio-energy (first and second generation), nuclear power and CCS technology, with a correspondingly lower reliance on fossil fuels.

In terms of land-based mitigation options, IMAGE accounts for three general types of options: bio-energy production, REDD (avoided deforestation) and reforestation of degraded forests. Bio-energy demand is determined by TIMER based on bio-energy yield, the carbon price, dynamics in the energy system, and land availability, following a food-first principle (Hoogwijk et al., 2009).

The demand for bio-energy in climate change mitigation scenarios is thereby directly linked to the carbon price required to reach the scenario-specific mitigation target (van Vuuren et al., 2017). More specifically, bio-energy is one of the energy carriers that competes to supply the demand for energy. In combination with carbon capture and storage (BECCS), bio-energy enables the production of negative emissions, by storing carbon that is captured from the atmosphere in the form of biomass. The price and amount of bio-energy in the model, is based on information from the IMAGE land system. The deployment of BECCS occurs in the electricity, hydrogen and industry sectors that adopt the use of BECCS according to its competitive position

REDD is implemented by protecting areas with high carbon stocks according to Ruesch and Gibbs (2008), thereby limiting the total amount of land available for producing food, feed and fibre. Three increasingly strict protection levels are defined at 200, 150 and 100 tC/ha. Reforestation on degraded forest areas restores areas that have been degraded for reasons other than agriculture (e.g. unsustainable forest management, mining, illegal logging). Two levels of reforestation are defined as mitigation options: either half or all of the degraded forest areas are reforested. The level of REDD and reforestation are scenario-specific (linked to the climate target) and thereby only indirectly linked to the carbon price. However, the mitigation level has been roughly calibrated to abatement curves on avoided deforestation as calculated by IIASA (Kindermann et al., 2008). For further details concerning the migration options we refer to Doelman et al. (2018).

Table 1: Levels of REDD and reforestation assumed to be implemented for mitigation targets. The data below is specific for the SSP2 scenario.

Climate target (W/m^2)	REDD*	Reforestation**
1.9	High REDD	Full reforestation
2.6	Medium REDD	Full reforestation
3.4	Low REDD	Half reforestation
4.5	No REDD	No reforestation
6.0	No REDD	No reforestation

* REDD is defined using a carbon density threshold: high REDD: 100 tC/ha, medium REDD: 150 tC/ha, low REDD: 200 tC/ha.

** Full reforestation assumes that all degraded forests are restored, half reforestation assumes that half of degraded forests are restored.

In non-CO_2 greenhouse gases, IMAGE utilises the cost curves approach to account for the future maximum attainable reduction potential and associated costs for these sources of emissions (see Lucas et al., 2007). The cost supply curves accounts for option-specific technical mitigation potentials and costs for CH_4 and N_2O emissions from agriculture sources. Technological options as accounted for in the cost supply curves includes options to reduce CH_4 emissions from rice production, enteric fermentation and animal waste, and options to reduce N_2O emission from animal waste and fertiliser use.

2.3.2 POLES model

The POLES scenarios presented here were finalised in July 2018. The POLES model explored emission pathways for achieving 1.5 °C and 2 °C targets. The scenarios were run through MAGICC 6.0 climate model [3] (Meinshausen et al., 2011a) and a carbon budget that was derived from multiple scenario runs with the targets of keeping warming below the 2 °C and 1.5 °C with a 66% probability, as defined by online MAGICC probabilistic runs [4]. The cumulative anthropogenic CO_2 emissions for the 2010–2100 period are around 1150 $GtCO_2$ for the 2 °C target, which is higher than the IMAGE projections (about 1000 $GtCO_2$ for 2 °C), and around 500 $GtCO_2$ for the 1.5 °C target, which is similar to the IMAGE projections (Appendix A).

The POLES current policies scenario is based on the GECO2017 Reference scenario (Kitous et al., 2017). It includes adopted energy and climate policies worldwide, for 2020, and the extension of the EU ETS to 2050 (with a constantly decreasing cap at -1.74%/yr); after 2020, CO_2 and other greenhouse gas emissions are driven by income growth, energy prices and expected technological development with no supplementary incentivising for low-carbon technologies (Kitous et al., 2017). A full list of the policies considered for the GECO2017 Reference scenario, and their implementation are provided in Annex 5 of the GECO2017 report (Kitous et al., 2017).

The POLES low-carbon scenarios analysed here are all based on the POLES current policies scenario. In the standard set-up of the model, the mitigation scenarios are implemented by a carbon tax, sectoral measures and policies, in all regions and sectors. The main assumptions are described below.

Carbon price:

- Increases over time at a decreasing annual rate
- Carbon price by country is differentiated according to per capita income until 2050, same price afterwards
- AFOLU sector (derived from GLOBIOM lookup tables): carbon price limited (where necessary) to maximum carbon price point provided by GLOBIOM [5]
- All other sectors are subject to the same carbon price

[3] According to MAGICC, see: http://live.magicc.org/ The results presented here used the online version of MAGICC as of October 2018 (nominally this is MAGICC 6.0).
[4] Temperature responses to CO_2 concentrations, CO_2 budgets, the accounting of land use CO_2 emissions and probabilities of reaching a temperature target from MAGICC, in particular those relating to 1.5 °C, should be reassessed in the future with input from new literature, e.g. the IPCC 1.5 °C Special Report.
[5] In order to consider the mitigation potential within the AFOLU sector, POLES need information about the economic potential for AFOLU mitigation. This, together with information about the economic potential for biomass supply and the related emissions, is provided by GLOBIOM in the form of lookup tables. These lookup tables jointly provide two critical pieces of information: i) the economic potential for biomass supply in the form of a supply function where the supplied quantity is a function of biomass price, ii) the economic mitigation potential is described in the form of marginal abatement cost supply curves where the emission reduction is a function of the carbon price. For a specific carbon and biomass price development, the lookup tables thereby provide the full information about the development of the AFOLU sector. In the standard set up, the mitigation potential within the land-use sector is quantified according to a total of 12 carbon price steps ranging from 0 USD/tCO_2eq to a maximum of 2000 USD/tCO_2eq.

Table 2: Carbon price differentiation in POLES scenarios

Income in 2030 (USD2005 per capita)	Countries	2020	2030	2050 and beyond
> 30,000	EU-28, Australia, Canada, Iceland, Japan, Korea (Republic), New Zealand, Norway, Switzerland, United States	100%	100%	100%
20,000–30,000	Chile, China, Malaysia, Russian Federation, Saudi Arabia, Turkey	60%	100%	100%
10,000–20,000	Algeria and Libya, Argentina, Brazil, Iran, Mediterranean countries and the Middle-East, Mexico, Rest of Balkans, Rest of CIS, Rest of Persian Gulf, Rest of South America, South Africa, Thailand, Tunisia, Morocco and western Sahara, Ukraine	40%	100%	100%
<10,000	Egypt, India, Indonesia, Rest of Central America and the Caribbean, Rest of Pacific, Rest of South Asia, Rest of Southeast Asia, Rest of Sub-Saharan Africa, Vietnam	20%	67%	100%

Sectoral measures:

- Buildings:
  - increased rate of renewal of the stock and of renovation of existing surfaces
  - new and renovated surfaces move closer to best-available practices in terms of insulation (country-dependent on the basis of heating and cooling degree days and energy prices)
- Transport:
  - Scenarios assume gradual development of refuelling infrastructure and consumer acceptance over time for electric vehicles
  - Private passenger vehicles: emissions per kilometre travelled in newly sold vehicles per country follow the decreases in emissions per kilometre, due to the fuel or emission standards for vehicles of EU average new sales, as defined by EU regulation on CO_2 emissions from passenger vehicles 2007–2021 and 2021–2030 (10-year delay for non-OECD)
  - Road freight: the decreases in emissions per kilometre across the EU car fleet, over 2007–2021 and 2021–2030, are used as a basis for the decreases in emissions from freight transport, with a 10-year delay (20-year delay for non-OECD)
- Industry:
  - Energy efficiency value (differentiated across countries on income per capita)

Policies:

- Copenhagen pledges (2020) and several energy-related policy targets announced in the NDCs (renewables deployment) are reached or exceeded (2025–2035)

- Carbon prices are at least of a level necessary for reaching the NDC emission level (2025–2035)
- Maritime freight: the IMO objective for 2050 (-50% vs 2008) is achieved
- HFCs: the reduction targets as prescribed by the Kigali Amendment to the Montreal Protocol are reached

2.4 Mitigation scenarios for meeting 1.5 °C and 2 °C targets

Different mitigation scenarios were constructed, along a temperature axis (2 °C or 1.5 °C maximum increase) and a technology axis (mix of technological constraints).

The low-carbon scenarios were calculated for the two climate targets (2 °C and 1.5 °C):

1. The below 2 °C scenarios: keeping global warming below 2 °C in the 21st century with a probability of at least 66% and varying availability of mitigation options, i.e. the use of BECCS, CCS and bio-energy, and alternatively, lifestyle changes.
2. The 1.5 °C scenarios: keeping global warming to 1.5 °C in 2100 with a probability of at least 50% and varying availability of mitigation options. These scenarios show a global mean average temperature increase with a limited overshoot of the 1.5 °C target by about 0.2–0.3°C, before returning to 1.5 °C by 2100.

A general description of the technological constraints is listed in Table 3.

Both models have **Full technology** 2 °C and 1.5 °C scenarios. The IMAGE Full technology 2 °C and 1.5 °C scenarios are described in detail in van Vuuren et al. (2018) (see IMAGE default 1.9 and 2.6 Wm^2 scenarios). In the POLES model, ambitious levels of bio-energy are assumed according to GLOBIOM, of <300EJ/yr by 2100. All POLES scenarios here could be considered as having limited CCS, as the model assumes a delay of the emergence of CCS technologies and limits the annual growth potential for CCS. The POLES scenarios all assume DACCS [6] (with the exception of the No DACCS and No CCS scenarios), first available from 2040; by 2100 can be limited by regional geological storage potential (no physical trade of CO2).

The IMAGE **Limited BECCS – Renewable electricity** scenario and the POLES **Limited Bio-energy**, **Limited Bio-energy – No CCS** scenarios are somewhat comparable, in terms of BECCS implementation. Under the POLES scenario, the limited bio-energy availability results in limited BECCS. Ambitious levels of bio-energy, as under the POLES Full technology scenarios, result in more BECCS, given the emission constraints in these scenarios.

The IMAGE **Limited BECCS – Lifestyle change** scenario assumes a lifestyle change that leads to a less meat-intensive diet, as well as a full package of lifestyle changes. The scenario includes dietary change, food waste reduction and changes in transportation and residential energy use. For dietary change, we assume a quick transition to a healthier diet (the so-called Wilett diet) between 2020 and 2050, with low levels of meat consumption (van Sluisveld et al., 2016). Earlier implementations of this scenario have been described in detail (Bijl et al., 2017; van Vuuren et al., 2018). These sets of assumptions are for IMAGE only

[6] Direct Air Carbon Capture & Storage

included in the Lifestyle scenario. In POLES, all scenarios include a food security constraint to avoid strong decreases in calorie intake (especially in developing countries) under high carbon prices on AFOLU emissions, which increase agricultural prices for greenhouse gas intensive products such as ruminant meat, milk, or rice. This constraint basically ensures that by 2030 the population at risk of hunger cannot be higher than 1% in developing countries. This constraint is in line with SDG2 Zero Hunger of around 10% in 2016 according to FAOSTAT. The food security constraint forces a certain level of calorie intake for vegetal and animal calories corresponding to an undernourishment of maximum 1% by 2030. If developing countries exceed this calorie intake threshold over time, they may reduce their consumption levels because of the carbon price response to that threshold, or they may not. Developed regions are able to decrease their calorie intake to 2010 consumption levels.

Table 3: Description of the mitigation scenarios included in this analysis, for 2 °C and 1.5 °C, in the IMAGE and POLES model

Scenario name	Scenario description
IMAGE SSP2 baseline	IMAGE implementation of the SSP2 scenario.
IMAGE current policies	Implementation of current policies until 2030 and constant reduction effort (compared to IMAGE SSP2 baseline) between 2030 and 2100.
POLES current policies	Implementation of current policies until 2020; no additional policies beyond 2020.

Scenario name	Scenario description
IMAGE 2 °C Full technology	Full technology implementation with a universal global carbon tax in all regions and sectors from 2020 onward. Selection of technologies based on relative costs.
POLES 2 °C Full technology	Full technology implementation with a carbon tax in all regions and sectors from 2018 onward (differentiated by region, uniform from 2050). Selection of technologies based on relative costs.
IMAGE 2 °C Limited BECCS – Lifestyle change	Limited deployment of BECCS through implementation of lifestyle changes. Consumers change their habits towards a lifestyle that leads to lower greenhouse gas emissions. This includes a less meat-intensive diet (conform health recommendations), less CO_2-intensive transport modes (following the current modal split in Japan), less intensive use of heating and cooling (change of 1 °C in heating and cooling reference levels) and a reduction in the use of certain domestic appliances. It assumes further optimistic afforestation levels from the SSP1 scenario.
IMAGE 2 °C Limited BECCS – Renewable electricity	Limited deployment of BECCS through higher electrification rates in all end-use sectors, in combination with optimistic assumptions on the integration of variable renewables and on costs of transmission, distribution and storage.
POLES 2 °C Limited Bio-energy	Limited availability of bio-energy (<180 EJ/yr, all years) achieved by additional demand-side measures targeted at bio-energy use.
POLES 2 °C Carbon tax only	Similar to the POLES 2 °C Limited Bio-energy scenario. However, the only mitigation measure applied is that of carbon pricing, uniformly implemented across sectors and countries; this scenario does not include

	specific measures on a sectoral level (e.g. vehicle fuel standards), hence a higher carbon tax level.
POLES 2 °C Limited Bio-energy – No DACCS	Similar to the POLES 2 °C Limited Bio-energy scenario, without deployment of DACCS
POLES 2 °C Limited Bio-energy – No CCS	Similar to the POLES 2 °C Limited Bio-energy scenario, without deployment of CCS.

Scenario name	Scenario description
IMAGE 1.5 °C Full technology	Full technology implementation with a universal global carbon tax in all regions and sectors, from 2020 onward. Selection of technologies based on least-cost options.
POLES 1.5 °C Full technology	Full technology implementation with a differentiated carbon tax in all regions and sectors, from 2018 onward (differentiated by region, universal from 2050). Selection of technologies based on least-cost options.
IMAGE 1.5 °C Limited BECCS – Lifestyle change	Limited deployment of BECCS through implementation of lifestyle changes.
IMAGE 1.5 °C Limited BECCS – Renewable electricity	Limited deployment of BECCS through higher electrification rates and implementation of renewables.
POLES 1.5 °C Limited Bio-energy	Limited availability of bio-energy for energy (<180 EJ/yr, all years) achieved by additional demand-side measures targeted at bio-energy use.

2.4.1 Model implementation of scenarios

As a full technology configuration, the implicit "subsidy" of BECCS, in the POLES model resulting from the negative carbon emissions, was capped for example to ensure that despite this "carbon subsidy" the electricity with BECCS is not produced at a negative or zero cost [7]. In addition, to limit the diffusion of BECCS, the JRC has limited the overall availability of 'bio-energy-for-energy' in all demand sectors. As a result, more electrification and penetration of non-bio-energy renewables is expected.

Conversely, the PBL IMAGE model used the opposite set-up by introducing alternative activity development and energy option availability, i.e. lifestyle changes and more electrification and renewables, leading to lower BECCs. For example, for the lifestyle scenario, we first apply the lifestyle change assumptions in the IMAGE model, leading to a lower emission trend compared to the SSP2 emission projections. Applying the same carbon tax as under the Full technology scenarios of 1.9 and 2.6 W/m^2 will lead to radiative forcing levels by 2100 of below the target levels of 1.9 and 2.6 Wm^2. In order to meet these

[7] BECCS as a sequestration technology would generate revenue from electricity sales and "carbon revenue" as a consequence of it being a net-negative emissions technology; this would potentially crowd out other generation technologies. This effect is limited in the model by using BECCS only in certain parts of the load (after wind and solar contribution and not during peak load hours) and by assuming BECCS is deployed only up to the point where it becomes competitive with the cheapest centralized electricity generation technology (but not beyond this point).

radiative forcing targets levels, a premium factor on the use of BECCS is introduced. The final level is calculated through an iterative process of multiple runs, in which each time the factor is continuously increased until the required forcing levels are reached.

While the POLES model showed that all selected 2 °C scenarios are feasible, two scenarios run with the IMAGE model were "infeasible". These were a **2 °C No CCS** and **2 °C No BECCS** scenario that do not permit the deployment of the respective technologies. An "infeasible" scenario means that a specific model in our set could not find a solution given the combination of limited action until 2020, and meeting the radiative forcing targets for the IMAGE, and the carbon budget targets for the POLES scenario. Infeasibilities may occur due to different reasons, such as lack of mitigation options to stay within the carbon budget or radiative forcing constraints or binding constraints for the diffusion of technologies (Riahi et al., 2015).

In the context of the 1.5 °C target, significantly fewer scenarios were found to be feasible. The POLES model only found feasible scenario outcomes under the Full Technology and Limited Bio-energy scenarios, and the IMAGE model found feasible outcomes only under the Full Technology and two Limited BECCS scenarios.

3 Current policies and Full technology mitigation scenarios

3.1 Current policies scenarios

Findings

- **The IMAGE and POLES global models have similar greenhouse gas emission projections under Current policies scenarios until 2030. After 2030, however, their projections diverge due to different assumptions about the post-2030 period.**

- **Bio-energy use, under the Current policies scenarios, increases throughout the century in both models, with a 62% increase by 2100 (compared to 2010) under the IMAGE Full technology scenario and a 71% increase under the POLES scenario.**

Results

This section compares the IMAGE Current policies scenario, as described in detail in Roelfsema et al. (2018), van Soest et al. (2017) and Kuramochi et al. (2017), with the POLES Current policies scenario. This IMAGE scenario assumes that current policies are implemented up to 2030, and that after 2030, the induced technology learning effects will lead to around 5% reduction in greenhouse gas emissions (excluding those from land use), compared to the IMAGE SSP2 baseline scenario. Mitigation efforts in the land-use sector also lead to enhanced REDD and increased reforestation of half the degraded forest, as described in more detail in Chapter 5 and in Doelman et al. (2018).

POLES assumes a different pathway for their current policies scenario in which current policies are implemented up to 2020 (except for the EU ETS, which is extended to 2050) and market prices and technological development drives emissions until the end of the century, resulting in roughly stable emissions from the 2050s onwards.

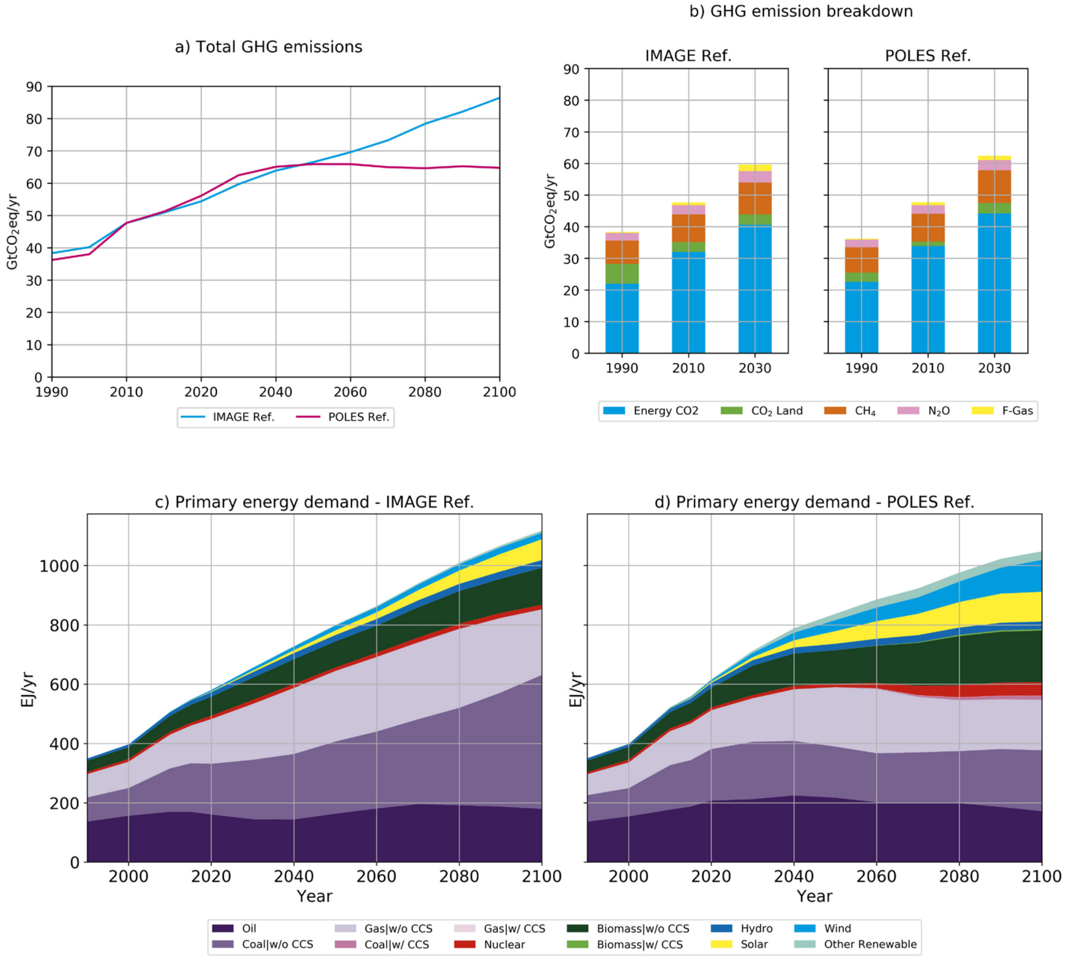

Figure 1. Global greenhouse gas emissions (panel a and b) and primary energy demand by energy carrier (panel c and d) for the IMAGE and POLES current policies (Ref.) scenarios

The top left plot of Figure 1a shows the development of total greenhouse gas emissions over time for the IMAGE and POLES current policies scenarios. It shows that both models have similar greenhouse gas emission projections of current policies scenarios until 2030, but after 2030, their projections diverge due to different assumptions about the post-2030 period. The relative reduction under the IMAGE current policies scenario, compared to the SSP2 baseline, is about 5%. The greenhouse gas emissions under the POLES current policy scenario stabilises after 2030.

Figure 1b shows the individual greenhouse gas emissions in 1990, 2010 and 2030 for both models. Breaking down the greenhouse gas emissions into separate gases, and differentiating between CO_2 emissions from the energy and land-use sectors, shows that main differences can be found in land-use-related CO_2 emissions (i.e. CO_2 emissions from land-use changes and removals). These emissions are lower under the POLES reference scenario, as a result of the use of the historical land-use emission estimates from national inventories. The latter are lower than the historical land-use emissions as simulated in integrated assessment models (Grassi et al., 2017) (see Section 5.1). Figure 1c and 1d (bottom two plots of the figure) shows the primary demand for current policies for both models. The historical primary energy demand is about the same for both models, which is expected as both models are calibrated on energy demand data from IEA. The breakdown into energy carriers reveals that the models assume that different technological pathways to evolve over the course of the century. POLES achieves the constant Kyoto emissions by switching from a fossil-dominated energy mix to one in which renewables play a larger role.

Even in the absence of targeted climate mitigation policies renewables become cost-competitive against fossil fuel use in many regions of the world for the POLES scenario. This is not the case for the IMAGE scenario. In the current policy scenario, coal is still a dominant energy by the end of the century. Both models however show that the use of bio-energy increases (with and without CCS), with an increase of 41% and 62% in 2050 and 2100 compared to 2010 for IMAGE and 54% and 71% in 2050 and 2100 compared to 2010 for POLES. The use of bio-energy combined with CCS however is negligible in both scenarios. BECCS does not become cost-competitive and plays no role in a world in which no additional mitigation efforts are required.

3.2 The 2 °C Full technology scenarios

Findings

- **Model-based scenarios show that Full technology scenarios exist in which all technologies are assumed to be available that limit global warming to below 2 °C in the 21st century, with at least 66% probability.**

- **The Full technology 2 °C scenarios of IMAGE and POLES reach emissions of 2.8 and -0.7 $GtCO_2eq$/yr by 2100. The POLES 2 °C scenario reaches greenhouse gas neutrality (net zero greenhouse gas emissions) after 2090. Greenhouse gas emissions are reduced by a respective 56% and 51% by 2050, from 1990 levels, under the 2 °C Full technology IMAGE and POLES scenarios.**

- **Global greenhouse gas emissions under the IMAGE and POLES Full technology 2 °C scenarios are in the lower emission range for 2050, and in the upper range for 2100 of all full technology 2.6 W/m^2 scenarios from all global models based on the SSP multi-model comparison study (Rogelj et al., 2018).**

- **Full technology scenarios rely on rapid and deep emission reductions through a mix of energy efficiency, rapid introduction of energy options without CO_2 emissions (e.g. renewable energy and CCS), negative emission options (e.g. bio-energy with CCS (BECCS) and afforestation) and reduction in non-CO_2 greenhouse gas emissions. The IMAGE 2 °C scenario has a higher contribution of energy efficiency improvements and CCS, whereas the POLES 2 °C scenario relies more on rapid penetration of renewable energy technologies.**

- **The increase in bio-energy use is substantial in both models, but higher in the POLES scenario due to the greater availability of biomass for energy.**

- **In the IMAGE scenario, CCS is being deployed early and the share between fossil fuel and bio-energy with CCS is roughly evenly distributed. In the POLES scenario, CCS is deployed later and is dominated by BECCS.**

Results

For the analysis of the 2 °C scenarios, the two models assume different climate constraints. The IMAGE model is used to explore 2 °C emission pathways assuming that radiative forcing reaches 2.6 W/m^2 by 2100, whereas the POLES model explores 2 °C pathways by finding the cumulative anthropogenic CO_2 emissions for the 2010–2100 period compatible with that maximum temperature increase (according to MAGICC). As a result, the cumulative CO_2 emissions for that period, under the IMAGE scenarios, reach about 1000 $GtCO_2$, which is slightly lower than under the POLES scenarios (around 1150 $GtCO_2$) (Appendix A).

This section only explores Full technology scenarios, in which the full portfolio of technologies is available and there are no limitations on the use of bio-energy, CCS, BECCS, or nuclear power. Chapter 4 explores the impact of limiting the use of BECCS and bio-energy on the 1.5 °C and 2 °C scenarios.

Figure 2 shows that the global greenhouse gas emissions for the Full technology 2 °C scenarios for both models are similar. Both models show strong, rapid reductions in greenhouse gas emissions from 2020 onward, reaching a reduction of 51%–56% below 1990, by 2050. The IMAGE scenario achieves slightly more emission reductions in the 2050–2070 period than the POLES scenario. This results in a lower mitigation effort at the end of the century.

Comparing our global emission pathways with similar Full technology 2 °C pathways from other global models from the SSP multi-model comparison exercise (Rogelj et al., 2018) (Riahi et al., 2017) shows that POLES and IMAGE are at the lower end of the emission range in 2050, and at the higher end of the range in 2100. In general, POLES and IMAGE do not show high negative emissions in 2100. This is shown in Figure 2 where the light blue lines represent a range of cost-optimal 2.6 W/m^2 scenarios run by multiple IAMs (Rogelj et al., 2018). It should be noted that the selected SSP scenarios, similarly to the IMAGE and POLES scenarios, assume limited action until 2020 and least-cost reductions from 2020 onwards in order to meet the radiative forcing objective of 2.6 W/m^2 by 2100. The POLES and IMAGE Full technology 2 °C scenarios reach between 51% and 56% below 1990 levels by 2050, and reach greenhouse gas neutrality after 2090 (carbon neutrality or net zero CO_2 emissions is achieved between 2070 and 2080, see Figure 4a). Most similar scenarios in literature consistent with the 2 °C target reach greenhouse gas neutrality in the second half of the century (Figure 2).

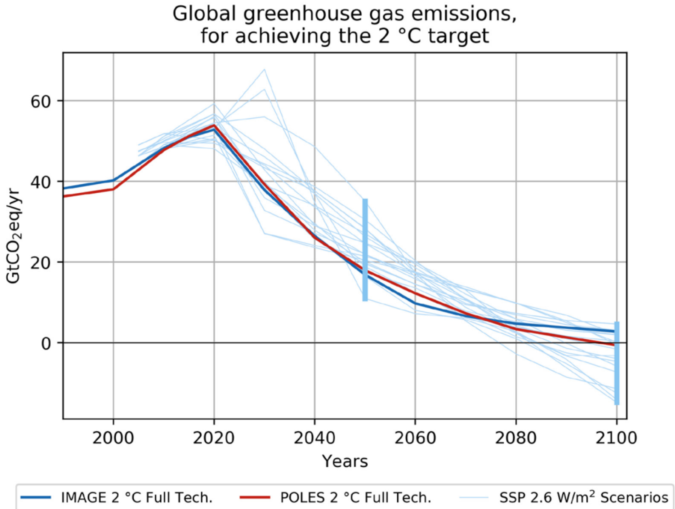

Figure 2. Global greenhouse gas emissions under the 2 °C Full technology scenarios of IMAGE and POLES, compared to a set of cost-optimal (2020) SSP2 2.6 W/m^2 scenarios.

Although in terms of total greenhouse gas emissions the models show similar results, there are differences noticeable when decomposing emissions into separate greenhouse gas categories, as has been done in Figure 3. Looking first at the non-CO_2 greenhouse gas emissions reveals that, although there is quite a reduction potential, these emissions cannot be reduced to zero (Figure 3). This is shown for both the IMAGE and POLES scenario and can in large part be explained that for several sources, only a constrained reduction potential has been identified, in particular from agriculture (e.g. for rice cultivation and animal husbandry) (Gernaat et al., 2015; Lucas et al., 2007). [8] N_2O emissions hardly change over time, under both scenarios, and are quite similar for both models. CH_4 emissions remain at around 3.5–4.5 $GtCO_2eq$ after 2050, with the POLES scenario showing slightly lower projections. The F-gas emissions reach zero, and are about the same for both models.

The land-use-related CO_2 emissions are projected to decrease over time, reaching zero under the POLES model by 2025, and for IMAGE by 2060. The land-use emission projections for the POLES scenarios remain about -2 $GtCO_2$ after 2030, whereas for the IMAGE scenario this level is not reached even by 2100. The 2010 emission levels are already lower in the POLES model, due to differences in the data sets being used by POLES and IMAGE to define the historical levels of emissions [9], as explained in Section 3.1, and will be explained in more detail in Section 5.1.

Concluding, the scale of reduction potential in terms of CO_2 emissions from land-use changes and non-CO_2 greenhouse gas emissions is lower compared to the emission reduction potential in the energy sector for both models, as analysed below.

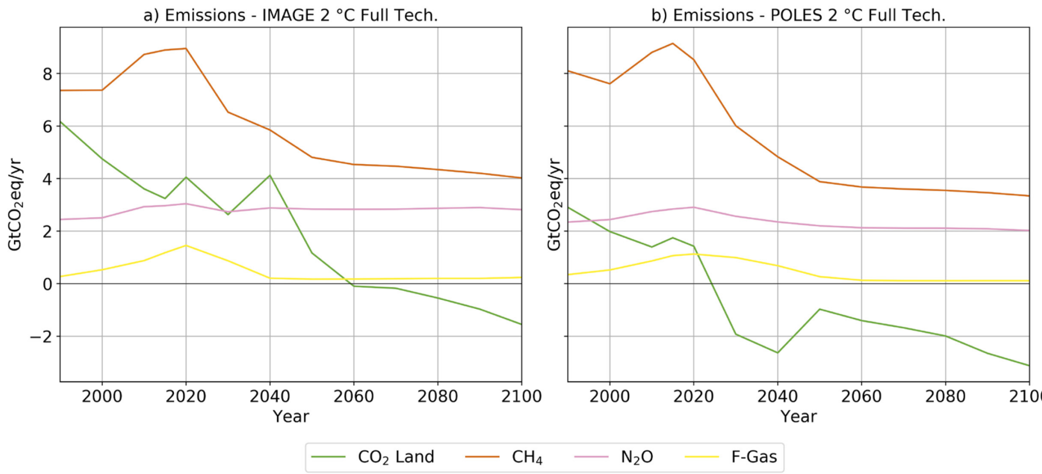

Figure 3. Global non-CO_2 greenhouse gas emissions and land-use-related CO_2 emissions, under the 2 °C Full technology scenarios of IMAGE (panel a) and POLES (panel b).

Significant reductions are achieved in both models in terms of energy- and industry-related CO_2 emissions. A useful method for analysing the differences between models in terms of energy- and industry-related CO_2 emissions and emission reductions is the Kaya identity (Kaya, 1989) that decomposes the emissions into four factors: population (Pop), per capita income (Pop/GDP), final energy (FE) intensity of economic production (FE/GDP), and carbon intensity of energy use (CO_2/FE). Here, we combine the first two factors, population (Pop) and per capita income (GDP/Pop), into the economic production (GDP). We also show primary energy demand instead of final energy use. Using the Kaya identities (Figure 4) we see that the lower energy- and industry-related CO_2 emissions under the IMAGE scenario (Figure 4a) are driven by a lower primary energy intensity of the economy (Figure 4b), (in

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[8] Including all potential reduction measures including management and structural changes would lead to a higher reduction potential, as has been done in Frank et al. (2017).
[9] Harmonising of the model projections implies that the starting point (2010) of the scenarios becomes the same as the inventory data, but the emissions trend of the projections remains unchanged. See Chapter 6.

the second half of the century) a lower increase in GDP (Figure 4c) and lower carbon intensity of energy (Figure 4d).

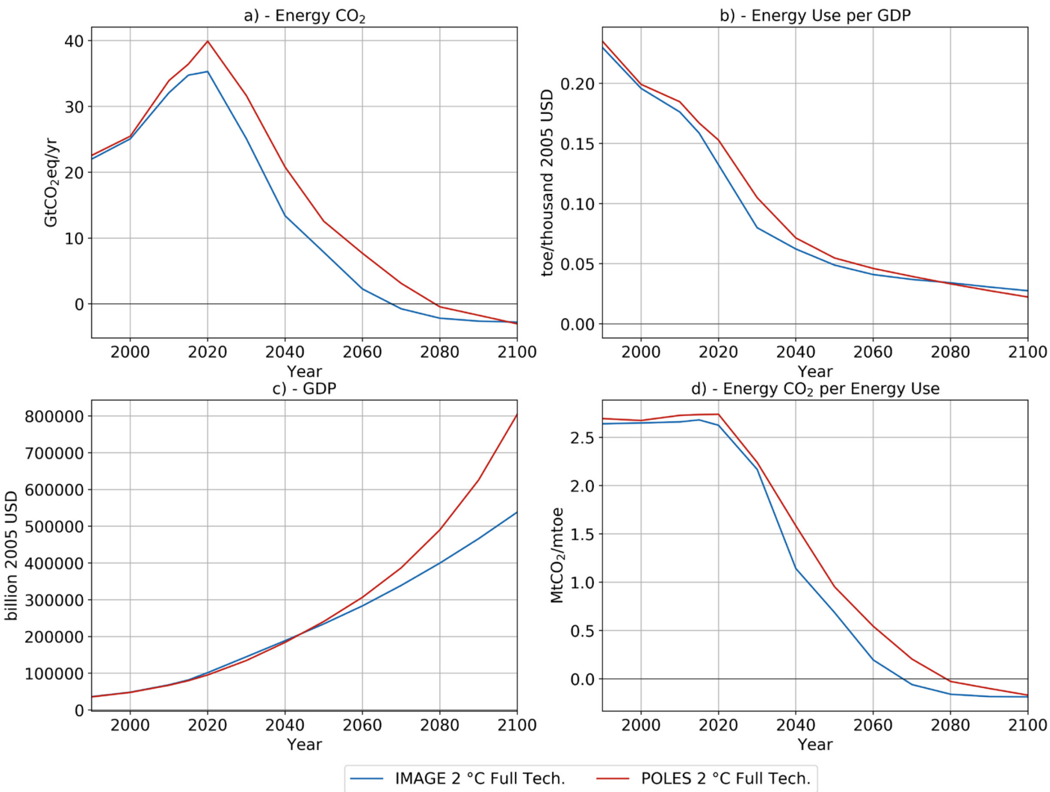

Figure 4. Global Kaya indicators under the Full technology 2 °C scenarios of IMAGE and POLES. The panels show the energy- and industry-related CO_2 emissions (panel a), primary energy intensity of economic production (panel b), GDP (panel c) and carbon intensity of energy use (panel d).

Relating these emissions to other indicators shows that the reductions in energy- and industry-related CO_2 emissions under the Full technology IMAGE scenario are driven more by improvements in energy efficiency than they are under the POLES scenario. It can be seen that, up to 2070, the IMAGE scenario has lower values for the energy per unit value of GDP and also lower values for energy-related CO_2 emissions per unit of energy.

The lower energy intensity and GDP projections for the IMAGE scenario result in primary energy demand being lower compared to the POLES scenario, as is also illustrated in Figure 5. Emission reductions for the POLES scenario are driven to a lesser extent by energy efficiency improvements and more by decarbonisation. This becomes clear when looking in more detail at the primary energy demand.

The shares of renewables increase considerably from 2020 onward for the POLES scenario, especially when compared to the IMAGE scenario. Figure 5 gives a decomposition of primary energy demand for both these scenarios, showing a substitution of fossil primary energy for renewables, and a corresponding decline of carbon intensity of the economy after 2020 (as shown in Figure 4b).

In order to stay below 2 °C, both models convert the global energy system from one that is based almost completely on fossil fuels (as it is currently) to one in which renewable energy, nuclear power or CCS play an important role. The POLES scenario shows a larger increase in renewables use. In the IMAGE scenario the increase in nuclear power is larger and there is an increase in the use of CCS, both fossil and bio-energy based. The overall use of bio-energy is however lower for the IMAGE scenario compared to POLES, which assumes high bio-energy availability.

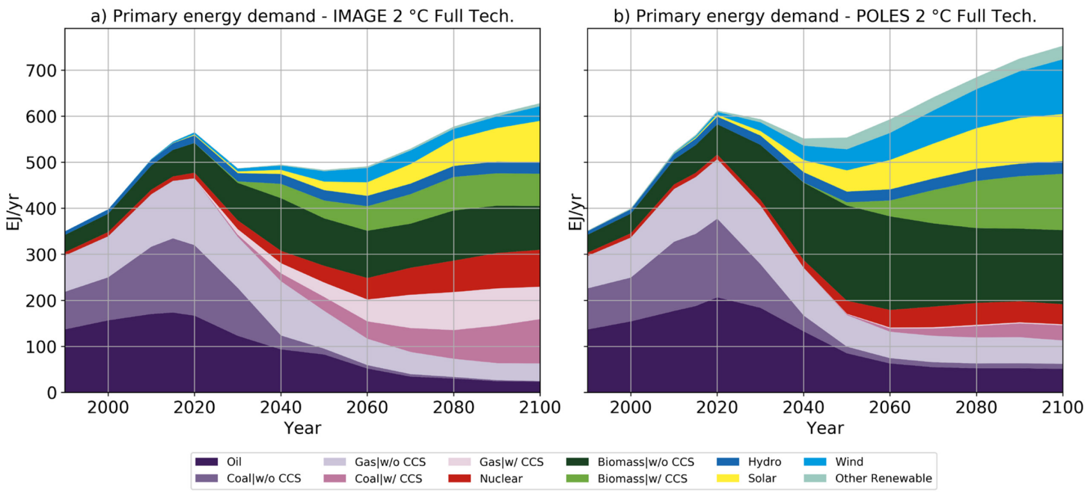

Figure 5. Global primary energy demand for the Full technology 2 °C scenarios of IMAGE (panel a) and POLES (panel b).

In the IMAGE scenario, the use of CCS starts already from 2025/2030 onwards, showing an increasing trend and leading to a large total share of CCS already by 2050, much larger compared to the POLES scenario. This large difference in the contribution of CCS is mainly caused by the cost-competitiveness of CCS versus other mitigation options in IMAGE. In addition, it is partly caused by the higher land-use-related CO_2 emissions under the IMAGE scenario and the more stringent climate target for the IMAGE scenario, which increases the need for greater reductions within the energy-system. This climate target leads to lower cumulative CO_2 emissions for the 2010–2100 period under the IMAGE scenario, about 1000 $GtCO_2$, compared to 1150 $GtCO_2$ under the POLES scenario; from 2010 until 2100, CCS technologies capture 770 and 480 $GtCO_2$ in IMAGE and POLES, respectively. In addition, all POLES scenarios consider CCS to be a technology that has not yet matured; the first CCS plants are only allowed to be installed in the 2030s and wider adoption just on the basis of costs happens only from 2050 onwards; as a result, the contribution of CCS in 2050 is lower in POLES. A more detailed analysis of the cumulative emissions is given in the Appendix A.

Both models also show a clear difference in contribution of CCS (Figure 6). IMAGE has a more even distribution of fossil fuels with CCS and BECCS than POLES. The large share of BECCS for POLES is a result of the cost-competitiveness of BECCS versus other options, despite high bio-energy prices because of biomass scarcity, and due to the high carbon price and capture rate of CCS being lower than 100%. In IMAGE, also fossil CCS remains competitive given the increasing bio-energy prices because of biomass scarcity.

Finally, while in both models total biomass use increases over time, the models reach different levels overall. Biomass use in POLES increases by 2100 to a level (280 EJ/yr) close to the total global potential (300 EJ/yr, according to GLOBIOM). In IMAGE biomass use increases significantly up to 2040, then increases much more gradually afterwards to reach a lower level (165 EJ/yr); this level of biomass use is lower than the maximum potential (see 1.5 °C scenario, where IMAGE reaches levels similar to POLES).

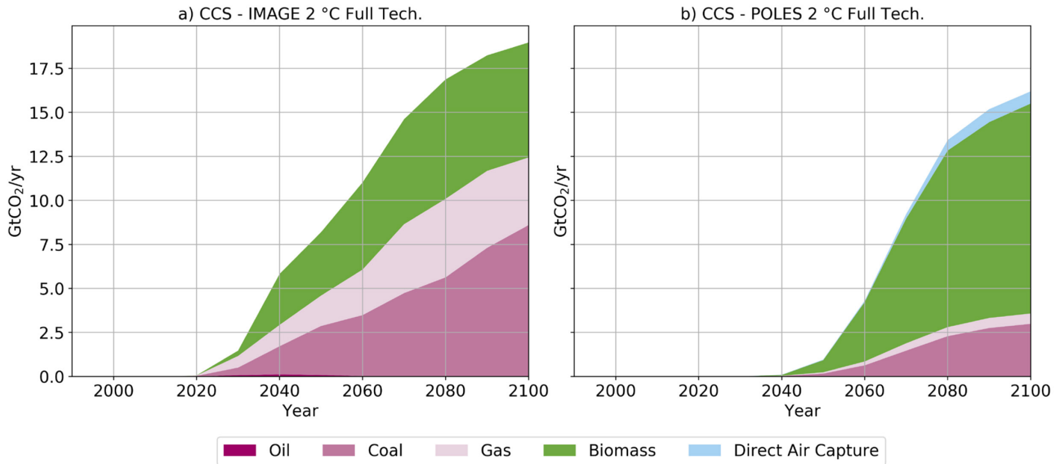

Figure 6. Carbon captured per energy carrier, or by technology in the case of direct air capture, under the Full technology 2 °C scenarios of IMAGE (panel a) and POLES (panel b), for the energy carriers with CCS.

3.3 The 1.5 °C Full technology scenarios

Findings

- **The Full technology 1.5 °C scenarios of both global models show that pathways exist that limit global warming to below 1.5 °C by 2100, relying strongly on bio-energy and negative CO_2 emission technologies.**
- **Global greenhouse gas emissions under the 1.5 °C scenarios reach net zero in the second half of the century, i.e. between 2050 and 2070, which is about 40 years earlier than under the 2 °C scenarios. Global emissions are reduced by 70% to 76% by 2050, from 1990 levels.**
- **Greenhouse gas emissions under the 1.5 °C scenarios of IMAGE and POLES reach about -10 to -5 $GtCO_2eq/yr$ by 2100. This is within the range of Full technology 1.5 °C scenarios from all global models in the SSP multi-model comparison study, albeit in the upper part of this range (Rogelj et al., 2018).**
- **Similar to the 2 °C scenarios, the IMAGE 1.5 °C scenario has greater energy efficiency improvements and more CCS than the POLES 1.5 °C scenario. The POLES 2 °C scenario focuses more on decarbonisation of the energy system through more renewable energy supply.**
- **Bio-energy use is significantly greater in the IMAGE 1.5 °C scenario, compared to that in the 2 °C scenario, but it is almost the same in the POLES 1.5 °C scenario.**
- **There is significantly more deployment of BECCS in the IMAGE 1.5 °C scenario than in the 2 °C scenario, whereas, in POLES, the deployment of BECCS is very similar in the 1.5 °C and 2 °C scenarios.**

Results

Similar to the 2°C scenarios, in the 1.5 °C scenarios, the IMAGE and POLES models assume different climate constraints. The IMAGE model explores emission pathways for 1.5 °C assuming that radiative forcing reaches 1.9 W/m^2 by 2100, whereas the POLES model explores emission pathways for achieving 1.5 °C by finding the cumulative anthropogenic CO_2 emissions for the 2010–2100 period compatible with that temperature increase (according to MAGICC) of around 550 GtCO_2. This section again focuses on the Full technology scenarios.

Figure 7 shows the greenhouse gas emission pathways for meeting 1.5 °C for the POLES and IMAGE model. It shows that POLES has slightly lower greenhouse gas emissions already in 2020. The emission reduction pathways for both models show a similar pattern, with emissions rapidly reducing after 2020, but the POLES scenario shows an even more rapid decline after 2020 and emissions go deeper in 2100 than they do for the IMAGE scenario.

Comparison with a range of cost-optimal SSP 1.9W/m^2 scenarios run by other models (Rogelj et al., 2018) shows that both the POLES and IMAGE 1.5 °C scenarios are clearly within the range, over the whole period. However, specifically in 2050, both scenarios are more on the high end of the range (Figure 7). This is in contrast with the 2 °C scenarios of IMAGE and POLES, which show greenhouse gas emissions in 2050 at the lower end of the SSP 2.9 W/m^2 scenario range. Under full technology assumptions the POLES and in particular IMAGE 1.5 °C scenarios lead to fewer negative emissions than other IAM full technology SSP 1.9W/m^2 scenarios.

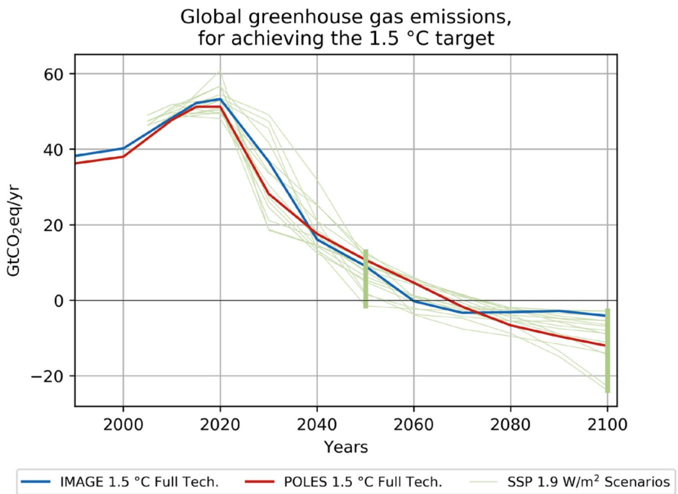

Figure 7 Global greenhouse gas emissions under the 1.5 °C Full technology scenarios of IMAGE and POLES, compared to a set of cost-optimal SSP 1.9 W/m^2 scenarios.

Under the 1.5 °C scenarios of IMAGE and POLES, global greenhouse gas emissions in 2050 are about 7 to 8 GtCO_2eq lower than under their 2 °C scenarios, reaching 76% to 70% reductions below 1990 levels, respectively. Global emissions under the 1.5 °C scenarios reach zero in the second half of the century, i.e. between 2060 and 2070, which is about 40 years earlier compared to under the 2 °C scenarios of IMAGE and POLES. Figure 7 shows that the time period (2060–2070) for which the zero emissions are reached are in the middle of the full range projected by all SSP 1.9 W/m^2 scenarios.

Looking at the pathways of individual greenhouse gases, we see that non-CO_2 and land-use-change-related CO_2 emissions are similar under the 1.5 °C and 2 °C scenarios of both models (Figure 8).

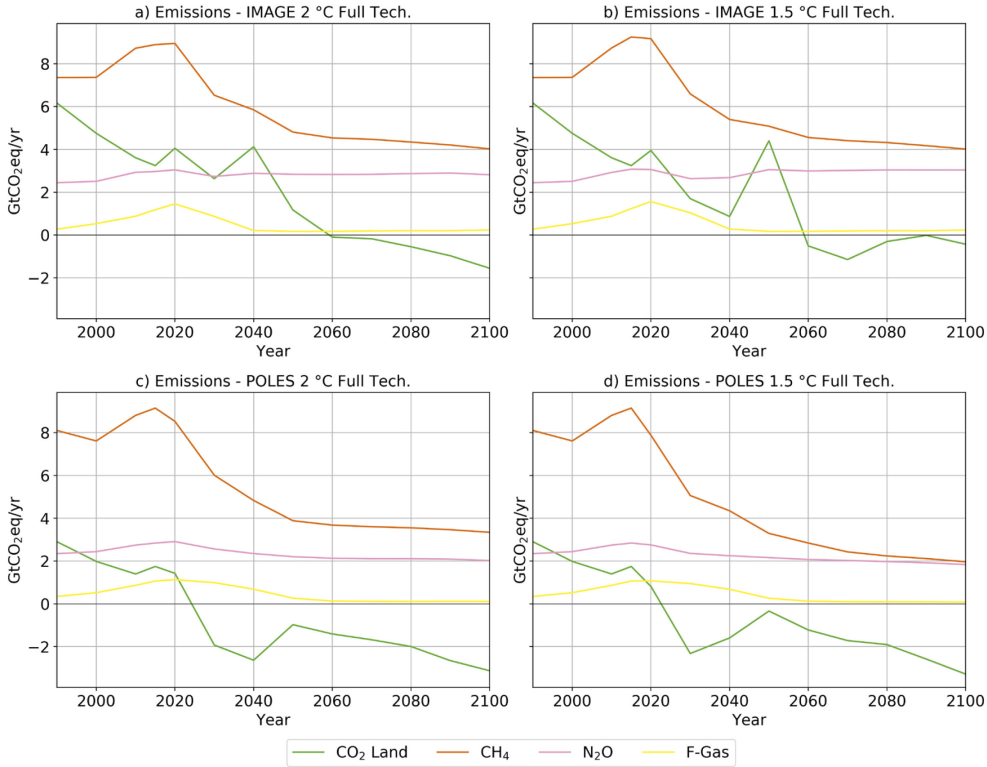

Figure 8. Global non-CO_2 greenhouse gas emissions and land-use-change-related CO_2 emissions in $GtCO_2eq/yr$, under the 2 °C and 1.5 °C Full technology scenarios of IMAGE (panel a and b) and POLES (panel c and d).

The sum of total non-CO_2 greenhouse gas emissions and land-use-related CO_2 emissions expressed as CO_2-equivalent emissions shows, for the IMAGE model, only a marginal difference between the 1.5 °C and 2 °C scenarios, reaching about 5 and 7 $GtCO_2eq/yr$, respectively, by 2100 (see Table 4). In 2050, under the IMAGE 1.5 °C scenario, the land-use emissions are somewhat higher due to the expansion in bio-energy production. However, given the uncertainty about the timing, it is more useful to see the long-term trend. As such, the 2050 emission reduction for the 1.5 °C target is not structurally dissimilar from the one for the 2 °C target. For the POLES model, the total emissions, under the 1.5 °C and 2 °C emissions, reach much lower levels by 2100 (i.e. 0.5 and 2.5 $GtCO_2eq/yr$), mainly due to lower CH_4 and land-use-related CO_2 emissions. These remaining emissions need to be compensated by more negative energy- and industry-related CO_2 emissions (Figure 9a), in particular under the 1.5 °C scenario, in order to reach negative greenhouse gas emission levels by 2100 (see Figure 6).

Table 4. Global total non-CO_2 greenhouse gas emissions and land-use-related CO_2 emissions in $GtCO_2eq/yr$, under the 2 °C and 1.5 °C Full technology scenarios of IMAGE and POLES, in 2010 and reductions in 2050 and 2100.

Scenario	2010 emissions	2050 reductions compared to 2010	2100 reductions compared to 2010
IMAGE 2 °C Full Technology	16.1	44%	66%
IMAGE 1.5 °C Full Technology	16.1	21%	58%
POLES 2 °C Full Technology	13.8	61%	83%
POLES 1.5 °C Full Technology	13.8	61%	96%

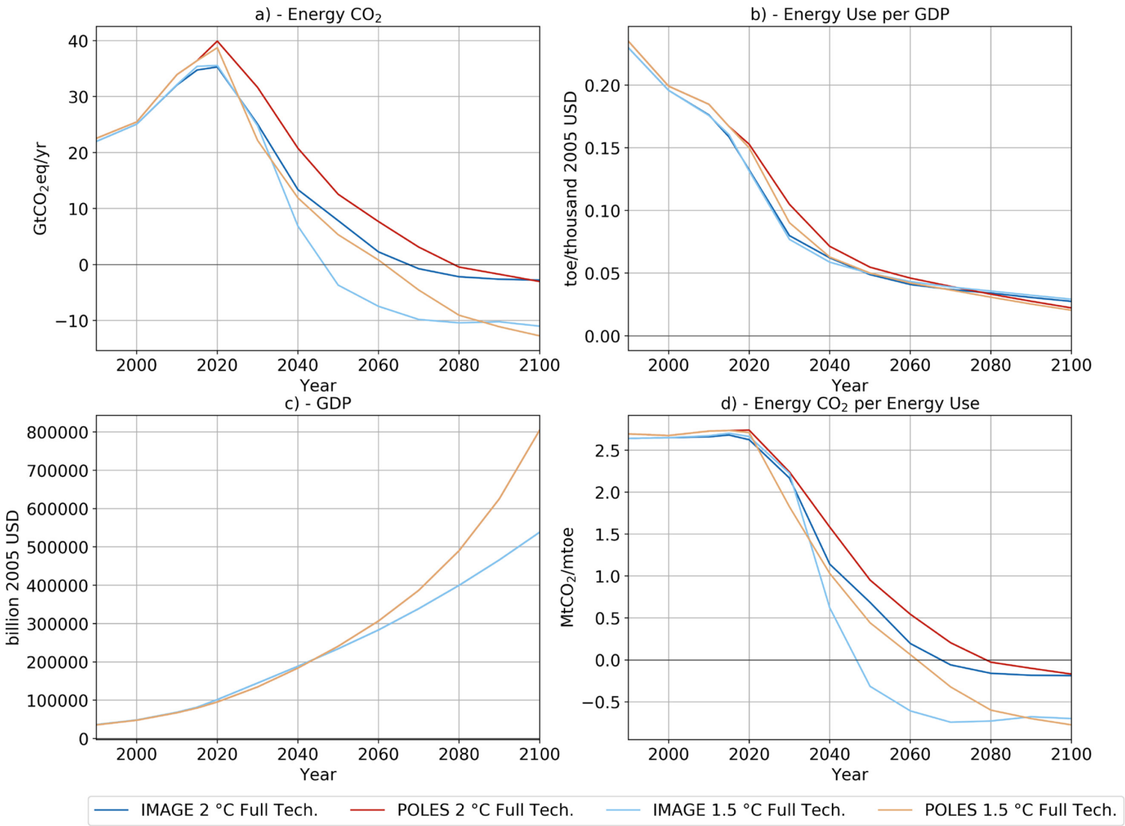

Figure 9. Global Kaya indicators for the Full technology 2 °C and 1.5 °C scenarios of IMAGE and POLES. The panels show the energy- and industry-related CO_2 emissions (panel a), primary energy intensity of economic production (panel b), GDP (panel c) and carbon intensity of energy use (panel d). GDP is the same under the 2 °C and 1.5 °C scenarios of the individual models and, hence, lines overlap in panel c.

Figure 9 shows the energy-related emissions, and the Kaya factors, as is done in the previous section, under the 2 °C and 1.5 °C Full technology scenarios of both models. The results shows large similarities between both models. Both models show the reduction in energy-related CO_2 emissions when comparing the scenarios with their 2 °C counterparts. The POLES scenario reduction starts earlier (Figure 9a). This is driven by an early decarbonisation of energy for the POLES scenario (Figure 9d). The projected carbon intensity of energy use, in each model, roughly reaches about the same level of CO_2 per GDP at the end of the century, under the 2 °C and 1.5 °C scenarios. The projected energy intensity of the economy (Figure 9b) shows that the IMAGE 1.5 °C scenario is almost identical to the

2 °C scenario, whereas for POLES there is a decrease with respect to the 2 °C scenario, signifying that not all potential had been used under the 2 °C scenario. This improvement in energy efficiency leads a lower projected total primary energy demand under the POLES 1.5 °C scenario, as illustrated in Figure 10. However, the primary energy demand is still higher compared to that under the IMAGE scenario (Figure 10).

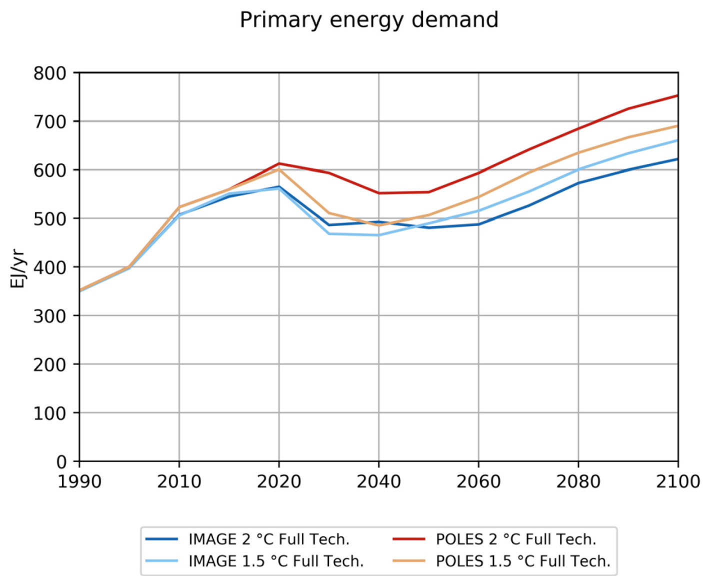

Figure 10. Global primary energy demand under the Full technology 2 °C and 1.5 °C scenarios of IMAGE and POLES.

For bio-energy and CCS, we see that the IMAGE 1.5 °C scenario, when compared to its 2 °C counterparts, relies more on these technologies than the POLES 1.5 °C scenario. This can be seen in Figure 11, where both indicators are shown for the 2 °C and 1.5 °C scenarios. Figure 10 shows that the primary energy demand under the IMAGE 1.5 °C scenario is higher compared to the IMAGE 2 °C scenario, which is a direct result of (i) higher bio-energy demand due to energy losses occurring with the conversion of primary biomass into energy and (ii) the larger share of bio-energy in energy supply. The additional emissions are compensated by a greater use of BECCS.

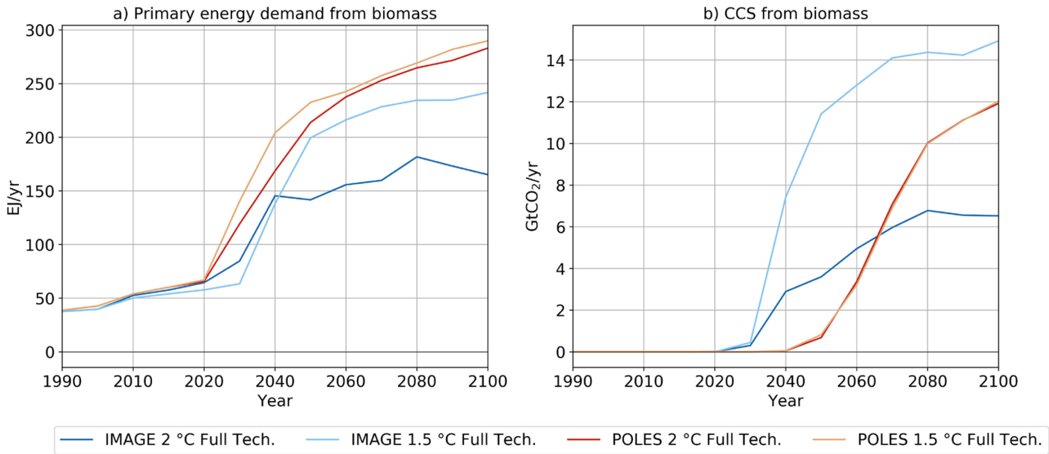

Figure 11. Global primary bio-energy demand (panel a) and BECCS (panel b), under the Full technology 2 °C and 1.5 °C scenarios of IMAGE and POLES.

4 Alternative scenarios

4.1 The 2 °C alternative scenarios

Findings

- **It is technically possible to rely less on negative emission technologies and bio-energy than in the Full technology scenarios and still meet stringent climate goals.**

- **Less reliance on BECCS can be achieved through, for instance, further penetration of renewable energy, rapidly implemented energy efficiency improvements, lifestyle change, greater reforestation effort and more rapid reduction in non-CO_2 gases.**

- **For instance, for lifestyle change, an IMAGE scenario is presented that includes a shift towards low-meat diets which leads to fewer land-use-related CO_2 emissions and non-CO_2 greenhouse gas emissions. Several of the scenarios that use less BECCS imply that sequestration takes place through other CDR options, such as reforestation, but also by CCS.**

- **Scenarios that rely less on bio-energy and BECCS show an emission trajectory in which enhanced emission reductions are achieved before the mid century, in order to compensate for the lower negative emissions at the end of the century.**

- **By 2050, greenhouse gas emissions under the alternative scenarios are lower than under the Full technology scenarios, but, by 2100, emission levels are higher. Greenhouse gas emissions are reduced by 51% to 63% (2 °C) by 2050, from 1990 levels, compared to 51% to 56% under the Full technology scenarios.**

- **Apart from the No CCS scenario, the alternative POLES scenarios (both variants of a scenario with limited use of bio-energy), have less variation in the projected level of global greenhouse gas emissions. Some of these scenarios do not need to result in net-negative greenhouse gas emission.**

- **The reliance on BECCS can be limited and delayed until 2040, but ultimately all scenarios end up using this technology, apart from the scenario that explicitly excludes the use of CCS.**

Results

This section explores a number of alternative scenarios for achieving the 2 °C target, which rely less on bio-energy and BECCS, and compares the results with the Full technology 2 °C scenarios, as described in Chapter 3. Under the IMAGE scenarios, the use of BECCS is limited and the POLES scenarios reduce the availability of bio-energy to 180 EJ/yr. Chapter 2 describes the alternative scenarios of IMAGE (two scenarios) and POLES (four scenarios) in more detail. A brief description of those scenarios is given below.

It is expected that these limited technology scenarios that reduce the use of bio-energy and BECCS have less flexibility in the portfolio of mitigation options, compared to the Full technology scenarios, and therefore need enhanced reduction efforts before 2050 in order to compensate the lower negative emissions by the end of the century. Table 5 and Figure 12 show the greenhouse gas emission pathways for the alternative and Full technology 2 °C scenarios. It shows that the 2050 emissions under the alternative scenarios are indeed lower than under the Full technology scenarios, and, by 2100, the emission levels are also higher, but the impact is relatively limited. The **IMAGE 2 °C Limited BECCS – Renewable electricity** scenario (assuming higher degrees of electrification) shows even lower 2050 and 2100 emissions, and this scenario leads to a lower radiative forcing (shown in Appendix A) than under the Full technology 2 °C scenario. In general, the emission pathways under the alternative 2 °C scenarios are quite similar to those under the 2 °C Full technology scenarios of both models.

The lower impact on the enhanced reduction efforts before 2050, under the **IMAGE 2 °C Limited BECCS – Lifestyle** (assuming lifestyle changes) and **IMAGE 2 °C Limited BECCS – Renewable electricity,** can be explained by the way in which the scenarios are constructed. Lifestyle and electrification measures are applied to the IMAGE SSP2 baseline. In doing so, emission reductions are achieved that are more ambitious than those required to stay within the climate target of 2 °C. Subsequently, BECCS are taken out of the energy system in order to increase emissions until levels are reached that comply with the climate target of 2 °C.

The **POLES Limited Bio-energy – No CCS** scenario, with its exclusion of CCS, clearly shows lower 2050 emissions, in order to compensate for the higher 2100 emissions.

Table 5. Global greenhouse gas emissions in $GtCO_2eq$, under the 2 °C Full technology and alternative scenarios, of the POLES and IMAGE model, in selected years. The two columns on the right show the reduction, in percentages, by 2050 and 2100, compared to 1990 levels.

Scenario	1990	2010	2050	2100	2050	2100
IMAGE 2 °C Full Technology	**38.2**	**48.2**	**16.8**	**2.8**	**56%**	**93%**
IMAGE 2 °C Limited BECCS – Lifestyle	38.2	48.3	16.5	3.8	57%	90%
IMAGE 2 °C Limited BECCS – Renewable electricity	38.2	48.4	15.9	0.5	59%	99%
POLES 2 °C Full Technology	**36.2**	**47.7**	**17.9**	**-0.7**	**51%**	**102%**
POLES 2 °C Limited Bio-energy	36.2	47.7	17.6	-0.2	51%	101%
POLES 2 °C Carbon tax only	36.2	47.7	17.5	0.5	52%	99%
POLES 2 °C No DACCS	36.2	47.7	16.9	0.2	53%	99%
POLES 2 °C No CCS	36.2	47.7	13.4	3.6	63%	90%

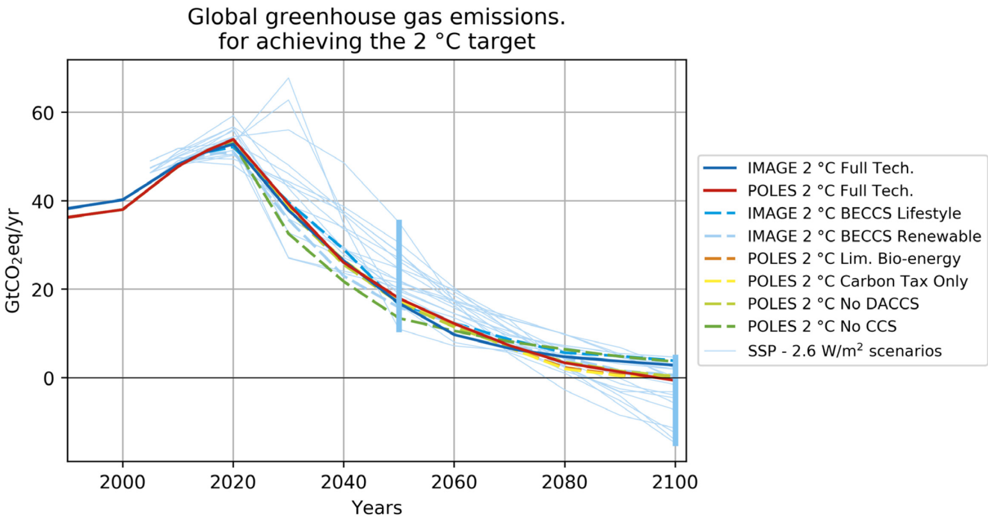

Figure 12. Global greenhouse gas emissions under the Full technology and alternative 2 °C scenarios of IMAGE and POLES, compared to the full set of cost-optimal SSP 2.6 W/m² scenarios.

Figure 13 gives a breakdown of the various greenhouse gases for the **IMAGE 2 °C Full technology** and **IMAGE 2 °C Limited BECCS – Lifestyle** scenarios (panel a and c) and the **POLES 2 °C Full Technology** and **POLES 2 °C Limited Bio-energy – No CCS** scenarios (panel b and d).
Under the **IMAGE 2 °C Lifestyle** scenario, lifestyle changes are assumed to decrease non-CO_2 greenhouse gas emissions, but, more importantly, also further decrease land-use-related CO_2 emissions. These lower emissions allow higher CO_2 emissions from the energy sector, as shown in Figure 13 (upper graphs). These additional energy-related CO_2 emissions are however not completely compensated by lower land-use CO_2 emissions. As a result, the radiative forcing under the lifestyle scenario slightly exceeds that under the Full technology scenario, but it does not exceed the allowed 2.6 W/m² radiative forcing target for 2100.

Under the **POLES 2 °C Limited Bio-energy – No CCS** scenario, lower energy-related CO_2 emissions in the first half of the century are noticeable, which are necessary to compensate for the higher CO_2 emissions after 2060. In addition, there are greater reductions in land-use-related CO_2 emissions and non-CO_2 greenhouse gas emissions.

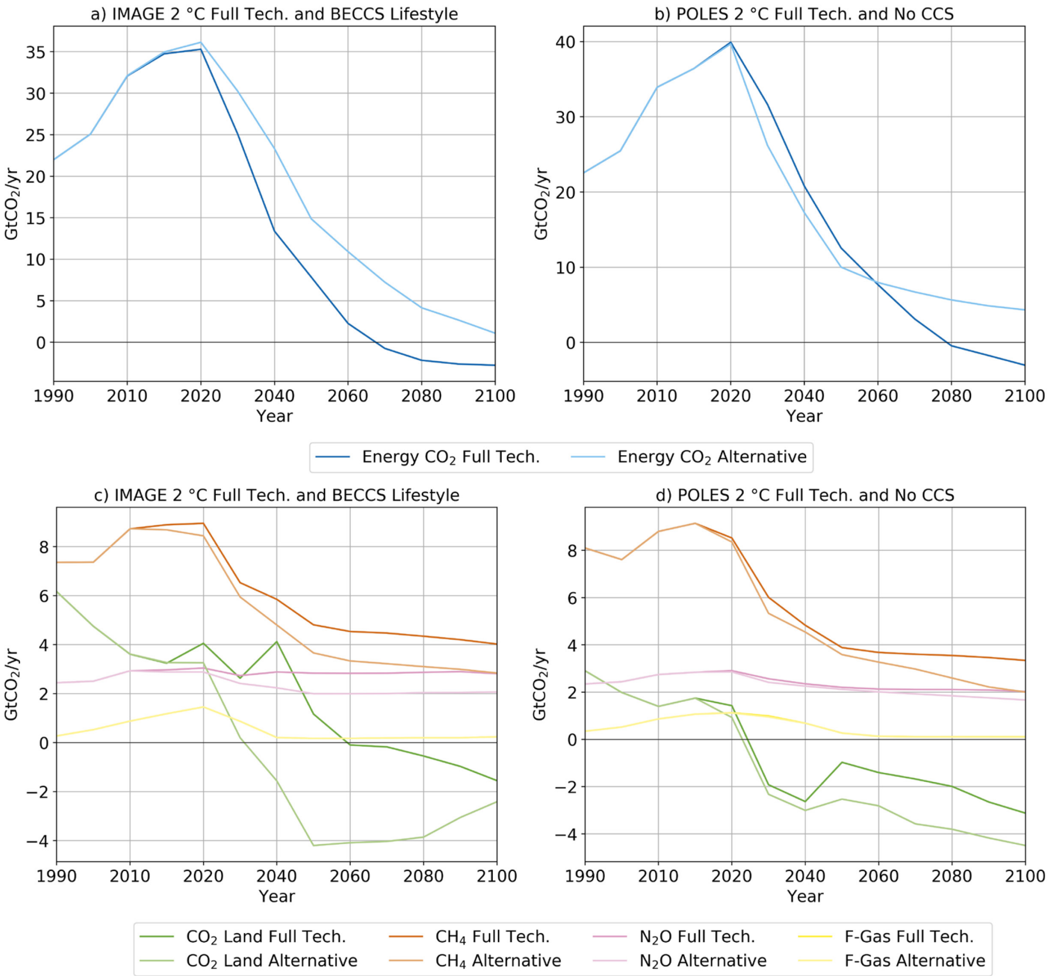

Figure 13. Global energy- and industry-related CO_2 emissions (panel a and b) and non-CO_2 greenhouse gas emissions and land-use-related CO_2 emissions (panel c and d), in $GtCO_2eq/yr$, under the IMAGE 2 °C Full technology and 2 °C Lifestyle scenarios (panel a and c) and the POLES 2 °C Full technology and No CCS scenarios (panel b and d).

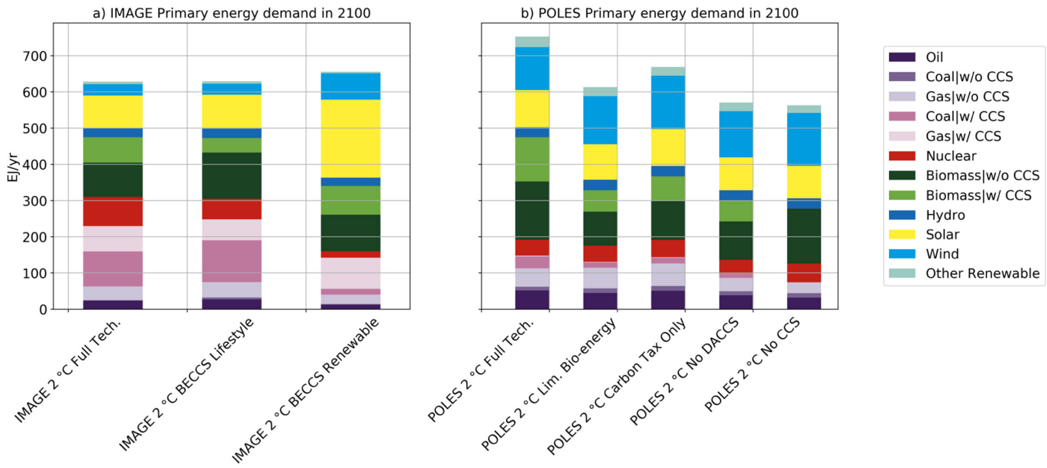

Figure 14. Global primary energy demand, under 2 °C scenarios in 2100 of IMAGE (panel a) and POLES (panel b)

Next, we analyse primary energy demand in the alternative Full technology 2 °C scenarios. Figure 14 illustrates this for the year 2100, with panel a for the IMAGE scenarios and panel b for those of POLES. In both panels, the first column shows the Full technology scenarios (of IMAGE and POLES).

The **IMAGE 2 °C Limited BECCS – Lifestyle** scenario shows less use of BECCS and an increase in coal with CCS and bio-energy without CCS, compared to the Full technology 2 °C scenario. This can be explained by the assumed premium on BECCS (carbon tax), making it more expensive. Bio-energy is therefore used without CCS, partly in the transport sector. Negative emissions are however still required and therefore the share of coal with CCS increases.

In the **IMAGE 2 °C Limited BECCS – Renewable electricity** scenario the shares of coal with CCS and nuclear power largely decrease and we see a significant increase in solar and wind. This scenario has the highest rates for renewable deployment due to the increased electrification. The share of BECCS is similar by the end of the century but the introduction of this technology in the energy mix starts a few decades later. The use of natural gas with CCS also increases, indicating that negative emissions are also required at the end of the century to achieve the 2 °C target. Nevertheless, the share of CCS is smaller compared to under the Full technology scenario.

Apart from the lower total primary energy demand, the POLES alternative scenarios differ only slightly from the POLES Full technology scenario. Comparing the **POLES 2 °C Full Technology** scenario with the **POLES 2 °C Limited Bio-energy – No CCS** scenarios shows that CCS is substituted by more nuclear and wind power. The other alternative scenarios have smaller shares of bio-energy (with and without CCS) and also larger shares of nuclear and wind power, compared to the Full technology scenario.

The primary bio-energy demand increases at a later point in time, under the alternative **IMAGE** scenarios, compared to that under the Full technology scenario, but by 2100, the differences are only small (Table 6). Under the **POLES** alternative scenarios, bio-energy demand already differs from that under the Full technology scenario, from 2050 onwards, but the alternative scenarios themselves differ only slightly.

Table 6. Global primary bio-energy energy demand in EJ/yr, under the 2 °C Full technology (in bold) and alternative scenarios in selected years.

Scenario	2010	2050	2100
IMAGE 2 °C Full Technology	**53**	**142**	**165**
IMAGE 2 °C Limited BECCS – Lifestyle	53	100	167
IMAGE 2 °C Limited BECCS – Renewable electricity	52	107	181
POLES 2 °C Full Technology	**54**	**214**	**283**
POLES 2 °C Limited Bio-energy	54	131	153
POLES 2 °C Carbon tax only	54	145	176
POLES 2 °C No DACCS	54	136	163
POLES 2 °C No CCS	54	160	152

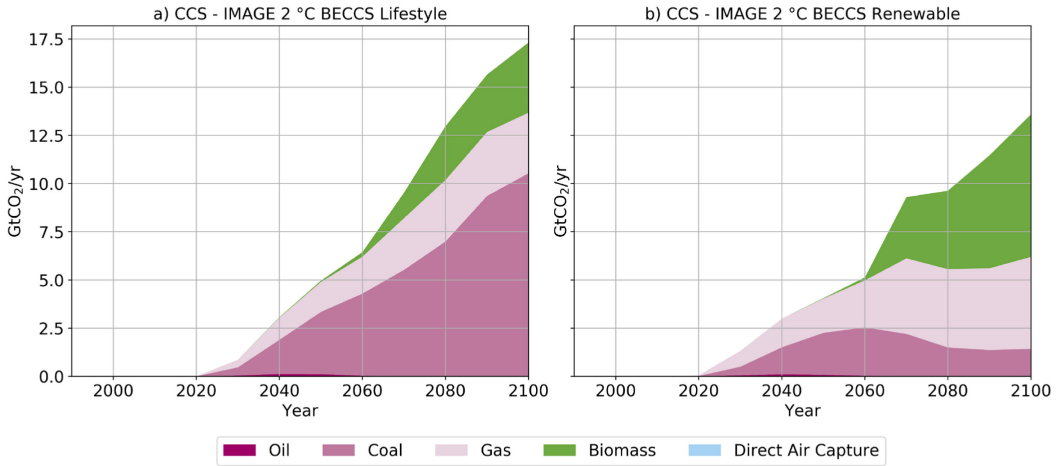

Figure 15. Carbon captured per energy carrier, or by technology in the case of direct air capture, under the alternative IMAGE scenarios

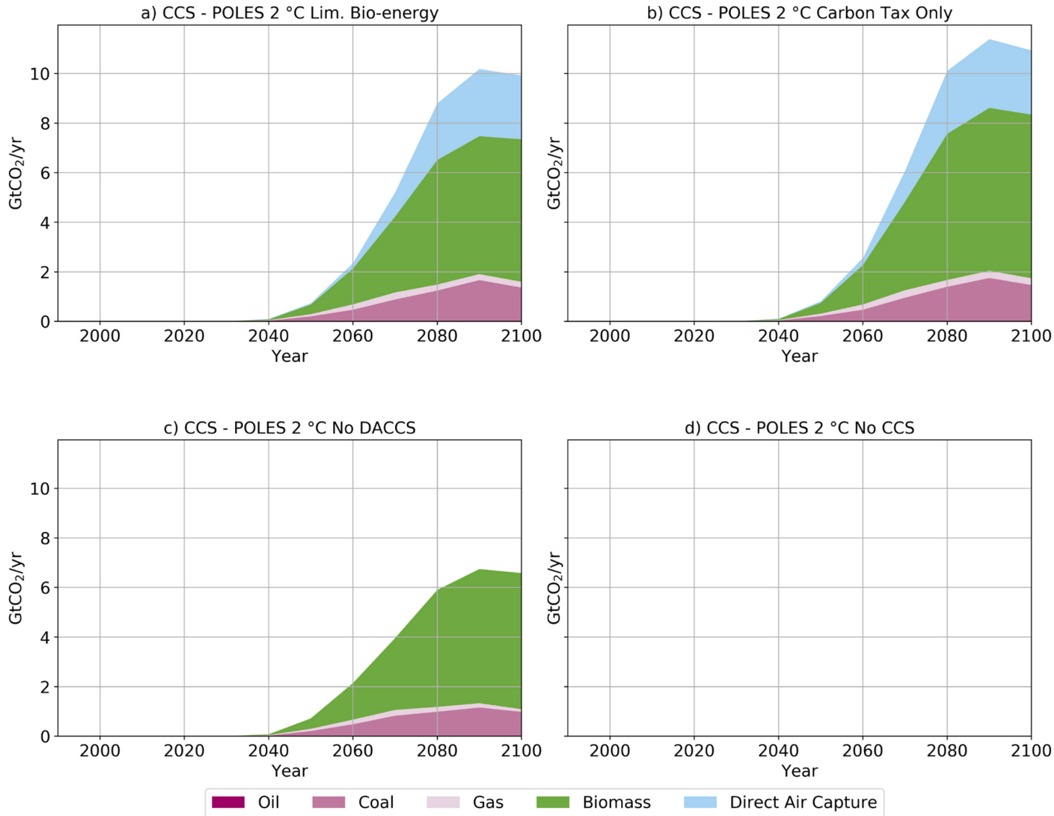

Figure 16. Carbon captured per energy carrier, or by technology in the case of direct air capture, under the alternative POLES 2 °C scenarios. Panel d shows no emissions because the POLES No CCS scenario has no CCS.

Finally, the **IMAGE 2 °C Limited BECCS – Lifestyle** and **IMAGE 2 °C Limited BECCS – Renewable electricity** scenarios have a significantly larger share of fossil fuel use with CCS in the energy system by 2100, compared to under the POLES alternative scenarios, as illustrated in Figures 15 and 16. Similar to under the Full technology scenario in IMAGE, the use of CCS starts in 2020, and the total carbon sequestered increases until the end of the century. Under the **IMAGE 2 °C Limited BECCS – Lifestyle** scenario, the annual sequestration is around 17.5 $GtCO_2$ by 2100, as opposed to roughly 11 $GtCO_2$ under the

POLES 2 °C Carbon tax only scenario, which has the largest use of CCS. We furthermore see that the level of sequestration stabilises under the POLES scenarios. This is due to bio-energy being used to its fullest supply potential as a world total, and because some countries reach their maximum geological storage potential for CO_2 (no CO_2 physical trade).

Looking at the cumulative sequestered carbon we see that all alternative 2 °C mitigation scenarios of the POLES and IMAGE model have smaller total shares of CCS than their Full technology scenarios. The same holds for bio-energy CCS.
Figure 17 illustrates this.

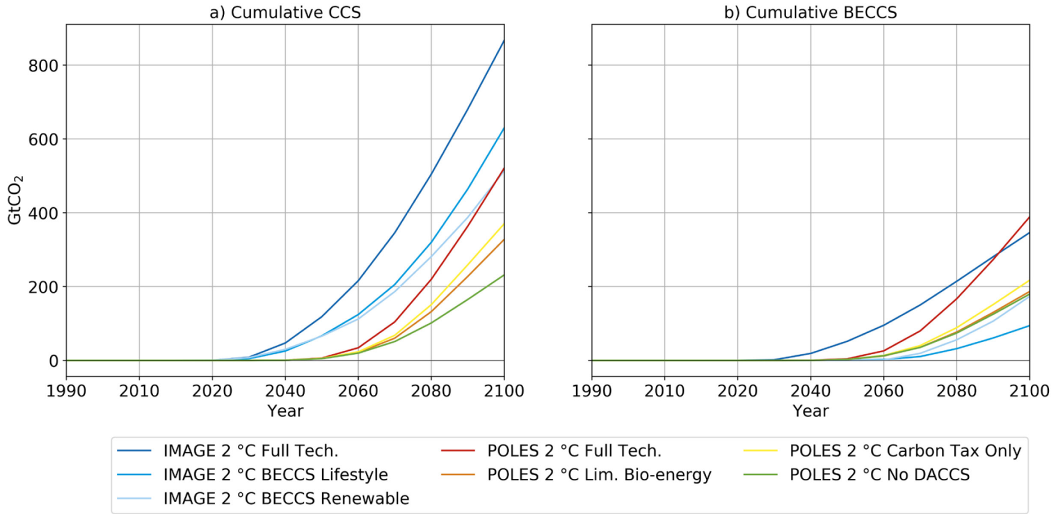

Figure 17. Global cumulative sequestered total carbon (panel a) and bio-energy carbon (panel b), under all 2 °C scenarios.

4.2 The 1.5 °C alternative scenarios

Findings

- **All 1.5 °C alternative mitigation scenarios show strong similarities with the Full technology 1.5 °C scenarios.**
- **It is technically possible to rely less on negative emission technologies and bio-energy than is the case in the Full technology scenarios and still achieve the 1.5 °C target.**
- **Global greenhouse gas emissions under the alternative 1.5 °C scenarios also reach net zero between 2060 and 2070, which is about the same as under the Full technology 1.5 °C scenarios. By 2050, global emissions will be reduced by 75% to 82%, from 1990 levels.**
- **The models show differences with regard to bio-energy and BECCS deployment. The POLES 1.5 °C scenarios show results that are nearly identical to those from the 2 °C scenarios, but the IMAGE 1.5 °C scenarios show higher projections.**

Results

This section explores alternative scenarios for 1.5 °C that rely less on bio-energy and BECCS, and compares the results with those from the Full technology 1.5°C scenarios.

The cumulative CO_2 emissions over the 2010–2100 period are significantly lower under the 1.5 °C scenarios than under the 2 °C scenarios, which implies lower total emission levels and primary energy demand. Greenhouse gas emissions under the POLES scenarios show small differences and are much lower by the end of the century, compared to those under the IMAGE scenarios. Compared to the Full technology scenarios, the alternative IMAGE and POLES 1.5 °C scenarios, with less flexibility in the mitigation options, also show lower emission levels before 2050, in order to compensate for the lower negative emissions by the end of the century, as illustrated in Table 7. The **IMAGE 1.5 °C Limited BECCS – Renewable electricity** scenario, similar to its 2 °C variant, shows even lower emission levels for 2050 and 2100, and also leads to a lower radiative forcing, compared to the Full technology 1.5 °C scenario (see Appendix A).

Table 7. Global greenhouse gas emissions in $GtCO_2eq$ (relative to 1990 levels), under the 1.5 °C mitigation scenarios of both IMAGE and POLES

Scenario	1990	2010	2050	2100	2050	2100
IMAGE 1.5 °C Full Technology	**38.2**	**48.3**	**9.0**	**-4.1**	**76%**	**111%**
IMAGE 1.5 °C Limited BECCS – Lifestyle	38.2	48.4	6.8	-0.8	82%	102%
IMAGE 1.5 °C Limited BECCS – Renewable electricity	38.2	48.3	6.8	-5.3	82%	114%
POLES 1.5 °C Full Technology	**36.2**	**47.7**	**10.7**	**-12.1**	**70%**	**133%**
POLES 1.5 °C Limited Bio-energy	36.2	47.7	9.0	-9.0	75%	125%

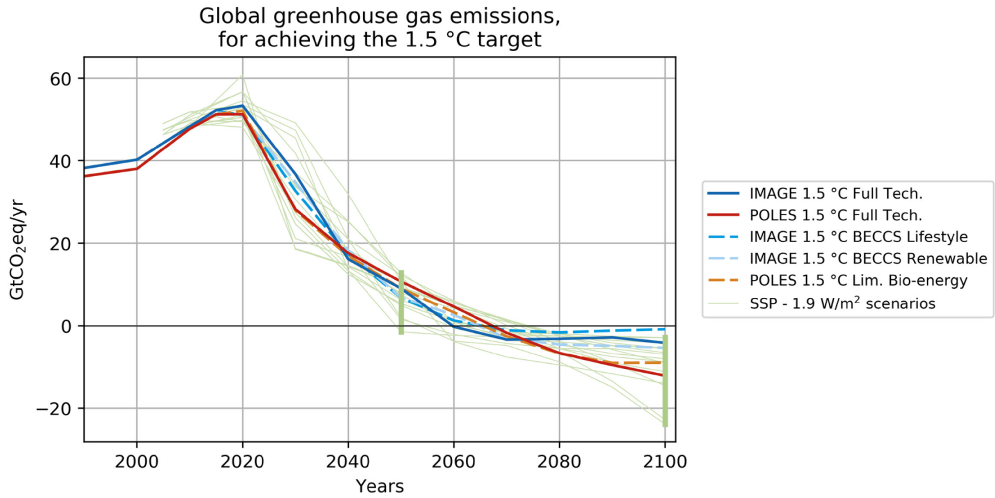

Figure 18. Global greenhouse gas emissions, under the Full Technology and alternative 1.5 °C scenarios of IMAGE and POLES, compared to the full set of cost-optimal SSP 1.9 W/m² scenarios.

The IMAGE 1.5 °C scenarios can be seen to diverge from 2050 onwards, with the **IMAGE 1.5 °C Limited BECCS – Renewable electricity** scenario having slightly lower (more negative) emissions by 2100 than does the IMAGE 1.5 °C Full Technology scenario, but overall, the emission pathways show similar trends.

The **IMAGE 1.5 °C Limited BECCS – Lifestyle** scenario has somewhat higher (fewer negative) emissions in 2100, compared to the Full technology scenario. When decomposing the greenhouse gas emissions for this scenario, however, we see the same difference as under the 2 °C scenarios, with higher levels of energy- and industry-related CO_2 emissions in the energy sector and lower non-CO_2 greenhouse gas emissions and lower land-use-related CO_2 emissions (Figure 19).

In terms of primary energy demand, bio-energy use and BECCS, we also see patterns similar to those under the 2 °C scenarios. The **IMAGE 1.5 °C Limited BECCS – Lifestyle** scenario has an overall lower primary energy demand and less BECCS by the end of the century, due to the behavioural measures in this scenario (Table 8 and Table 9).

Table 8. Total primary energy demand in EJ/yr.

Scenario	2010	2050	2100
IMAGE 1.5 °C Full Technology	**506**	**490**	**661**
IMAGE 1.5 °C Limited BECCS – Lifestyle	506	408	598
IMAGE 1.5 °C Limited BECCS – Renewable electricity	506	457	755
POLES 1.5 °C Full Technology	**523**	**506**	**690**
POLES 1.5 °C Limited Bio-energy	523	457	538

Table 9. Global annual sequestered carbon from bio-energy in $GtCO_2$/yr.

Scenario	2010	2050	2100
IMAGE 1.5 °C Full Technology	**0.0**	**11.4**	**14.9**
IMAGE 1.5 °C Limited BECCS – Lifestyle	0.0	1.2	7.8
IMAGE 1.5 °C Limited BECCS – Renewable electricity	0.0	6.5	14.8
POLES 1.5 °C Full Technology	**0.0**	**0.8**	**12.0**
POLES 1.5 °C Limited Bio-energy	0.0	0.5	6.5

Figure 19. Global greenhouse gas emissions in $GtCO_2eq$/yr, comparisons between the IMAGE 2 °C Full technology and Lifestyle scenario (left plots) and the IMAGE 1.5 °C Full technology and Lifestyle scenario (right plots).

Under the **IMAGE 1.5 °C Limited BECCS – Renewable electricity** scenario, fossil CCS is less than under the Full technology scenario and shares of renewables greatly increase (Tables 10 and 11).

Table 10.Global annual sequestered carbon from oil, coal and natural gas, in GtCO$_{2}$/yr.

Scenario	2010	2050	2100
IMAGE 1.5 °C Full Technology	**0.0**	**5.0**	**10.6**
IMAGE 1.5 °C Limited BECCS – Lifestyle	0.0	5.8	10.5
IMAGE 1.5 °C Limited BECCS – Renewable electricity	0.0	3.6	4.2
POLES 1.5 °C Full Technology	**0.0**	**0.2**	**0.4**
POLES 1.5 °C Limited Bio-energy	0.0	0.2	0.4

Table 11.Global non-bio-energy renewable primary energy demand, in EJ/yr.

Scenario	2010	2050	2100
IMAGE 1.5 °C Full Technology	**14**	**54**	**132**
IMAGE 1.5 °C Limited BECCS – Lifestyle	14	74	157
IMAGE 1.5 °C Limited BECCS – Renewable electricity	14	144	290
POLES 1.5 °C Full Technology	**17**	**145**	**320**
POLES 1.5 °C Limited Bio-energy	17	147	289

Under the POLES scenarios, again, we see that the total primary energy demand is lower under the **1.5 °C Limited Bio-energy** scenario then under the Full technology scenario, and that this reduced demand is largely achieved by decreasing the deployment of both total CCS and biomass energy production (Tables 12 and 13).

Table 12. Global total annual sequestered carbon from all sources, in GtCO$_{2}$/yr.

Scenario	2010	2050	2100
IMAGE 1.5 °C Full Technology	**0.0**	**16.4**	**25.5**
IMAGE 1.5 °C Limited BECCS – Lifestyle	0.0	7.1	18.3
IMAGE 1.5 °C Limited BECCS – Renewable electricity	0.0	10.1	19.0
POLES 1.5 °C Full Technology	**0.0**	**1.1**	**15.6**
POLES 1.5 °C Limited Bio-energy	0.0	0.9	9.8

Table 13.Global primary bio-energy demand, in EJ/yr.

Scenario	2010	2050	2100
IMAGE 1.5 °C Full Technology	**50**	**199**	**242**
IMAGE 1.5 °C Limited BECCS – Lifestyle	50	90	174
IMAGE 1.5 °C Limited BECCS – Renewable electricity	50	130	234
POLES 1.5 °C Full Technology	**54**	**233**	**290**
POLES 1.5 °C Limited Bio-energy	54	177	171

Looking specifically at the amount of carbon sequestered, the POLES scenarios show identical values. Under both the Full technology and low bio-energy scenarios, there is no difference between 2 °C and 1.5 °C scenarios; however, due to different primary energy levels, the contribution of bio-energy and BECCS differs. Under the IMAGE scenarios, however, we see that sequestration of carbon from bio-energy sources is higher under all 1.5 °C scenarios than under their corresponding 2 °C scenarios. This is particularly the case under the IMAGE 1.5 °C Full Technology and **IMAGE 1.5 °C Limited BECCS – Renewable electricity** scenarios. The reason that these two scenarios differ from the **IMAGE 1.5 °C Limited BECCS – Lifestyle** scenario is that they have fewer options to abate emissions in the land-use sector. Keep in mind that the IMAGE scenarios are constructed with the aim to minimise the use of BECCS. For the **IMAGE 1.5 °C Limited BECCS – Lifestyle** scenario, this implies measures that reduce emissions in the land-use sector and in the **IMAGE 1.5 °C Limited BECCS – Renewable electricity** scenario this implies measures that reduce emissions in the energy sector. Figure 20 shows that, under the IMAGE 1.5 °C Full Technology and **IMAGE 1.5 °C Limited BECCS – Renewable electricity** scenarios, annual BECCS levels come to around 15 $GtCO_2$ (Figure 20a and Table 9). The delayed implementation of BECCS under the **IMAGE 1.5 °C Limited BECCS – Renewable electricity** scenario, however, results in cumulative sequestered carbon from bio-energy being approximately 150 $GtCO_2$ lower by the end of the century (panel b).

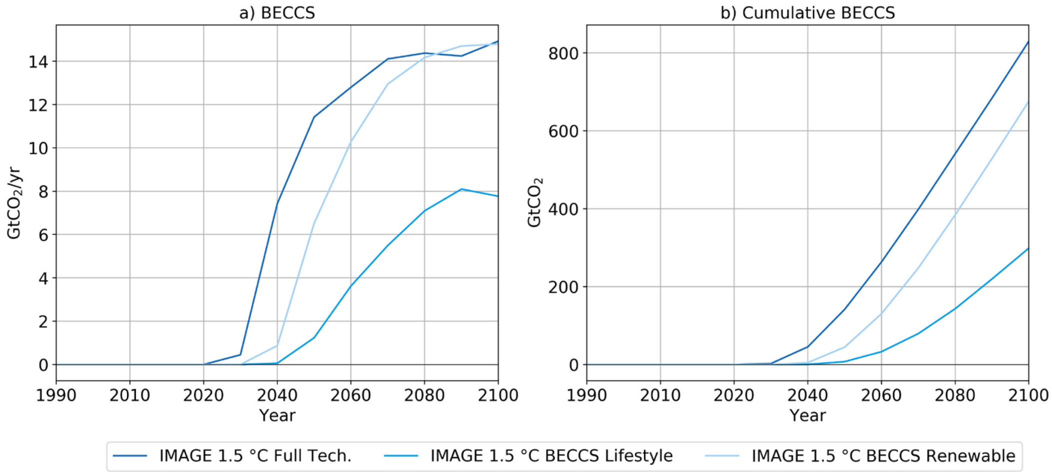

Figure 20. Annual globally sequestered carbon from bio-energy (panel a) and cumulative sequestered carbon from bio-energy (panel b), under all 1.5 °C IMAGE scenarios.

5 Land-use system

Findings

- **The global IMAGE and POLES models both project a reduction in net LULUCF emissions under the current policy scenarios, but the models diverge in reduction sizes. Between 2010 and 2100, net LULUCF emissions in POLES and IMAGE are expected to be reduced by 0.6 GtCO_2/yr and 4.6 GtCO_2/yr, respectively.**

- **The two models show similarities in the reduction in net LULUCF emissions, under the Full Technology 2 °C and 1.5 °C scenarios. Between 2010 and 2100, net LULUCF emissions are expected to be reduced by 4.5–4.7 GtCO_2/yr and 4.0–5.2 GtCO_2/yr, in POLES and IMAGE, respectively.**

- **The two models show differences with regard to the mitigation of emissions from agriculture, under the Full Technology 2 °C and 1.5 °C scenarios. POLES projects a reduction in N_2O and CH_4 emissions by 2100 (as compared to the current policy scenario) of 3.9–4.2 GtCO_2eq/yr, whereas IMAGE projects a reduction of 2.0–2.2 GtCO_2eq/yr.**

- **Both models project a reduction in the global average calorie intake, under the Full Technology 2 °C scenario, as compared to the current policy scenario. However, food security issues can also be addressed directly through the design of the mitigation policy itself.**

Results

This chapter explores and highlights the implications of the current policies, 2 °C and 1.5 °C scenarios in the context of the land-use sector. In particular, it describes the scenario outcomes on aspects such as LULUCF emissions and removals (Section 5.1), agricultural sector and non-CO_2 greenhouse gases (Section 5.2), land-cover change (Section 5.3), and food security (Section 5.4). As for the other sections, while IMAGE and POLES do generate output on both global and regional levels, here, we mainly focus on and describe the outcomes at the global level.

5.1 LULUCF emissions and removals

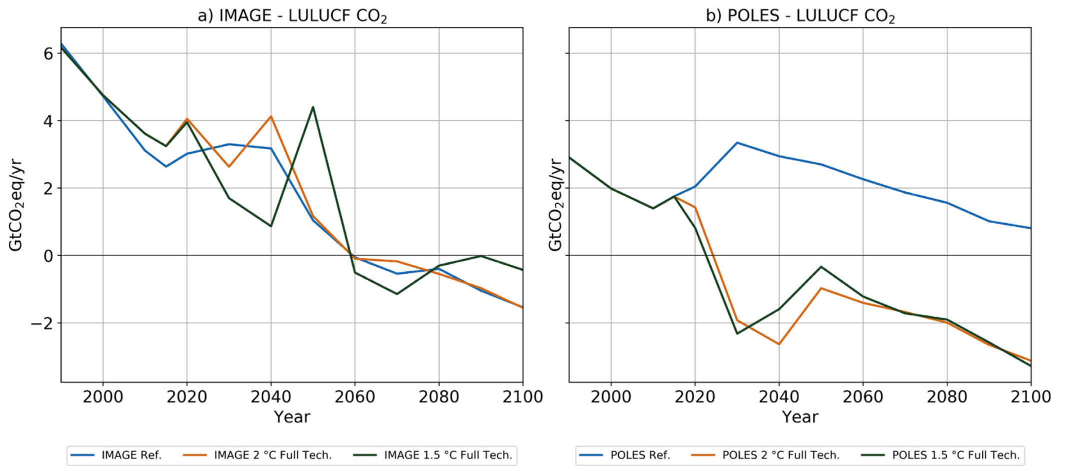

Figure 21. Global net LULUCF CO_2 emissions in $GtCO_2$/yr, under the IMAGE (panel a) and POLES (panel b) current policy, 2 °C and 1.5 °C scenarios.

Figure 21 show the global development of CO_2 emissions by sources and removals by sinks for the land use, land-use change, and forestry (LULUCF) sector. It should be noted that, from here on, when referring to net LULUCF emissions, we are referring to the joint development of emissions by sources and removals by sinks for the LULUCF sector.

A difference can be noted between IMAGE and POLES, in terms of the historical net LULUCF CO_2 emissions that the models are reporting for the period from 1990 to 2010. This is mainly due to the difference between data sets used by the two models. POLES employs a harmonisation approach where historical estimates are reported for the period 1990 until about 2014, after which GLOBIOM annual changes are reported (i.e. from about 2014 onwards). The results of the POLES model for period of 1990 until the last year available (2012–2016, depending on the country) correspond to data collected by the POLES team from the national greenhouse gas inventories for Annex I countries and a combination of data sources (e.g. national communications, biennial update reports, FAO) for non-Annex I countries (UNFCCC, 2018a, b, c, d). Beyond the historical data, the year-on-year evolution of emissions obtained from GLOBIOM are applied to the starting point obtained by historical inventories data. As a consequence, the difference between GLOBIOM data for past years and historical data sources is kept constant over time; the starting point of the scenarios becomes the same as the inventory data but the emissions trend of the projections remains unchanged. The historical period in IMAGE is calibrated to land-use data but does not include harmonisation of the historical land-use emission data resulting in an estimate that differs from that by POLES. Further details and explanations as to the reason for the difference in estimates provided by IAMs and national greenhouse gas inventories is provided in Grassi et al. (2017).

Both IMAGE and POLES project a reduction in net LULUCF emissions (i.e. reduction in emissions and enhancement of sinks) from 2010 to 2100, under the current policies scenario. However, the size of the reduction in the net LULUCF emission varies between the models (see Table 14 for an overview of the estimates as reported by the two models). In POLES, net LULUCF emissions are projected to be reduced by 0.6 $GtCO_2$/yr, between 2010 and 2100. This is due to a combination of effects. The deforestation rate is expected to be reduced over time, thereby reducing the emissions from the LULUCF sector. At the same time, removals associated with afforestation is expected to increase, mainly related to trees in historically afforested areas getting older and thereby having a higher increment. However, the forest management sink [10] is expected to significantly decrease over time due to aging forests [11] and an increasing demand of wood for material and energy purposes. In IMAGE net LULUCF emissions are projected to be reduced by 4.6 $GtCO_2$/yr, between 2010 and 2100. The reason for this is increasing yield productivity and stabilisation of food demand, leading to abandonment of agricultural land and regrowth of natural forests. This, overall, leads to an increase in net LULUCF removals, over time.

It should be noted that both IMAGE and POLES LULUCF trajectories show strong shifts in trend over time. These are related to the fact that LULUCF emission are driven by land-use change and thus quite sensitive. The peak in the IMAGE model, for instance, is caused by an expansion of bio-energy use in that period. It should be noted, however, that these results should not be interpreted as projections for a specific period – but much more as a gradual trend over time.

POLES projects a stronger reduction in net LULUCF emissions, under the 1.5 °C and 2 °C scenarios, as compared to the current policies scenario. In the POLES model, the land-use sector provides a reduction, relative to 2010 levels, of 4 to 4.1 $GtCO_2$/yr by 2100, under its 1.5 °C and 2 °C scenarios, compared to a reduction of 0.6 $GtCO_2$/yr under the current policies scenario. Roughly half of this mitigation is achieved by reducing the deforestation rate, and the other half by increasing the afforestation rate. The POLES 1.5 °C and 2 °C scenarios project a similar level of net LULUCF emissions by 2100. The fact that the 1.5 °C and 2 °C scenarios lead to lower net LULUCF emissions than under the current policies scenario is mainly due to more afforestation and more rapid and stronger reductions in rate of deforestation.

In IMAGE, the reduction in net LULUCF emissions under the 1.5 °C and 2 °C scenarios are substantially smaller than those in POLES. In IMAGE, the 2 °C scenario only leads to a minor reduction in net LULUCF emissions by 2100, compared to under the current policies scenario. However, the 1.5 °C scenario leads to an increase in net LULUCF emissions by 2100 of 1.1 $GtCO_2$/yr, compared to under the current policies scenario. That the 1.5 °C scenario leads to higher net LULUCF emissions, compared to the 2 °C scenario, is due to increased land use for bio-energy production, thus resulting in less reforestation as well as in a loss of vegetation due to land conversion for bio-energy production.

IMAGE projects net LULUCF emissions to remain relatively close to zero, from 2060 onwards, under the 1.5 °C and 2 °C scenarios. This is the result of opposing trends; area expansion for bio-energy production increases emissions due to loss of vegetation, whereas REDD and afforestation decreases emissions. Under the POLES 1.5 °C and 2 °C scenarios, net LULUCF emissions are projected to remain negative, from 2030 onwards. This is mainly the result of strong global reductions in deforestation rates and increased afforestation efforts.

To summarise, a difference can be noted between the models, in terms of the projected reductions in net LULUCF emissions, between 2010 and 2100, under the current policies scenario. However, under both the 1.5 °C and 2 °C scenarios, these reductions are similar. Under the POLES 1.5 °C and 2 °C scenarios, reductions in net LULUCF emissions of 4.5–4.7 $GtCO_2$/yr are projected, for the period between 2010 and 2100. Meanwhile, the IMAGE 1.5

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[10] Above and below ground biomass in the land category "Forest Land remaining Forest Land"
[11] Generally, as trees grow older, the increment decreases, which, in turn, reduces the enhancement of the forest carbon sink.

°C and 2 °C scenarios project reductions in net LULUCF emissions of 4.0–5.2 $GtCO_2$/yr, between 2010 and 2100.

Table 14: Global net LULUCF emissions ($GtCO_2$/yr), under the current policies, 2 °C and 1.5 °C scenarios.

	POLES			IMAGE		
Scenario	2010	2050	2100	2010	2050	2100
Current policies	1.4	2.7	0.8	3.1	1.0	-1.5
2 °C	1.4	-0.9	-3.1	3.6	1.2	-1.6
1.5 °C	1.4	-0.3	-3.3	3.6	4.4	-0.4

5.2 Agricultural sector and non-CO_2 greenhouse gases

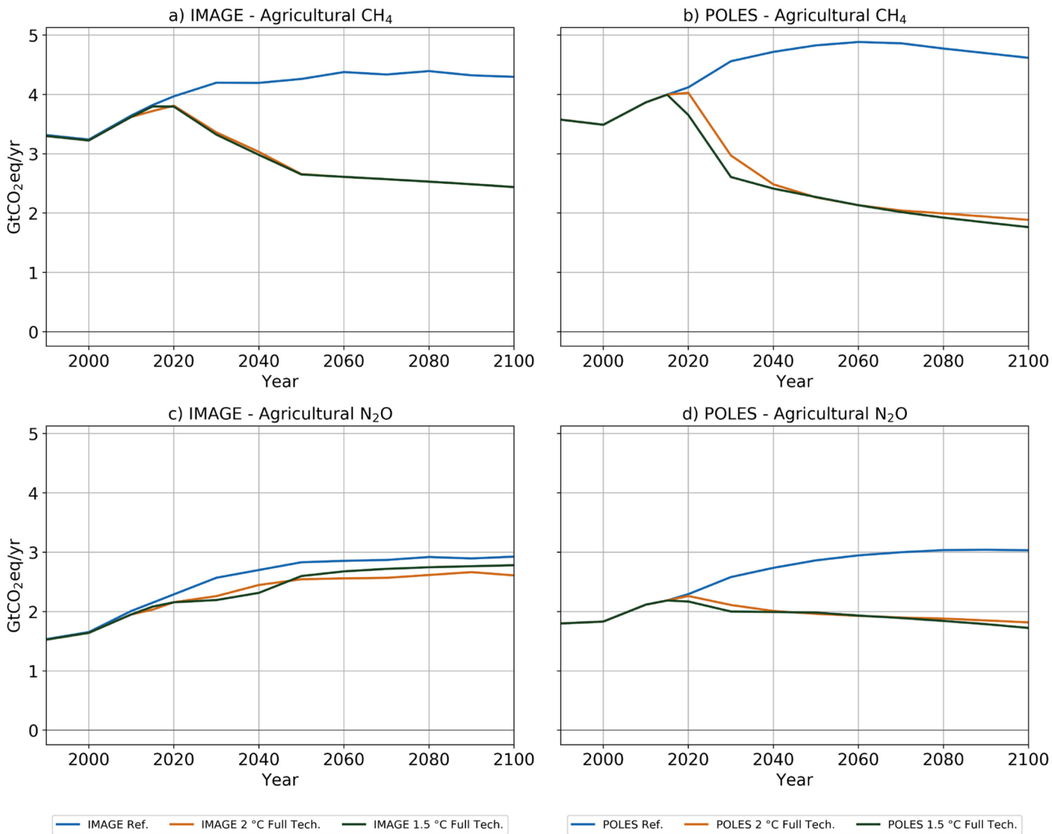

Figure 22. Global emissions of agricultural non-CO_2 greenhouse gases in $GtCO_2eq$/yr, under the IMAGE (panel a and c) and POLES (panel b and d) current policies, 2 °C and 1.5 °C scenarios. Panels a) and b) depict CH_4 emissions, and panels c) and d) depict N_2O emissions.

Figure 22 shows the projected global development of N_2O and CH_4 emissions by POLES and IMAGE. Under the current policies scenario, both models project a general increase in total emissions of non-CO_2 greenhouse gases (i.e. N_2O and CH_4 emissions) from agriculture, between 2010 and 2100. However, the POLES current policies scenario projects a peak in CH_4 emissions in 2060. This development is mainly due to global human consumption of crops, which is projected to peak in 2070, while meat consumption is expected to continue to grow until 2100. In the IMAGE model, CH_4 and N_2O continue to increase until the year 2100, as absolute levels of crop and meat consumption both continue to grow until the end of the century.

The projected reduction in emissions between 2010 and 2100 from the agricultural sector is lower in IMAGE than in POLES, under both the 2 °C and 1.5 °C scenarios. This is the case for both CH_4 and N_2O emissions and is to a large extent explained by the fact that POLES considers a larger set of mitigation options for the agriculture sector than IMAGE does (see Section 3). The mitigation options in POLES are estimated by GLOBIOM and cover technical, structural and demand-related mitigation options (Frank et al., 2018), while IMAGE currently only accounts for technical mitigation options (see Lucas et al. (2007) and Gernaat et al. (2015)).

Under the POLES 2 °C and 1.5 °C scenarios, the mitigation of CH_4 emissions in the year 2100 will be 2.7 and 2.9 $GtCO_2eq/yr$, respectively, compared to the situation under the current policies scenario. The mitigation of N_2O emissions will be1.2 and 1.3 $GtCO_2eq/yr$, by 2100. Under the IMAGE 2 °C and 1.5 °C scenarios, the mitigation of CH_4 emissions in the year 2100 will be around 1.8 $GtCO_2eq/yr$, compared to the current policies scenario. For N_2O emissions, mitigation by the year 2100 will be a respective 150 and 320 $MtCO_2eq/yr$, under the 2 °C and 1.5 °C scenarios, compared to the current policies scenario. The main reason for the differences in mitigation are assumptions about the mitigation potential. In both cases, the mitigation potential is limited compared to that of CO_2, but IMAGE is more conservative in emission reduction options, especially for N_2O.

To summarise, POLES projects a reduction in N_2O and CH_4 emissions from agriculture, under the 1.5 °C and 2 °C scenarios (compared to the current policies scenario), of a respective 3.9 and 4.2 $GtCO_2eq/yr$, between 2010 and 2100. IMAGE projects a reduction in N_2O and CH_4 emissions under the 1.5 °C and 2 °C scenarios, of 2.0 and 2.2 $GtCO_2eq/yr$, respectively, between 2010 and 2100. See Tables 15 and 16 for an overview of the estimates by the two models.

Table 15: Global CH_4 emission ($GtCO_2eq/yr$) from agriculture, under the Current Policies, 2 °C and 1.5 °C scenarios.

	POLES			IMAGE		
Scenario	2010	2050	2100	2010	2050	2100
Current Policies	3.9	4.8	4.6	3.6	4.3	4.3
2 °C	3.9	2.3	1.9	3.6	2.7	2.4
1.5 °C	3.9	2.3	1.8	3.6	2.7	2.4

Table 16: Global N_2O emission ($GtCO_2eq/yr$) from agriculture, under the Current Policies, 2 °C and 1.5 °C scenarios.

	POLES			IMAGE		
Scenario	2010	2050	2100	2010	2050	2100
Current Policies	2.1	2.9	3.0	2.0	2.8	2.9
2 °C	2.1	2.0	1.8	2.0	2.5	2.6
1.5 °C	2.1	2.0	1.7	2.0	2.6	2.8

5.3 Land-cover change

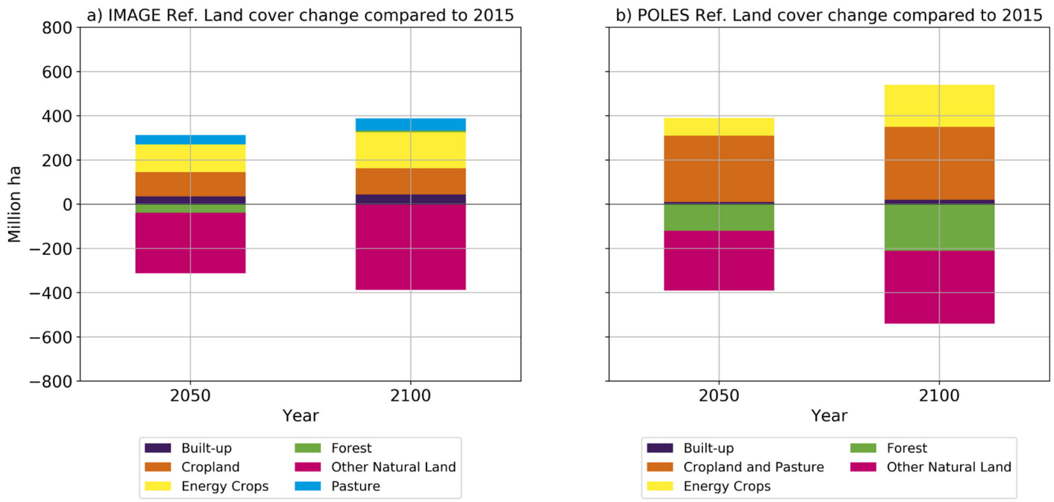

Figure 23. Global land-cover change in million ha in 2050 and 2100, compared to 2015, under the IMAGE (panel a) and POLES (panel b) Current Policies scenarios. It should be noted that, here, energy crops are presented separately from cropland results, even though they are at times reported as part of agricultural land in greenhouse gas inventories.

The total land-cover change in 2050 and 2100, compared to 2015 levels, are roughly in the same order of magnitude and develop in the same way in IMAGE and POLES, under the current policies scenario (see Figure 23). The area allocated to cropland and pasture (excluding that for energy crops [12]) is expected to increase in POLES and IMAGE, and this is driven by population growth and increasing global food demand. Land is also expected to be set aside to grow energy crops for the bio-energy sector, as is already the case under the current policies scenario (i.e. without carbon tax), bio-energy is projected to play a substantial role in the energy system. At the same time, the area of other natural land is expected to decrease due to the expansion of food and feed crops, as well as energy crops. However, while POLES projects that the total area of forest will decrease over time, meaning that that the global deforestation rate continues to be higher than that of the global afforestation rate, IMAGE projects that the area of forest will remain stable after 2010, as the scenario includes avoided deforestation policy.

In general, POLES projects a stronger increase in the area of cropland and pasture, after 2050 and 2100, than is projected by IMAGE. This difference in projection of land area is likely due to differences in the models in land-use intensity and regional crop yields improvements but may also relate to differences in assumptions concerning food consumption patterns and dietary preferences. Different assessments of land available for cropland expansion also play an important role.

Both IMAGE and POLES project that the total area of forest will continue to decrease until 2050, under the current policies scenario. After 2050, POLES projects that the total area of forest will continue to decrease until 2100, while IMAGE projects a moderate increase. In

[12] Energy crops are here being used as an aggregate term to represent short rotation tree plantations including short-rotation coppices and fast-growing grass species. It should be noted that the term does not include agriculture land used to grow traditional crops grown and used for first generation biofuel production (e.g. corn, wheat and sugar beet).

other words, POLES project that global deforestation rate continues to be higher than that of the global afforestation rate after 2050, while IMAGE projects that after 2050 the global afforestation rate will be higher than that of the deforestation rate. The net deforestation rate does vary between the POLES and IMAGE models due to differences in underlying assumptions for the scenarios (see Section 3) and due to differences in the drivers considered as impacting the future deforestation and afforestation levels. In POLES, deforestation and afforestation rates are price sensitive and impacted by the global development of food, feed and fibre markets. This means that as the market price of woody commodities increases (for example due to increasing demand of wood for material and energy purposes), afforestation rates increase and deforestation rates decrease. On the other hand, as the market price of agriculture and livestock products increase, deforestation rates increase and afforestation decreases. In IMAGE, changes in forest area are driven by changes in cropland, pasture and bio-energy which depends on development in the agro-economic system and the energy system. In addition, moderate forest protection is assumed in the current policy scenario favouring conversion of other land as opposed to forest.

In terms of land set aside to grow energy crops for bio-energy production, POLES projects a steady increase in this land-use category, from 2010 onward. POLES projects that 77 Mha of energy crop (short rotation tree plantations) will be established by 2050, and 188 Mha of energy crop to be established by 2100. IMAGE also project an increase in the area dedicated to energy crops (including short-rotation copies and fast-growing grass species), leading to 161 Mha of energy crops established by 2050, and 199 Mha of energy crops established by 2100. In addition to these surfaces, the increase in forest area in POLES can be partly attributed to increased mobilisation of forestry for the provision of biomass for energy.

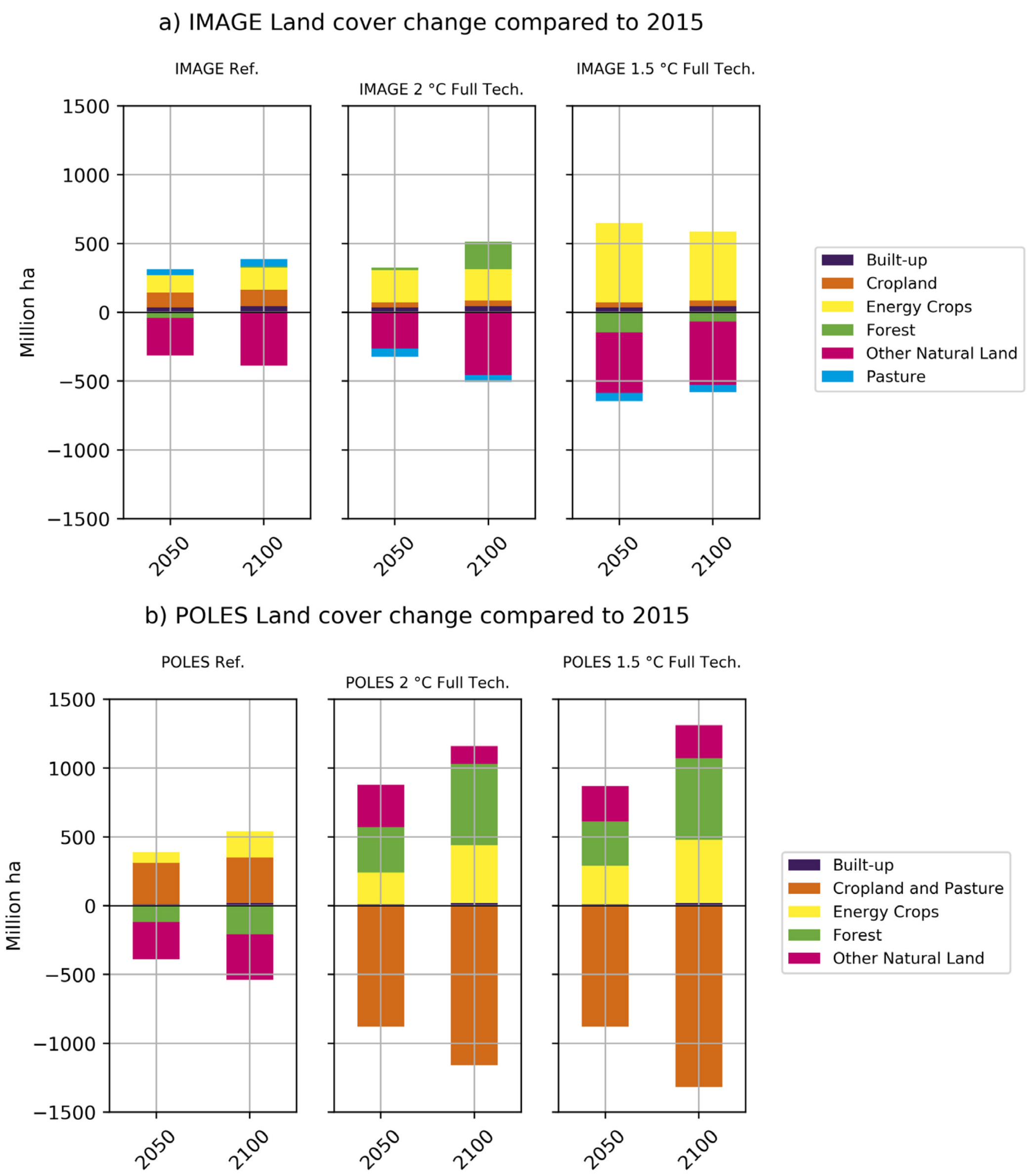

Figure 24. Global land-cover change in million ha in 2050 and 2100, compared to 2015, under the IMAGE (panel a) and POLES (panel b) Current Policies, 2 °C and 1.5 °C scenarios.

Both IMAGE and POLES expect an increase in land dedicated to energy crops, under the 2 °C scenario, compared to the current policies scenario. However, a difference can be noted between the models in that POLES projects that the area of energy crops will only increase marginally, under the 1.5 °C scenario, compared to under the 2 °C scenario, while IMAGE projects that the area of land dedicated to energy crops will more than double under the 1.5 °C scenario, compared to under the 2 °C scenario. See Table 17, for an overview of the projected area of land allocated to energy crops by the models for the various scenarios.

The expansion of energy crops in IMAGE are projected to occur mainly at the expense of other natural land, under the 2 °C scenario. Under the 1.5 °C scenario, bio-energy also expands at the expense of forests, with the assumption that the removed biomass is also used for bio-energy production. Allocation mainly takes place on abandoned agriculture land in central Europe, southern China and eastern United States, and on natural grassland in central Brazil, eastern and southern Africa, and northern Australia. In POLES, the expansion of energy crops is projected not only take place on abandoned agriculture land, natural grassland and pasture, but also at times at the expense of cropland and pasture.

Table 17: Global area of land (Mha) dedicated to growing energy crops, under the Current Policies, 2 °C and 1.5 °C scenarios. Estimates, in this table, are shown as the land area for a specific year, not as land-cover change compared to 2015.

Scenario	POLES			IMAGE		
	2015	2050	2100	2015	2050	2100
Current policies	0	77	188	36	161	199
2 °C	0	229	424	29	260	255
1.5 °C	0	278	456	29	609	532

A difference between the models can be noted in terms of the development of cropland and pasture. In IMAGE, the area of cropland and pasture is roughly the same, under the 2 °C, 1.5 °C and current policies scenarios. The mitigation efforts as implemented under the 2 °C and 1.5 °C scenarios do lead to a slight increase in the area of cropland and a slight decrease in the area of pasture. However, in POLES, the area of cropland and pasture are significantly lower, under the 2 °C and 1.5 °C scenarios, compared to under the current policies scenario. The main reason for this is that the carbon price as introduced in these scenarios induces an additional cost for producing livestock and crop-based products (as based on the emissions associated with the production system). This leads to intensification in the land use, reduction in production of animal-based products in areas with low yields (see Figure 27), and displacement of production to less emission intensive areas. Overall, these factors together lead to abandonment of grassland and pastures, which are being converted back to other natural land.

Differences can also be noted between the IMAGE and POLES projections of forest area development, under the 2 °C and 1.5 °C scenarios. In POLES, the trend of continued loss of forest area (i.e. the deforestation rate is higher than the afforestation rate) as seen in the current policies scenario, is expected to be halted and turned into a trend of increasing forest area (i.e. the deforestation rate is smaller than the afforestation rate), under both the 2 °C and 1.5 °C scenarios. In POLES, the area of forest by 2100 is projected to be more than 800 Mha larger under the 2 °C and 1.5 °C scenarios, compared to under the current policies scenario. Key drivers for this increase in forest area are the carbon price and the projected increase in the price of wood, which jointly increase the value of keeping forests and reduce the monetary value of deforestation. In addition, part of this increase can be attributed to managed forestry resources dedicated to the provision of biomass for energy. In IMAGE, the deforestation rate, as seen under the current policies scenario, is reduced under the 2 °C scenario. It is only under the 2 °C scenarios that the annual deforestation rate is smaller than the annual afforestation rate (i.e. a net global afforestation rate is observed) as the 1.5 °C scenario leads to an increase in the net deforestation rate, compared to the current policies scenario. The main reason for these differences between the projections by IMAGE and POLES directly relates back to the differences in forest-related mitigation options, as considered by the two models (see Section 3).

In POLES, the area of other natural land increases, under the 2 °C and 1.5 °C scenarios, compared to under the current policies scenario. This is because the carbon price induces a cost for producing livestock products (as well as crop-based products), which leads to a reduction in production of animal-based products (see Figure 27). This, in turn, leads to the abandonment of grassland and pastures, which then revert to other natural land. Some of the abandoned grasslands and pastures are being converted to produce energy crops, but the land area that is abandoned is generally larger than the increase in land used for energy crops.

It can be noted that the 2 °C scenario, which assumes lifestyle changes (i.e. the IMAGE 2 °C Limited BECCS – Lifestyle scenario), leads to very different land-use changes (see Figure 25). Under this scenario, the area of cropland and pasture decreases, which is directly related to a lower demand for food and feed crops. This, in turn, leads to an increase in the area of other natural land and more forests.

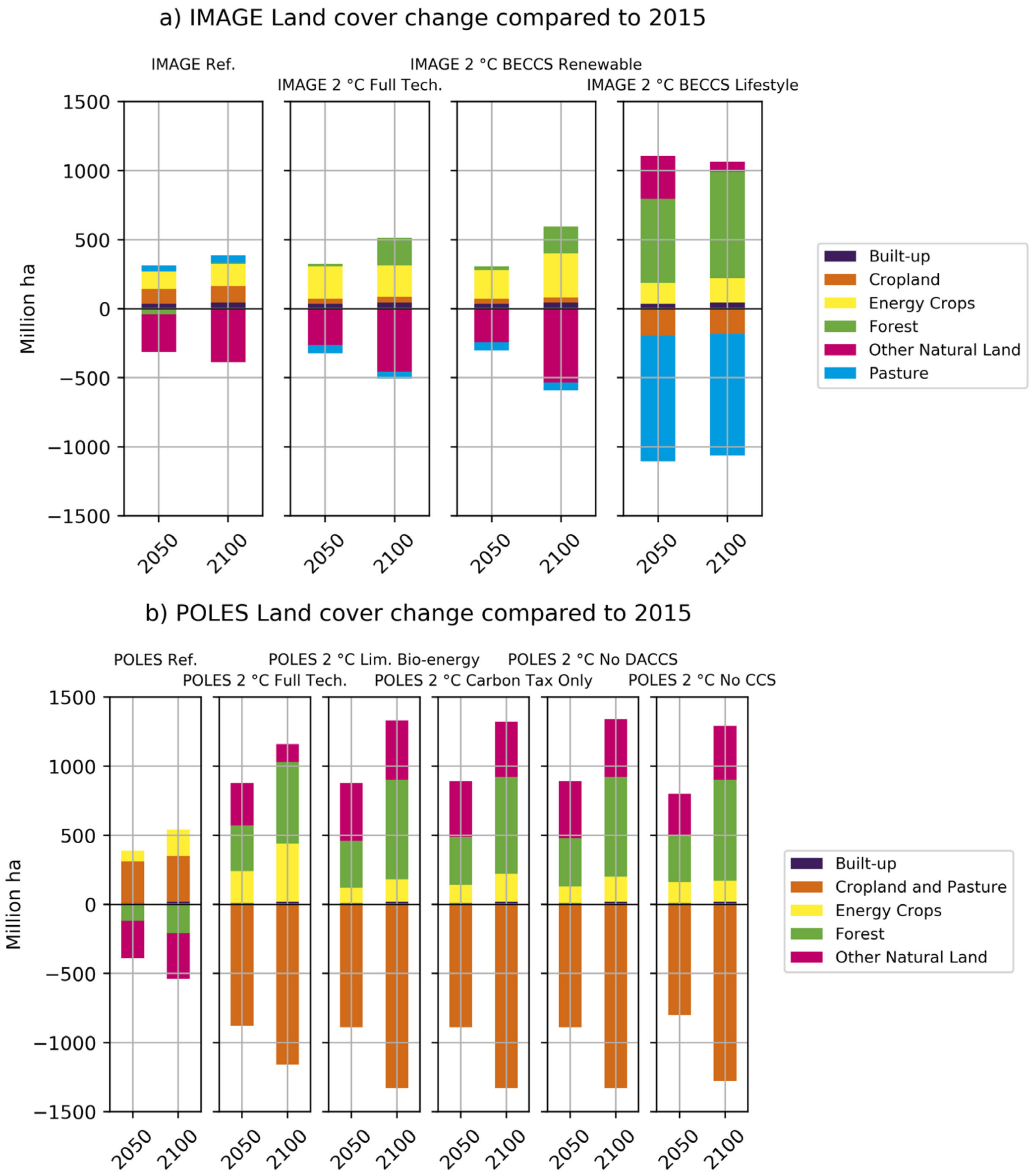

Figure 25. Global land-cover change in million ha in 2050 and 2100, compared to 2015, under the IMAGE (panel a) and POLES (panel b) Current Policies and 2 °C scenarios.

5.4 Food security

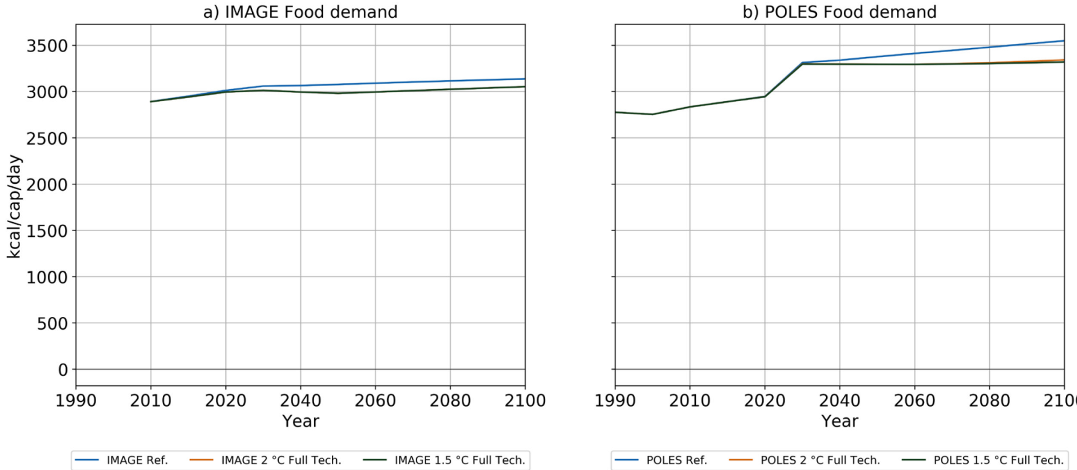

Figure 26. Global total average calorie intake in kcal/capita/day, under the IMAGE (panel a) and POLES (panel b) Current Policies, 2 °C and 1.5 °C scenarios.

Global average calorie intake (kcal/capita/day) is projected to increase over time, under the current policy scenarios of both IMAGE and POLES (see Figure 26). However, the increase in calorie intake over time is projected to be higher under the POLES scenarios than under the IMAGE scenarios, which is mainly due to the fact that POLES projects a higher increase in calorie intake from animal origin (see Figure 27). In 2010, the global average calorie intake according to POLES and IMAGE was 2830 and 2890 kcal/cap/day, respectively. By 2100, global average calorie intake is expected to reach 3140 kcal/cap/day in IMAGE, and 3550 kcal/cap/day in POLES.

POLES and IMAGE both project that efforts to reduce climate change (through the use of a global carbon tax on greenhouse gas emissions (POLES), and through avoided deforestation policy (IMAGE)) will negatively impact calorie intake. Both models project a reduction in the global average calorie intake, under the 2 °C and 1.5 °C scenarios, compared to the situation under the current policies scenario (i.e. Full Technology 2 °C and 1.5 °C scenarios of IMAGE and POLES). Overall, POLES projects that the mitigation efforts will have a stronger impact on calorie intake than does IMAGE. POLES projects a reduction in global average calorie intake by roughly 210–230 kcal/cap/day by 2100 (under the 2 °C and 1.5 °C scenarios, compared to the current policies scenario), while IMAGE projects a reduction in the global average calorie intake of around 80 kcal/cap/day. However, under the POLES 2 °C and 1.5 °C scenarios, the reduction in calorie intake is limited by food security constraints as considered in these scenarios (see Chapter 2).

Both models project that the average global calorie intake will be the same under the Full technology 2 °C and 1.5 °C scenarios. In other words, enhancing mitigation efforts to limit global mean temperate increase to 1.5 °C instead of 2 °C is not expected to impact the global average calorie intake. However, it should be noted that under these POLES scenarios (data derived from GLOBIOM), food security constraints force a certain level of calorie intake. It may be that relaxing these constraints would reduce the average global calorie intake under the 1.5 °C scenario than that that under the 2 °C scenario. Also, land availability in IMAGE follows a food-first principle, which may also be the reason for this specific outcome.

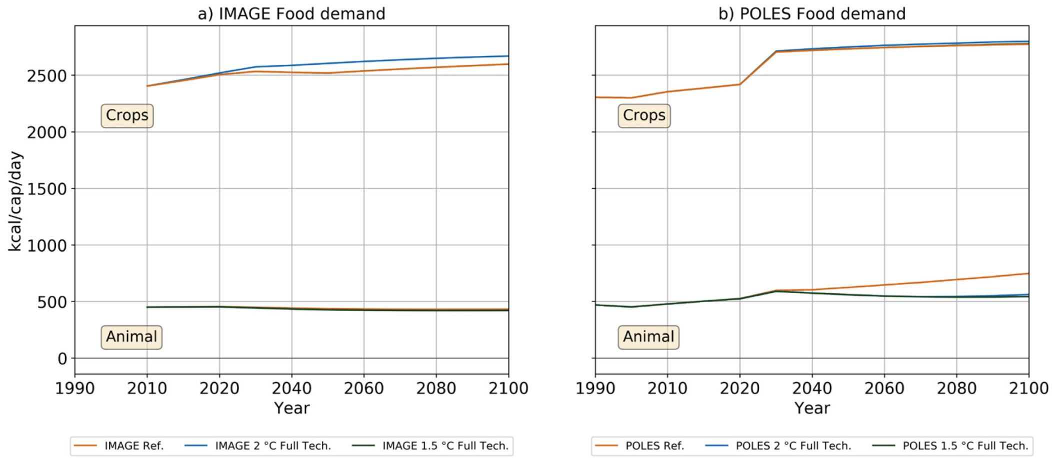

Figure 27. Global average calorie intake in kcal/capita/day, separated into calories from crops and animal origin, under the IMAGE (panel a) and POLES (panel b) Current Policies, 2 °C and 1.5 °C scenarios. All estimates are shown at the global level.

Another difference between the IMAGE and POLES models is also seen in terms of what types of calories are being reduced under the 2 °C and 1.5 °C scenarios, compared to under the current policy scenario. Under the POLES 2 °C and 1.5 °C scenarios, the reduction in calorie intake is mainly from an animal origin, while under the IMAGE scenarios it is mainly related to crops.

It should be noted that, for these assessments, IMAGE has REDD policy affecting food security. The use of bio-energy is also driven by carbon price but does not affect food security, following the food-first principle. POLES scenarios apply a global carbon tax on greenhouse gas emissions/removals from agriculture and the land-use sector. The implementation of such a carbon price leads to an increase in the production costs and food prices, through three main channels, simultaneously: i) the carbon tax on agricultural greenhouse gas emissions directly increases the production costs depending on the greenhouse gas intensity of the production; ii) the carbon tax on the carbon emissions/sequestration associated with land-use change makes expansion of agriculture land expensive, and hence leads to higher land rents; and iii) the carbon tax induces an increase in the biofuel demand from the energy system, which further increases the demand for land, and hence again pushes the land rents upwards. It should also be noted that the impact on food production has been shown to be different if mitigation is not achieved by applying a uniform carbon tax on emissions, but through subsidising the least-carbon-intense production systems (Cohn et al., 2014). As such, food security issues can be tackled directly through the design of the mitigation policy (Hasegawa et al., 2018a).

6 EU analysis

Findings

- **Under the Full Technology scenarios, which assume efficient global implementation of reductions, beyond 2020, across regions and consistent with the 2 °C and 1.5 °C targets, emission reductions for the EU are about 80% and 90% below 1990 levels, by 2050.** The Full Technology and alternative 2 °C scenarios show a range of reductions for the EU of between 76% and 84% below 1990 levels, by 2050. The Full Technology and alternative 1.5 °C scenarios show reductions of about 91% below 1990 levels, by 2050. Scenarios based on other equity principles lead to emission reduction targets that differ from those resulting from least-cost scenarios and often lead to higher reductions in high-income regions (den Elzen and Höhne, 2008; Höhne et al., 2014).

Results

This section analyses results from the 2 °C and 1.5 °C scenarios of both the IMAGE and POLES models, for the EU-28. It should be noted that IMAGE generates results for the entire Europe region, including non-EU Member States, such as Norway and Switzerland, and LULUCF CO_2 emission levels in IMAGE are higher compared to in POLES, as IMAGE does not include the sinks of managed land, based on indirect human-induced effects.

Table 18 shows greenhouse gas emissions, including LULUCF CO_2 emissions for Europe (IMAGE) and the EU-28 (POLES), under all scenarios with the exception of the IMAGE 1.5 °C Limited BECCS – Renewable electricity scenario. As explained in Chapter 6, the LULUCF CO_2 emissions under the POLES scenario are harmonised with the greenhouse gas emissions estimates from the national data inventory of the EU, and the trend of IIASA GLOBIOM is used for the projection. The reductions in greenhouse gases in 2050, including LULUCF, under the Full technology and alternative scenarios, however, are comparable, amounting to approximately 76% to 84% and about 91%. under the 2 °C and 1.5 °C scenarios, respectively.

It should be noted that the projected reductions depend strongly on how the negative emissions that are achieved through BECCS are allocated—to the bio-energy producing region, or to the region for which CCS is applied. In the IMAGE and POLES models, the latter is generally used as a definition, which we, therefore, also used here. Future research could explore the implications of other allocation rules for the projection of regional reductions as well as neutrality.

*Table 18. European greenhouse gas emissions, **including** LULUCF CO_2, in $MtCO_2eq/yr$ (annual values and reductions compared to 1990 emission levels)*

Scenario	1990	2015	2050	2050 vs 1990
IMAGE 2 °C Full Technology	**6114**	**4848**	**1318**	**-78%**
IMAGE 2 °C Limited BECCS – Lifestyle	6114	4848	1473	-76%
IMAGE 2 °C Limited BECCS – Renewable electricity	6114	4848	1282	-79%
POLES 2 °C Full Technology	**5399**	**4304**	**998**	**-82%**
POLES 2 °C Limited Bio-energy	5399	4304	1117	-79%
POLES 2 °C Carbon tax only	5399	4304	1159	-79%
POLES 2 °C No DACCS	5399	4304	1057	-80%
POLES 2 °C No CCS	5399	4304	846	-84%
IMAGE 1.5 °C Full Technology	**6114**	**5066**	**540**	**-91%**
IMAGE 1.5 °C Limited BECCS – Lifestyle	6114	5066	560	-91%
POLES 1.5 °C Full Technology	**5399**	**4304**	**466**	**-91%**
POLES 1.5 °C Limited Bio-energy	5399	4304	488	-91%

7 References

Beach RH, Creason J, Ohrel SB, et al. (2015) Global mitigation potential and costs of reducing agricultural non-CO2 greenhouse gas emissions through 2030. Journal of Integrative Environmental Sciences 12:87-105.

Bijl DL, Bogaart PW, Dekker SC, et al. (2017) A physically-based model of long-term food demand. 45:47-62.

Cohn AS, Mosnier A, Havlík P, et al. (2014) Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. Proceedings of the National Academy of Sciences:201307163.

den Elzen M, Admiraal A, Roelfsema M, et al. (2016) Contribution of the G20 economies to the global impact of the Paris agreement climate proposals. Climatic Change 137:655-665.

den Elzen MGJ, Höhne N (2008) Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets. Climatic Change 91:249-274.

Doelman JC, Stehfest E, Tabeau A, et al. (2018) Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. Global Environmental Change 48:119-135.

Foley JA, DeFries R, Asner GP, et al. (2005) Global consequences of land use. 309:570-574.

Frank S, Beach R, Havlík P, et al. (2018) Structural change as a key component for agricultural non-CO2 mitigation efforts. Nature Communications 9:1060.

Gernaat DEHJ, Calvin K, Lucas PL, et al. (2015) Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. Global Environmental Change 33:142-153.

Grassi G, House J, Dentener F, et al. (2017) The key role of forests in meeting climate targets requires science for credible mitigation. Nature Clim. Change 7:220-226.

Hasegawa T, Fujimori S, Havlík P, et al. (2018) Risk of increased food insecurity under stringent global climate change mitigation policy. 8:699.

Havlík P, Valin H, Herrero M, et al. (2014) Climate change mitigation through livestock system transitions. Proceedings of the National Academy of Sciences 111:3709-3714.

Herrero M, Havlík P, Valin H, et al. (2013) Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences 110:20888-20893.

Höhne N, den Elzen MGJ, Escalante D (2014) Regional greenhouse gas mitigation targets based on equity principles: a comparison of studies. Climate Policy 14:122-147.

Hoogwijk M, Faaij A, de Vries B, et al. (2009) Exploration of regional and global cost–supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. Biomass and Bioenergy 33:26-43.

Kaya (1989) Impacts of carbon dioxide emissions on GWP: Interpretation of proposed scenarios., IPCC/Response Strategies Working Group. IPCC. Geneva.

Keramidas K, Kitous A, Després J, et al. (2017) POLES - JRC model documentation. Joint Research Centre (JRC), EUR 28728 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-71801-4, doi:10.2760/225347, JRC107387.

Kindermann G, Obersteiner M, Sohngen B, et al. (2008) Global cost estimates of reducing carbon emissions through avoided deforestation. Proceedings of the National Academy of Sciences of the United States of America 105:10302-10307.

Kitous A, Keramidas K, Vandyck T, et al. (2017) Global Energy and Climate Outlook 2017: How climate policies improve air quality - Global energy trends and ancillary benefits of the Paris Agreement. Joint Research Centre (JRC), EUR 28798 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-73864-7, doi:10.2760/474356, JRC107944.

Kuramochi T, Fekete H, Hans F, et al. (2017) Greenhouse gas mitigation scenarios for major emitting countries: Analysis of current climate policies and mitigation commitments 2017 update, NewClimate Institute (Cologne, Germany), PBL (The Hague, the Netherlands), IIASA (Austria), https://newclimate.org/2017/11/01/greenhouse-gas-mitigation-scenarios-for-major-emitting-countries-2017/.
Lucas P, van Vuuren DP, Olivier JA, et al. (2007) Long-term reduction potential of non-CO2 greenhouse gases. Environmental Science & Policy 10:85-103.
Luderer G, Vrontisi Z, Bertram C, et al. (2018) Residual fossil CO2 emissions in 1.5–2 °C pathways. Nature Climate Change 8:626-633.
Meinshausen M, Raper SCB, Wigley TML (2011a) Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. Atmospheric Chemistry and Physics 11:1417-1456.
Meinshausen M, Smith SJ, Calvin K, et al. (2011b) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109:213-241.
Muhammad A, Seale JL, Meade B, et al. (2011) International evidence on food consumption patterns: an update using 2005 international comparison program data.
Riahi K, Kriegler E, Johnson N, et al. (2015) Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change 90:8-23.
Riahi K, van Vuuren DP, Kriegler E, et al. (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change 42:153-168.
Roelfsema M, Fekete H, Höhne N, et al. (2018) Reducing global GHG emissions by replicating successful sector examples: the 'good practice policies' scenario. Climate Policy 18:1103-1113.
Rogelj J, Popp A, Calvin KV, et al. (2017) Transition pathways towards limiting climate change below 1.5°C. Nature Climate Change (under review), http://unfccc.int/files/adaptation/application/pdf/2.9_iiasa_rogelj.pdf.
Rogelj J, Popp A, Calvin KV, et al. (2018) Scenarios towards limiting global mean temperature increase below 1.5 °C. Nature Climate Change 8:325-332.
Ruesch A, Gibbs HK (2008) New IPCC Tier-1 global biomass carbon map for the year 2000.
Schaeffer M, Stehfest M (2010) The climate subsystem in IMAGE updated to MAGICC 6.0. Report. Netherlands Environmental Assessment Agency (PBL), Bilthoven, the Netherlands.
Smith P, Davis SJ, Creutzig F, et al. (2016) Biophysical and economic limits to negative CO2 emissions. Nature Climate Change 6:42-50.
Stehfest E, van Vuuren DP, Bouwman AF, et al. (2014) Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, the Hague: PBL Netherlands Environmental Assessment Agency, http://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0.
UNFCCC (2015) FCCC/CP/2015/L.9/Rev.1: Adoption of the Paris Agreement. UNFCCC, Paris, France, pp. 1-32.
UNFCCC (2018a) Greenhouse Gas Inventory Data - Detailed data by Party, http://di.unfccc.int/detailed_data_by_party
UNFCCC (2018b) National Communication submissions from Non-Annex I Parties. UNFCCC, Bonn, Germany.
UNFCCC (2018c) Submitted Biennial Update Reports (BURs) from Non-Annex I Parties, http://unfccc.int/national_reports/non-annex_i_natcom/reporting_on_climate_change/items/8722.php.
UNFCCC (2018d) Third Biennial Reports - Annex I. UNFCCC, Bonn, Germany.
van Sluisveld MAE, Martínez SH, Daioglou V, et al. (2016) Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. Technological Forecasting and Social Change 102:309-319.
van Soest HL, de Boer HS, Roelfsema M, et al. (2017) Early action on Paris Agreement allows for more time to change energy systems. Climatic Change 144:165-179.
van Vuuren DP (2007) Energy systems and climate policy:Long-term scenarios for an uncertain future. PhD Thesis, University of Utrecht, Utrecht.

van Vuuren DP, Stehfest E, Gernaat D, et al. (2017) Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environmental Change 42:237-250.
van Vuuren DP, Stehfest E, Gernaat DEHJ, et al. (2018) Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nature Climate Change 8:391-397.
Vandyck T, Keramidas K, Saveyn B, et al. (2016) A global stocktake of the Paris pledges: Implications for energy systems and economy. Global Environmental Change 41:46-63.
Vrontisi Z, Luderer G, Saveyn B, et al. (2018) Enhancing global climate policy ambition towards a 1.5 °C stabilization: a short-term multi-model assessment. Environmental Research Letters 13:044039.

Appendix A. Climate implications

Findings

- **The POLES 2 °C scenarios assume slightly higher cumulative CO_2 emissions of about 1150 $GtCO_2$ for the 2010–2100 period, versus 1000 $GtCO_2$ under the IMAGE 2 °C scenarios.**
- **IMAGE uses the MAGICC model, which is embedded in the modelling framework, whereas POLES uses the online model version of MAGICC. Therefore, the projections of concentrations and radiative forcing, as well as temperature increases may differ, due to different climate model assumptions, which makes a comparison between these models difficult.**
- **The radiative forcing, under the POLES 2 °C scenarios reaches about 2.7–2.8 W/m^2 by 2100. This difference is rather small and could also be caused by differences in albedo-related forcing categories, which are higher under the online model version of MAGICC.**
- **The IMAGE and POLES 1.5 °C scenarios result in similar cumulative CO_2 emissions and radiative forcing by 2100.**

Results

Levels of temperature increase are generally calculated during post processing by IAMs. The IMAGE model uses the MAGICC model (Meinshausen et al., 2011a; Meinshausen et al., 2011b), that is embedded in the model (Schaeffer and Stehfest, 2010; Stehfest et al., 2014). POLES uses the on-line model version of MAGICC (Meinshausen et al., 2011a; Meinshausen et al., 2011b). The outcomes of both MAGICC models can be different, in particular as IMAGE-MAGICC uses its terrestrial carbon uptake modelling from the IMAGE model (Stehfest et al., 2014). In addition, the MAGICC-online uses its own algorithm to harmonize input data with own assumptions on land-use-related CO_2 emissions, and converges by 2050 towards the original input of POLES. The on-line version of MAGICC also has a probabilistic component, and therefore projects temperature increase projections for different percentiles (including the median, 66th percentile), whereas the MAGICC model of IMAGE only projects the median temperature increase projection. These aspects make it difficult to compare the outcomes of both MAGICC versions, and therefore only the cumulative emissions and radiative forcing projections are presented below (Figure 28).

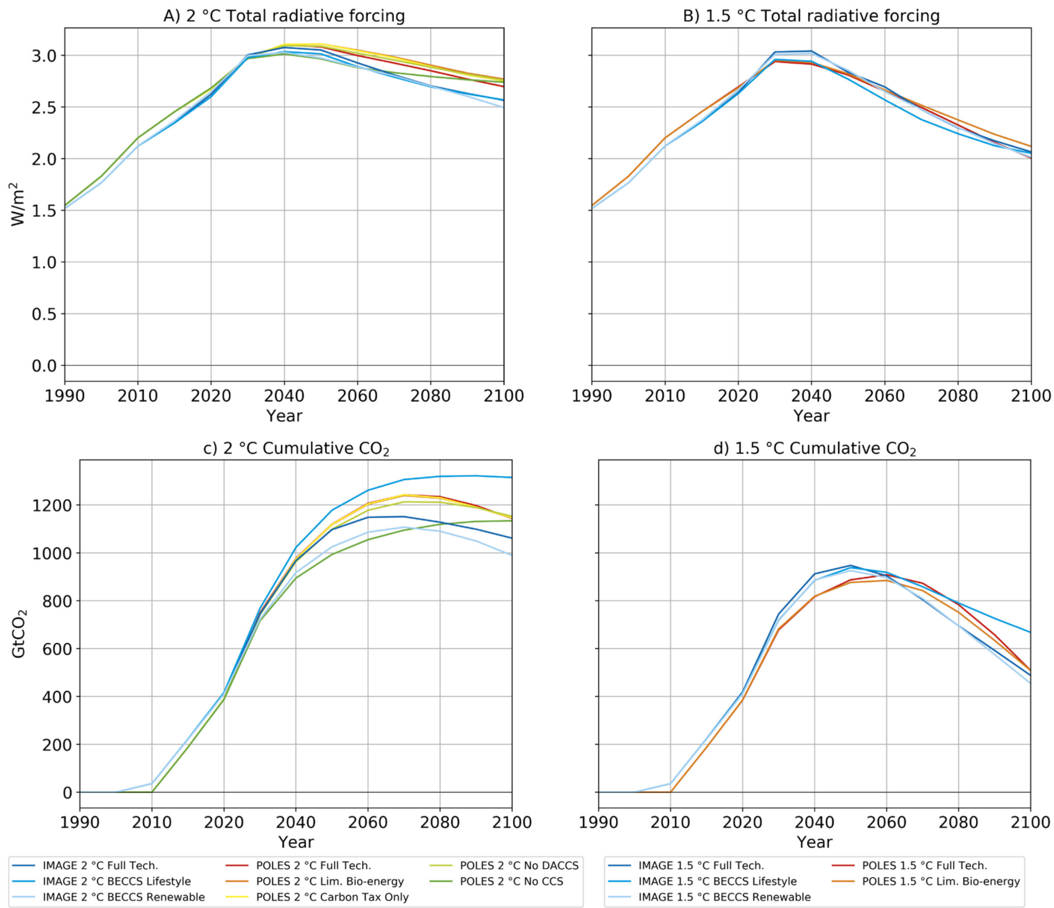

Figure 28. Radiative forcing (panel a and b) and cumulative CO_2 emissions (panel c and d), under the 2 °C and 1.5 °C scenarios of IMAGE and POLES.