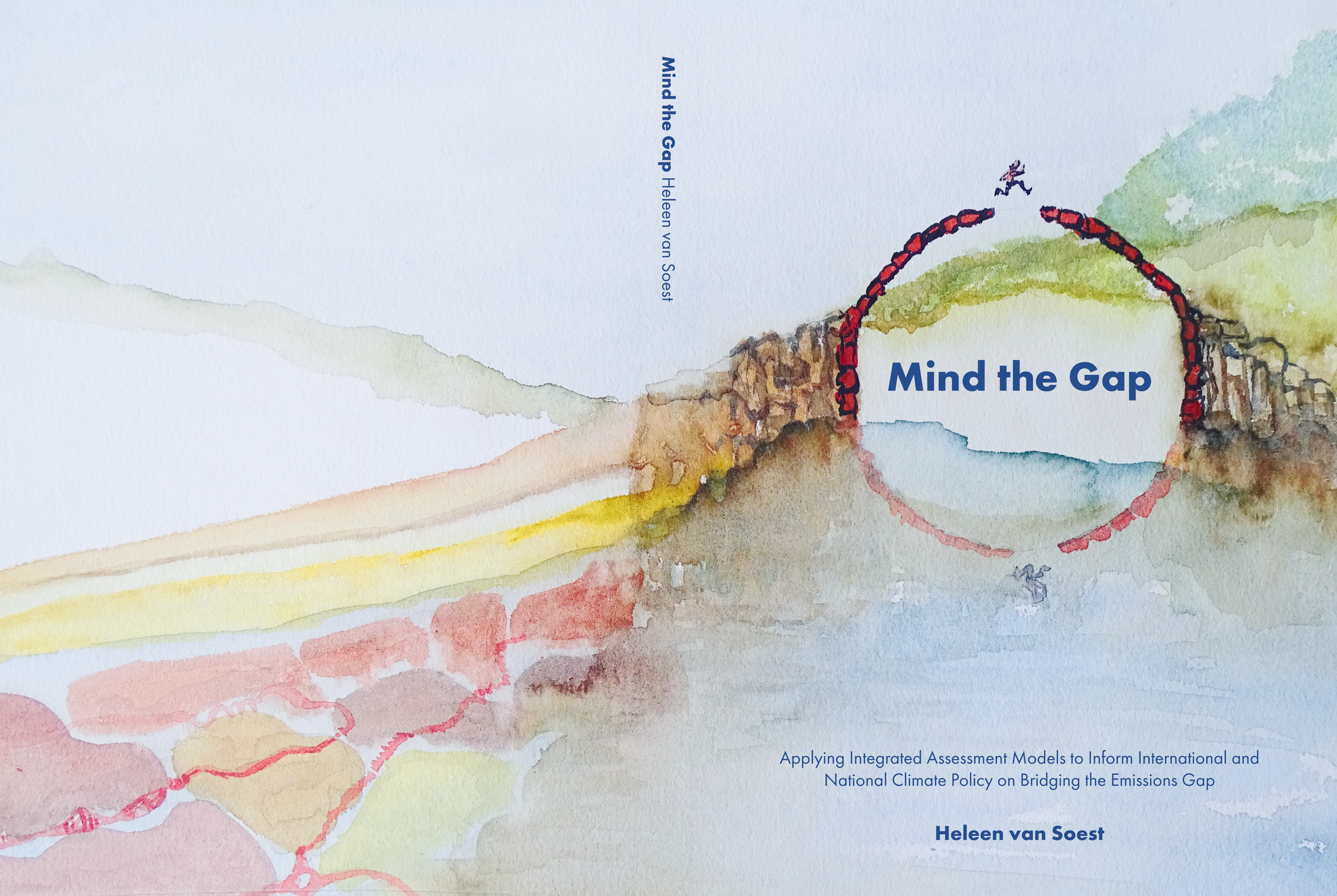

Mind the Gap Heleen van Soest

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Applying Integrated Assessment Models to Inform International and National Climate Policy on Bridging the Emissions Gap

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Applying Integrated Assessment Models to Inform International and National Climate Policy on Bridging the Emissions Gap

Let op de kloof

Toepassing van *Integrated Assessment*-modellen om internationaal en nationaal klimaatbeleid te informeren over de emissiekloof en hoe die te overbruggen

(met een samenvatting in het Nederlands)

Proefschrift

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Universiteit Utrecht
op gezag van de
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door

Heleen Laura van Soest

geboren op 4 december 1989
te Delft

Promotoren:

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Contents

Units and abbreviations

CBDR-RC	common but differentiated responsibilities and respective capabilities
CCS	carbon capture and storage (or sequestration)
CD-LINKS (project)	Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing
CDR	Carbon Dioxide Removal
CFC	chlorofluorocarbon
CGE	Computable General Equilibrium (model)
CO_2	carbon dioxide
COMMIT (project)	Climate pOlicy assessment and Mitigation Modeling to Integrate national and global Transition pathways
COP	Conference of the Parties
DPSIR	Driver-Pressure-State-Impact-Response
ENGAGE (project)	Exploring National and Global Actions to reduce Greenhouse gas Emissions
ESM	Earth System Model
GST	Global Stocktake
IAM	Integrated Assessment Model
INDC(s)	Intended Nationally Determined Contribution(s)
IPCC	Intergovernmental Panel on Climate Change
LTS	long-term strategy
MIT	Massachusetts Institute of Technology
NDC(s)	Nationally Determined Contribution(s)
SDGs	Sustainable Development Goals
SSPs	Shared Socioeconomic Pathways
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention of Climate Change
WGIII	IPCC working group III
WMO	the World Meteorological Organization

Overview of models

Model	Full name	Host	Host country
AIM/CGE	Asia-Pacific Integrated Model/Computable General Equilibrium	NIES, Kyoto University	Japan
ASF	Atmospheric Stabilization Framework	US Environmental Protection Agency	USA
BLUES	Brazilian Land Use and Energy System	COPPE/UFRJ (Cenergia)	Brazil
China TIMES	The Integrated MARKAL-EFOM System	Tsinghua University	China
COFFEE-TEA	COmputable Framework For Energy and the Environment - Total-Economy integrated Assessment	COPPE/UFRJ (Cenergia)	Brazil
DNE21+	Dynamic New Earth 21+	RITE	Japan
GCAM	Global Change Analysis Model	JGCRI	USA
GEM-E3	General Equilibrium Model for Economy-Energy-Environment	ICCS	Greece
IMAGE	Integrated Model to Assess the Global Environment	PBL	Netherlands
IPAC-AIM/technology	Integrated Policy Assessment Model for China	ERI	China
MARKAL	MARKet Allocation	TERI	India
MESSAGEix-GLOBIOM	Model for Energy Supply Strategy Alternatives and their General Environmental Impact - GLobal BIOsphere Management	IIASA	Austria
MWC	Model of Warming Commitment	WRI	USA
POLES	Prospective Outlook on Long-term Energy Systems	JRC	Spain
PRIMES	Price-Induced Market Equilibrium System	E3Modelling	Greece

Model	Full name	Host	Host country
PROMETHEUS	PROMETHEUS	E3Modelling	Greece
REMIND-MAgPIE	REgional Model of Investment and Development - Model of Agricultural Production and its Impacts on the Environment	PIK	Germany
TIAM-Grantham	TIMES Integrated Assessment Model	UCL, Grantham Institute	United Kingdom
WITCH	World Induced Technical Change Hybrid	RFF-CMCC EIEE	Italy

Preface

I will not say much here. Notes of a more personal nature can be found in the acknowledgements. I just needed a place to explain the title of this thesis. 'Mind the Gap' seemed fitting in three ways.

First, this thesis, as much of my work at PBL, revolves around the emissions gap, that is: the difference between emission levels needed to limit global warming to 1.5 °C or 2 °C and those expected to result from current climate policies and pledges. So, mind the emissions gap that needs to be closed if we are to limit global warming.

Second, I find my work, and this thesis, to be on the science–policy interface, which may sometimes manifest itself as a gap. One clear example of that relates to speed: once a scientific publication about a 'current policies scenario' is out there, it is already outdated. So, mind the differences between the somewhat slower scientific process and the fast developing field of climate policy.

Third, I have tried to bridge the gap between the rather abundant scientific publications on the global level and the growing, but still rather limited number of scientific publications on the level of individual countries. So, mind the information gap that will need to be closed to stay relevant for climate policymaking.

Knowing that closing these gaps will take time, I hope this thesis contributes to bridging these gaps.

1

Introduction

1.1 A short history of climate science and policy

The foundations for climate science, based on classic physics, were laid in the 19th century (Verheggen, 2020). In 1824, Joseph Fourier discovered the ability of the atmosphere to retain heat (later dubbed the greenhouse effect, a term introduced by John Henry Poynting in 1909). In 1856, Eunice Foote suggested that carbon dioxide (CO_2) has a warming effect, and in 1859, John Tyndall started his study of the heat-trapping ability of water vapour, CO_2, ozone and hydrocarbons. In 1896, Svante Arrhenius performed the first calculations regarding the response of the Earth's temperature to an increase in greenhouse gas concentrations (now called climate sensitivity). These pioneers were among the first to understand that greenhouse gas emissions heat the Earth's atmosphere (global warming), inducing changes in the climate (Weart, 2021).

Moving from a theoretical understanding to observations, amateur scientist Guy Stewart Callendar started measuring temperatures around the world and studied the work of these early climate scientists, resulting in an analysis submitted to the Royal Meteorological Society in 1938. Callendar showed that global temperatures had risen 0.3 °C over the previous 50 years, which he attributed to increasing CO_2 levels caused by fossil fuel burning. The Fellows of the Royal Meteorological Society did not immediately accept these conclusions. However, Callendar continued his research, prompting Charles Keeling to set up an observatory on the volcano Mauna Loa (Hawaii) for measuring greenhouse gases in the atmosphere (resulting in the now famous Keeling curve), with the first measurements starting in 1957 (Keeling & Bacastow, 1977). The demonstrations that CO_2 concentrations in the atmosphere were rising spurned growing concern in the 1950s and 1960s. Making the link to human activities, U.S. president Lyndon B. Johnson's Science Advisory Committee noted the harmful effect of fossil fuel emissions in a 1965 report. Modelling of climate change began in the 1970s with Syukuro Manabe[1] and Richard Wetherald (Manabe & Wetherald, 1975) making detailed calculations of the greenhouse effect (modelling of the oceans in relation to carbon cycles and human interference had started some 10 years earlier, e.g. Bolin & Eriksson, 1958).

The academic discussion on climate change continued through the seventies, with, for instance, James Lovelock and V. Ramanathan discovering the enormous global warming potential of chlorofluorocarbons (CFCs) around 1975 (Ramanathan, 1975). Although not directly addressing climate change, the work of the Club of Rome also

1 In 2021, Manabe won the Nobel Prize in Physics "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming", sharing it with Klaus Hasselmann and Giorgio Parisi - NobelPrize.org. (2022). *Syukuro Manabe – Facts – 2021*. Nobel Prize Outreach AB 2022. Retrieved 19 January from https://www.nobelprize.org/prizes/physics/2021/manabe/facts/.

emphasized the risks involved in global pollution. The 1973-74 oil crisis spurred the development and use of energy-economy models such as MARKAL and the work of the Energy Modelling Forum (EMF). This was also followed by the first attempts to look at the economic aspects of climate change, among others, by Bill Nordhaus (late 1970s). During the 1980s, concerns about climate change further increased. Around the same time, Integrated Assessment Modelling started, aiming to support climate policy (van Beek et al., 2020). Integrated Assessment Models (IAMs) are computational models to assess complex, long-term interactions between humans and their environment to better understand global environmental problems (see Chapter 1.4 for a more elaborate discussion of these models and their use in this thesis). Notable first IAMs were, in addition to Nordhaus' work (Nordhaus, 1980), the Model of Warming Commitment (MWC, Mintzer, 1987), the Atmospheric Stabilization Framework (ASF, Lashof & Tirpak, 1989), and the Integrated Model to Assess the Global Environment (IMAGE, Rotmans, 1990). At the same time, climate science was still beset with uncertainties, making it relatively easy for actors against policy to oppose regulations (van Soest, 2014). The year 1988 marks a turning point, with James Hansen's testimony to Congress putting the topic on the political agenda during an unprecedented hot summer. An impartial commission was established to facilitate that discussion: the Intergovernmental Panel on Climate Change (IPCC). It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), which was endorsed by the UN General Assembly in 1988 (IPCC, 1990, 2021). A few years later, in Rio de Janeiro, in 1992, more than 150 countries joined the United Nations Framework Convention of Climate Change (UNFCCC, 1992, 2021). In this agreement, they agreed to cooperate internationally to achieve a *"stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"* (UNFCCC, 1992). They further established the still leading principle of *"common but differentiated responsibilities and respective capabilities"* in addressing climate change across countries, often shortened to CBDR-RC (UNFCCC, 1992).

1.2 The Paris Agreement on climate change

The UNFCCC formulation was an important step, but the next critical question was how to achieve its objectives. Negotiations on this, formally known as Conference of the Parties (COP), commenced in 1995. The thinking at the time was that the richer countries that had caused the lion's share of the problem should 'take the lead' (in line with CBDR-RC) and that a binding regime would be most effective. That resulted in the adoption of the Kyoto Protocol at COP 3 in 1997 (UNFCCC, 1997). The Kyoto Protocol set legally binding targets for developed countries (so-called Annex I Parties) to reduce their greenhouse gas emissions. However, it became clear that for a thorough solution, all countries would need to contribute, both as a result of rapidly increasing emissions in Asia and the fact that it was not possible to involve the USA without the participation of large developing countries. A negotiation process was planned to lead to a binding agreement at COP 15 in Copenhagen in 2009. However, the Copenhagen negotiations failed in that goal as countries felt unable to sign a binding agreement. The COP's result, the Copenhagen Accord (UNFCCC, 2010b), aiming to limit temperature rise to 2 °C, was only 'taken note of'.

Even so, a new era of climate policy began in Copenhagen, working towards COP 21. Although the Kyoto Protocol had legally binding targets, participation was limited, and enforcement was impossible. Therefore, a new framework was established based on a combination of global goals and voluntary national[2] contributions to that overall goal. As this does, in principle, not lead to binding action, this structure enabled nearly all countries to participate. The Paris Agreement was adopted at COP 21 in 2015 (UNFCCC, 2015b). Parties to the Paris Agreement agreed to limit global warming to 'well below' 2 °C relative to pre-industrial levels, and strive to limit it further to 1.5 °C; to reach a peak in global greenhouse gas emissions as soon as possible, and achieve a 'balance' between anthropogenic sources and sinks of greenhouse gases in the second half of the century. In the years following, this 'balance' has often been interpreted as net-zero emissions by 2050.

The broad participation was enabled by the bottom-up nature of the agreement, in contrast with the top-down nature of the Kyoto Protocol: Parties to the Paris Agreement were asked to submit their self-determined mitigation targets in so-called Intended Nationally Determined Contributions (INDCs). Upon ratification of the Agreement, an INDC would become a Nationally Determined Contribution (NDC). However, the Parties foresaw that such voluntary pledges were not likely to lead to the global emission levels in line with the goals of the Paris Agreement. Therefore, they also agreed on processes to regularly take stock of the aggregate effect of individual NDCs and ensure ambition levels would be raised over time: the Global Stocktake (GST) and ratchet mechanism, a process that will be repeated every five years. As the first round of the GST would only be in 2023 (starting in 2021 and concluding in 2023), an informal test round was conducted in 2018: the Talanoa Dialogue. It centred around three overarching questions: where are we, where do we want to go, and how do we get there?

1.3 The Global Stocktake and the emissions gap

The evaluation as part of the Global Stocktake process needs to assess 1) what is needed to achieve the global climate goals of the Paris Agreement, 2) what current pledges and mitigation actions will deliver, and 3) how we can close any gaps between

2 For brevity, we will refer to 'countries' and 'national', also applying to the EU as Party to the Paris Agreement, although the EU is not a country.

these. That implies, as recognised in the Talanoa Dialogue, that we need to be able to estimate, quantitatively, 1) where global emissions are heading (where are we?), 2) what levels would be in line with the Paris goals (where do we want to go?), and 3) what specific measures can deliver in terms of emissions reductions (how do we get there?). Projections about the future are needed to answer these questions. That is where models come in. IAMs are typically used to develop scenarios to explore alternate futures, linking global and national scales. Even though they are not perfect, their geographical and temporal representation makes them well suited to study the three questions above.

Many researchers (Roelfsema et al., 2020; Rogelj et al., 2016), often applying such IAMs, have observed a gap between emission levels needed to stay on a pathway in line with the 2 °C and 1.5 °C goals of the Paris Agreement and global emission levels expected as a result of full implementation of the conditional[3] NDCs[4] and currently implemented climate policies (Figure 1.1). UNEP synthesises these findings in its yearly Emissions Gap Reports (Rogelj et al., 2016; United Nations Environment Programme, 2020). The **total emissions gap** can be further broken down into two distinct gaps: the **ambition gap**, i.e. the difference between emissions promised by countries in their NDCs and those in line with the well-below 2 °C and 1.5 °C targets, and the **implementation gap**, i.e. the difference between emissions expected under currently implemented climate policies and those needed to achieve the NDCs (a new dimension introduced by Roelfsema et al., 2020, and used in this thesis). In other words: a country may close the ambition gap if it raises the ambition level of its NDC, but it will be left with an implementation gap if it does not introduce policy instruments to ensure meeting the NDC targets. The UNEP Gap report uses the term emissions gap to describe what is called the ambition gap here. This thesis' distinction of ambition and implementation gaps enables more targeted policy recommendations: should only the ambition level of the NDC be strengthened, should additional climate policy be implemented to achieve the NDC, or do both need a boost?

These gaps can be viewed both at the global and national levels. For the ambition gap, the global level is most suited. In contrast, the national level better fits the implementation gap. A 'global implementation gap' of zero would not mean that all countries are on track to meet their NDCs: some countries may overachieve their NDCs with currently implemented climate policies, compensating for others that are

3 Many Parties to the Paris Agreement have at least an unconditional mitigation target, as part of their NDC. In addition, Parties may add a more stringent target that they strive to meet under certain conditions, such as finance and technology transfer. When referring to 'conditional NDCs', we generally mean both the unconditional NDCs and the more stringent conditional NDC targets.

4 All publications contained in this PhD thesis used the targets from the first NDCs (submitted in 2015-2016), i.e. no updates submitted around COP26 in Glasgow.

not on track. Therefore, next to analysing the global ambition gap, the UNEP gap report (in its Chapter 2, United Nations Environment Programme, 2020) synthesises to what extent countries are on track to meet their NDCs with currently implemented policies without presenting it as a global implementation gap. This synthesis draws from national communications and studies (such as impact assessments) and global and national IAMs.

There are several complications in estimating the emissions gap, ambition gap, and implementation gap. An important one, for example, is the uncertainty around global emissions levels required in 2030 to limit global warming to 'well below' 2 °C. Different scenarios with different 2030 emissions levels may all be consistent with the temperature goals. A related and critical complication is that most models only run cost-optimal scenarios consistent with the Paris Agreement. Using these globally cost-optimal outcomes at the country level might not be consistent with what is considered a fair division of mitigation effort[5]. In addition, NDC scenarios typically assume full implementation of NDC targets, i.e. no underachievement and no overachievement, thereby possibly distorting the size of the ambition gap. However, these complications in determining 1) what the world should do to achieve the goals of the Paris Agreement, and 2) what countries should do, do not prohibit using the emissions gap concept, as they will typically influence the numerical uncertainty, not the high-level conclusions. These conclusions are: despite progress, collectively, countries still do not achieve their pledges, and, collectively, they need to be more ambitious if they want to meet the Paris goals.

5 These considerations also imply that scenario outcomes should be used with care; see Chapter 7.4.2.2 for a more elaborate discussion.

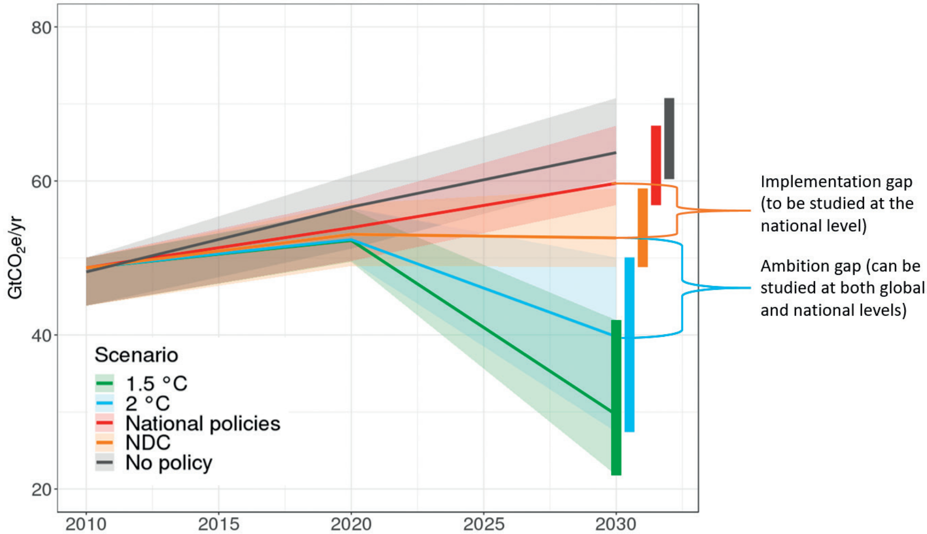

Figure 1.1: The global emissions gap (COMMIT & CD-LINKS, 2018), which can be broken down into an ambition gap and an implementation gap (included for illustration, as it needs to be studied at the national level).

Globally, the emissions gap reported by UNEP (focusing on the ambition part) has stayed roughly the same between 2015 (adoption of the Paris Agreement) and 2020 (latest available Emissions Gap Report at the time of writing): projected warming under the NDCs decreased slightly from 3.5 °C in the 2015 report and 3.4 °C in the 2016 report, to 3.2 °C in the 2017-2020 reports (Höhne et al., 2020; Rogelj et al., 2016; United Nations Environment Programme, 2015, 2016, 2017, 2018, 2019, 2020). The 2018, 2019 and 2020 reports all state that the level of ambition needs to be tripled for a 2 °C scenario and increased fivefold for a 1.5 °C scenario. The countries assessed by Roelfsema et al. (2020) have either an ambition gap with cost-optimal 1.5 °C and 2 °C scenarios or an implementation gap (or, in rare cases, even both). The implementation gap for individual countries has been studied in more detail by a consortium consisting of the NewClimate Institute, PBL Netherlands Environmental Assessment Agency, and IIASA. Over the years between 2015 and 2020 (den Elzen et al., 2016; den Elzen et al., 2015; Kuramochi et al., 2017; Kuramochi et al., 2018; Kuramochi et al., 2016; Kuramochi et al., 2019; Kuramochi et al., 2021), some progress can be seen: the number of countries assessed as being on track to meet their NDC targets with current policies increased from roughly a third to half of the countries studied.

While the ‘ambition gap’ has received plenty of attention, increasingly so by the wave of net zero emissions targets for around mid-century, the ‘implementation gap’ is the one to focus on in this crucial decade for climate action. Put differently, the focus should be broadened: not only the Talanoa Dialogue question ‘where do we want to go?', but also 'how do we get there?'. For setting targets ('where do we want to go?'), Integrated Assessment Models have proven to be useful (Rogelj et al., 2018; van Beek et al., 2020). With their sectoral and increasing spatial and temporal granularity, they can also inform the 'how' – with a detailed analysis of mitigation pathways.

1.4 Integrated Assessment Models and climate policy

Integrated Assessment Models are computational models to assess complex, long-term interactions between humans and their environment (Edelenbosch, 2018; Harmsen, 2019; van Beek et al., 2020; van Sluisveld, 2017). IAMs typically follow the Driver-Pressure-State-Impact-Response (DPSIR) framework (Kristensen, 2004) to some extent: they describe or prescribe Drivers (such as demographic and economic development), leading to environmental Pressure (such as greenhouse gas emissions), changing the State (such as concentration of greenhouse gases in the atmosphere and change in climate), causing Impacts (such as sea-level rise), and inducing a Response (such as climate policy). This means that IAMs describe both the human and earth systems. As such, IAMs are different from some other models used to study climate change and climate policy, such as Earth system models (ESM; only looking at the earth system), and, for instance, pure Computable General Equilibrium (CGE) models, only studying the human system (PBL, 2020). Ideally, the level of detail in IAMs is chosen such that it includes all relevant processes while being simple enough to be transparent and explore uncertainties. Still, IAMs come in many forms, with different objectives and scopes, (solution) methods, representations of technology, spatial and temporal resolution, and level of anticipation (simulation or foresight). Their history can partly explain this: some IAMs have evolved from technical process models, others are based on economics, while others originate mostly from natural science-oriented models. Broadly speaking, two types of IAMs can be distinguished: high-resolution or process-based IAMs, and cost-benefit IAMs. Although most process based IAMs focused on climate change at their inception, they have expanded to assess other processes and impacts, such as biodiversity and water quality. IAMs disaggregate the world in multiple regions, which can either be single-country or multi-country. The IAMs that divide the world in more than one region are called global IAMs here, while those that focus on a country are called national IAMs (or energy system models).

The strength of IAMs lies in their ability to integrate insights from various scientific disciplines for coherent analysis of complex phenomena. They are not meant to produce predictions; instead, they can help explore uncertain futures through scenarios (Riahi et al., 2017; van Vuuren et al., 2011). Such scenarios are plausible descriptions of how socio-economic, technological and environmental trends may develop. IAMs are frequently used to develop emissions scenarios and study the implications for energy systems, land use, and, in some cases, Sustainable Development Goals (SDGs).

Two types of emission scenarios can be distinguished: baseline and mitigation scenarios. There are no explicit measures to reduce greenhouse gas emissions in baselines, but they can have different assumptions on basic drivers such as population, economic and technology development. A prominent example are the SSPs: Shared Socioeconomic Pathways (O'Neill et al., 2014). The five SSPs are based on narratives that describe alternate socio-economic developments (Riahi et al., 2017), including "sustainable development" (SSP1, van Vuuren et al., 2017), "middle-of-the-road" (SSP2, Fricko et al., 2017), "regional rivalry" (SSP3, Fujimori et al., 2017), "inequality" (SSP4, Calvin et al., 2017), and "fossil-fuelled development" (SSP5). SSP2 is most commonly used, also in this thesis. On the other hand, mitigation scenarios aim to achieve specific policy goals, such as a 50% reduction in global emissions in a specific year, adhering to a carbon budget, and a radiative forcing[6] or temperature outcome. A key example are the RCPs: Representative Concentration Pathways (van Vuuren et al., 2011), which are often combined with the SSPs (van Vuuren et al., 2014). The four RCPs span the literature range of potential 2100 radiative forcing values: 2.6, 4.5, 6.0 and 8.5 W/m^2, which can be associated with different warming levels.

6 An externally imposed perturbation in the radiative energy budget of the Earth's climate system.

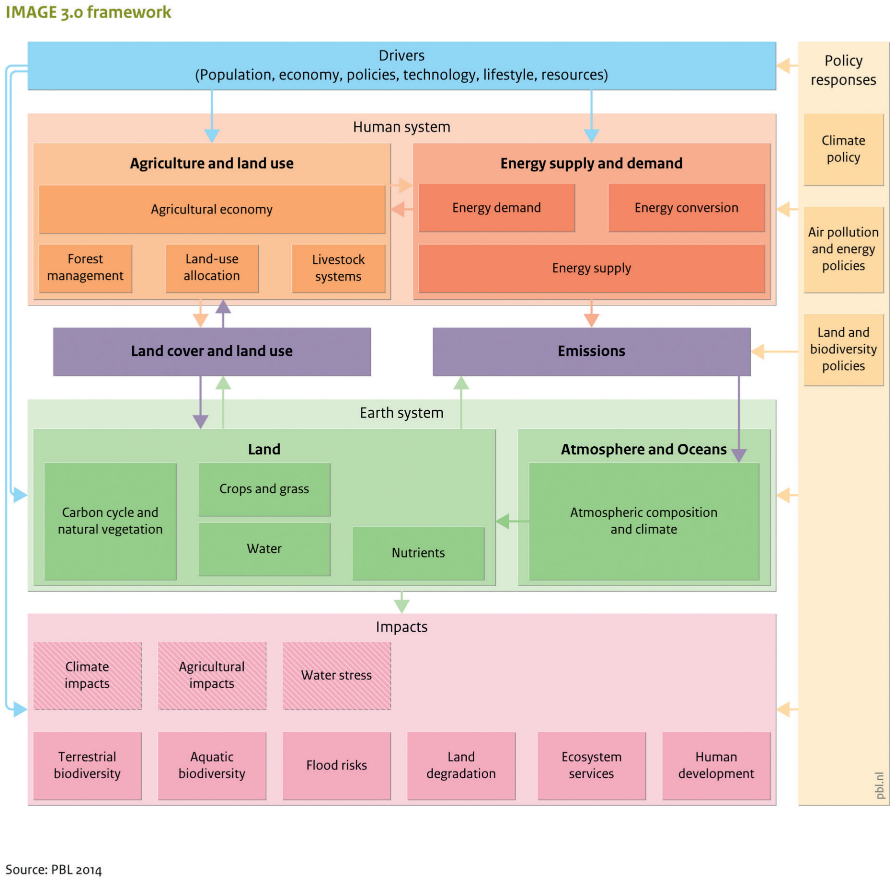

Figure 1.2: a schematic overview of IMAGE (PBL, 2020), one of the IAMs used here and probably the first process-based IAM (van Beek et al., 2020)

This thesis uses models that focus on climate change mitigation, processes, and cost-effectiveness (and not IAMs engaging in cost-benefit analysis). Specifically, we use results from the models summarized in Table 1.1. They have different basic characteristics: most are IAMs, some are energy system models; 'solution methods' can be simulation, optimisation or a combination; some are general equilibrium models, others are partial equilibrium models ('solution concept'); and as to the 'solution horizon', some have perfect foresight (intertemporal optimisation), while others are myopic (recursive-dynamic). This diversity sometimes complicates comparison but can also make conclusions more robust in multi-model studies: even though models may be very different, if they all indicate that emissions need to decrease in order to limit the temperature increase to 1.5 °C or 2 °C, confidence in such qualitative statements can be high, even though precise numbers will differ. That is why multi-model comparison studies have become increasingly popular.

Table 1.1: Overview of models of which the results are used here: their host institution; solution method and horizon; and geographical scope (IAMC, 2021).

Model	Host	Type and solution method (implementation)	Solution horizon	Scope
AIM-CGE	NIES, Kyoto University	CGE, simulation	Recursive-dynamic	Global (17 regions)
BLUES	COPPE/UFRJ (Cenergia)	IAM, optimisation	Intertemporal optimisation	National (Brazil)
China TIMES	Tsinghua University	Energy system model, optimisation	Intertemporal optimisation	National (China)
COFFEE-TEA	COPPE/UFRJ (Cenergia)	IAM, mixed	Intertemporal optimisation	Global (18 regions)
DNE21+	RITE	IAM, optimisation	Intertemporal optimisation	Global (54 regions) and national (Japan)
GCAM	JGCRI	IAM, simulation	Recursive-dynamic	Global (32 regions) and national (USA)
GEM-E3	ICCS	CGE, optimisation	Recursive-dynamic	Global (46 regions) and national (EU)
IMAGE	PBL	IAM, simulation	Recursive-dynamic	Global (26 regions)
IPAC-AIM/ technology	ERI	Energy system model, optimisation	Recursive-dynamic	National (China)
MESSAGEix-GLOBIOM	IIASA	CGE, optimisation	MESSAGEix: Often intertemporal optimisation but can run with limited or no foresight + GLOBIOM: recursive-dynamic	Global (11 regions)

Table 1.1: Continued.

Model	Host	Type and solution method (implementation)	Solution horizon	Scope
POLES	JRC	IAM, simulation	Recursive-dynamic	Global (66 regions)
PRIMES	E3Modelling	Energy system model, simulation + optimisation	Intertemporal optimisation	National (EU)
PROMETHEUS	E3Modelling	Energy system model, simulation	Recursive-dynamic	Global (10 regions)
REMIND-MAgPIE	PIK	CGE, REMIND: optimisation + MAgPIE: cost minimisation	REMIND: intertemporal optimisation + MAgPIE: recursive-dynamic	Global (12 regions)
TIAM-Grantham	UCL, Grantham Institute	Energy system model, linear optimisation	Intertemporal optimisation	Global (16 regions)
WITCH	RFF-CMCC EIEE	CGE, optimisation	Intertemporal optimisation	Global (17 regions)

IAMs play an important role in international negotiations under the UNFCCC, but mostly indirectly by their influence on the IPCC and UNEP gap reports. Van Beek et al. (2020) identified five phases in the role of IAMs in the science-policy interface, in which a shift can be observed from agenda-setting to formulation of targets and monitoring of political ambition:

1. Phase 1: the emergence of global modelling (1970–1985), including the first global models describing finite resources, energy-economic modelling after the oil crisis, and climate–economic modelling.
2. Phase 2: first applications in policy (1985–1992), including the use of IAMs in acid rain negotiations.
3. Phase 3: from agendas to targets in emerging climate regime (1992–1997), including adoption in IPCC working group III (WGIII) and supporting target setting under the Kyoto Protocol.
4. Phase 4: growing significance in IPCC WGIII (1997–2009), including a role for IAMs to connect IPCC working groups and to assess the feasibility of the 2 °C goal.
5. Phase 5: prominent tools for mitigation analysis (2009–2015), including exploration of stringent temperature targets and monitoring progress in UNEP Emissions gap reports.

1.5 From global to national

In the previous section, we saw that IAMs had gained prominence in informing international climate policy. However, as a world government does not exist, implementing the Paris Agreement's goals will need to happen at the national and other levels. Nationally, implementation is further specified at the sectoral level. Therefore, countries will need information that is tailored to their circumstances. National and sectoral models can be used to study national mitigation pathways with high granularity (Fragkos et al., 2021b; Schaeffer et al., 2020b). However, the application of national models in isolation will not be able to shed light on whether these pathways are in line with the global mitigation goals. In addition, analytical capacity differs strongly between countries: some may have multiple models and studies, others just a few, and others none. However, a joint information base is crucial for negotiations to focus discussions on opinions rather than on (disputed) facts or numbers.

That is why global IAMs have been applied in conjunction with national IAMs or energy system models in projects such as CD-LINKS (McCollum et al., 2018; Roelfsema et al., 2020; Schaeffer et al., 2020a; Schaeffer et al., 2020b; van den Berg et al., 2020), COMMIT (Baptista et al., 2022; Fragkos et al., 2021b; van Soest et al., 2021), and ENGAGE (Bertram et al., 2021; Brutschin et al., 2021; Fujimori et al., 2021). Global models provide the boundary conditions, such as cost-optimal national carbon budgets in line with a 1.5 °C or 2 °C goal, biomass availability, or energy prices (Hof et al., 2020). National models can use these as a constraint for their mitigation pathways. Both types of models work on the same set of scenarios. The outcomes of the national models can then be compared with those of the global models that cover the same region in their regional disaggregation, and models and scenarios can be improved accordingly. Such studies are needed given the bottom-up nature of the Paris Agreement: are national targets and policies in line with the global goals?

Schaeffer et al. (2020a), for example, introduced the Special Issue dedicated to the CD-LINKS project with the remark that the papers based on national models show a diversity of national mitigation pathways in terms of where (sectors) and how (technologies) emission reductions take place. This diversity comes from the different national circumstances concerning, among others, availability of resources and mitigation technologies, investment needs, socio-economic developments, sectoral make-up, and stage of climate policy formulation and implementation (Fragkos et al., 2021b; Schaeffer et al., 2020b). Despite the diversity, some common elements can be identified in the low-carbon pathways, which are in line with the high-level findings by global IAMs: almost complete decarbonization of the power sector by 2050, electrification of end-use sectors, notably transportation, an increasing share of biofuels in transportation for modes that are hard to abate (e.g. aviation, heavy trucks), and energy efficiency improvements in all end-use sectors.

These elements were also found to be important in the national mitigation scenarios developed in the more recent COMMIT project (Fragkos et al., 2021b). Electrification, coupled with the uptake of renewable energy and energy efficiency improvements, played a role in all countries studied. At the same time, the use of nuclear power, carbon capture and storage (CCS), and advanced biofuels differed per country. Additionally, the national scenarios were compared to regionally differentiated carbon budgets derived from global models and found to be in line with those limiting global warming to well below 2 °C. A new element in this study was its look into investment requirements for the low-carbon pathways, finding that reallocation towards low-carbon technologies would be needed and not significantly affect affordability in most countries.

In slightly older work, Fragkos et al. (2018) coupled a global CGE model to national models to study the effects of NDCs. The methodology, they state, "…*enhances the credibility of global model-based scenarios…",* as the global model results were complemented by detailed representations of national policy priorities and structural heterogeneities captured in national models. They showed that increased deployment of renewable energy would be a significant contributor to the emission reductions induced by the NDCs, resulting in more labour-intensive economies.

These studies clearly show the similarities and differences between global and national models. Schaeffer et al. (2020b) state: "*The finding that in many cases national models show global model projections to be rather ambitious points to the enormous challenge of meeting the Paris Agreement's objectives and also highlights the importance of accumulating national model experience toward the global stocktaking process agreed upon in Paris in 2015."* Accumulating national model experience is indeed an important element, but also a more detailed look at the national mitigation pathways from global IAMs is warranted, which is the focus of this work. As the stage of global target setting is behind us, the translation to what the Paris Agreement implies nationally is of immediate interest. What can Parties to the Paris Agreement now do to bring those goals within reach?

1.6 Aim of the thesis

The previous sections indicate that considerable analysis has been conducted on the emissions gap and scenarios that limit global warming to well below 2 °C and 1.5 °C, both at the global and national level. Still, critical questions remain. These are partly related to the emerging work on the linkages between global and national models and the new phase of international climate policy after the Paris Agreement.

This new phase means that the focus is mostly on how to reach net-zero emissions and which policies to implement in the next one to two decades. At the same time, the transitions in the energy and land systems needed to meet the Paris goals need to be combined with the Sustainable Development Goals. We focus on these critical issues, leading to the following research questions, inspired by the Talanoa Dialogue:

1. **Where are we?**
   a. How large are the global ambition and implementation gaps?
   b. How large are the national ambition gaps?
2. **Where do we want to go?**
   a. When can countries achieve net-zero greenhouse gas emissions?
3. **How do we get there?**
   a. How can the global ambition gap be bridged?
   b. If we want to use the SDGs to inform increased national mitigation ambition, are IAMs fit for the purpose of studying the interactions between climate action and broader sustainable development?

To answer the first question (1a), we compared the emission levels of three scenarios: (i) current policies, (ii) implementation of the NDCs, and (iii) various trajectories consistent with achieving a radiative forcing level of 2.8 W/m^2 in 2100. For question 1b, we assessed emission trajectories and the energy system transition of 11 major economies projected by IAMs for baseline and cost-optimal 450 ppm CO_2eq mitigation scenarios and compared the results with the NDCs.

To answer question 2a, we developed a stylised *Bridge* scenario to analyse which emission trajectories could be consistent with the goals of the Paris Agreement. We also looked at national-level neutrality-years based on cost-effective 1.5 °C and 2 °C scenarios from integrated assessment models and explained differences between countries.

To answer question 3a, we developed a new *Bridge* scenario based on nationally relevant measures informed by interactions with country experts. We implemented this scenario with an ensemble of global IAMs. Finally, to answer question 3b, we investigated the suitability of IAMs to perform such analyses by comparing key interactions identified by experts with their current representation in models, including planned developments.

1.7 Outline

These research questions lead to the following outline of this thesis:

- Chapter 2 provides the global context in answering the question *Where are we?* It shows that globally, more mitigation effort is needed to achieve the Paris Agreement's climate goals.
- Chapter 3 dives into the national level. A comparison of model results with NDCs shows that also nationally, more mitigation effort is needed.
- Chapter 4 supports those aiming to answer *Where do we want to go?,* by translating the global Paris Agreement's climate goals to national targets. It assesses national net-zero emissions targets and reasons for differences in timing between countries.
- Chapters 5 and 6, finally aim to inform the ratcheting mechanism of the Paris Agreement, helping to answer the question *How do we get there?*
  - Chapter 5 presents a *Bridge* scenario comprising a concrete list of options to close the ambition gap, presenting the global-level effect of applying these measures nationally.
  - Chapter 6 discusses elaborate surveys of how SDGs are represented in IAMs to assess whether they are fit for purpose and may be used to inform national ratcheting up.

Chapter	Where are we?	Where do we want to go?	How do we get there?
2 Early action	(Q1a)	(Q2)	
3 Low-emission pathways	(Q1b)		
4 Net-zero emission targets		(Q2a)	
5 Global roll-out			(Q3a)
6 Sustainable Development Goals			(Q3b)

2

Early action on Paris Agreement allows for more time to change energy systems

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Abstract

The IMAGE integrated assessment model was used to develop a set of scenarios to evaluate the Nationally Determined Contributions (NDCs) submitted by Parties under the Paris Agreement. The scenarios project emissions and energy system changes under (i) current policies, (ii) implementation of the NDCs, and (iii) various trajectories to a radiative forcing level of 2.8 W/m^2 in 2100, which gives a probability of about two thirds to limit warming to below 2 °C. The scenarios show that a cost-optimal pathway from 2020 onwards towards 2.8 W/m^2 leads to a global greenhouse gas emission level of 38 gigatonne CO_2 equivalent ($GtCO_2eq$) by 2030, equal to a reduction of 20% compared to the 2010 level. The NDCs are projected to lead to 2030 emission levels of 50 $GtCO_2eq$, which is still an increase compared to the 2010 level. A scenario that achieves the 2.8 W/m^2 forcing level in 2100 from the 2030 NDC level requires more rapid transitions after 2030 to meet the forcing target. It shows an annual reduction rate in greenhouse gas emissions of 4.7% between 2030 and 2050, rapidly phasing out unabated coal-fired power plant capacity, more rapid scale-up of low-carbon energy, and higher mitigation costs. A bridge scenario shows that enhancing the ambition level of NDCs before 2030 allows for a smoother energy system transition, with average annual emission reduction rates of 4.5% between 2030 and 2050, and more time to phase out coal capacity.

2.1 Introduction

All Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in Paris in December 2015 agreed to reduce global greenhouse gas (GHG) emissions to keep the increase in global mean temperature to well below 2 °C relative to pre-industrial levels, and furthermore to pursue efforts to limit this increase further to 1.5 °C (UNFCCC, 2015b). Outlining the contribution to these GHG emission reductions, 161 Parties (representing over 97% of global GHG emissions in 2012) had submitted post-2020 Intended Nationally Determined Contributions (INDCs) to the UNFCCC by February 2016 (UNFCCC, 2015a). The Paris Agreement entered into force on 4 November 2016, after it had been ratified by the required number of countries.[7] This re-asserts the process that started earlier. By 2009 in Copenhagen, countries had agreed to implement non-binding emission reduction proposals (pledges) for 2020 (UNFCCC, 2009). Many countries representing about 75% of global 2010 emissions (United Nations Environment Programme, 2014) had submitted reduction plans or pledges, which were later anchored in the Cancún Agreements (UNFCCC, 2010a).

The effect of the 2020 pledges on global emissions in that year has been analysed in various studies (e.g. Fekete et al., 2013; Hof et al., 2013; Kriegler et al., 2013a) and summarised in the UNEP Gap reports (United Nations Environment Programme, 2013, 2014). In addition, several studies analysed whether countries are on track to meet their pledges and concluded that current policies are projected to result in global 2020 emission levels at the upper limit of the emission range resulting from the pledges (Climate Action Tracker, 2015; den Elzen et al., 2015; Roelfsema et al., 2014; United Nations Environment Programme, 2015). In a next step, both the pledges and current policies were found to lead to higher 2020 global emissions than cost-optimal 2 °C pathways (e.g. Jakob et al., 2012; Kriegler et al., 2014b; Kriegler et al., 2013a; Kriegler et al., 2013b; Kriegler et al., 2014c; Luderer et al., 2016; Luderer et al., 2013; Riahi et al., 2015; Rogelj et al., 2013a; Rogelj et al., 2013b; van Vliet et al., 2012). However, these studies also concluded that achieving the 2 °C target with a likely chance (>66% probability) would still be technically feasible under delayed mitigation scenarios consistent with the pledges, i.e. only modest emission reductions up to 2020 and deep reductions thereafter.

Similar questions now apply to the NDCs for 2030. Recently, UNEP (2015) assessed the 2030 global emission levels consistent with meeting 2 °C with a likely chance based on existing delayed scenarios starting with cost-effective reduction after 2020. Several studies (e.g. den Elzen et al., 2016; Fawcett et al., 2015; Rogelj et al., 2016;

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7 By 10 April 2017, 143 of 197 Parties to the Convention had ratified, representing about 83% of global greenhouse emissions. With each country's ratification, its INDC becomes an NDC, which we use throughout this paper.

Vandyck et al., 2016) concluded that the global emission level in 2030 resulting from the NDCs is considerably higher than the emission level of a cost-effective pathway to keep the global temperature increase below 2 °C (Clarke et al., 2014; United Nations Environment Programme, 2015). This gap was acknowledged in the Paris Agreement and Parties agreed to submit new or updated national climate plans by 2020 (known as nationally determined contributions, so-called NDCs). The Agreement also established a process in which Parties put forward more ambitious NDCs every 5 years.

The effect of the NDCs and enhanced mitigation ambition needs to be assessed in light of this agreement. Such analyses could build on earlier studies that analysed the long-term impacts of short-term policies (e.g. Riahi et al., 2015) and could include the most recent assessments of the outcomes of the NDCs (e.g. Fawcett et al., 2015; Vandyck et al., 2016).

Our study assessed the long-term impacts of the NDCs and whether the internationally agreed 2 °C target can still be achieved in mitigation scenarios taking into account the NDCs. We also assessed the implications of enhancing the mitigation ambition of the NDCs, focusing on long-term effects on energy and land-use systems and the level of mitigation costs in achieving 2 °C emission pathways. This study goes beyond existing literature by building upon a detailed assessment of existing national policies, 2020 pledges and NDCs (i.e. as assessed by den Elzen et al., 2016). This consideration of current policies and the most recent international pledges and NDCs enables new insights into 2020 and 2030 emissions and energy projections and into how differences in timing and level of ambition of climate policy affect transition pathways.

2.2 Methods

2.2.1 Model framework

The scenarios in this study were analysed using the IMAGE integrated assessment modelling framework (Stehfest et al., 2014; van den Berg et al., 2015). The IMAGE framework is a simulation model with a recursive-dynamic (myopic) solution method, a partial equilibrium solution concept (price elastic demand), 26 world regions, and five economic sectors. This framework consists of a set of soft-linked models,[8] including a detailed energy-system model (TIMER), a land-use model (IMAGE land), and a global climate policy model (FAIR).

TIMER describes the long-term energy demand and production for different end-use and supply sectors. One hundred eighty energy end-use technologies and 54 energy conversion technologies are used, and substitution among technologies is

8 Models run independently and exchange data.

described using the multinomial logit formulation. For most innovative technologies, technological progress is endogenously formulated on the basis of learning by doing. Inertia in capital stocks is included in the electricity generation sector, using a vintage formulation for the autonomous increase in energy efficiency. Retrofitting in the electricity sector is not simulated. The IMAGE land model looks into the long-term dynamics of the agricultural system and consequences for global land-cover. The agricultural system is described for seven agricultural crops and five animal product types.

Information of both baseline and mitigation options in the energy and land-use systems is forwarded to the climate policy model FAIR. The model is able to optimise global greenhouse gas emission pathways over time and across sectors and gases to achieve emission levels or climate targets at lowest cost, based on cumulative discounted abatement costs (using a 5% discount rate). For this purpose, the optimisation procedure employs a nonlinear, constrained, optimisation algorithm (the MATLAB FMINCON procedure; for further details, see van den Berg et al., 2015). The abatement costs in FAIR depend on baseline emissions and time-, baseline-, and regional-specific marginal abatement cost (MAC) curves from the other IMAGE framework models. Subsequently, the information on mitigation action (mostly carbon prices) is fed back from FAIR to the TIMER and IMAGE land models (in response, TIMER will for instance invest more in renewable energy).

2

For energy- and industry-related CO_2 emissions, MAC curves are determined by imposing a carbon price in the TIMER energy model and recording the induced reduction in CO_2 emissions. In order to capture the time- and pathway-dependent dynamics (due to technology learning and inertia related to capital-turnover rates) of the underlying TIMER model, MAC curves are derived for different reduction pathways and scaled in the FAIR model based on the actual implementation (van Vliet et al., 2012). For non-CO_2 emissions, the agriculture-related emissions from IMAGE land are combined with MAC curves based on Lucas et al. (2007) using updates of U.S. EPA (2013), Harnisch et al. (2009), and Schwarz et al. (2011). Given the detailed analysis of current policies and NDCs for land-use change and forestry (LULUCF), CO_2 emissions by the GLOBIOM/G4M team were used here instead of using IMAGE land, in combination with the response curves from the GLOBIOM/G4M models (Böttcher et al., 2011; Havlík et al., 2014; Kindermann et al., 2008) (see also S2.1 Supplementary text to section 2.2.1). For calculating CO_2-equivalent emissions, 100-year Global Warming Potentials from IPCC AR4 are used (GHGs covered are CO_2, CH_4, N_2O, PFCs, HFCs, SF_6). The total abatement costs for each future year are calculated by FAIR as the total area under the MAC curves (TIMER-derived MACs, non-CO_2 MACs, and G4M land-use change MACs) at the determined regionally and time-specific carbon price levels.

2.2.2 Scenarios

The starting point for the calculations was the SSP2 (Shared Socioeconomic Pathways) scenario and its storyline as implemented in IMAGE (as described in detail in van Vuuren et al., 2017). The GDP and population projections were based on median assumptions, with population stabilising at 9 billion by 2050. Based on this scenario, a set of policy relevant scenarios was developed (see Table 2.1).

Table 2.1: Overview of scenarios developed for this study

Scenario	Characteristics	Start year of cost-optimal mitigation	Emission level ($GtCO_2eq$)	
			2020	2030
Current policies scenario	Current policies of major emitting countries, assuming no new climate policies after policy target year			
Current policies	Implemented policies based on Den Elzen et al. (2015) (Table S2.2.1)	–	53.0	58.3
NDC scenarios	Following the 2020 pledges and 2030 emissions resulting from NDCs, constant carbon tax at 2030 value after 2030			
NDC high	Higher end of the 2030 emission projection range resulting from NDCs	–	48.7	50.1
NDC low	Lower end of the 2030 emission projection range resulting from NDCs	–	48.7	49.5
2.8 W/m² scenarios	Scenarios consistent with the 2 °C target, varying in level of ambition and timing of cost-optimal mitigation			
2.8 W/m² -2020 action	Starting from 2020 pledges	2020	48.7	38.1
2.8 W/m² -NDC	Starting from 2020 pledges and 2030 emission levels from *NDC high*	2030	48.7	47.6
2.8 W/m² -NDC bridge	Starting from 2020 pledges and moving to 2030 emission levels from *NDC low*	2025	48.7	40.0

The current policies scenario was derived from the original SSP2 baseline by introducing explicit policy measures (Section 2.2.2.1 Current policies scenario). Subsequently, the two NDC scenarios were implemented by introducing a carbon price in order to meet the NDC goals of different countries (Section 2.2.2.2 NDC scenarios). In response to the price, measures are introduced in a cost-effective way throughout the model (i.e. in the energy and land-use system). Finally, three long-term climate policy scenarios were implemented meeting a long-term radiative forcing target consistent with staying below 2 °C, using a global carbon price (Section 2.2.2.3 Mitigation scenarios consistent with the 2 °C climate target). These long-term policy scenarios start from different years (i.e. 2020, 2025, and 2030, as described below). Our study focused on the results for the 2010–2050 period, but the scenarios were developed for the full century.

2.2.2.1 Current policies scenario

The current policies scenario includes current climate and energy policies of major emitting countries, such as the assumed implementation of renewable energy share or capacity targets, power plant standards, fuel efficiency standards for cars, and carbon prices (den Elzen et al., 2015; Roelfsema et al., 2014). Carbon prices mainly impact the energy and industry sectors, by changing the price for energy carriers and as such influencing the choice for technologies in the multinomial logit equation, making low-carbon technologies relatively cheaper and high-carbon technologies more expensive. The measures are described in detail in Table S2.2.1. After the policy target year, the policy driver was discontinued. 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). LULUCF policies were implemented in the GLOBIOM/G4M model framework. The 2020 pledges were not included in this scenario, resulting in greenhouse gas emission projections deviating from the NDC and mitigation scenarios from 2010 onwards.

2.2.2.2 NDC scenarios

The *NDC high* and *low* scenarios start from emission levels in 2020 resulting from current policies and 2020 pledges, and 2030 emission levels resulting from the full implementation of the NDCs (based on den Elzen et al., 2016, see Supplementary Table S2.2.1). However, we assumed that Kazakhstan, the Russian Federation, Turkey and Ukraine followed the current policies scenario, as it resulted in lower emissions than their respective NDCs (see also den Elzen et al., 2016). If current policies (Section 2.2.2.1 Current policies scenario) were found to be insufficient to reach the NDC targets, a carbon price was introduced to reach the emission levels resulting from the implementation of the 2020 pledge and the NDCs. The regional carbon prices that emerged under the NDCs in 2030 were kept constant thereafter, implying that emissions remain below the original current policies scenario. For model regions in which not all countries have a pledge or an NDC, the absolute emission reductions in 2020 and 2030 resulting from the country pledges and NDCs within the region were subtracted from the BAU. The emission projection resulting from South Korea's NDC was combined with BAU emission projections for North Korea because the IMAGE model has one Korea region. Similarly, the emission projections resulting from Australia's and New Zealand's NDCs were added to the Oceania region of IMAGE. Finally, Brazil's indicative 2030 target was used, while the USA's NDC for 2025 was extended to 2030 by linearly interpolating between the 2025 NDC and the USA's long-term emission reduction target for 2050.

2.2.2.2.1 NDC high

The *NDC high* scenario represents the upper end of the range of emission levels expected to result from NDC targets. In addition to unconditional NDCs, some countries also have stronger targets, conditional on financial support. In the *NDC high* scenario, we considered only unconditional NDCs and the least ambitious of NDC emission target ranges, where applicable. Next to Kazakhstan, the Russian Federation, Turkey and Ukraine, India followed the current policies scenario, as it resulted in lower emissions than its NDC. The NDCs for all other countries were assumed to be achieved domestically by not allowing international trade of emission credits until 2030.

2.2.2.2.2 NDC low

The *NDC low* scenario represents the lower end of the range of NDC emission levels. In addition to unconditional NDCs, we also considered conditional NDCs in *NDC low*. Where countries provided emission target ranges, the most ambitious value was taken. For India, *NDC low* followed the current policies scenario (which satisfied the intensity target as stated in the NDC) like the *NDC high* scenario, but in addition included the effect of the renewable energy target.

2.2.2.3 Mitigation scenarios consistent with the 2 °C climate target

The three long-term mitigation scenarios start from the emission levels in 2020, 2025, and 2030 based on the NDC scenarios. The long-term climate target of the various scenarios in this group was set to 2.8 W/m^2 in 2100. This value is within the "likely below 2 °C" range from IPCC: 2.3–2.9 W/m^2 (Clarke et al., 2014). The 2.8 W/m^2 scenarios have a chance of about two third of staying below 2 °C at the end of the century, allowing for a lower chance or a temperature overshoot before. We assumed this to be consistent with the Paris Agreement's goal to limit global warming to well below 2 °C. Achieving more ambitious targets, e.g. staying below 2 °C with a higher likelihood, is difficult in the model given the delay assumed in the *NDC high* scenario. The mitigation scenarios assumed full availability of mitigation technologies, meaning the model was allowed to use negative emission technology, specifically biomass with CCS, reforestation, and afforestation.

2.2.2.3.1 2.8 W/m^2-2020 action

Up until 2020, the pledge assumptions determined the emission pathways. After 2020, a cost-optimal emission reduction pathway towards the long-term climate target by means of a global carbon price was implemented. In the *2.8 W/m^2 -2020 action* scenario, Brazil, India, Japan, Russia, and Ukraine followed the current policies scenario, because it resulted in lower emissions than the 2020 pledges.

2.2.2.3.2 2.8 W/m²-NDC

To analyse the transition from the unconditional NDCs in 2030 to the 2.8 W/m² climate target, the *2.8 W/m² -NDC* scenario started from the 2030 emission levels of the *NDC high* scenario. International trade was not allowed until 2030, reflecting the domestic nature of the unconditional NDCs. After 2030, a cost-optimal emission reduction pathway by means of a global carbon price was implemented. Some unconditional NDCs are overachieved in this scenario due to mitigation effort starting in 2030 (a result of TIMER using projected future carbon prices to steer investment decisions; de Boer & van Vuuren, 2017).

2.2.2.3.3 2.8 W/m²-NDC bridge

To study the implications of strengthening the ambition level of NDCs, the *2.8 W/m² -NDC bridge* scenario followed the emission pathway of the *NDC low* scenario up to 2025, effectively starting in 2020 from the 2020 pledges moving towards the 2030 emission levels of the *NDC low* scenario. However, after 2025, a cost-optimal emission reduction pathway by means of a global carbon price was implemented.

2.3 Results

2.3.1 Global greenhouse gas emissions

We focus the discussion of results on the current policies scenario and the 2.8 W/m² scenarios. Under the current policies scenario, global emission levels are projected to increase between 2020 and 2050 (Figure 2.1, and Figure S2.3.1 for projections through 2100). In contrast, implementation of NDCs is projected to result in a peak in global GHG emissions in 2030. By 2030, GHG emissions reduce by 14% (*NDC high*) to 15% (*NDC low*) compared to the current policies scenario. Between 2030 and 2050, emissions stabilise due to an autonomously decreasing GHG intensity of the economy. Enhancing NDC ambition as in the *2.8 W/m² -NDC bridge* scenario resulted in a GHG emission reduction of 31% by 2030 relative to the current policies scenario. GHG emissions are projected to be approximately 38 $GtCO_2eq$ in 2030 under the *2.8 W/m² -2020 action* scenario, a reduction of 20% on 2010 levels. In contrast, the NDCs are projected to lead to 2030 emission levels of approximately 50 $GtCO_2eq$, an increase of 5% on 2010 levels (see Figure S2.3.1).

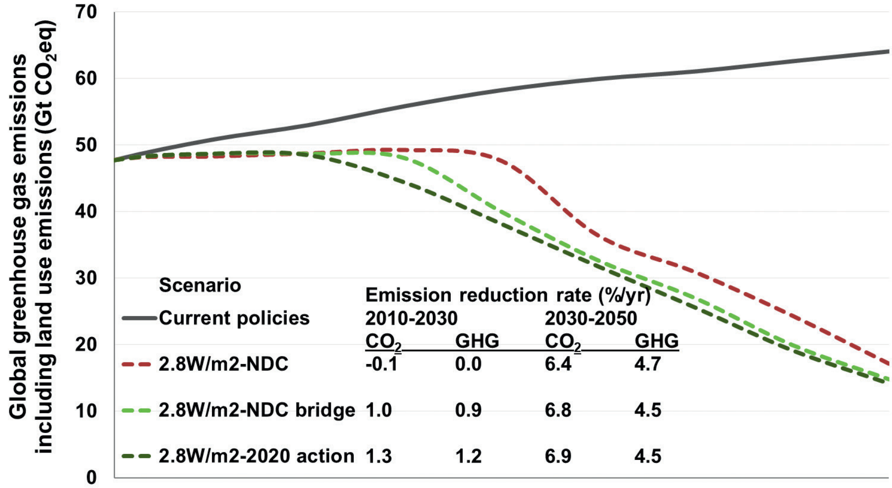

Figure 2.1: Global GHG emissions ($GtCO_2eq$/year) between 2010 and 2050, including CO_2 emissions from land use, under the current policies scenario (*solid line*), and the 2.8 W/m^2 scenarios (*2.8 W/m ^{2} -NDC*, *2.8 W/m ^{2} -NDC bridge* and *2.8 W/m ^{2} -2020 action*; *dashed lines*)

GHG emission reductions between 2010 and 2050 in the three 2.8 W/m^2 scenarios range from 64 to 70% (including LULUCF). In the *2.8 W/m ^{2} -NDC* scenario, GHG emissions are projected to be reduced from 47.6 $GtCO_2eq$ in 2030 to 17.1 $GtCO_2eq$ in 2050. This required average rates of GHG emission reduction of 4.7%/year between 2030 and 2050. The *2.8 W/m ^{2} -NDC bridge* scenario showed a similar GHG emission level by 2050 (14.8 $GtCO_2eq$), but the reduction rate was lower (4.5%/year) as emissions in 2030 are projected to be 40.0 $GtCO_2eq$. The *2.8 W/m ^{2} -NDC* scenario also showed larger emission reductions after 2050 to compensate for the extra emissions before 2050 (Figure S2.3.1).

Figure 2.2 shows global sectoral emissions until 2050. Under the current policies scenario, emissions in most sectors are projected to remain constant or increase between 2010 and 2050, except for LULUCF emissions. In contrast, emissions are projected to decrease strongly under the 2.8 W/m^2 scenarios. Total emissions are projected to be reduced by 18% in the *2.8 W/m ^{2} -NDC* scenario and by over 30% in the *2.8 W/m ^{2} -NDC bridge* and *2.8 W/m ^{2} -2020 action* scenarios by 2030, compared to the current policies scenario (see also Figure S2.3.2). By 2050, the smaller short-term emission reductions in the *2.8 W/m ^{2} -NDC* scenario are starting to be compensated, with total emission reductions of 73% relative to the current policies scenario, compared to 77% under *2.8 W/m ^{2} -NDC bridge* and *2.8 W/m ^{2} -2020 action*.

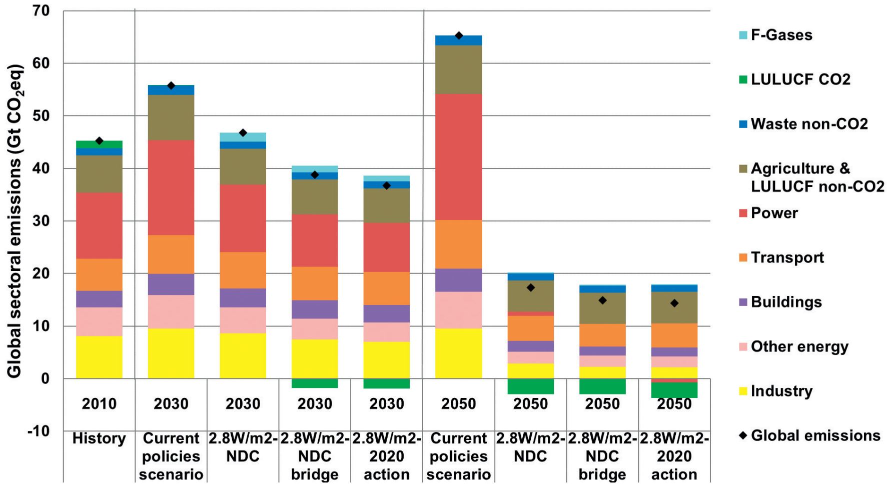

Figure 2.2: Global GHG emissions (GtCO_2eq) in 2010, 2030 and 2050 per sector and scenario. LULUCF: land use, land-use change and forestry. The category 'Other energy' consists of energy CO_2 emissions in other sectors than transport, power, industry and buildings, as well as energy non-CO_2 emissions

Although all sectors contributed to reducing GHG emissions, the power sector showed the largest reductions between 2020/2030 and 2050, as this sector is assumed to have the largest potential to reduce emissions by changing the power mix (from fossil fuels to renewables, nuclear, and fossil fuels/biomass with CCS; see Figure S2.3.3). The power sector is projected to be fully decarbonised before 2050 under all 2.8 W/m^2 scenarios, but decarbonisation took place at a higher rate under *2.8 W/m^2-NDC* than under *2.8 W/m^2-NDC bridge* to compensate for the delay in optimal mitigation. Early retirement of existing coal-fired power plants was required in all 2.8 W/m^2 scenarios, but especially in the *2.8 W/m^2-NDC* scenario (as discussed further in Section 2.3.2 Effects on the global energy system). Reductions in the industry sector were related to reduced energy intensity, most notably in steel production. Most emission reductions in the building sector were achieved through efficiency improvements in space heating, space cooling, and household appliances. These efficiency improvements resulted in lower electricity use and final energy intensity of GDP. In the transport sector, electrification played a large role in reducing emissions.

Land-use CO_2 emissions were projected to decrease strongly as well, turning negative between 2020 and 2030. Reductions in land-use CO_2 emissions resulted from enhanced CO_2 uptake by forests due to afforestation and reforestation, and decreased CO_2 emissions due to reduced deforestation. Non-CO_2 emission reductions between 2020 and 2050 in the 2.8 W/m^2 scenarios mainly came from reductions in energy-related CH_4 and F-gas emissions. F-gases and energy-related N_2O and CH_4 emissions ('Other energy' in Figure 2.2) showed the strongest relative reductions, both between 2020 and 2050 and against the current policies scenario in 2050. Reducing agricultural non-CO_2 emissions is assumed to be challenging, as the 2.8 W/m² scenarios showed only minor reductions in this category (Figure 2.2).

2.3.2 Effects on the global energy system

Under the *2.8 W/m ² -NDC* scenario, primary energy use is projected to be 9% lower than under the current policies scenario by 2030, while under the *2.8 W/m ² -NDC bridge* and *2.8 W/m ² -2020 action* scenarios, the reduction is about 17 to 20%. The *2.8 W/m ² -NDC* scenario showed the largest reductions in primary energy use between 2030 and 2050: 16%, versus only 5% in *2.8 W/m ² -2020 action* and 7% in *2.8 W/m ² -NDC bridge* (Figure 2.3). The reductions in the *2.8 W/m ² -NDC* scenario were mostly realised by rapidly scaling down the use of coal without CCS, which helped compensate for the smaller reduction in energy use until 2030. Penetration of non-biomass renewables is similar in all 2.8 W/m² scenarios by 2050, as the *2.8 W/m ² -NDC* scenario already includes quite a lot of non-biomass renewables in 2030. In the current policies scenario, in contrast, primary energy use is projected to increase further towards 2050, including the use of fossil fuels without CCS.

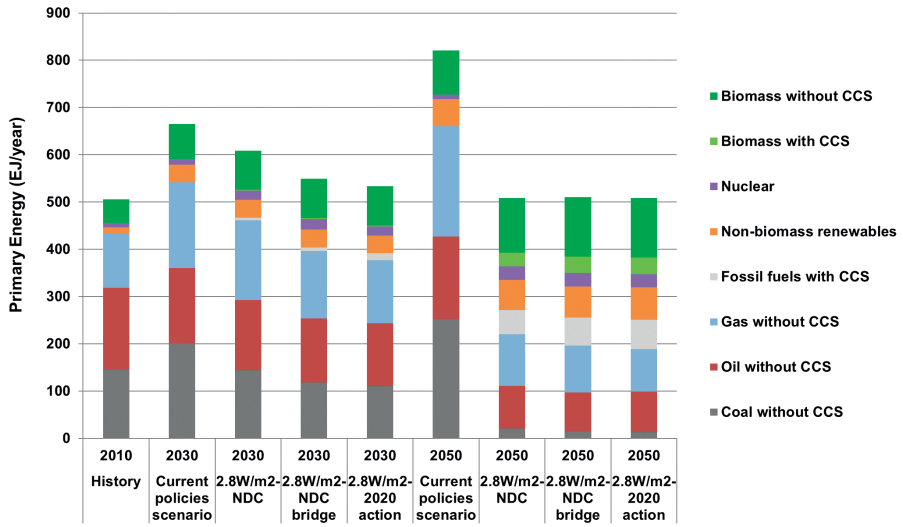

Figure 2.3: Global primary energy use (EJ/year) in 2010, 2030 and 2050 in the current policies scenario and the 2.8 W/m² scenarios (*2.8 W/m ² -NDC*, *2.8 W/m ² -NDC bridge*, and *2.8 W/m ² -2020 action*). Non-biomass renewables are solar energy, wind energy, hydropower, and geothermal energy. *CCS* carbon capture and storage

Under the *2.8 W/m ² -NDC* scenario, electricity demand is projected to be 7% lower than under the current policies scenario by 2030, while under the *2.8 W/m ² -NDC bridge* and *2.8 W/m ² -2020 action* scenarios, the reduction is about 15 to 18%. By 2050, electricity demand in all *2.8 W/m ²* scenarios is projected to be approximately 30% lower than under the current policies scenario, which indicates that by 2050, the delayed 2.8 W/m^2 scenarios have caught up with the *2.8 W/m ² -2020 action* scenario. Energy savings, measured as the difference in secondary energy use between the 2.8 W/m^2 scenarios and the current policies scenario, are 16% for *2.8 W/m ² -2020 action*, 13% for *2.8 W/m ² -NDC bridge*, and 6% for *2.8 W/m ² -NDC* in 2030, and around 35% (*2.8 W/m ² -2020 action* and *2.8 W/m ² -NDC bridge*) and 34% (*2.8 W/m ² -NDC*) in 2050.

The 2.8 W/m^2 scenarios resulted in lower total installed electricity capacity compared to the current policies scenario, approximately 4 to 10% in 2030 and 16 to 21% in 2050. Coal capacity is projected to be phased out starting in 2036 and before 2070 due to the increasing price of carbon in the 2.8 W/m^2 scenarios (electricity production based on coal is phased out earlier, around 2050). From 2025 (*2.8 W/m ² -2020 action*) to 2029 (*2.8 W/m ² -NDC*) onwards, no investment in new plants occurs. In addition, early retirement of existing capacity contributes to the decline of coal capacity from 2036 (*2.8 W/m ² -2020 action*) to 2040 (*2.8 W/m ² -NDC*) onwards, driven by the carbon price. Under the *2.8 W/m ² -NDC bridge* scenario, almost all existing coal-fired power plant capacity is projected to be phased out between 2030 and 2060. The *2.8 W/m ² -NDC* scenario required a faster transition: phase-out of coal-fired power plants started about 5 years later than under *2.8 W/m ² -NDC bridge*, but took place over a shorter period (Figure 2.4 and Figure S2.3.4). After coal, electricity production based on gas is projected to be phased out, with some gas capacity remaining as backup. In contrast, the installed power capacity of renewable energy is projected to increase between now and 2050 (Figure 2.4), with larger increases, also after 2050, for *2.8 W/m ² -NDC* than for *2.8 W/m ² -NDC bridge*. As a result of these early retirements and the increased use of renewable energy sources, the share of fossil fuels (coal, oil, and natural gas) without CCS in primary energy supply is projected to be reduced considerably in the 2.8 W/m^2 scenarios, from 85% in 2010 to 37–43% in 2050.

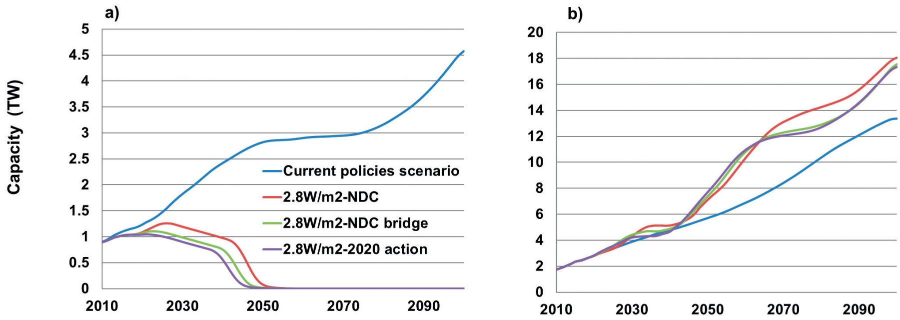

Figure 2.4: Installed power capacity (TW) between 2010 and 2100 in the current policies scenario and the 2.8 W/m^2 scenarios (*2.8 W/m ^{2} -NDC*, *2.8 W/m ^{2} -NDC bridge*, and *2.8 W/m ^{2} -2020 action*). Panel a coal without CCS, panel b renewables and nuclear

The mitigation scenarios relied on the availability of all possible technologies, especially on energy efficiency improvements and negative emissions from the land use, energy, and industry sectors. CCS was deployed to reach negative emissions in the energy and industry sectors, but it only started playing a significant role after 2050. The share of CCS (used with biomass and fossil fuels) is projected to increase from 0% of total electricity production in 2010 to approximately 13–18% in 2050 under the 2.8 W/m^2 scenarios, with BECCS taking up 7–8% of total electricity production (Figure S2.3.3). Also the share of nuclear is projected to increase after 2020, reaching 5.5% (*2.8 W/m ^{2} -2020 action*) to 5.6% (*2.8 W/m ^{2} -NDC*) of total primary energy use and 21% (*2.8 W/m ^{2} -2020 action)* to 23% (*2.8 W/m ^{2} -NDC*) of electricity production by 2050.

In the near term, the share of renewables and low-carbon energy sources[9] in primary energy use in the 2.8 W/m^2 scenarios (23–26% in 2030) is projected to be only slightly higher than in the current policies scenario (18%) (Table S2.2.2). In the long-term, however, the energy system shows a complete transformation with the share of low-carbon energy sources in primary energy supply increasing from 15% currently to 61–63% by 2050 and further increasing afterwards in the *2.8 W/m ^{2} -2020 action* and *2.8 W/m ^{2} -NDC bridge* scenarios. The *2.8 W/m ^{2} -NDC* scenario catches up in the second half of the century, reaching 57% by 2050 and the highest installed renewable power capacity of all scenarios after 2050 (Figure 2.4), with extra wind, solar and nuclear capacity going into operation around 2050. The shares of low-carbon energy sources in power supply are even higher, due to a phase-out of fossil fuels without CCS and increased investments in renewable energy. Solar PV, wind, hydropower and nuclear are responsible for about three-quarters of global power supply by 2050 under the mitigation scenarios. The remainder is approximately equally divided between fossil fuels with CCS and BECCS.

9 Biomass with and without CCS, nuclear, non-biomass renewables, and oil, coal, and gas with CCS

2.3.3 Effects on global costs

The implementation of climate policies, pledges, and NDCs in the 2.8 W/m^2 scenarios is projected to significantly reduce GHG emissions and energy use, but this comes with additional costs. As a metric of costs, annual abatement costs expressed as percentage of GDP were used. The annual abatement costs are projected to be high early in the *2.8 W/m ^{2} -2020 action* scenario, but these are compensated by lower costs than the other scenarios later on in the century (Figure S2.3.5). While the *2.8 W/m ^{2} -NDC* scenario is projected to lead to lower costs in the short term, its annual abatement costs are the highest of all scenarios from 2050 onwards. The *2.8 W/m ^{2} -NDC bridge* scenario resulted in costs similar to the *2.8 W/m ^{2} -2020 action* scenario, with slightly lower costs until 2035. Costs are very similar across scenarios by 2025, because even though the reductions in the *2.8 W/m ^{2} -2020 action* scenario are higher, these reductions are assumed to be implemented cost-optimally over regions. In the other scenarios, every region has a different carbon price level to achieve their NDCs domestically, which leads to higher global costs per ton of GHG emissions reduced. Cumulative abatement costs are projected to be highest in the *2.8 W/m ^{2} -NDC* scenario, being 18% higher than cumulative costs of the *2.8 W/m ^{2} -2020 action* scenario in the 2010–2100 period (with a 5% discount rate; Figure S2.3.5). The scenario that delays action thus resulted in both higher annual abatement costs in the long run and higher cumulative abatement costs, compared to a scenario that takes early action.

2.4 Discussion and conclusions

This study assessed the long-term impacts of the NDCs and the effect of enhancing their mitigation ambition on changes in energy systems and the level of mitigation costs in achieving 2 °C emission pathways (2.8 W/m^2 radiative forcing target; about a two third chance of holding warming to below 2 °C). In the 2.8 W/m^2 pathways, GHG emission reductions between 2020 and 2050 mainly came from reductions in energy-related CO_2 emissions. These emission reductions in the energy system were achieved by a combination of enhancing efficiency and scaling down the use of fossil fuels (no investment in new plants and early retirement of existing capacity), while increasing deployment of low-carbon energy sources.

The results are relevant in light of the review mechanisms and instruments to enhance mitigation ambition included in the Paris Agreement. Our results confirm findings of earlier studies, based on more abstract representations of current policies and pledges, that achieving the 2 °C target is possible under scenarios that delay optimal mitigation if fast emission reduction are realised after 2020 (Kriegler et al., 2013a; Riahi et al., 2015; Tavoni et al., 2015). Projected 2050 emissions resulting from the 2.8 W/m^2 scenarios are in line with other estimates, such as Riahi et al. (2015), who reported 18–28 $GtCO_2eq$ by 2050 for scenarios that assumed pledges emission levels in 2020 and delayed action until 2030. The range in emission projections resulting from the 2.8 W/m^2 scenarios is further in line with the 40–70% emission reduction on 2010 levels by 2050 globally, as reported by the IPCC for RCP 2.6 scenarios[10] (IPCC, 2014).

Differences in sectoral emissions are larger between the *2.8 W/m² -NDC* scenario and the *2.8 W/m² -NDC bridge* scenario than between the *2.8 W/m² -NDC bridge* and *2.8 W/m² -2020 action* scenario. This suggests that the effects of a 5-year delay in action between 2020 and 2025 are smaller than the effects of 5-year delay between 2025 and 2030.

The emission reduction rates found for the 2.8 W/m^2 scenarios fall within the range reported in IPCC AR5 (CO_2 approximately −2 to −7.5% per year between 2030 and 2050 for scenarios with 2030 emissions between 50 and 55 GtCO_2eq; Clarke et al., 2014). Riahi et al. (2015) reported an average CO_2 emission reduction rate of 7% per year between 2030 and 2050 for a scenario that accounted for a continuation of the unconditional 2020 pledges towards 2030. The *2.8 W/m² -NDC* scenario showed comparable CO_2 emission reduction rates of 6.4% per year in that period. The 2.8 W/m^2 scenarios are ambitious compared to historical 20-year average annual emission reduction rates; only in short time periods, rates of 2 and 3% have been observed and primarily due to economic recessions (Riahi et al., 2015).

The projected emission reduction rates and energy transition may be difficult to accomplish in reality for various reasons. First of all, the modelled energy system transformations depended on the availability of all technologies, including socially debated ones such as biomass or CCS, which are needed to realise negative emissions. The reliance on negative emissions technology in the second half of this century is larger in the *2.8 W/m² -NDC* scenario than in the other 2.8 W/m^2 scenarios. Social preferences and non-rational behaviour are not included in our model, but these are expected to impact the structure of the energy system and thus global emission projections. These preferences could lead to an acceleration of the energy system transition in specific sectors (e.g. electric transport or residential solar), but also to lock-in in conventional systems in other sectors, resulting in a delay and a lower probability of meeting the Paris Agreement's 2 °C goal. Especially social resistance against the use of biomass (in light of food security or biodiversity) and CCS, as well as investors' resistance to early retirements of power plants, could decrease the probability of meeting the 2 °C goal in practice. Second, the rapid emission reductions shown by the model may be difficult to realise due to political and institutional inertia. It should be noted that also different assumptions on the main drivers of technology change may play a role (see also Gerlagh et al., 2009; and van Vuuren et al., 2004 for a discussion of optimal timing of climate policy). To account for these factors, an

10 2.8 W/m^2 belongs to this category (2.3–2.9 W/m^2).

analysis of the transitions at the country level would be an interesting topic for future research (e.g. Van Sluisveld et al., 2013).

Given these considerations, the following conclusion can be drawn.

Enhancing the ambition level of NDCs before 2030 can allow for a smoother energy system transition, with lower annual emission reduction rates (4.5% instead of 4.7% between 2030 and 2050) and more time to phase out unabated fossil fuels. It can further result in lower total mitigation costs for meeting the 2.8 W/m ^{2} target. Implementing no further GHG emission reductions by 2030 than currently formulated NDC reductions would require very rapid reductions after 2030 to meet the 2 °C target with a chance of about two thirds. The cost-optimal pathway towards 2.8 W/m^2 leads to global greenhouse gas emissions of 38 $GtCO_2eq$ by 2030, a reduction of 20% on 2010 levels. In contrast, the NDCs are projected to lead to 2030 emission levels of 50 $GtCO_2eq$, an increase of 5% relative to 2010. The NDC 2.8 W/m^2 scenario delays mitigation and thus requires more rapid transitions after 2030 to meet the 2.8 W/m^2 target.

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Author contributions

H.v.S. coordinated the scenario development and analysis, wrote the paper, and created the figures; H.S.d.B., M.R., M.d.E., A.A., D.v.V., A.H., M.v.d.B., M.H., D.G. contributed to scenario development with the IMAGE model; N.F. developed the land-use emissions scenarios; all authors contributed to the article review.

3

Low-emission pathways in 11 major economies: comparison of cost-optimal pathways and Paris climate proposals

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Abstract

In order to evaluate the effectiveness of climate policy, it is important to understand emission trends and policies at the national level. The 2015 Paris Agreement includes (Intended) Nationally Determined Contributions, so-called (I)NDCs, outlining the contribution of different Parties to the overall target of the agreement to limit global mean temperature increase to well below 2 °C. Here, we assess emission trajectories and the energy system transition of 11 major economies (in the remainder: countries) projected by integrated assessment models (IAMs) for baseline and cost-optimal 450 ppm CO_2eq mitigation scenarios and compare the results with the (I)NDCs. Limiting global temperature increase to below 2 °C implies a substantial reduction of the estimated available carbon budget for each country. The national carbon budgets between 2010 and 2100 showed reductions between the baseline and the 2 °C consistent mitigation scenario ranging from 52% in South Korea to 95% in Brazil. While in the baseline scenario, the share of low-carbon primary energy sources is projected to remain around 15% (with Brazil being a notable exception, reaching 30%); in the mitigation scenarios, the share of low-carbon energy is projected to increase to over 50% in 2050 in nearly all countries, with the EU, Japan and Canada reaching the largest shares. Comparison with the (I)NDCs shows that in Brazil, Canada, the EU, Mexico (conditional target), South Korea and the USA, the emission reduction targets of the NDCs are closer to the mitigation requirement of the 2 °C scenario; in other countries, however, there is still a large gap. The national detail of the indicators adds to the literature on low-carbon emission pathways, assists the assessment of the Paris Agreement and provides support to national policymakers to identify focus areas for climate policy in the coming years.

Keywords
Emission reduction, climate policy, baseline scenario, marginal abatement cost, mitigation scenario

3.1 Introduction

At the twenty-first Conference of Parties in Paris in December 2015, governments worldwide agreed that the increase of global mean temperature should be limited to well below 2 °C with respect to pre-industrial levels (UNFCCC, 2015b) and possibly even below 1.5 °C. The IPCC Fifth Assessment Report (AR5) indicated that without new climate policies, global mean temperature will increase by approximately 3–4 °C by 2100 (Clarke et al., 2014). Urgent and far-reaching emission reductions are required in all regions to remain well below 2 °C (Tavoni et al., 2015). In this context, 189 Parties to the United Nations Framework Convention on Climate Change (UNFCCC) submitted their *Intended* Nationally Determined Contributions (INDCs) to the Paris Agreement. When a country ratifies the Paris Agreement, its INDC becomes an NDC (127 Parties have done so at the time of writing).

Integrated assessment models (IAMs) are a useful tool to assess the implications of these (I)NDCs for the energy system and for regional and global emissions. IAM scenarios for international climate policy have been developed in projects such as AMPERE (Kriegler et al., 2014a), LIMITS (Kriegler et al., 2013b; Riahi et al., 2015; Tavoni et al., 2015), RoSE (Luderer et al., 2016) and the Energy Modelling Forum (Kriegler et al., 2014c). These scenarios cover emission trajectories without new climate policies, estimates of current policies and different variants of scenarios aiming at a 2 °C target. These scenarios, which vary on probability of achieving the target, technology assumptions and the timing of climate policy, have played a key role in the analysis for the most recent IPCC report (Clarke et al., 2014).

The design of the Paris Agreement, based on a pledge-and-review process, calls for national assessments due to the bottom-up nature of the (I)NDCs and because Parties are invited to submit 'long-term low greenhouse gas emission development strategies' (UNFCCC, 2015b). At the same time, the effectiveness of climate policy needs to be analysed at the global level. The assessment of regional outcomes of global IAM frameworks, as done in this paper, provides an opportunity to bridge both levels. The IAM models with which the scenarios were developed typically include regions, ranging from 10 to 30. Only a few studies have focussed on these national results (e.g. Herreras Martínez et al., 2015; Tavoni et al., 2015; Van Sluisveld et al., 2013; Veysey et al., 2016). We built on this work and analysed the national results for 11 major economies, including countries that have not been studied in detail in similar assessments. While national scenarios can also contribute to informing decarbonisation pathways (e.g. Bataille et al., 2016), we restrict this analysis to results of global IAMs to maximise comparability of results across regions.

So far, most of the analysis has been focused on the global results of these scenarios. Yet, climate policy, although also driven by international negotiations and a global goal, is formulated at the national level. The main objective of this study was to focus on the regional emission trajectories (Sections 3.3.2 Greenhouse gas emissions and 3.3.3 Peak years) and the national energy system changes (Section 3.3.4 Energy mix). In light of the Paris Agreement, the regional baseline and cost-optimal 2 °C scenario results were compared to the (I)NDCs (UNFCCC, 2016). We present various policy relevant indicators (such as national carbon budgets; Section 3.3.1 Carbon budgets) under baseline projections and pathways consistent with a 2 °C target. This analysis helps positioning countries regarding cost-effective low-emission pathways, promoted by the Paris Agreement. It could further inform the global stocktake under the Paris Agreement, starting with a 'facilitative dialogue' in 2018 and official stocktake in 2023. The focus of the analysis is on national results and not on model comparison (for the latter, see for instance Kriegler et al., 2013b; Riahi et al., 2015; Tavoni et al., 2015).

3.2 Methods

The analysis presented here builds upon the Modelling and Informing Low-Emission Strategies (MILES) project. MILES is an international cooperation project between 19 international research teams.[11] In the analysis, the results from IAM scenarios developed in previous studies were compared for 11 major economies. These studies included AMPERE, LIMITS and EMF27 (Kriegler et al., 2014a; Kriegler et al., 2013b; Kriegler et al., 2014c; Riahi et al., 2015; Tavoni et al., 2015), with each of these studies including several models. The models covered by the studies are DNE21+, GCAM, GEM-E3, IMAGE, MESSAGE, POLES, REMIND and WITCH. In addition, some new GCAM scenarios were included in the MILES database (Spencer and Pierfederici (eds.), 2015). From each study, we selected the baseline scenarios and the cost-optimal 450 ppm CO_2eq scenarios, as described in Table 3.1. The main reason is that these scenario categories were the most clearly defined across the different studies. Cost-optimal scenarios are further often used as benchmark for policy analyses (e.g. Clarke et al., 2014). The target of 450 ppm CO_2eq is considered equivalent to limiting temperature increase below 2 °C by 2100 with a 66% chance.

11 ERI, RUC, TU, TERI, IIM, COPPE, PNNL, NIES, RITE, ICCS, IIASA, PIK, PBL, CMCC, CLU, IDDRI, CCROM, CRE, INECC

Table 3.1: Scenario categories used in this study. For regions covered by less than three models, only the range (minimum–maximum) is shown

Category	Description
Baseline	Scenarios that assume no new climate policies are put into place from 2005 onwards, and the data is calibrated to the historical period (to 2010). This scenario category thus acts as a counterfactual scenario providing a consistent reference across all regions for showing the impact of climate policies.
Cost-optimal 450 ppm CO_2 equivalent	Idealised scenarios that project global greenhouse gas concentrations below 450 ppm CO_2 equivalent by 2100. A universal global carbon tax is implemented immediately from 2010 to 2012 onwards, in order to reach the 450 ppm CO_2eq concentration level, resulting in the lowest costs (within the model). Therefore, the term 'optimal' represents the solution that maximises the regional welfare and attains the carbon budget constraint. Treatment of climate policy revenues (e.g. recycling of carbon tax revenues) was left to the modeller's decision, considering some guidelines. The target of 450 ppm CO_2eq is considered equivalent to limiting temperature increase below 2 °C by 2100 with a 66% chance.

The 11 major economies[12] studied were Brazil, Canada, China, EU, India, Japan, Mexico, Russia, South Korea, Turkey and USA. These countries were responsible for 70% of global emissions in 2012 (EC-JRC & PBL, 2014) and are largely covered by the models in the MILES database. Not all models include all of these countries in their spatial aggregation, implying that for many countries, the results were based on a lower number of models.

In the models, the contribution of each country in global reductions is determined by equal marginal abatement costs across all countries driven by a uniform global price. Therefore, emissions are reduced where it is most cost optimal according to the model's marginal abatement costs. This implies that the costs of achieving these reductions are covered by the countries where the measures are implemented. It is still possible to share these costs on the basis of equity and fairness criteria. For example, countries can be compensated for their mitigation by means of direct transfers or by establishing an international carbon trading system (e.g. S. Fujimori et al., 2016) with emission rights allocated on the basis of equity principles. This is, however, not further explored in this article. In addition to the cost optimisation at the regional level, DNE21+, MESSAGE, REMIND and WITCH are perfect foresight models, that is, they optimise over time. The other models are recursive-dynamic simulation models (except for GEM-E3, which is a recursive-dynamic optimisation model). Some of these, such as the IMAGE model, still minimise costs over time using iterative

12 In the remainder: countries, while there is one exception (EU).

procedures or by prescribing a carbon price trajectory. The 450 ppm CO_2eq scenarios considered here are assumed to start global cost-optimal mitigation in 2010–2012, which is not realistic given the current international climate policy landscape and historical trends in greenhouse gas emissions. However, these idealised scenarios are a useful modelling convention and provide a sense of the effort required to meet the 2 °C target.

The national model results were compared with the possible emission reductions resulting from implementing the (I)NDCs. The emission and peak year projections resulting from full implementation of the (I)NDCs were based on Den Elzen et al. (2016) and results from the WITCH model (Emmerling et al., 2016). Den Elzen et al. (2016) used official estimates for (I)NDC submissions, where available, supplemented with calculations based on documents submitted by countries to the UNFCCC, such as national communications and greenhouse gas inventories. The projections are in line with the median estimates presented in UNEP (2015). If no emission projection from these official studies could be calculated, i.e. for China and India, alternate sources were used. Emmerling et al. (2016) implemented the (I)NDC emission reductions aggregated to the native regions of WITCH, using the Shared Socioeconomic Pathway 2 (SSP2) assumptions. For the comparison, three types of (I)NDC ranges were defined: range in the reduction targets as defined in the (I)NDCs (Russia, USA), range resulting from unconditional and conditional reduction targets (Mexico) and range resulting from various model studies (China, India). For China, the central estimate from Den Elzen et al. (2016) was used. The national results of the global models were reviewed by national experts.

3.3 Results

3.3.1 Carbon budgets

The scenario results could be used to calculate cumulative CO_2 emissions over a given period, here 2010–2100. For the cost-optimal 450 ppm CO_2eq scenario, the global carbon budget is projected to be 1062 Gt CO_2, within a range of 905–1307 Gt CO_2. For the 2 °C scenario, the cumulative CO_2 emissions per country can be interpreted as a national carbon budget consistent with achieving the climate target assuming cost-efficient implementation of the emission reductions across countries. Other budgets based on specific emission allocation schemes can also be designed. National carbon budgets can be used by national policy makers to evaluate their policies (see also Seneviratne et al., 2016; Tavoni & van Vuuren, 2015). On average, the national carbon budgets showed a reduction of approximately 79% between the baseline and cost-optimal 450 ppm CO_2eq scenario. The reduction in carbon budget between the baseline and the mitigation scenario was over 90% in Brazil, Mexico and Turkey, indicating these countries' relatively high mitigation potential according to the models (mostly related to land use in Brazil and to deployment of renewable energy, including biomass, and CCS in Mexico and Turkey; Figure 3.1). After full implementation of the (I)NDCs, 471 Mt CO_2 (conditional (I)NDCs) to 453 Mt CO_2 (unconditional (I)NDCs) of the global carbon budget would be left to be nationally distributed until 2100 (similar to Rogelj et al., 2016).

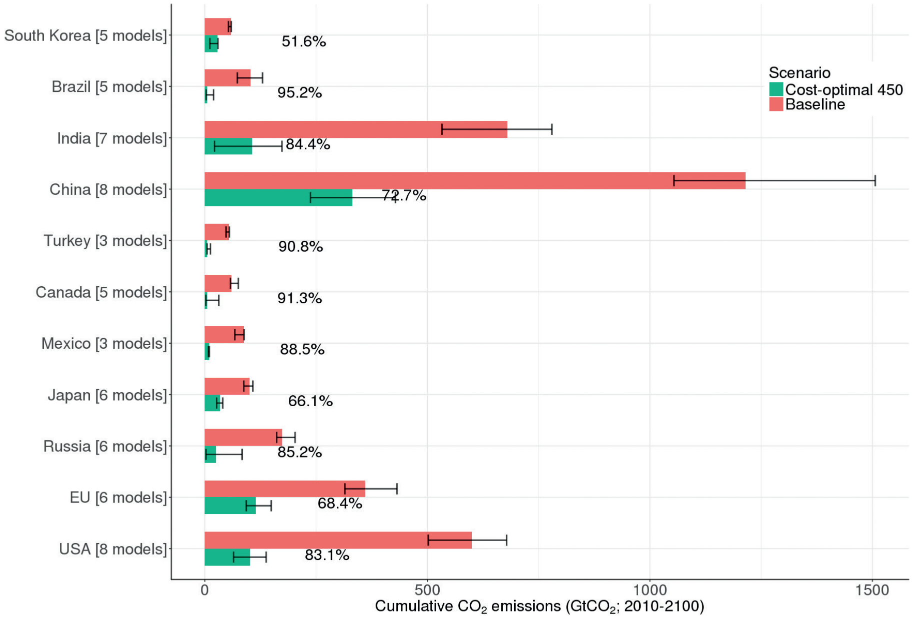

Figure 3.1: Regional cumulative CO_2 emissions (Gt CO_2) between 2010 and 2100, for cost-optimal 450 ppm CO_2eq and baseline scenarios. *Filled bars* represent the median; *error bars* give the 10th to 90th percentile ranges across models. The number of models per country is indicated (number may differ per variable because not all variables are reported by all models), as well as the median reduction between baseline and cost-optimal 450 ppm CO_2eq (%). The order of countries from top to bottom was determined by the baseline carbon budget in two groups, non-OECD and OECD90 countries (member of the OECD in 1990), and kept the same throughout the paper

3.3.2 Greenhouse gas emissions

Worldwide, greenhouse gas emissions are projected to increase strongly under the baseline scenarios, mostly driven by rapidly increasing emissions for the developing countries. Figure 3.2 shows the model average per capita CO_2 emissions as a function of GDP per capita under the baseline and cost-optimal 450 ppm CO_2eq scenarios. Per capita emissions of Canada, the EU, Japan, South Korea and the USA are projected to remain stable or decline in the baseline, consistent with historical trends (Olivier et al., 2016). This is mainly driven by the assumptions on energy efficiency improvement in these countries. At the same time, driven by income growth, the per capita emissions of low-income to mid-income countries are projected to grow rapidly in the baseline. The picture drastically changes for the cost-optimal 450 ppm CO_2eq scenarios, in which nearly all countries, including the low-income to mid-income countries, are projected to reduce their per capita emissions. All countries are projected to have emissions below 5 t CO_2/capita by 2050, but with still generally higher per capita emissions in high-income countries than in low-income to mid-income countries.

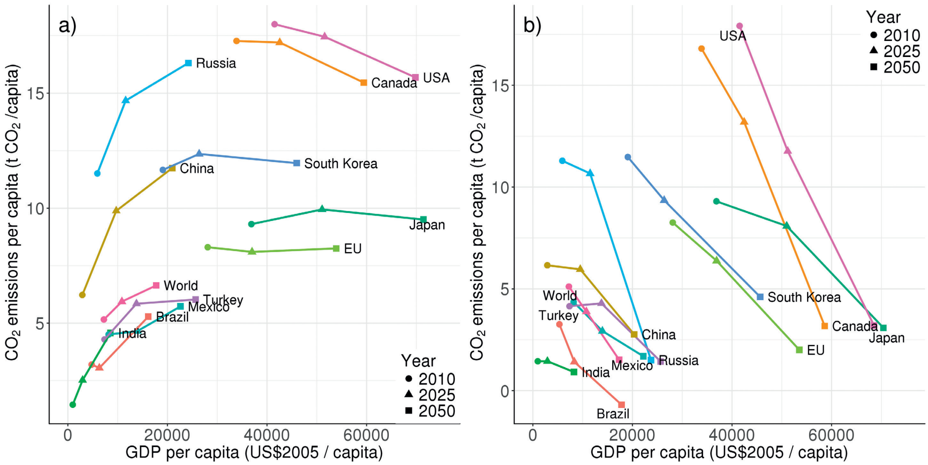

Figure 3.2: Model average per capita CO_2 emissions (tCO_2/capita) versus GDP (in market exchange rate, MER) per capita (US$2005/capita) in 2010 (*circles*), 2025 (*triangles*) and 2050 (*squares*). a Baseline scenario. b Cost-optimal 450 ppm CO_2eq scenario

Greenhouse gas emissions in 2030 would need to decrease significantly below the baseline in all countries to remain on a 2 °C pathway, as assumed in the cost-optimal 450 ppm CO_2eq scenario (Figure S3.1). However, the cost-optimal 450 ppm CO_2eq scenario still allows an increase in emissions compared to 2010 levels for India. The differences in emission reductions across the countries reflect differences in mitigation potentials calculated by the models.

Comparing the (I)NDCs to these cost-optimal pathways informs about the level of ambition of the (I)NDCs, providing more national detail to analyses of the emission gap between global emission levels resulting from the (I)NDCs and global emission levels consistent with a likely chance of staying below 2 °C (e.g. Rogelj et al., 2016) (see also Figure S3.2, showing what percentage of 450 ppm CO_2eq scenarios nationally fall above the estimated (I)NDC emissions in 2030). Full implementation of the NDCs of Canada, the EU, South Korea and the USA[13] is projected to result in 2030

13 The USA's NDC target for 2025 was extrapolated to 2030 by assuming a linear pathway to the national long-term target (83% reduction below 2005 levels by 2050).

emissions close[14] to the median model projections for the cost-optimal 450 ppm CO_2eq scenario (Figure 3.3). For Mexico, only the conditional NDC target is close to the model projection. The NDCs of China and India are projected to result in emissions well above model projections for the cost-optimal 450 ppm CO_2eq scenario. However, the NDC projections for these countries are subject to many uncertainties, including uncertainties related to GDP growth rate projections and the implementation of policies announced in the NDCs. The NDC of Brazil is projected to result in emissions lower than the model projections for the cost-optimal 450 ppm CO_2eq scenario. The Japanese NDC is projected to be higher than the median model projection, but close to the lower end of the model range. The INDC emission target levels of Russia and Turkey are projected to be above the model range for cost-optimal 450 ppm CO_2eq, but these INDC levels are also above the projected baseline scenario levels. These countries are thus expected to overshoot their INDC targets with baseline developments.

14 Here defined as less than 10 percentage point difference between the (I)NDC and cost-optimal 450 ppm CO_2 eq scenario projections (Figure 3.3).

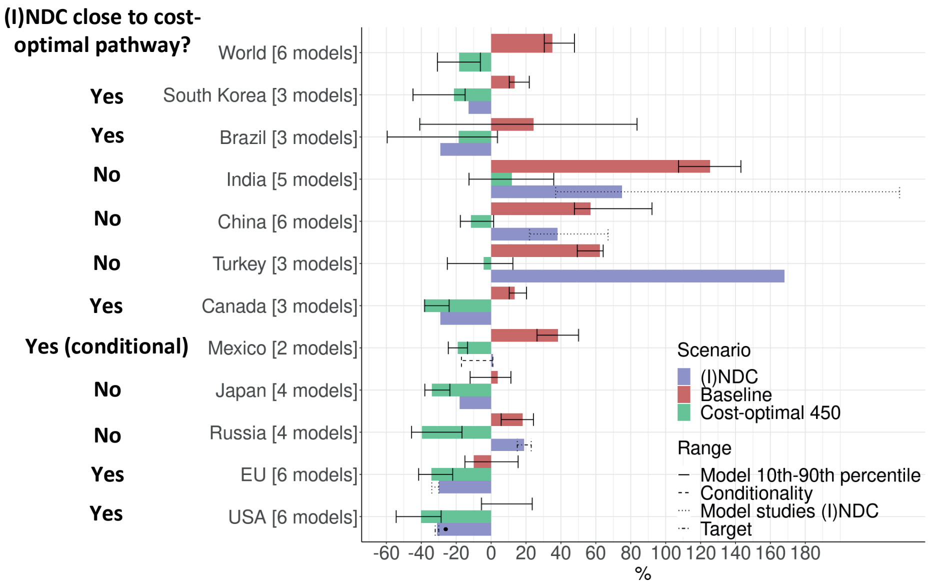

Figure 3.3: Kyoto gas emissions in 2030 projected by models for baseline and cost-optimal 450 ppm CO_2eq scenarios, compared to (I)NDCs. Total emissions are shown with respect to 2010 (%, with positive numbers indicating emission increase). The number of models per country is indicated. *Filled bars* for baseline and cost-optimal 450 ppm CO_2eq show the median value across models; *error bars* show the 10th to 90th percentile range of the model results (‘*Model 10th–90th percentile*’). For regions covered by less than three models, the range (minimum–maximum) is shown. *Filled bars* for (I)NDC show the central estimate from Den Elzen et al. (2016), error bars the range. (I)NDC ranges are of three types: range in the reduction target mentioned in the (I)NDCs themselves (‘*Target*’; Russia, USA), range resulting from unconditional and conditional targets (‘*Conditionality*’; Mexico; *filled bar* shows the unconditional target; *error bar* shows the effect of moving to the conditional target) and range resulting from various model studies analysed in UNEP (2015) (‘*Model Studies (I)NDC*’; India, China). For the USA, the (I)NDC range consists of both ‘*Target*’ (error bar, based on den Elzen et al., 2016) and ‘*Model Studies (I)NDC*’ (filled circle, based on Emmerling et al., 2016). The *column on the left* shows whether a country’s (I)NDC is close to the cost-optimal 450 ppm CO_2eq projection, where ‘close’ is defined as less than 10 percentage point difference

Thus, all countries would need to realise larger emission reductions after 2030 to either get or remain on a globally cost-optimal pathway for 2 °C stabilisation. Table 3.2 presents the projected greenhouse gas emission reductions in 2050, relative to 2010, for the cost-optimal 450 ppm CO_2eq scenario. The median emission reduction is projected to be 46% globally but ranges from 78% in Canada to 8% in India.

Table 3.2: Greenhouse gas emissions (including from land use, land use change and forestry, LULUCF) in 2050 relative to 2010 (%) for the cost-optimal 450 ppm CO_2eq scenario. For regions covered by less than three models, only the range (minimum–maximum) is shown

Region	10th percentile	Median	90th percentile
Brazil [3 models]	−81.6	−72.7	−23.9
Canada [3 models]	−86.6	−77.6	−43.9
China [6 models]	−58.3	−49.1	−42.6
EU [6 models]	−75.5	−70.2	−58.3
India [5 models]	−54.9	−7.8	11.8
Japan [4 models]	−81.6	−66.8	−65.3
Mexico [2 models]	−61.8		−31.9
Russia [4 models]	−77.7	−74.0	−52.4
South Korea [3 models]	−76.9	−63.6	−48.0
Turkey [3 models]	−80.3	−26.1	−22.2
USA [6 models]	−86.4	−73.4	−66.9
World [6 models]	−58.1	−46.2	−42.8

The emission pathways provide a general sense of each country's contribution to GHG emissions, but each country realises emission reductions differently. Figure 3.4 shows the projected greenhouse gas emissions in 2050 in terms of CO_2 emissions from fossil fuels and industry, CO_2 emissions from land use and non-CO_2 emissions. The emissions in each of these categories are projected to decline in the cost-optimal 450 ppm CO_2eq scenario with respect to the baseline projections, with land use emissions declining in relative importance towards 2050 and even turning negative in all countries except Indonesia and South Korea. Globally, CO_2 emissions from fossil fuels and industry represent the majority of total emissions in both scenarios, but the relative contribution of non-CO_2 emissions is projected to grow under the cost-optimal 450 ppm CO_2eq scenario. However, national differences can be observed. In China, for example, CO_2 emissions from fossil fuels and industry are projected to remain the major contributor to total emissions, in line with the focus on CO_2 in the Chinese NDC. In Brazil, in contrast, non-CO_2 emissions represent the largest share of remaining emissions in the cost-optimal 450 ppm CO_2eq scenario, while land use emissions are projected to turn negative. This is in line with Brazil's NDC, which covers all greenhouse gases and includes measures to reduce emissions from land use change.

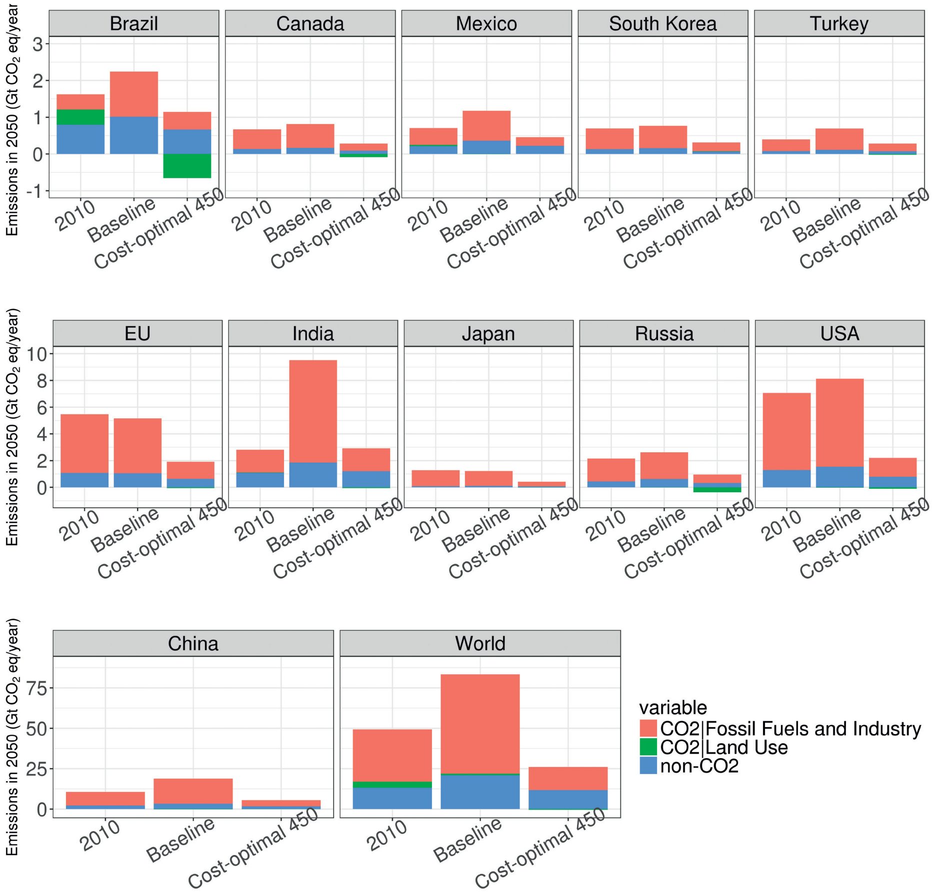

Figure 3.4: CO_2 emissions from energy supply and from land use and non-CO_2 emissions in 2050 (Gt CO_2eq/year) in baseline and cost-optimal 450 ppm CO_2eq scenarios (median across scenarios). Note the different *y*-axis scales across the three sets of panels

3.3.3 Peak years

Full implementation of (I)NDC targets is projected to result in emission trajectories with different emission peak years and peak emission levels across countries, as calculated in Den Elzen et al. (2016). The same holds for cost-optimal mitigation scenarios. Figure 3.5 presents peak years in greenhouse gas emissions per country. Under the cost-optimal 450 ppm CO_2eq scenario, most countries' greenhouse gas emissions are projected to peak before 2025, while India is projected to peak shortly after 2025. Canada, EU, Japan, Russia, South Korea and USA already peaked before 2015. CO_2 emissions are generally projected to peak earlier (Figure S3. 3). Three groups of countries can be distinguished in comparing the modelled greenhouse gas peak years under the cost-optimal 450 ppm CO_2eq scenario to the projected (I)NDC peak years. First, countries with projected NDC peak years close to the model median for the cost-optimal 450 ppm CO_2eq scenario: Canada, India, Japan and USA. Second, countries with projected (I)NDC peak years earlier than or at the lower end of the model range: EU, Russia and South Korea. And third, countries with projected (I)NDC peak years later than or at the upper end of the model range: Brazil, China, Mexico and Turkey.

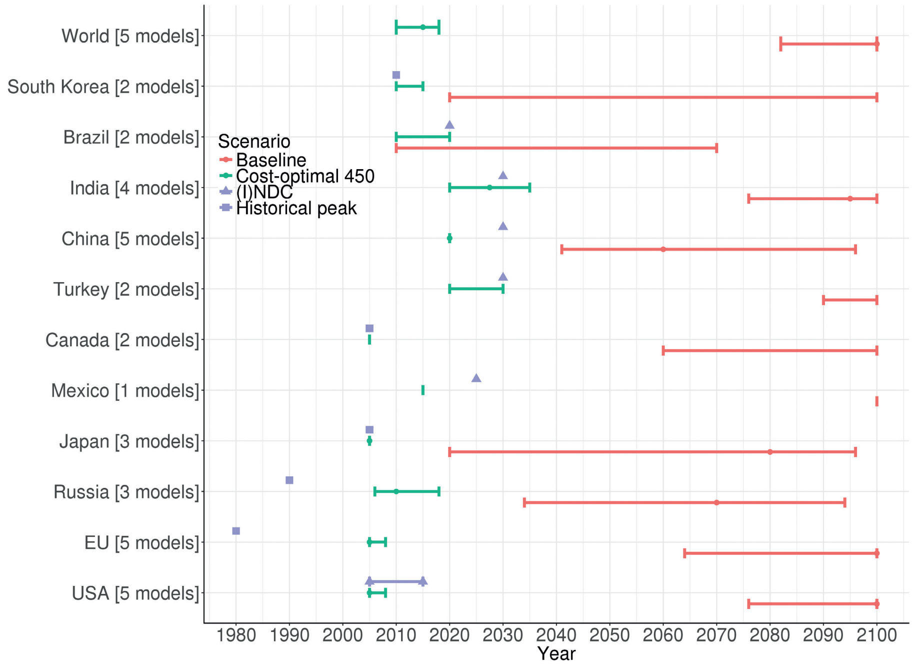

Figure 3.5: Regional peak years of greenhouse gas emissions (Kyoto gases) for cost-optimal 450 ppm CO_2eq and baseline scenarios. *Dots* give the median of the models; *error bars* give the 10th to 90th percentile ranges. The median results can be at the outer end of the range, for instance for OECD90. For regions covered by less than three models, only the range (minimum–maximum) is shown. Projected peak years under (I)NDCs are indicated by *triangles* (two estimates for USA, based on den Elzen et al., 2016; and Emmerling et al., 2016), while historical peak years are shown as *squares*. For most OECD90 countries, the cost-optimal 450 ppm CO_2eq scenario shows a peak year before 2015. For example for the EU, the models show 2005 as peak year under the cost-optimal 450 ppm CO_2eq scenario, because the start year for model analysis was 2005. As indicated for the EU's NDC, the actual peak year was around 1980. China's NDC peak year is for CO_2 only

3.3.4 Energy mix

Figure 3.6 shows that the share of low-carbon energy sources[15] in energy supply is projected to increase substantially in the cost-optimal 450 ppm CO_2eq scenario, compared to the baseline scenario. In the baseline scenario, the contribution of low-carbon energy technology is projected to remain around 15%, i.e. similar as today. In some countries, the baseline share in 2030 is projected to be lower than the 2010 share due to a phase-out of traditional biofuels. Still, in most countries, the share of low-carbon energy sources is projected to increase significantly. In the mitigation scenario, the share of low-carbon energy is scaled up further towards over 50% in 2050 (Figure S3. 4), with little differences between the countries (in 2030, differences between countries are still more pronounced because of different starting points). For developed countries, the mitigation scenario generally meant a substantial increase on 2010 levels. Some developing countries, such as Brazil and India, on the other hand, showed 2010 shares of low-carbon primary energy sources that were already close to the range reached in the mitigation scenario (over 25% of total primary energy supply in these cases).

15 All primary energy sources except coal, gas and oil without carbon capture and storage (CCS)

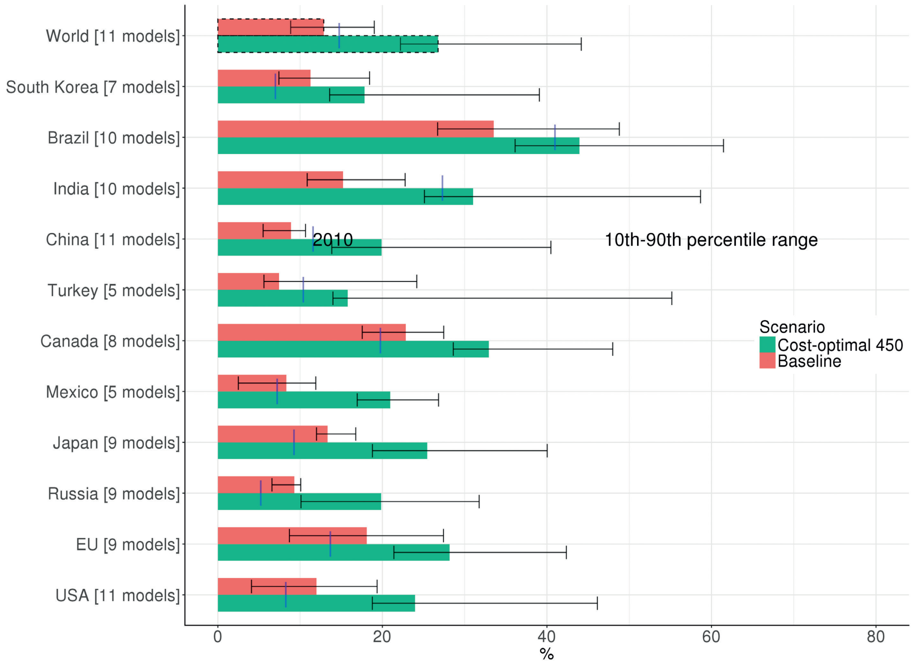

Figure 3.6: Share (%) of low-carbon primary energy sources (all energy sources except oil, coal and gas without carbon sequestration) in total primary energy supply in 2030, for cost-optimal 450 ppm CO_2eq and baseline scenarios. *Filled bars* represent the median; *error bars* give the 10th to 90th percentile ranges across models, and *vertical blue lines* give the 2010 shares (model median). Primary energy conversion for non-fossil fuels according to IEA statistics (physical energy content method)

3.4 Discussion and conclusions

The objectives of this study were to assess national emission trajectories and energy system changes for 11 major economies projected by global models and to compare the scenario results to the (I)NDCs. We derived policy-relevant indicators of these pathways in 11 countries, adding more national detail to the literature describing global model scenarios.

The global model-derived national carbon budgets add to the growing body of literature focusing on the relation between global climate change and regional impacts. For example, Seneviratne et al. (2016) noted that regional information would help political decision making and developing solutions. The indicators presented here and their comparison with (I)NDCs could thus help local policymakers identify focus areas for climate policy in the coming years, especially in relation to the UNFCCC global stocktaking set out in the Paris Agreement.

The ranges presented here are the result of several scenario runs from several models with different assumptions; thus, the national ranges of model results are interdependent, i.e. a pathway in a given country depends on the other countries' pathways. This means that the model range for a country might correspond only to a narrow range in all other countries. However, these national corridors remain indicative of what would be cost optimal in global mitigation scenarios.

The comparison of the results with (I)NDCs should be regarded as indicative given that the global model scenarios do not directly account for national policies and might not always thoroughly represent national energy systems. For example, the Fukushima accident makes it difficult for Japan to increase its nuclear power capacity, while most models still project a large increase in the share of nuclear energy. The Japanese NDC assumes a more modest share, leading to an emission gap between the NDC and the 450 ppm CO_2eq scenario. In addition, the definition of regions might be slightly different across models (especially for Europe). Fragkos et al. (2017) did a detailed model-based assessment of the EU's NDC and found that its targets are consistent with a cost-optimal distribution of physical emission reductions in a 2 °C pathway, similar to our findings. As the estimates for (I)NDC outcomes are still under development, this analysis is based on the information available to date. China, India and Mexico show large ranges in NDC emission projections. Finally, the fact that some projected (I)NDC emission reductions and peak years are not in line with the cost-optimal mitigation scenario should not be interpreted to mean that the 2 °C target will not be met. Alternate pathways (based on delay) might still be possible, although these could be considerably more expensive.

As indicated earlier, the scenarios in this study often used 2010–2012 as start year of comprehensive climate policies, which leads to lower emissions in subsequent years for the cost-optimal scenario. For policy scenarios, the differences are much smaller given the 2020 targets. Using a later starting year implies that the cost-optimal pathways would have somewhat higher emissions in the short run and somewhat higher costs and lower emissions in the long run. Given the trends in the 2010–2015 period, a later start year would especially influence results for China and India (in other countries, emission growth has been more modest), possibly reducing the difference between the (I)NDC and cost-optimal pathway to some extent (Figure S3. 5). Altogether, we expect that this might imply slightly different quantitative results but would not impact the overall conclusions.

For some countries, greenhouse gas emissions are projected to peak before the end of the century even in the baseline scenario, due to autonomous developments incorporated in this scenario. The limited model coverage for some countries means that these results should be seen as being indicative of the projected emission trajectories and energy system changes. Especially land use emissions are a source of uncertainty in model projections.

The range in baseline greenhouse gas emission projections would affect relative abatement costs under the mitigation scenario and the (I)NDC. Uncertainty in emission reductions is especially large for Brazil, EU, Japan and USA, with model ranges crossing the zero reference line in the baseline. This not only reflects different assumptions on energy efficiency but also the uncertainty on the role of land use, land use change and forestry (LULUCF), most notably for Brazil. However, 2030 emissions for the cost-optimal 450 ppm CO_2eq scenario are robustly projected to be below the baseline, with the higher end of the cost-optimal 450 ppm CO_2eq scenario range below the lower end of the baseline range for all countries except the EU. This is even clearer when using per capita emissions. National differences in projected per capita emissions might evoke discussions on equity and fairness, with Brazil, India and Mexico projected to remain below the global average under the mitigation scenario. This points to the need for financial transfers in line with the principle of common but differentiated responsibilities to compensate developing countries and emerging economies with high mitigation potential. The model results presented here were derived from scenarios in which emission reductions were distributed across countries in a cost-optimal way, but actual costs could be distributed differently if aspects of equity are considered.

Given the discussion above and based on the results, the following main conclusions can be drawn.

Limiting global temperature increase to below 2 °C implies a substantial reduction of the cumulative CO_2 emissions (carbon budget) between 2010 and 2100 for each country

Our results confirm the general conclusion that major total and per capita emission reductions are needed in all countries to limit global warming to below 2 °C. The national carbon budgets between 2010 and 2100 showed on average a 79% reduction between the baseline and the mitigation scenario, with the largest reductions projected for Brazil (95%) and Canada (91%) and the smallest for South Korea (52%). After full implementation of the (I)NDCs, the world would be left with approximately 40% of the carbon budget for 2 °C for the rest of the century. Under the mitigation scenario, most countries' greenhouse gas emissions are projected to peak before 2025. Only Brazil, China, Mexico and Turkey have projected (I)NDC peak years later than the model peak years for the mitigation scenario.

In general, the (I)NDCs are insufficient to reach the mitigation level of the cost-optimal 2 °C scenarios

However, the NDCs of Brazil, Canada, the EU, Mexico (conditional NDC), South Korea and the USA are projected to be relatively close. The NDCs of China and India are projected to result in emissions well above levels consistent with the cost-optimal 2 °C scenario. The NDC projections for these countries are surrounded with uncertainties, driven by uncertain GDP projections. The (I)NDCs of Japan, Russia and Turkey are projected to result in emissions higher than the model projections for the cost-optimal 450 ppm CO_2eq scenario. For Russia and Turkey, the emission projections of the INDCs are even above the baseline projections. At the global level, the sum of emission reductions projected to result from implementation of the (I)NDCs falls short of the reductions required in the cost-optimal 2 °C pathway. As shown here, however, the results differ significantly for the individual countries.

All countries show increasing shares of low-carbon primary energy sources in the mitigation scenario

In the baseline scenario, the share of low-carbon primary energy sources is projected to remain around 15% (except for Brazil 30%). All countries showed increasing shares of low-carbon energy in the mitigation scenario, towards approximately 40% in some countries and over 50% in the other countries in 2050. Although these projected shares could not be compared directly to the (I)NDCs, they indicate that scaling up the share of low-carbon energy sources is needed for the (I)NDCs to follow a cost-optimal pathway to the 2 °C target.

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Author contributions

H.v.S. coordinated the analysis, wrote the paper, and created the figures; L.A.R. helped with the figure layout; all authors provided scenario data and contributed to the analysis and article review.

4

Net-zero emission targets for major emitting countries consistent with the Paris Agreement

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“Net-zero emission targets for major emitting countries consistent with the Paris Agreement.” Nature Communications 12 (2021): 2140.

Abstract

Over 100 countries have set or are considering greenhouse gas emissions neutrality targets. However, most of the information on emissions neutrality—e.g. timings—has been established at the global level. Here, we look at national-level neutrality-years based on cost-effective 1.5 °C and 2 °C scenarios from integrated assessment models. According to these socio-economic models, globally cost-optimal mitigation implies domestic net zero greenhouse gas and CO_2 emissions in Brazil and the USA are reached a decade earlier than the global average, and in India and Indonesia later than global average. These results depend on choices like the accounting of land-use emissions. The results, indicative of domestic mitigation, are discussed in light of equity-based mitigation trajectories. The results also show that carbon storage and afforestation capacity, income, share of non-CO_2 emissions, and transport sector emissions affect the variance in projected phase-out years across countries. These results can inform policymakers on net-zero targets.

4.1 Introduction

In the 2015 Paris Climate Agreement (UNFCCC, 2015b), Parties agreed to keep the increase in global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit temperature rise further to 1.5 °C (Article 2). To reach these objectives, Parties further agreed to "reach global peaking of greenhouse gas emissions as soon as possible [...] and [...] to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century." (Article 4) (UNFCCC, 2015b). This balance between greenhouse gas (GHG) emission sources and sinks can be defined as GHG emissions neutrality (Matthews, 2018). This is elaborated by Rogelj et al. (2015) who define carbon neutrality as the total annual CO_2 emissions from all anthropogenic sources being net-zero and GHG emissions neutrality as the sum of all Kyoto GHG emissions being net zero (in CO_2-equivalent). The latter is also referred to as climate neutrality. The concept of emissions neutrality has gained interest among policy-makers and an increasing number of governments have formulated neutrality targets (Höhne, 2020). The strength of neutrality targets is that they constitute a clear vision for the long-term ambition of climate policy. Earlier, scenarios from integrated assessment models (IAMs) were used to determine neutrality targets at the global level. In most of the cost-optimal scenarios consistent with limiting global warming to 2 °C relative to pre-industrial levels with at least 66% probability, net-zero GHG emissions occurs shortly after 2085; in 1.5 °C scenarios, this occurs between 2060 and 2085, i.e., roughly 25 years earlier (Rogelj et al., 2018). The use of less or no net negative emissions would imply an earlier year of neutrality (phase-out year), achieved through other means such as drastic efficiency improvements. Net-zero CO_2 emissions occur earlier than net-zero GHG emissions, i.e., between 2065 and 2080 for 2 °C and between 2045 and 2060 for 1.5 °C, on a global level. The exact value of the phase-out year also depends on methodological choices. For instance, the phase-out year depends on the GHG-equivalence metric used (such as the Global Warming Potential, GWP) (Tanaka & O'Neill, 2018). It further depends on the interpretation of the word balance in Article 4 of the Paris Agreement (Fuglestvedt et al., 2018), e.g., whether it corresponds to stable global mean temperature, radiative forcing or emissions, and whether it includes only anthropogenic or all GHG sources and sinks (M. R. Allen et al., 2016).

So far, studies on GHG and carbon neutrality have mostly focused on the global level. However, as more than 100 national governments (e.g., EU, China, Japan and South Africa) and over 800 cities (Höhne, 2020) have set or are considering net-zero emissions targets, it is more policy-relevant to look at the implications at the national level. Therefore, we use a set of scenarios by IAMs that represent major emitting countries individually, to analyse national neutrality targets for major emitting countries (for brevity, we will refer to countries and national, although the EU is not a country). We focus on the phase-out year for CO_2 and GHG emissions in

4

scenarios consistent with the Paris Agreement temperature targets, the influence of methodological choices and the key factors that could determine the differences between countries. By presenting detailed information for ten countries based on the CD-LINKS database (CD-LINKS project, 2018), directly relevant for national policy-making and international negotiations, we go beyond the existing literature. Although IAMs have developed to represent individual countries and current climate policies in more detail, IAMs are not the only tools for analyses such as presented here—national energy system models, e.g., can do so too, often with greater granularity. These tools are already applied jointly to develop national-level pathways that account for national circumstances but still meet the global goals of the Paris Agreement. The results that we present here should be complemented with an assessment of feasible reductions at the national level, considerations of equity and national model results, among others.

4.2 Results

4.2.1 National phase-out years for large countries

We analysed a set of existing globally cost-optimal scenarios from six IAMs for which detailed, national-level results were available (assuming optimal climate policy to be implemented from 2020 onwards; see “Methods”). The six models included are AIM (Fujimori et al., 2012), IMAGE (Stehfest et al., 2014), MESSAGE-GLOBIOM (Messner & Schrattenholzer, 2000), POLES (Keramidas et al., 2018), REMIND-MAGPIE (Luderer et al., 2015) and WITCH (Emmerling et al., 2016) (see also S4.3 Supplementary Methods: Overview of models per country). These scenarios can be used to look into cost-optimal phase-out years, without fairness considerations. The scenarios address both 1.5 °C and 2 °C targets (relative to pre-industrial levels, with at least 66% probability of achieving the targets). In the scenario set, global GHG emissions are projected to reach net zero between 2050 and 2070 in 1.5 °C scenarios and after 2080 in 2 °C scenarios. That is consistent with findings in the Special Report on 1.5 °C by the Intergovernmental Panel on Climate Change (IPCC), in which more models and scenarios are included, but for which the required national-level results are not available. CO_2 is projected to be phased out earlier: between 2045 and 2060 in 1.5 °C scenarios and between 2065 and 2080 in 2 °C scenarios. At the same time, there are clear differences in phase-out years of different countries (Figure 4.1). As there are also large differences between the models, we look at both the median and the spread of the model results, and refer the reader to S4.4 Supplementary Results: Additional indicators for more details.

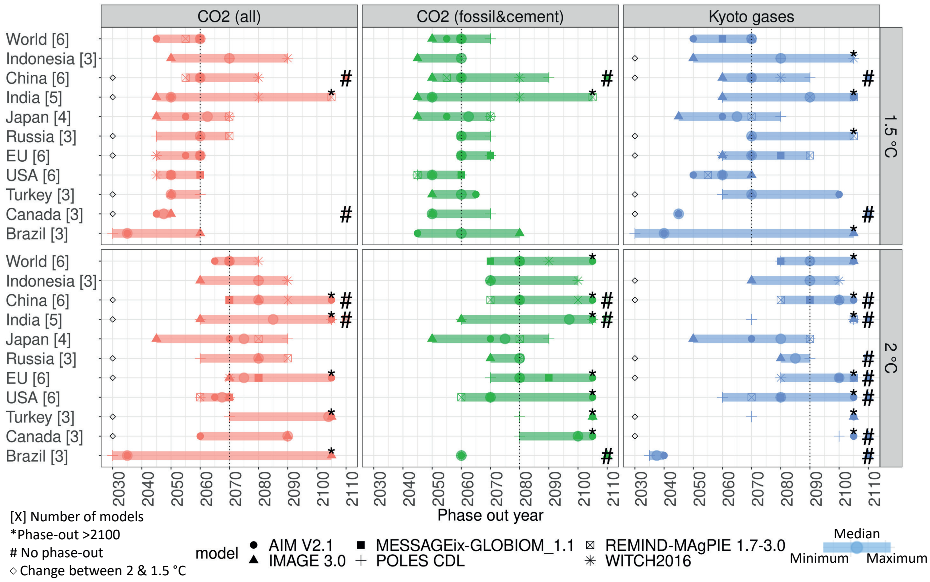

Figure 4.1: Year when projected emissions reach net zero, per country (number of models representing that country between brackets), for 2 °C and 1.5 °C scenarios, for CO_2 emissions, CO_2 emissions from fossil fuels and cement (energy and industrial processes), and total GHG emissions (Kyoto Gases, including land-use emissions). Individual models are indicated by symbols, whereas the bars show the minimum–maximum range (enlarged circles: model median). In some cases, individual models show a phase-out after 2100 in the extrapolated data (indicated by an asterisk) or no phase-out at all (#). Diamonds plotted at the 2030 mark indicate a change between the 2 °C and 1.5 °C scenario in terms of a country reaching net zero earlier than, similar to, or later than global average. Vertical dotted lines indicate the global average phase-out year.

For the median of the 2 °C scenarios, GHG emissions (including land use) are projected to reach net zero earlier than the global average in Brazil, Japan, Russia (across models) and the United States (with a larger model spread), but later than global average in Canada (across models), as well as in China, EU, India and Turkey (with a larger model spread). Indonesia's median projected phase-out year is equal to the global average. For most regions, the order is similar in the 1.5 °C scenario, but Canada (now earlier) and Indonesia (now later) are the main exceptions. The difference between Canada and the United States in the 2 °C scenario (only projected by one model) can be explained as follows. That model uses national inventory data for land use, land-use change and forestry (LULUCF) emissions (see next section), unlike the other two models that cover both Canada and the United States. As the inventory data show a sink for the United States but an emissions source for Canada, the United States can phase out emissions earlier than Canada. For CO_2 only (including land use), countries that reach net-zero emissions earlier than global average are again Brazil and the United States (the former with a large model spread, but it is worth noting that

Brazil is only covered by three models, two of which project similar phase-out years). Results are somewhat similar in the 1.5 °C scenario, but now Canada, India and Turkey join the early group. Focusing on fossil CO_2 only (thus excluding land use), Brazil, Indonesia, Japan and the United States are projected to have net-zero CO_2 emissions earlier than the global average in the 2 °C scenario (only Canada and the United States in the 1.5 °C scenario). This finding is confirmed by Schaeffer et al. (2020b) who show net-zero energy CO_2 emissions by or before 2050 for Brazil and the United States, based on national model studies. In contrast, Canada, India and Turkey show a later than global average phase-out in the 2 °C scenario (only India and Japan in the 1.5 °C scenario). The other countries have a phase-out year comparable to the global average. Comparing the phase-out years for CO_2 emissions with those for only fossil CO_2 shows that countries in which land use is a source of emission (e.g., Indonesia) will see a later phase-out of CO_2 than of fossil CO_2 only, whereas in countries in which land-use forms a sink (e.g. Canada), the reverse is true.

All-in-all, this means that Brazil and the United States typically have a phase-out year earlier than the global average, whereas India is projected to reach net-zero emissions later than the global average (in four out of six scenario–source combinations). China and the EU are relatively similar to the global average (namely in four out of six scenario–source combinations and later than global average in the remaining two). The remaining five countries show a mixed picture: results vary across sources of emissions and temperature targets.

Table S4.4.1 shows additional information on the emissions projections, to support thinking about linking longer-term, net-zero emissions goals to shorter-term action such as formulated in Nationally Determined Contributions (NDCs). For example, GHG emissions are projected to peak in 2020 in many countries that have not yet seen peak emissions and be reduced by between 12% (India) and 36% (Japan, Canada and Indonesia) by 2030 relative to 2015 levels, under the 2 °C scenario. By 2050, these reductions amount to 52% (Brazil) to 72% (USA), and up to 90% (USA) under the 1.5 °C scenario.

4.2.2 The influence of definitions

A number of technical issues has a strong influence on the reported phase-out year at the national level. We explore four that are highly debated but not yet in the context of neutrality targets, i.e., the use of inventory data for LULUCF-related emissions, the allocation of negative emissions, the GWPs and equity considerations (respectively, Figure 4.2a-d).

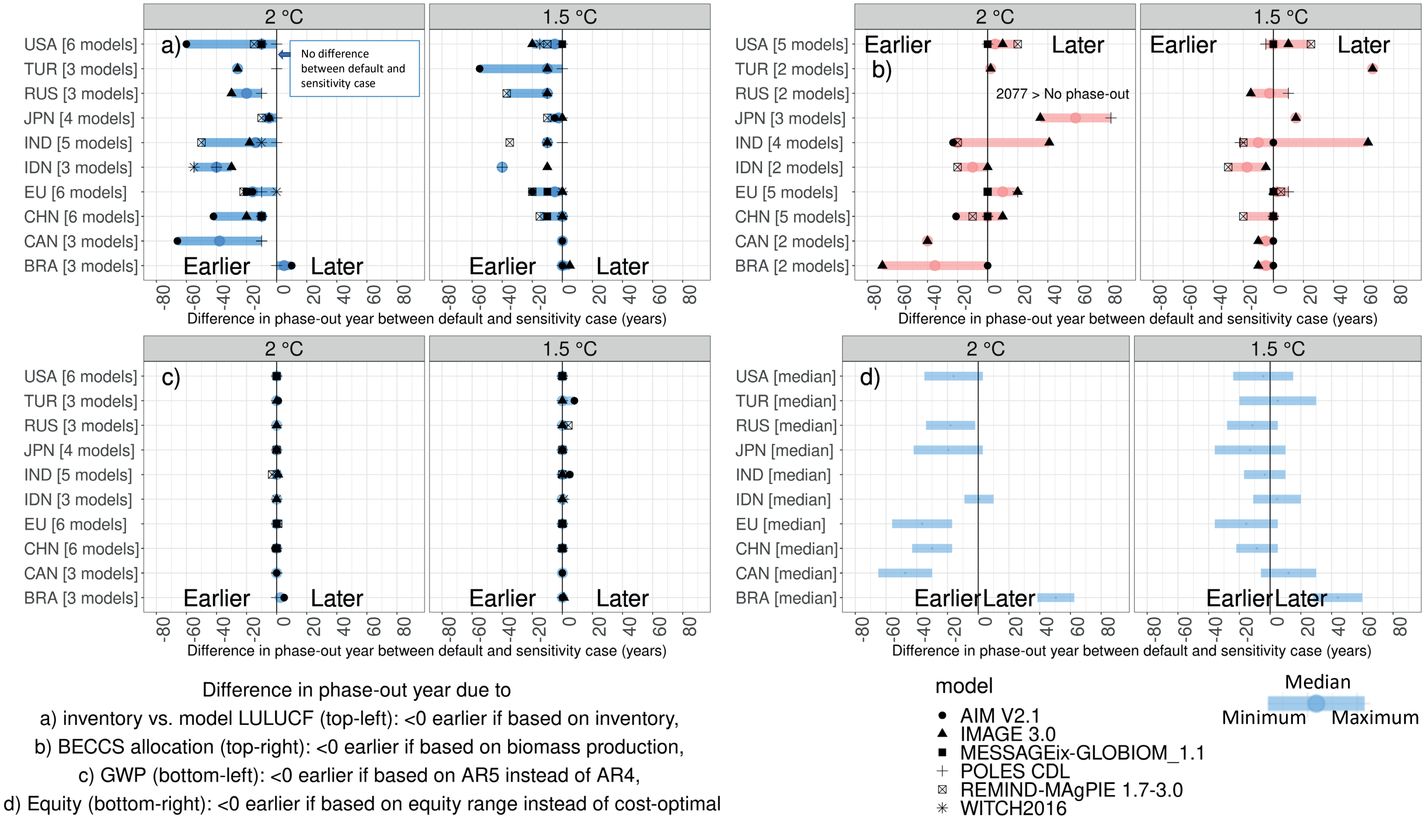

Figure 4.2: Influence of definitions on projected phase-out years. Change in projected phase-out years for a all GHG emissions including land use when harmonizing the model projections towards the countries' land-use emissions estimates, i.e., by adding the absolute emissions difference in

2010 between the inventory data and the model data to the model projections; values smaller than 0 indicate an earlier phase-out when emissions projections of individual models are harmonized to the inventory LULUCF data. b CO_2 emissions when negative emissions from BECCS are allocated to the biomass producer instead of the carbon-storing country (note that results are shown for fewer models, as POLES did not report the required variable agricultural production of energy crops). c The sum of CO_2, CH_4, N_2O and SF_6 emissions when using 100-year global warming potentials from the Fifth Assessment Report (AR5) of IPCC instead of the fourth (AR4). d All GHG emissions when the equity ranges from Robiou du Pont et al. (2017) are used instead of the model median for the default cost-optimal approach, noting that the results reported by Robiou du Pont et al. (2017) do not go beyond 2100, whereas the cost-optimal scenarios do. Therefore, India and Turkey are not shown for the 2 °C scenario, because the equity range included 2100 (which may actually mean somewhere after 2100), while the cost-optimal median phase-out year was calculated as being beyond 2100 in these two cases. Individual models are indicated by symbols, whereas the error bars show the minimum–maximum range from models (enlarged circle: median). Extrapolated emissions data were used to calculate the phase-out year difference, so as to not introduce a bias when calculating differences in phase-out years. Vertical lines at 0 indicate no difference between the default and sensitivity cases. BRA: Brazil, CAN: Canada, CHN: China, EU: European Union (EU27 + UK), IND: India, IDN: Indonesia, JPN: Japan, RUS: Russian Federation, TUR: Turkey, USA: United States.

First of all, there are large differences between the land-use change (LUC) emissions produced by the models (and scientific inventories) and LULUCF emissions reported by countries in their national GHG inventories (Grassi et al., 2017; Grassi et al., 2018; SEEG, 2018; UNFCCC, 2019a, 2019b). The latter focus on the balance of sinks and sources on managed land, including CO_2 uptake by forests. On the other hand, the former typically focus on direct human-induced effects of changes in vegetation type. It has been suggested that it is possible to use the inventory data for the base year in combination with the model projections. Figure 4.2a shows how projected phase-out years change when harmonizing the model projections towards the countries' reported land-use emission estimates (see also Figure S4.1.1 and Table S4.1.1 of S4.1 Supplementary Methods and Results: Emission pathways and the influence of definitions). As the inventory data have lower LULUCF emissions mainly due to the sink of the managed forests, net-zero GHG emissions are projected to be reached earlier when using inventory LULUCF data (except for Brazil, see below). In other words, adjusting countries' GHG and CO_2 emission projections through harmonization of the LUC CO_2 emission projections by models with the current (2010) LULUCF emissions from the national inventories data will require countries to phase out GHG emissions earlier. The impacts are quite considerable with the exception of the POLES model (Keramidas et al., 2018), because it uses the inventory data for Annex I countries. In countries where LULUCF emissions play a relatively large role or are uncertain (e.g., Indonesia), the effect is most pronounced. Brazil is a special case, because that is the only country for which the models report lower LUC emissions than the inventory (SEEG, 2018), resulting in a later phase-out when using inventory data.

Regarding allocation of negative emissions from bioenergy with carbon capture and storage (BECCS, Figure 4.2b), in models these are normally allocated to the country where the carbon is stored. If the allocation of negative emissions from BECCS is changed, ex-post, to the country where the biomass is produced, projected phase-out years change. We have changed the allocation ex-post by using the share in global bioenergy production (see S4.1 Supplementary Methods and Results: Emission pathways and the influence of definitions) and have calculated the difference in phase-out years as follows: phase-out year of CO_2 emissions when negative emissions are allocated to the biomass producer (Emissions|CO_2|Allocation) − phase-out year of CO_2 emissions when negative emissions are allocated to the carbon-storing country (default: Emissions|CO_2). In that case, Brazil, Canada, India (albeit with a large model spread) and Indonesia show earlier net-zero GHG emissions, because these countries produce and export a lot of biomass in the models. On the other hand, the EU, Japan and Turkey show a later phase-out, as these countries generally import biomass. Figure S4.1.2 shows emission pathways for two illustrative countries for the default case and the sensitivity cases of LUC data and negative emissions allocation.

The effect of using different GWPs is illustrated by looking at the impact of using 100-year GWP values (excluding feedback, Myhre et al., 2013) from the IPCC's Fourth Assessment Report (AR4) and Fifth Assessment Report (AR5), focusing on CO_2, CH_4, N_2O and SF_6 emissions. We focus on GWP100, as it is prescribed for NDCs, but countries are free to choose an additional metric (UNFCCC, 2019c). We further focus on AR4 and AR5, as GHG reporting and accounting are moving to more recent GWPs, in line with the decisions made at the COP in Katowice. The results in Figure 4.2c show that changing the GWPs from AR4 to AR5 does not result in significant shifts in projected phase-out years (up to 8 years earlier or later), similar to findings by Fuglestvedt et al. (2018). Choosing other metrics, such as Global Temperature change Potential (Collins et al., 2020), would result in larger effects on phase-out years (Fuglestvedt et al., 2018; Tanaka & O'Neill, 2018).

Finally, the effect of equity considerations (Figure 4.2d) is also important. As indicated earlier, cost-optimality is only one consideration in target setting. To compare these results to those based on equity principles, we took the most extreme (earliest and latest) phase-out years based on five different equity approaches as presented by Robiou du Pont et al. (2017) (see their Supplementary Tables S3 and S4) and we calculated the difference with the model median of the cost-optimal (default) phase-out year per region. This is not a perfect comparison, however, as Robiou du Pont et al. (2017) excluded LULUCF from the equity allocation calculations, whereas the cost-optimal scenarios included LULUCF. This difference could lead to earlier phase-out years in this study (on a global level: 10–20 years). The comparison showed that when taking a different equity approach, many of the countries studied here would have to phase out GHG emissions earlier than under a cost-optimal allocation, notably developed countries such as Canada and the EU, but also China. Brazil would be allowed to phase out emissions later, as well as other countries with lower per-capita emissions or developing economies, although with larger uncertainty (e.g., Indonesia). This implies that countries with later equity-based phase-out years could receive support from countries with earlier equity-based phase-out years, to help them meet their earlier domestic targets.

4.2.3 Factors influencing the timing of the phase-out year

A key question is whether the different phase-out years can be explained. One would, for instance, expect the phase-out years for developed countries to be earlier than for developing countries, given the differences in baseline emission growth. However, Figure 4.1 shows this is not consistently the case. We have, therefore, correlated the phase-out years with possible explanatory variables related to the mitigation potential. For this, we first selected 15 potentially explanatory variables as shown in Figure 4.3 and listed in Table S4.2.1 in S4.2 Supplementary Methods and Results: Multiple linear regression and Principal Component Analysis. To test for redundancy (internal correlation) in the dataset, the 15 factors were also used in a principal component analysis (PCA; Jolliffe & Cadima, 2016; see S4.2 Supplementary Methods and Results: Multiple linear regression and Principal Component Analysis) to try and reduce the number of explanatory variables to the 5 most important ones. More detailed findings are provided in S4.2 Supplementary Methods and Results: Multiple linear regression and Principal Component Analysis (Table S4.2.2 and Figure S4.2.2), as the PCA did not reveal clear patterns. Subsequently, Figure 4.3 shows the relationship between each of the 15 variables and phase-out years across the 10 countries, 2 models (POLES and IMAGE) and the 2 scenarios (Figure S4.2.1 in S4.2 Supplementary Methods and Results: Multiple linear regression and Principal Component Analysis does so for all countries and models available in the dataset, for 1.5 °C and 2 °C separately). The IMAGE and POLES data subset was used to maximize the number of countries covered (and thereby the number of records as input to the statistical analyses), while ensuring the same number of models per country so as to not introduce a bias. Figure S4.4.1 shows that the six models in the full dataset show largely similar trends in emission-reduction pathways across regions, justifying the focus on two models here (Figure S4.4.2 shows that model differences are more pronounced for the share of solar and wind in electricity production, but not structurally explaining different phase-out years). Having different models per country makes it more difficult to distinguish clear patterns in the relationship between explanatory variables and phase-out years, but it is clear that some variables are indeed correlated with the phase-out year.

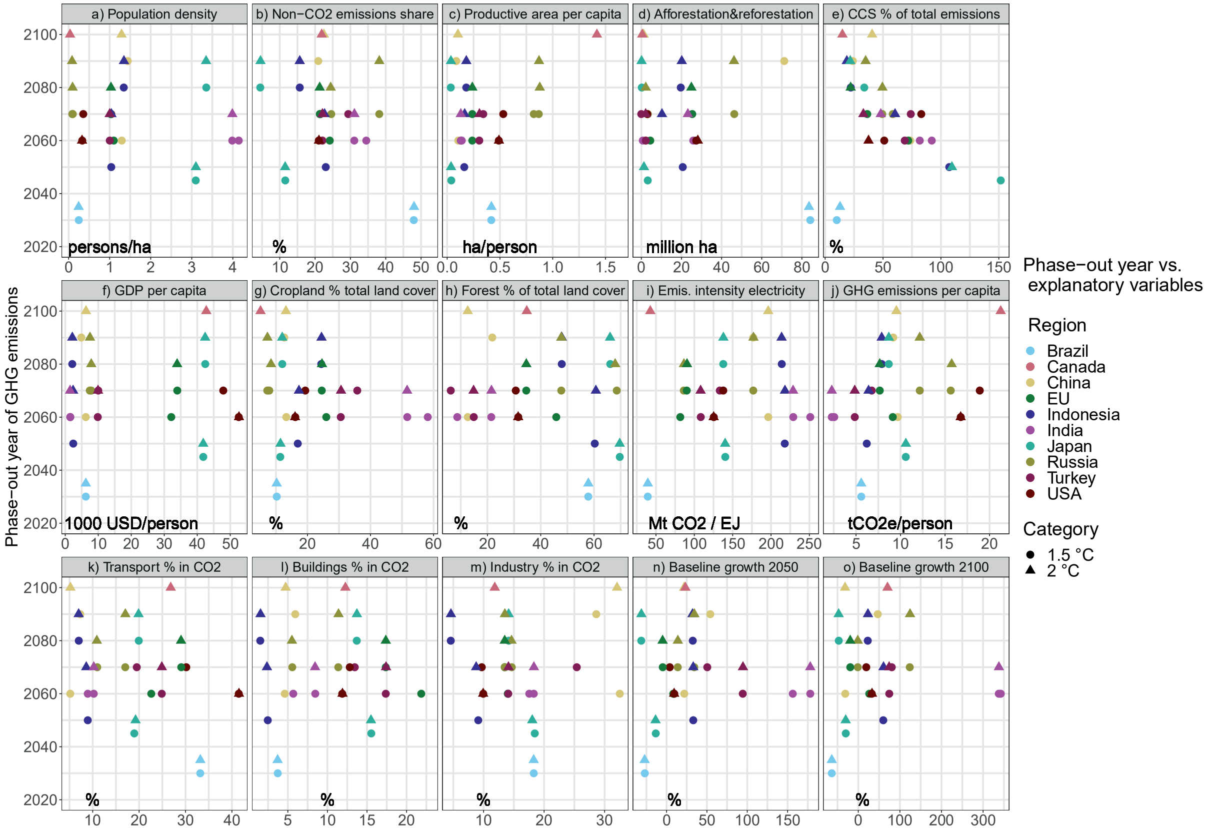

Figure 4.3: Fifteen explanatory variables vs. phase-out years across the ten countries (colours), the POLES and IMAGE models, and the 1.5 °C and 2 °C scenarios (shapes). See Table S4.2.1 for details of how the variables were calculated (units are displayed in the lower left corner of each panel).

Finally, we used multiple linear regression. Different models to explain national phase-out years under 1.5 °C and 2 °C scenarios were tested, based on all possible combinations of four, five, six and seven variables (Table S4.2.4). Table S4.2.5 and Table S4.2.6 in S4.2 Supplementary Methods and Results: Multiple linear regression and Principal Component Analysis show the results for these multiple linear regression models. Six turned out to be the optimal number of variables (see "Methods"). The model would then be (uncertainty range indicates two times SE):

$$(1)\ y_i = 2079[\pm 6.7] - 18.0[\pm 7.4] * \text{CCSshare} - 12.3[\pm 10.0] * \text{Afforestation} - 22.6[\pm 13.6] * \text{transportshare} + 13.7[\pm 11.9] * \text{nonCO2share} + 20.9[\pm 16.8] * \text{GDPcap} - 6.5[\pm 7.1] * \text{forestshare} + \varepsilon_i$$

Where CCSshare stands for CO_2 uptake from CCS as share of net total GHG emissions in 2050, Afforestation refers to CO_2 uptake from afforestation and reforestation in 2050, transport share is the share of transportation emissions in total CO_2 emissions in 2015, nonCO_2share is the share of non-CO_2 emissions in total GHG emissions in 2015, GDPcap is the gross domestic product (GDP) per capita in 2015, and forestshare is the share of forests in total land cover in 2015. A more parsimonious (simpler) model would contain only the variables with p-value smaller than 0.05, i.e. without forestshare. That model has slightly lower explanatory power, but the benefit is having further reduced the number of explanatory variables. The formula for the final model then becomes:

$$(2)\ y_i = 2079[\pm 7.0] - 18.7[\pm 7.6] * \text{CCSshare} - 16.3[\pm 9.4] * \text{Afforestation} - 20.1[\pm 13.9] * \text{transportshare} + 15.5[\pm 12.2] * \text{nonCO2share} + 17.6[\pm 17.0] * \text{GDPcap} + \varepsilon_i$$

The signs can be explained as follows: the larger the CCS capacity and afforestation, the more potential for negative emissions contributing to faster reductions and an earlier phase-out year. The higher the current share of non-CO_2 emissions, the more difficult to decarbonize so the later the phase-out. In addition, the higher the GDP per capita, the stronger the growth in emissions; thus, ceteris paribus, the later the phase-out. A higher GDP per capita could also imply greater capacity or willingness to mitigate emissions, but we only look at the default, cost-optimal case here, excluding equity considerations. The share of transport emissions showing a negative correlation is less straightforward. It seems to imply that this sector is relatively easy to decarbonize, which may hold for passenger transport, but not for freight and also not for international aviation. However, countries with a relatively large share of transport emissions often also have a relatively high GDP and smaller baseline emissions growth. A large transport share could also imply slower growth of this sector and smaller shares of other, more difficult to decarbonize sectors. All of these factors would contribute to earlier phase-out.

4.2.4 Breakdown of emissions in the phase-out year

It may also be possible to understand differences in phase-out years by looking at the different sources and sinks of emissions when net zero is achieved. Net zero means remaining emissions can be compensated by negative emissions elsewhere or in another sector. Figure 4.4 shows the emissions by GHG in the phase-out year. Results highlight that especially methane and N_2O are hard to abate in most countries. In some models, also F-gases are a big source of remaining emissions in China and Japan, and to a smaller extent the United States. In developed and middle-income countries, the building sector forms a large share of the remaining CO_2 emissions (this applies to the EU, China, Japan, the United States and, to some extent, to Russia). This is also true for the industry sector, although here some exceptions can be noted. The transport sector contributes to the remaining CO_2 emissions in all countries studied here, except in Russia. In all countries except in Brazil, the energy supply sector is the largest contributor to negative CO_2 emissions (through BECCS). Brazil, in contrast, is projected to realize most negative emissions through afforestation (see also Doelman et al., 2019). Negative emissions through afforestation play a role in many other countries, but not so much in Japan, Canada and Russia. The POLES model projects more negative emissions from afforestation than IMAGE, contributing to its generally earlier phase-out, because it uses the inventory data. Some models project negative emissions in the industry sector in Brazil, Russia, Canada and, to a smaller extent, in the EU. Table S4.4.1 shows the total negative emissions in 2100, which range from 188 Mt CO_2 in Turkey to 2951 Mt CO_2 in the USA, amounting to 22.4 Gt CO_2 globally under the 1.5 °C scenario.

It should be noted that Brazil presents an exception for many indicators, as it has a relatively large share of non-CO_2 emissions but an early phase-out. This can be explained by the breakdown of emissions in the phase-out year, which shows that a large potential for negative emissions can compensate for those remaining emissions. Other countries with an early phase-out (USA) generally also have a relatively large potential for negative emissions. Countries with a late phase-out (India and, to some extent, China and the EU) have relatively large remaining emissions of both CO_2 and non-CO_2 GHGs.

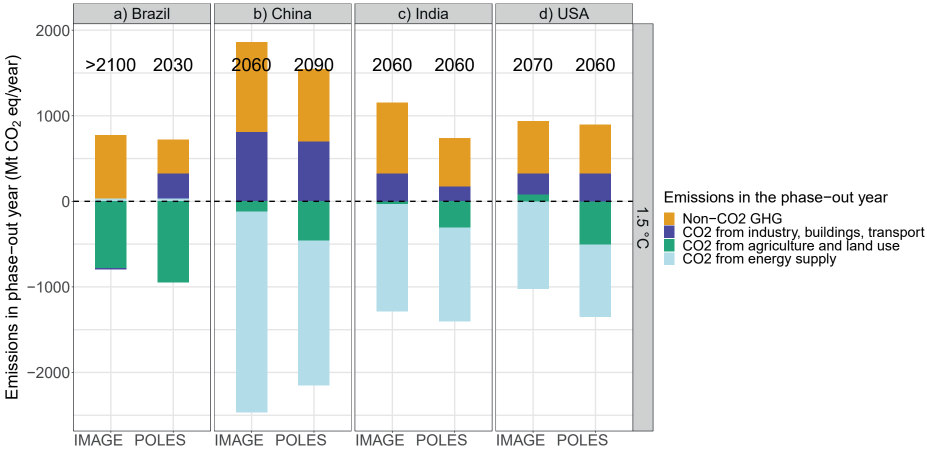

Figure 4.4: Breakdown of emissions in the phase-out year of total greenhouse gas emissions. Emissions in the phase-out year of GHG (year indicated per model—focusing on the same two models as in the previous section, for readability), by greenhouse gas (colours) and country (panels), focusing on a country with an average phase-out year (b China), a country with a late phase-out (c India), and two with an early projected phase-out of GHG emissions (a Brazil and d USA). Positive numbers denote remaining emissions of CH_4, N_2O and F-gases (non-CO_2 GHG), and of CO_2 in industry, buildings and transport, whereas negative numbers denote negative emissions in energy supply and in Agriculture, Forestry and Other Land Use (IPCC Category 3). CO_2 from energy supply includes CO_2 emissions from fuel combustion and fugitive emissions from fuels: electricity and heat production and distribution (IPCC category 1A1a), other energy conversion (e.g., refineries, synfuel production, solid fuel processing, IPCC category 1Ab, 1Ac), including pipeline transportation (IPCC category 1A3ei), fugitive emissions from fuels (IPCC category 1B) and emissions from carbon dioxide transport and storage (IPCC category 1C). Negative emissions in this sector result from the use of (BE)CCS.

4.3 Discussion

We analysed when major emitting countries are projected to reach CO_2 and GHG emissions neutrality using 1.5 °C and 2 °C scenarios from IAMs. We also looked into the question how this depends on definitions and the reasons behind differences between countries.

In cost-optimal scenarios, Brazil, the United States (CO_2 and all GHGs) and Japan (GHG only) are projected to have an earlier phase-out year than the global average. In contrast, India and Indonesia typically have a late phase-out year. For China, the EU and Russia, the phase-out year is typically near the global average. For several countries, the position vs. the global average is different for CO_2 and all GHGs, and the specific climate target. The model spread is fairly large for Brazil and India, and to a smaller extent China, making these results less certain, and is smaller for the United States and the EU.

Definition factors (such as harmonization of data in the base year and the allocation of negative emissions) play a role in the phase-out year and this works out differently for different countries. These findings highlight the importance of clear definitions and political agreement on issues such as the use of land-use data and allocation of negative emissions. When harmonizing the model projections towards the countries' reported net land-use emissions estimates in their GHG inventories, net-zero GHG emissions are projected to be reached earlier in all countries, except Brazil. The difference between inventory data and the model output for net land-use emissions is caused by a systematic difference in definition of anthropogenic land sources and sinks. As a result, inventory data are lower in all countries, except Brazil. The differences between these data sources are relatively large for China, India and the United States. When allocating negative emissions from biomass with CCS (BECCS) to the biomass-producing country instead of the carbon-storing country, phase-out years are earlier in Brazil, Indonesia, Canada, India and Russia (biomass producers, with a large model range for Brazil and India), but later in the EU, Japan and Turkey (importers). Updating GWPs from IPCC AR4 to IPCC AR5 values does not significantly affect phase-out years. Applying equity approaches rather than a cost-optimal allocation of mitigation effort would imply earlier phase-out years for many of the countries studied here, but later phase-out years for Brazil and other countries with lower per-capita emissions or developing economies (e.g., Indonesia, although with larger uncertainty).

The multiple linear regression showed that factors affecting negative emissions (e.g., afforestation and CCS) explain the lion's share of the variance in phase-out years. Mitigation potential and especially the potential for negative emissions are dominant factors, determining when a country can reach net-zero emissions. Future CCS and afforestation capacity, as well as the current shares of transport emissions, non-CO_2 emissions and GDP per capita, have the strongest relationship with phase-out years (negative for the former three, positive for the latter two). In addition to showing a relatively large potential for negative emissions, countries with a projected early phase-out (Brazil and the United States) generally have relatively low emission levels of CO_2 from the energy demand sectors, a relatively high GDP per capita, low baseline growth, a low current share of non-CO_2 emissions (except Brazil) and low population density.

That potential for negative emissions is high enough in Brazil to compensate for its relatively high levels of non-CO_2 emissions, explaining the early phase-out. Countries with late phase-out (India and Indonesia, and to a smaller extent also China and the

EU) show the reverse pattern and have relatively large remaining emissions of both CO_2 and non-CO_2 GHGs.

It should be noted that, so far, we focused on the outcomes of cost-optimal scenarios (using an equal marginal GHG price across all countries). In reality, national targets might also be based on equity principles (Robiou du Pont et al., 2017; van den Berg et al., 2020) (in line with the Paris Agreement's common but differentiated responsibilities and respective capabilities). Therefore, Figure 4.2d compares the results to those based on equity principles (Robiou du Pont et al., 2017). This has an impact on phase-out years. There are different ways to account for equity principles in international climate policy. Countries may choose to set different (in case of higher income countries more ambitious) domestic target years. Alternatively, it is also possible to use flexible instruments (emission trading, investments in other countries). The IAM results indicate mitigation measures that countries should implement domestically under a globally cost-optimal distribution. These results do not answer the question of how these measures are funded and how much effort or finance each country is providing. Equity frameworks can distribute the emissions of IAMs (Holz et al., 2018; Pan et al., 2017; Robiou du Pont et al., 2017). As such, this could still lead to the outcomes as described in this study. It does mean, however, that policy-makers should not simply use the phase-out years presented here to set national targets. This study can be seen as a first step to inform such target setting, but national models or other tools will need to be applied, to fully incorporate relevant domestic circumstances. That will need to include the country's perspective of a national contribution to the global mitigation effort, also reflecting equity considerations, as well as account for the outcome of negotiations on Article 6 and international transfer of mitigation outcomes (ITMOs). As such, a country could implement an equitable emission target based on a combination of domestic targets (informed by IAMs and national models) and ITMOs. The Convention of the UNFCCC (1992) already states that climate policies should be cost-effective and equity considerations can be dealt with through, e.g., trading and financial support (Rogelj, 2019). Further, the Paris Agreement recognizes that countries could make use of ITMOs. The national target setting can further be informed by studies on co-benefits such as Markandya et al. (2018), which suggest a significant share of mitigation costs could be covered by accounting for air quality and other co-benefits, making additional domestic mitigation more attractive.

Another critical point is that the scenarios were created in the period 2016–2018. This implies that cost-optimal policies were assumed to be implemented from 2020 onwards. This means that in some countries (e.g., Brazil) the political reality is not likely to lead to the pathways as described in the models. On the other hand, many other countries have now adopted or announced net-zero emission targets. China's announced 2060 carbon neutrality goal, the EU's 2050 net-zero GHG goal, Japan's announced 2050 net-zero GHG goal and the USA's tentative 2050 net-zero GHG emissions goal (suggested in the Biden–Harris climate plan; Biden, 2020) are all in line with the models' domestic cost-optimal mitigation pathways for 2 °C and 1.5 °C, and in some cases are even more ambitious (e.g., rely less on negative emissions). Although several countries have announced net-zero emission goals, it should be noted that the (aggregated) impact of the NDCs seems insufficient to be on a pathway to meet these (Roelfsema et al., 2020). Canada's foreseen 2050 net-zero emissions goal does not specify whether it would apply to all GHG or CO_2 only, but both would need to be phased out slightly earlier than 2050 to be in line with the models' cost-optimal 1.5 °C scenarios (for 2 °C, 2050 net-zero emissions would suffice according to these models). Either way, the specification of target coverage is important. Our findings show that to meet these targets, countries should pay special attention to enhancing the capacity to realize negative emissions, clearly specify the land-use emissions accounting and related data (especially important for Canada and the USA), agree on the accounting of negative emissions from BECCS (important for Brazil and Japan) and clarify their approach to equity and the use of ITMOs (all countries).

Future work could analyse a few other factors that affect national differences in phase-out years but that we did not consider here: metrics other than GWPs (Fuglestvedt et al., 2018; Tanaka & O'Neill, 2018) and consumption-based vs. production-based emissions accounting (Karakaya et al., 2019). It could further analyse more scenarios from more, different types of models (national, sectoral and macro-economic) for more countries. With such an enlarged dataset, a PCA would be more useful. Alternatively, one could dive into the results of one model and tease out underlying dynamics. A comparison of scenario results with countries' submitted long-term strategies would further be useful: on the one hand, to identify additional mitigation potential for these strategies and, on the other hand, to make the scenarios better reflect political realities. That is also where social sciences could add value to this work: guide the social acceptance and practical implementation of net-zero targets, with an understanding of relevant actors and their motivations. Ongoing work on political feasibility of mitigation scenarios (Jewell & Cherp, 2020), e.g., could shed light on governments' capacity to implement net-zero targets.

Our results can inform the national target setting, as they present an advancement in knowledge on national-level results from IAM scenarios, as often used in IPCC assessments. The results notably address the Talanoa Dialogue questions of Where do we want to go? and How do we get there? They can also inform international negotiations related to Article 6 and methodological choices, such as LUC data and accounting for negative emissions from BECCS. Furthermore, non-state actors can help their governments define realistic and potentially more ambitious targets.

4.4 Methods

4.4.1 Overall method

We used a set of scenarios from six IAMs to analyse the projected phase-out years for different countries. Subsequently, we applied a number of methods to determine which factors explain differences in phase-out years between countries. First, we made a selection of 15 variables that potentially explain why some countries see earlier phase-out and others later. Second, we tested for redundancy using PCA (see S4.2 Supplementary Methods and Results: Multiple linear regression and Principal Component Analysis) and visually inspected the data. Third, multiple linear regression was applied to select those variables with the strongest relation to phase-out year. This was required because of the limited number of records in the dataset: ten countries, two scenarios and six models with varying country coverage. This selection of variables best explaining phase-out year differences was constructed by trying out all 3003 possible combinations of 4, 5, 6 and 7 of the 15 variables in multiple linear regression, selecting those combinations resulting in the highest R^2 (degree to which the data are explained by the model). We ended up with six variables, because it improved the R^2 (as well as adjusted the R^2 that penalizes having more explanatory variables) with respect to four and five variables, whereas selecting seven did not result in significant improvements (see Table S4.2.4). In the multiple linear regression, we used standardized variables given their different units. We only used the projections by the POLES and IMAGE models for the multiple linear regression, because these are the only two models that cover all ten countries. Therefore, that data subset had an equal number of records for each country (i.e., four: two scenarios for each model), while still representing more than one model for robustness.

4.4.2 Scenario data

The analysis presented here uses the scenario projections of the six models from a multi-model study (CD-LINKS project, 2018; McCollum et al., 2018) using the same protocol for reaching a cost-optimal pathway to adhere to global carbon budgets of 1000 and 400 Gt CO_2 for the 2011–2100 period, allowing temporal overshoot. The two budgets represent limiting global warming to below 2 °C during the twenty-first century and below 1.5 °C in 2100 with more than 66% probability. In the scenarios, cost-optimal mitigation was assumed to start in 2020 (i.e., emission reductions where and when they are cheapest to achieve). Up to 2020, it was assumed that only existing policies were implemented (historical data up to 2020 was not yet available when these scenarios were developed between 2016 and 2018). Non-CO_2 emissions were taxed with the same carbon price as that of CO_2 in the cost-optimal scenarios.

The regional coverage of the models differs (see Table S4.3.1 in S4.3 Supplementary Methods: Overview of models per country). For some countries, therefore, the results are based on a lower number of models (with obvious consequences for certainty of the results, we indicated the number of models per country). In some cases, the existing model output was made more comparable with the country definitions used in this study (see Table S4.3.1). Results are shown for ten selected major emitting economies, i.e., Brazil (covered by three out of six models), Canada (three), China (six), EU (six; it is noteworthy that all projections for the EU in this study include the United Kingdom), India (six), Indonesia (three), Japan (four), Russia (three), Turkey (three), and USA (six), representing two-thirds of the global GHG emissions including land-use change and international transport emissions in 2018 (FAOSTAT, 2019; Olivier et al., 2016).

Emission pathways for the ten countries were linearly extrapolated to 2200 based on the 2050–2100 trajectory, to estimate the phase-out years beyond 2100 where needed. We used the CO_2-equivalent emissions based on GWPs from IPCC AR4 (time horizon of 100 years) as default and show the effect of using those from AR5. The text of the Paris Agreement leaves the choice of metric open and refers to the common metrics assessed by the IPCC.

For the equity-sensitivity analysis in Figure 4.2d, we used phase-out years directly from Robiou du Pont et al. (2017). They based their equity calculations on 2 °C and 1.5 °C scenarios from the IPCC AR5 database and on PRIMAP data for historical and projected population, GDP and GHG emissions to model country allocations under different equity approaches. The parameterization of the equity approaches follows Robiou du Pont et al. (2016).

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Author contributions

H.v.S. coordinated the analysis, wrote the paper and created the figures. M.d.E. and D.v.V. contributed to the analysis and article review

5

Global roll-out of comprehensive policy measures may aid in bridging emissions gap

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Abstract

Closing the emissions gap between Nationally Determined Contributions (NDCs) and the global emissions levels needed to achieve the Paris Agreement's climate goals will require a comprehensive package of policy measures. National and sectoral policies can help fill the gap, but success stories in one country cannot be automatically replicated in other countries. They need to be adapted to the local context. Here, we develop a new Bridge scenario based on nationally relevant, short-term measures informed by interactions with country experts. These good practice policies are rolled out globally between now and 2030 and combined with carbon pricing thereafter. We implement this scenario with an ensemble of global integrated assessment models. We show that the Bridge scenario closes two-thirds of the emissions gap between NDC and 2 °C scenarios by 2030 and enables a pathway in line with the 2 °C goal when combined with the necessary long-term changes, i.e. more comprehensive pricing measures after 2030. The Bridge scenario leads to a scale-up of renewable energy (reaching 52%-88% of global electricity supply by 2050), electrification of end-uses, efficiency improvements in energy demand sectors, and enhanced afforestation and reforestation. Our analysis suggests that early action via good-practice policies is less costly than a delay in global climate cooperation.

Keywords
Paris Agreement, emissions gap, Bridge scenario, good practice policies, climate policy, Integrated Assessment Models

5.1 Introduction

In the Paris Agreement, countries agreed to limit global warming to well below 2 °C, and preferably 1.5 °C (UNFCCC, 2015c). For implementation, the Paris Agreement relies on mitigation action at the national level. These actions are communicated via nationally determined contributions (NDCs) and long-term strategies, containing each country's pledged contribution to global mitigation. A key question is whether the collective action of all countries leads to the implementation of the Paris Agreement's climate goals (Rogelj et al., 2016; Vrontisi et al., 2018). For this, countries agreed on a global stocktake process to periodically review collective progress and, if needed, stimulate additional efforts to meet the Paris Agreement's global climate mitigation goals.

Several publications have already shown that the aggregated impact of NDCs is insufficient (Fujimori et al., 2016; Roelfsema et al., 2020). In addition, global emissions implied by nationally implemented policies are, collectively, even exceeding the global emissions levels projected under current NDCs (Roelfsema et al., 2020). This means that current NDCs and policies need to be strengthened. Scenarios from global integrated assessment models (IAMs) can provide guidance on how to do this. These include scenarios that provide information on how to implement reductions cost-optimally. However, in reality, it is not always possible to implement the measures included in these cost-optimal pathways (Staub-Kaminski et al., 2014). For instance, influential societal actors might be able to block certain measures if they go against their interests. Market distortions can also make certain measures unattractive. Other solutions might lack societal support (e.g. carbon capture and storage), and also the rate at which a transition can be implemented may be slowed down (e.g. in the case of closing coal mines given the impact on coal miners and coal-dependent regions and communities). At the same time, however, there is also evidence of effective implementation of climate policies (Fekete et al., 2021). Here, good practice policies are defined as successfully implemented policies in one or more countries with a noticeable impact on greenhouse gas (GHG) emissions. In some cases, these policies are not even part of the cost-optimal mix suggested by models but could be easier to implement. It has been suggested that scaling up these good practice policies to other parts of the world might in the short-term be a more feasible and convincing strategy (Baptista et al., 2021; Bertram et al., 2015; Fekete et al., 2015; Höhne et al., 2019; Kriegler et al., 2018; Roelfsema et al., 2018).

First of all, history has shown that costs are only one factor influencing policy choices (see, e.g. Trutnevyte (2016), and the example of investments in renewable energy in the period that costs were still high). Other factors that influence policy choices include societal support, the influence of specific actors, and possible (perceived) co-benefits and trade-offs, including impacts on competitiveness. Secondly, such good practice policies have already been implemented in some countries, showing their effectiveness, at least in some places. Thirdly, earlier work (Zhang et al., 2019) suggests that strengthening administrative and firm capabilities involved with monitoring, reporting and verification of emissions to support trading systems requires time and effort. Literature on policy sequencing (Meckling et al., 2017; Pahle et al., 2018) shows how policies go through stages and at some point gain enough traction, experience, and political momentum to eventually move to efficient carbon pricing.

Fekete et al. (2021), Roelfsema et al. (2018) and Kriegler et al. (2018) investigated the impact of replicating such good practice policies in other parts of the world by focusing on global GHG emissions and indicators related to implementability (such as maximum annual average emissions reduction rate, carbon price increase per decade or cumulative CCS deployment). Although helpful as a first step, this earlier work is limited by 1) the formulation of good practice policies at the global scale and 2) being based on a limited number of models. Better information on such good practice policies is needed to support the UNFCCC global stocktake in 2023.

Here, we build on the earlier work (Fekete et al., 2021; Kriegler et al., 2018; Roelfsema et al., 2018), also going beyond relatively abstract cost-optimal pathways as guidance for policy-making by focusing on concrete policy measures that can be implemented to close the emissions gap. We do this for the first time using multiple models (both global and national) to assess a common set of reduction measures. These measures have been defined in consultation with national experts, making the scenarios more relevant (see Methods for details). The key scenario is referred to as the *Bridge* scenario, as it aims to bridge the gap between the ambition levels set out by countries by 2030 and those consistent with limiting global warming to 2 °C. This scenario includes a set of well-defined measures that can be implemented in the 2020-2030 period and go beyond the ambition of the NDCs (good practice policies), and that would still allow reaching the Paris climate goals by transitioning to a cost-optimal path towards 2 °C after 2030 (see Methods), assuming that governments prepare the ground for comprehensive (pricing) measures that are socially acceptable, e.g. through the use of revenues (Klenert et al., 2018). A focus on successfully implemented policies, as done in the *Bridge* scenario, will likely have near-term advantages in terms of political feasibility compared to an approach that focuses solely on cost-effectiveness (see above). The *Bridge* scenario, for example, allows to follow the steps identified in work on policy sequencing and thus move more smoothly than scenarios focusing on cost-effectiveness. The sequencing of policies can be attractive for other reasons as well. This allows, for instance, a gradual phase-in of climate policy per sector, e.g. to give households time to adjust. This concern applies particularly to investments related to residential energy use, where the lifetime of infrastructure typically extends beyond a few years. Additionally, the policy package that we apply is regionally differentiated, with higher-income countries taking more significant action in the 2020s. This can address some of the feasibility concerns observed in cost-optimal scenarios, allocating mitigation efforts to low-income countries in the near term (given the high potential for low-cost options, but with considerable feasibility concerns). We show that the *Bridge* scenario closes two-thirds of the emissions gap between NDC and 2 °C scenarios by 2030 and enables a pathway in line with the 2 °C goal when combined with more comprehensive pricing measures after 2030. Our analysis suggests that early action via these good-practice policies is less costly than a delay in global climate cooperation.

5.2 Results

In order to discuss the possible impacts of the *Bridge* scenario, we compare it to four other scenarios, i.e. the impacts of current policies (*CurPol*), the conditional NDCs (*NDCplus*), and the models' cost-optimal pathways towards 2 °C (starting immediately: *2Deg2020,* and with a delay: *2Deg2030*) (see Methods and Supplementary Information, S5, for more details). For the first two scenarios, the current policies and NDCs were extended beyond 2030 by assuming equivalent effort, i.e. by extrapolating the equivalent carbon price in 2030, using the GDP growth rate of the different regions up to 2050 for the extrapolation (see S5.3 Supplementary Methods: COMMIT WP2&3 Scenarios for ratcheting up mitigation ambition). For the *Bridge* scenario, the defined set of measures was implemented up to 2030 (Table 5.1) and a cost-optimal path towards 2 °C was implemented after 2030 (see S5.3 Supplementary Methods: COMMIT WP2&3 Scenarios for ratcheting up mitigation ambition). A full description of the scenarios and additional results can be found in the Supplementary Information (S5). In the context of the global stocktake, here we focus on the results at the global level and several large countries, while more detailed national-level results by national models can be found elsewhere (Baptista et al., 2021).

Table 5.1: The good practice policies that were assumed to be replicated globally in the Bridge scenario, with differentiated targets for high-income and low-/medium-income countries, adapted from earlier analysis of good practice policies (Fekete et al., 2021; Kriegler et al., 2018; Roelfsema et al., 2018).

Sector	Measure	High-income countries	Low-/medium-income countries	Other (differs per measure)
AFOLU (Agriculture, Forestry and Other Land Use)	Treat manure from livestock with anaerobic digesters – Reduction of CH_4 emissions from manure, relative to 2015	33% by 2030	15% by 2030	
	Increase nitrogen use efficiency – Reduction of N_2O emissions from fertilizer, relative to 2015	10% by 2030	5% by 2030	
	Selective breeding to reduce CH_4 emissions from enteric fermentation – Emission factor reduction (CH_4/tonne milk and/or beef) or emissions reduction, relative to 2015	10% by 2030	0% by 2030	
	Increase natural forest afforestation and reforestation – rates for three tiers (different than high- and low-income): % increase in forest area per year, for 2015-2030	Tier 1 (China, Latin America): 2%/year	Tier 2 (South & South East Asia, Sub-Saharan Africa, Australia): 1%/year	Tier 3 (Europe, Turkey, 23% of Russia, USA): 0.5% /year
	Halt natural forest deforestation	0 ha/year by 2030	0 ha/year by 2030	

Table 5.1: *Continued.*

Sector	Measure	High-income countries	Low-/medium-income countries	Other (differs per measure)
Energy supply	No new installations of unabated coal power plants	By 2025	By 2030	
	Increase of the share of renewables in total electricity generation per year (starting in 2020, until 2050 and up to 50%, maximum)	1.4 %-point increase per year	1.4 %-point increase per year	
	Coal mine CH_4 emissions recovery	30% by 2030	30% by 2030	
	Reduce venting and flaring of CH_4 and CO_2 – emission reduction, relative to 2015	36% by 2030	36% by 2030	
Buildings	Improve final energy efficiency of appliances compared to 2015 (autonomous improvement as well as due to policy)	17% by 2030 (starting in 2018)	7% by 2030 (starting in 2025)	
	Improve final energy intensity of new residential and commercial buildings	22 & 30 kWh/(m^2.yr) by 2025	22 & 30 kWh/(m^2.yr) by 2035	EU: 35 & 40 kWh/(m^2.yr) by 2025
	No new installations of oil boiler capacity in new and existing residential and commercial buildings	By 2030	By 2040	EU: by 2020
	Improve efficiency of existing buildings – Share of existing buildings being renovated	11% by 2030	6% by 2030	

Table 5.1: *Continued.*

Sector	Measure	High-income countries	Low-/medium-income countries	Other (differs per measure)
Industry	Apply CCS - Carbon captured and stored as share of industry's total CO_2 emissions (model-dependent)	1.5% by 2030	1.5% by 2040	
	Improve final energy efficiency, relative to 2015	11% by 2030	6% by 2030	
	Reduce N_2O emissions from adipic acid production – reduction, relative to 2015	99% by 2030	99% by 2030	
Transport	Improve energy efficiency of aviation, starting in 2018	0.78% per year by 2030	0.78% per year by 2030	
	Improve average fuel efficiency of new passenger cars	38 km/l by 2030	27 km/l by 2030	
	Increase the share of non-fossil in new vehicle sales	50% by 2030	25% by 2030	China: 25% by 2025
Waste	Reduce CH_4 emissions, relative to 2015	55% by 2030	28% by 2030	
Economy-wide	Carbon pricing – pathways for three tiers (different than high- and low-income)	Tier 1 (OECD, EU): 40 USD/tCO_2 by 2030	Tier 2 (Russia, Eastern Europe, China, Korea, Latin America): 25 USD/tCO_2 by 2030	Tier 3 (all others): 10 USD/tCO_2 by 2030
	Reduce F-gas emissions, induced by policies, relative to 2015	60% by 2030	38% by 2030	

5.2.1 A bridge over the emissions gap

The model outcomes (Figure 5.1, Figure S5.2.8 and Figure S5.2.9) show that the *CurPol* and *NDCplus* scenarios both fall considerably short of the emission reductions needed to limit global warming to 2 °C (consistent with earlier work). In contrast, the good practice policies included in the *Bridge* scenario can reduce GHG emissions close to the needed levels in 2030, followed by a longer-term trajectory similar to the ambitious benchmark of *2Deg2020.* The *Bridge* scenario has a less steep reduction than the *2Deg2030* scenario in the 2030s, offering a pathway that largely closes the 2030 emissions gap without adding substantial challenges in the 2030s and 2050s. The emissions gap is defined as the difference between the *NDCplus* scenario and the *2Deg2020* scenario (median: 11.8 $GtCO_2eq$). The *Bridge* scenario closes that global emissions gap by 7.2 $GtCO_2eq$ or 60% (median, range 26%–275%) by 2030 and compensates the slower start by a slightly deeper emission reduction in 2050, 106% (92%–112%). Some recently submitted NDCs could not be considered as they came after the cut-off date of this work. Based on the Synthesis report by the UNFCCC (UNFCCC Secretariat, 2021), global emissions levels under the NDCs would be 398 Mt CO_2eq lower in 2030 when taking these into account (i.e. 3.4% of the median emissions gap found here and 5.5% of the 2030 emissions reductions under the *Bridge* scenario). Compared to a 1.5 °C scenario instead of *2Deg2020* (1.5 °C scenarios were not run here but included from the CD-LINKS project (Roelfsema et al., 2020) for comparison), the global emissions gap would be closed by 31% (21%-57%) by 2030 and by 81% (71%-85%) by 2050. The difference in 2030 emissions between *NDCplus* and *2Deg2020* is closed by 16% in the USA, 49% in India, 56% in the EU and 68% in China.

Figure S5.2.1 shows the national rates of GHG emissions reductions in the *Bridge* scenario, compared to the *CurPol*, *NDCplus,* and cost-optimal cases (immediate: *2Deg2020* and delay: *2Deg2030*). In contrast to the increase in GHG emissions under current policies in some countries, emissions decline everywhere in the *Bridge* scenario, especially in the 2030–2050 period. In most countries, the *Bridge* scenario shows smaller reductions than the immediate action *2Deg2020* scenario in the short term (2030), and smaller reductions than the *2Deg2030* scenario in the longer term (2050). As such, good practice policies can constitute an alternate pathway in line with limiting global warming to 2 °C, without relying on carbon pricing alone as in cost-optimal scenarios, while not significantly increasing the burden in the 2050s.

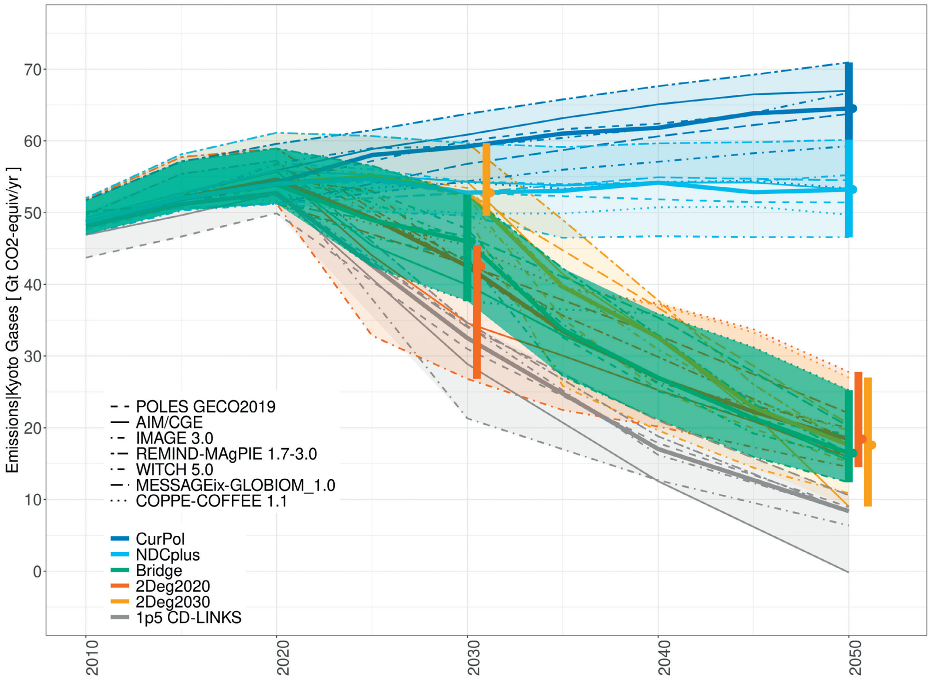

Figure 5.1: Global GHG emissions (Gt CO_2eq/year) between 2010 and 2050, as projected by the global models. Vertical bars: model range in 2050. Circles: model median in 2050. Thick solid lines: median. Grey: 1.5 °C scenarios from the IPCC SR1.5 database are included for comparison (a selection was made to cover the same models as represented here, with most similar scenario set-up, i.e. the 1.5 °C scenarios developed in the CD-LINKS project, Roelfsema et al., 2020). Projections for the Bridge scenario without the carbon tax measure are shown in Figure S5.2.7, for NDCplus variant NDC_2050convergence in Figure S5.2.8, and for 2050 – 2100 in Figure S5.2.9.

5.2.2 Which measures have the largest effect on emissions?

The emissions gap between the *NDCplus* and *2Deg2020* scenarios amounts to approximately 12 $GtCO_2$eq in 2030 (model median). The *Bridge* scenario closes this gap with 60% (a 7.2 $GtCO_2$eq reduction). The energy supply sector (through higher renewable energy share, electrification, energy efficiency improvement) is the largest contributor to emissions reductions between the *NDCplus* and *Bridge* scenarios, both in 2030 and in 2050 (Figure 5.2 and Table 5.2). In most models, mitigation of non-CO_2 emissions, the transport sector (zero-carbon vehicles and efficiency improvements), and AFOLU (notably in 2030) also play an important role. This indicates potential to enhance ambition in specific areas, which will need to be explored at the national level.

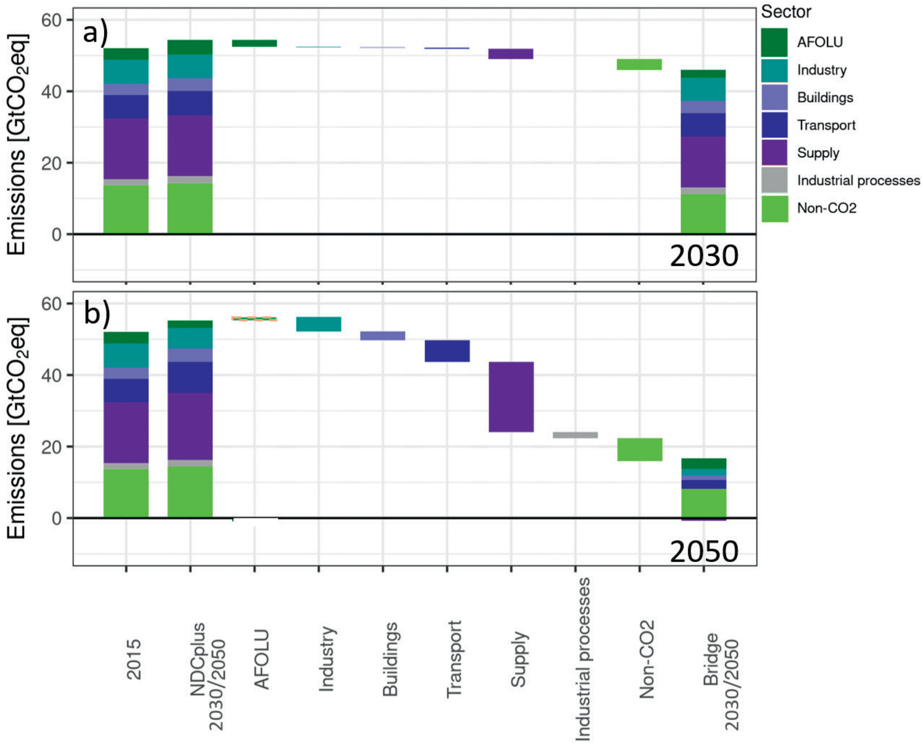

Figure 5.2: Contribution of each sector to emission reductions between the NDCplus and Bridge scenario (negative values denote an increase in emissions between NDCplus and Bridge, and are indicated with hashes). First bar: Emissions by sector in 2015. Second bar: emissions by sector in 2030 (panel a) and 2050 (panel b), under NDCplus. Third – ninth bar: emission reduction in AFOLU (Agriculture, Forestry and Other Land Use), industry, buildings, transport, energy supply, industrial processes, non-CO_2 emissions. Last bar: emissions by sector in 2030 (panel a) and 2050 (panel b), under Bridge. The IMAGE model is shown here as an illustrative example; full model ranges are shown in Table 5.2, while individual model results are shown in the SI (Figure S5.2.5). In addition, Figure S5.2.6 shows the sectoral contributions to emission reductions between the Bridge and 2Deg2020 scenarios in 2030.

Table 5.2: Share of sector in total GHG reduction from NDCplus to Bridge scenario (%), model range: minimum – maximum (median). AFOLU: Agriculture, Forestry and Other Land Use

Year	AFOLU	Industry	Buildings	Transport	Energy supply	Industrial Processes	Non-CO_2
2030	-28.7 – 21.6 (7.8)	-10.1 – 14.8 (6.6)	-4.6 – 5.6 (2.3)	1.0 – 21.7 (8.9)	26.0 – 82.9 (50.1)	-0.2 – 5.4 (0.5)	2.9 – 50.6 (36.3)
2050	-2.4 – 11.8 (7.3)	7.9 – 31.4 (13.9)	2.9 – 9.5 (6.5)	6.5 – 15.6 (13.1)	34.6 – 49.8 (41.9)	0.1 – 8.1 (4.0)	9.6 – 20.0 (16.4)

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5.2.3 Changes in energy and land-use systems

Figure 5.3 shows projected changes in energy and land-use systems under five scenarios: *CurPol, NDCplus, Bridge, 2Deg2020, and 2Deg2030*. The *Bridge* scenario significantly increases mitigation action compared to the *CurPol* and *NDCplus* scenarios. In fact, on several indicators, the prescribed policies (Table 5.1 and S5.1 Supplementary Tables: implementation of good practice policies per model) close the gap with the cost-optimal *2Deg2020* scenario almost completely. By 2050, the *Bridge* scenario is more ambitious than the *2Deg2020* scenario for many indicators, compensating for the delay with respect to the cost-optimal pathway. Figure 5.3 Panel a, for example, shows that the target to increase the renewable electricity share by 1.4% per year in the *Bridge* scenario leads to deployment far beyond the *CurPol* and *NDCplus* scenarios in 2050 (i.e. towards 70%, versus around 50%), but similar to *2Deg2020* (in line with previous research, Luderer et al., 2018) and lower than *2Deg2030*. In 2030, however, the *Bridge* scenario is similar to *2Deg2020*, so it does not increase the global trend in terms of installing renewables in the short term (it may do so regionally, however, see Baptista et al., 2021). As a result of the assumed penetration of non-fossil fuelled vehicles, the *Bridge* scenario shows a significant increase in the share of electricity in transport, even more so in *Bridge* than in *2Deg2020* (Panel b). This starts in 2030, but manifests especially in 2050. However, in some models, the target to increase non-fossil fuelled vehicles actually leads to an increase of biofuel powered engines (Figure S5.2.2) rather than electrification (explaining the relatively large range), but less so than the *2Deg2030* scenario in 2050. Following CCS, efficiency improvement, and F-gas emission reduction targets in industry, industrial emissions (expressed as CO_2 emissions from industrial processes as well as F-gases, panel c), are projected to decrease in *Bridge* slightly more so than in *2Deg2020* (by 2050). Because the measures in the buildings sector focus on energy efficiency improvements, the share of electricity in buildings (panel d) is not projected to change significantly in the 2030s, but *Bridge* makes up for that by 2050. Panel e shows that the afforestation policy leads to slightly more afforestation in 2030, followed by a large scale-up in 2050, but not as large as in *2Deg2030*. As such, CO_2 emissions from agriculture, forestry and other land-use (AFOLU) are projected to be reduced by 38% (model median) by 2030 and by 151% by 2050 in the *Bridge* scenario, relative to 2015 levels. Figure S5.2.3 shows the same indicators but for the *NDCplus-convergence* scenario instead of *NDCplus*: by 2050, the *convergence* scenario is closer to the *Bridge* scenario than *NDCplus* for most indicators. Figure S5.2.4, finally, shows the projected changes in the primary energy mix. *Bridge* sees lower total primary energy supply mainly due to the efficiency improvement and transport electrification measures, but not as low as *2Deg2020*, and a shift from fossil fuels to renewable energy sources, especially by 2050. As a result of the scale-up of renewable energy, electrification of energy demand, and efficiency improvements, CO_2 emissions from the energy sector are projected to decrease. The *Bridge* scenario has notable co-benefits: emissions of air pollutants such as black carbon, carbon monoxide, nitrogen oxides, organic carbon, sulphur, and volatile organic compounds are projected to decrease, compared to *NDCplus* (Figure S5.2.12).

5.2.4 Costs of building the bridge

While the good practice policies may have benefits in terms of social and political acceptability, earlier work (Kriegler et al., 2018) has highlighted that a set of regulatory measures may be more costly than a comprehensive carbon pricing scheme, leading to a non-cost-optimal transition across regions and sectors. A uniform price signal would ensure that mitigation happens first where costs are lowest, leading to the overall most efficient outcome, in absence of other market failures. Although unlikely to be achieved globally, this stylised assumption therefore remains a useful benchmark. Furthermore, climate action as represented in the *Bridge* scenario implies a more gradual path for emission reductions in the period 2020-2030 compared to the immediate implementation of the cost-optimal policy (*2Deg2020*). This delay can further raise costs of the *Bridge* scenario, depending on the evolution of technology costs. The salience of a carbon price, however, may also raise opposition especially from low-income households facing energy poverty and food-insecurity (Fujimori et al., 2019), carbon-intensive regions and vulnerable trade-exposed industries that may complicate or delay its implementation (Jenkins, 2014). Arguably, the good practice policies included in the *Bridge* scenario face lower feasibility barriers and could speed up climate action compared to a scenario in which only cost-optimal policy measures are pursued. A fair evaluation of the costs of the *Bridge* scenario therefore involves two comparisons: one with the immediate and cost-optimal climate policy (*2Deg2020*), and one with a delayed implementation of uniform carbon pricing, starting in 2030 (*2Deg2030*) which requires more disruptive action to meet the 2 °C target.

Our results (Figure 5.4) indicate that although the *Bridge* scenario raises policy costs (as expressed by GDP cost per tonne CO_2eq abated relative to the Current Policies scenario) in 2050 by more than 20% (1%–38%) compared to an immediate implementation of a cost-optimal 2 °C scenario with globally uniform carbon prices (*2Deg2020*), it has lower policy costs (Figure 5.4a) and carbon prices (Figure 5.4b and Figure S5.2.10) in the near term (2030). The *Bridge* scenario also outperforms a delayed 2 °C scenario (*2Deg2030*, see S5.3 Supplementary Methods: COMMIT WP2&3 Scenarios for ratcheting up mitigation ambition) with costs being more than 10% (-6%–33%) lower in 2050. As such, our analysis suggests that early but non-cost-optimal action is preferred over climate policy delay.

Interestingly, not all models in the ensemble agree on the size and sign of the trade-off between early and cost-optimal policy implementation. Multiple and counteracting effects are at play. Generally, good practice regulatory policies would raise costs particularly when the resulting energy system deviates strongly from the cost-optimal one. If the necessary changes are obvious, or when there are low-hanging fruits for

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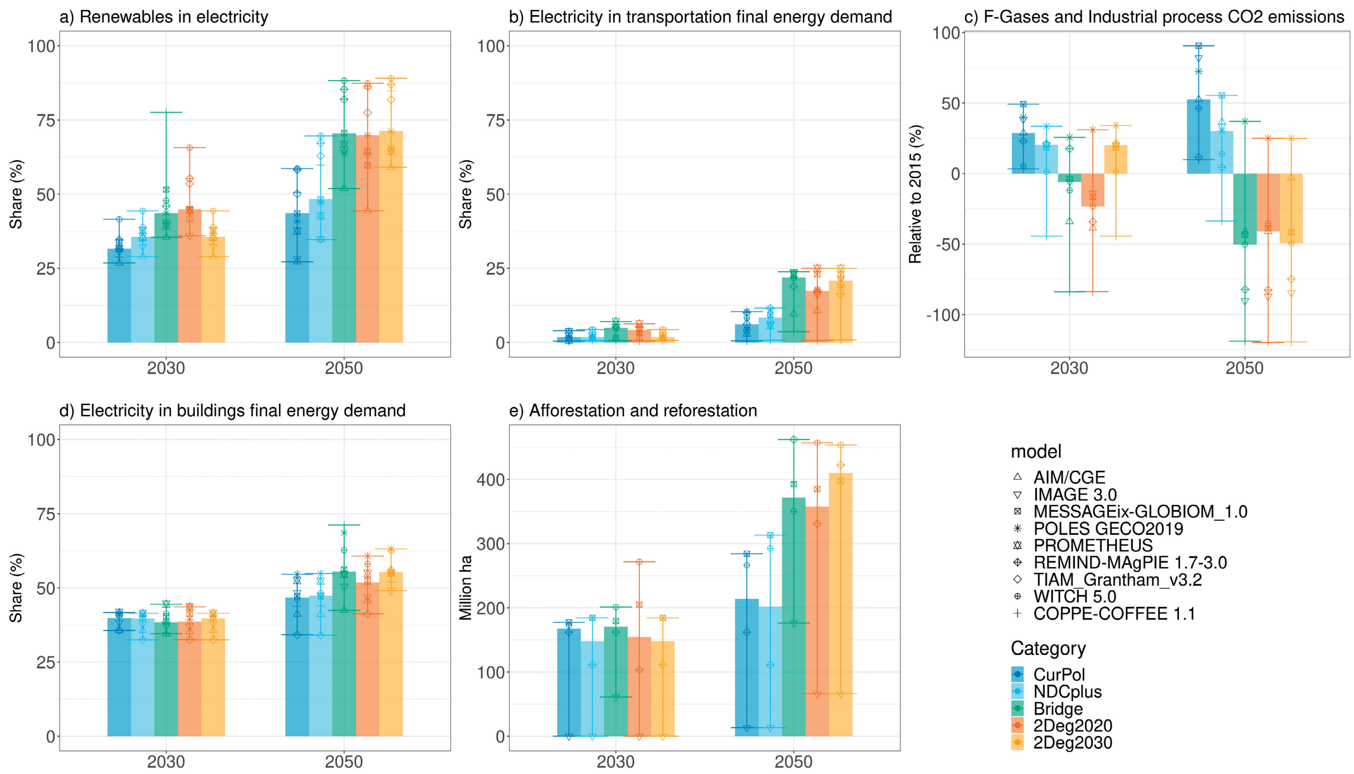

Figure 5.3: Projected changes in various indicators, for 2030 and 2050, for the CurPol, NDCplus, Bridge, 2Deg2020, and 2Deg2030 scenarios. Bars show model median, error bars show the full range, and symbols show individual model results. Panel a) share of renewables in electricity production (%), panel b) share of electricity in final energy demand of transportation (%), panel c) Emissions of F-gases and industrial process CO_2 emissions, relative to 2015 levels (%), panel d) share of electricity in final energy demand of buildings (%), panel e) total afforestation and reforestation (million ha).

climate policy, then a similar outcome may be achieved through regulation and carbon prices. The phase-out of coal and the scale-up of renewable power generation technologies (IEA, 2020a, 2020b; IRENA, 2020) may be an example that comes close (Figure S5.2.11 shows that investments in the electricity sector are projected to shift from fossil fuels to renewables). However, for other trade-offs, such as efficiency improvements versus fuel shift, or the allocation of emission reductions across sectors, a mix of regulatory measures that leads to an outcome resembling the cost-optimal one may be more difficult to achieve. Therefore, while regulatory policies can be a pragmatic entry-point for climate policy, cost-efficiency in the medium and long-term (beyond 2050) is more easily achieved via comprehensive carbon pricing schemes across all sectors and regions to avoid inter-sectoral and inter-regional leakage (Bertram et al., 2015). The costs of delaying climate action, on the other hand, depend on technological progress and the availability and scalability of negative emission technologies (NETs) in the future, among others (Daioglou et al., 2020). For three out of four models that capture economic growth endogenously, the costs of delay outweigh the additional cost of regulatory good practice policies in 2050.

An advantage of the regulatory measures as implemented in the *Bridge* scenario is that carbon prices remain at lower levels in the near term, which may facilitate public acceptability and implementation of carbon pricing schemes with a broad sector coverage. If political consensus in favour of a comprehensive pricing scheme is not found over time, then a further intensification of the good practice policies may serve as a practical way forward to close the emissions gap. At the same time, the advantages of good practice policies in terms of acceptability may be challenged if ambitious climate targets bring cost elements to the forefront of the political debate.

Hence, our results suggest that a global roll-out of good practice policies can be a useful approach to close the emissions gap in the near term, while their role in climate policy in the longer term should be reconsidered in the context of a broader policy mix (Pahle et al., 2018), including carbon pricing (Oshiro & Fujimori, 2020).

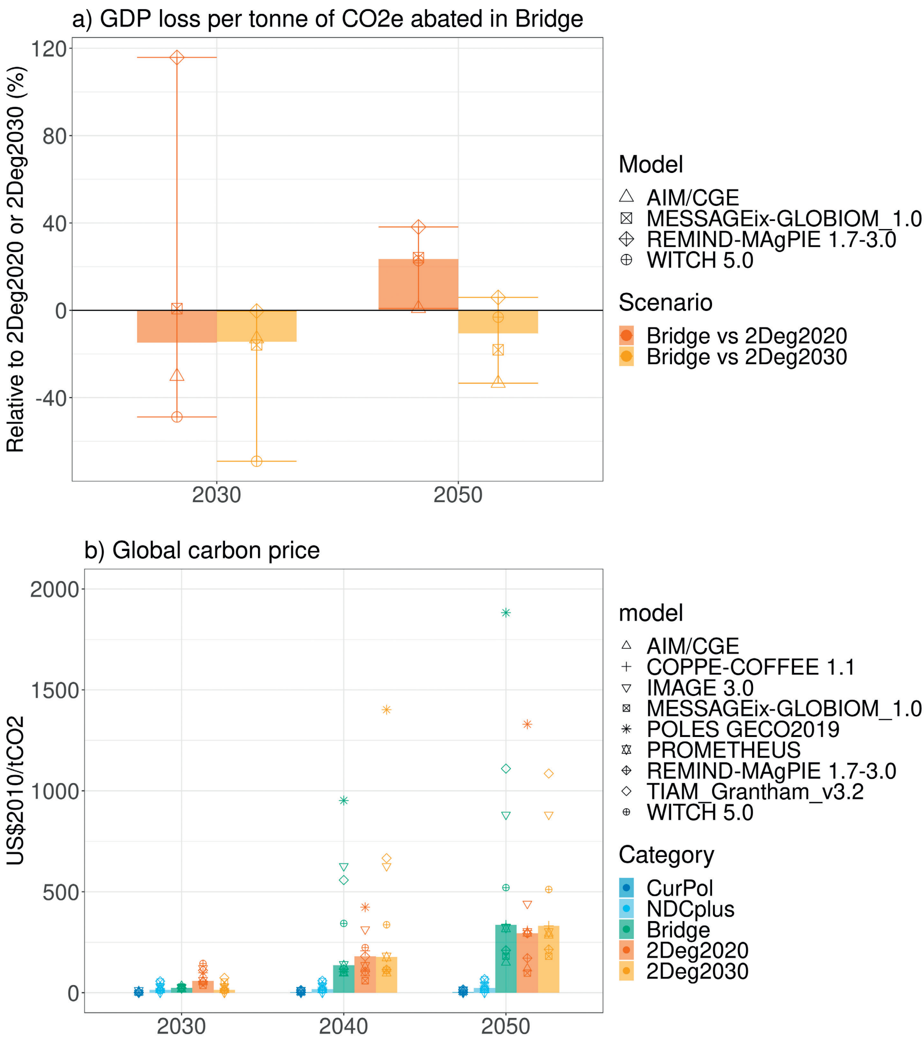

Figure 5.4: Cost indicators for the Bridge scenario, compared to the other scenarios. Panel a) GDP (in market exchange rates, MER) loss (relative to the CurPol scenario) in Bridge, relative to 2Deg2020 (dark orange) and 2Deg2030 (yellow), for 2030 (left) and 2050 (right). Panel b) Carbon price (US$2010/t$CO_2$), in 2030, 2040 and 2050. Bars: median, error bars: full range, symbols: individual models.

5.3 Discussion

Parties to the Paris Agreement were supposed to submit updated NDCs and communicate their long-term strategies to the UNFCCC in 2020. Due to the COVID-19 pandemic, these timelines have been delayed and some countries have announced that they will not submit an updated NDC, while some others have not increased ambition in their updated NDC. However, scaling up climate ambition and action remains necessary to keep the Paris Agreement goals within reach. As the emissions gap seems hard to close, we built a set of relevant scenarios that may provide a pathway based on successful examples of policies. The mitigation measures were defined in a two-way interaction with country experts and assumptions were adjusted for different regions if necessary. These scenarios, especially the good practice policies (*Bridge* scenario), can support the ratcheting up of mitigation ambition of NDCs.

Although the granularity of the *Bridge* scenario has improved in terms of country differentiation compared to earlier studies, some limitations remain. In most cases, we only distinguished high-income and low-/middle-income countries, which (while an advance on existing scenarios) is only a second-best option. However, we did not find good arguments for country-specific groupings in policy categories other than afforestation, where the groupings are motivated by explicit afforestation targets in the respective NDCs. Differentiating by income group is a pragmatic approach that was approved by stakeholders from various countries. While the measures were assessed to be implementable, this might not always be the case when moving to the country-level. Therefore, Baptista et al. (2021) discuss the same set of scenarios in the context of national feasibility considerations. Future work could further analyse the sustainable development implications of the *Bridge* scenario; for example, whether it has synergies with the goal to eradicate poverty. The other way around, a bridge scenario could be developed that takes the sustainable development goals as a starting point to identify nationally relevant areas for increased ambition in the 2030s.

Models implemented the set of measures in different ways. For example, not all models were able to implement all measures related to non-CO_2, given their scope; while others show relatively cheap abatement and high potential to implement measures in the 2030s, resulting in a large range for the sector's share in emission reductions. The ranges, however, do tell a robust story about the *Bridge* scenario in relation to the reference scenarios. Although set at a relatively low level, the carbon price measure was the single most effective policy in the 2030s. Removing it from the set of measures resulted in significantly higher emissions (Figure S5.2.7). However, as many countries or regions already have a form of carbon pricing, it deserves a spot in the selection of good practice policies, especially given the differentiated timelines and pricing levels assumed in the *Bridge* scenario. Finally, we have not considered the impact of the COVID-19 pandemic quantitatively, effectively assuming a full recovery without significant effect on long-term, global emissions (IEA, 2020b). The policy measures explored here, however, can inform governments that aim for green recovery packages (Andrijevic et al., 2020), by showing potential for ratcheting up mitigation ambition with a concrete set of measures.

We have shown that good practice policies can help to reach the 2 °C target in the long-term. They ensure closing the global emissions gap between NDCs and a cost-optimal 2 °C scenario by two-thirds (model median) by 2030. After 2030, more ambitious measures are needed. Such a *Bridge* scenario leads to lower energy sector emissions due to scale-up of renewable energy, electrification of energy demand, and efficiency improvements, and to lower land-use emissions due to afforestation—at levels and rates of change that are somewhat less than the *2Deg2020* case and less than the *2Deg2030* case. The scenario is still in a position that allows meeting the 2 °C goal, and, importantly, is less disruptive than *2Deg2030*. However, although we included a wide set of good practice policies, they are jointly insufficient to put the world on track to meet the 1.5 °C target. The *Bridge* scenario further illustrates that good practice policies alone—without implementation of additional instruments such as a comprehensive carbon pricing scheme—are not enough to reach the 2 °C target. The *Bridge* scenario raises policy costs (as expressed by GDP loss per tonne of CO_2 abated relative to the *CurPol* scenario) in 2050 by approximately 20% compared to a cost-optimal 2 °C scenario (*2Deg2020*). When put in perspective of economic growth in the coming three decades, this 20% cost increase implies that annual economic growth rates in the *Bridge* would be around 0.02 percentage points below the annual GDP growth in *2Deg2020*. The *Bridge* scenario outperforms the delayed 2 °C scenario (*2Deg2030*) with global economic impacts being more than 10% lower in 2050. As such, early but non-cost-optimal action is preferred over climate policy delay. In the absence of immediate, all-encompassing and ambitious climate policy measures, therefore, a global roll-out and successful implementation of good practice policies can put the world on track to a 2 °C-compatible pathway without posing large additional challenges.

In short, acting stringently on 2 °C (*2Deg2020*) is needed, but, collectively, we are not on track (*NDCplus*). If we do not strengthen collective action until 2030, the best chance at limiting global warming may be *2Deg2030*. However, if we manage to accelerate action until 2030 (*Bridge*), major disruption can be avoided, even if we do not fully reach *2Deg2020*. These results illustrate that short-term (2030) implementation of practical regulation-based policies is preferable over delayed climate action. At the same time, the institutional set-up should aim to avoid inefficient policy lock-in, as more efficient instruments may gain political and societal support over time.

5.4 Methods

5.4.1 Models

Both national and global model teams followed the same scenario protocol for comparability. The global models included here are: AIM/CGE (Fujimori et al., 2012), COPPE-COFFEE (COPPE/UFRJ, 2020), IMAGE (Stehfest et al., 2014), MESSAGEix-GLOBIOM (Huppmann et al., 2019), POLES (Després et al., 2018), PROMETHEUS

(Fragkos & Kouvaritakis, 2018), REMIND-MAgPIE (Aboumahboub et al., 2020), TIAM-Grantham (Loulou, 2008), WITCH-GLOBIOM 5.0 (RFF-CMCC EIEE, 2019). National-level results are presented in Baptista et al. (2021)

5.4.2 Scenarios

In line with the global stocktake, the ratcheting up mechanism has been applied in constructing the scenario protocol (see S5.3 Supplementary Methods: COMMIT WP2&3 Scenarios for ratcheting up mitigation ambition for the full protocol text and S5.1 Supplementary Tables: implementation of good practice policies per model for the detailed lists of good practice policies). This means that the scenarios build upon one another in terms of ambition and modelling assumptions. The Current policies scenario is the least ambitious and the 2 °C scenario is the most ambitious.

5.4.2.1 Reference scenarios

The **Current policies (CurPol)** scenario incorporates middle of the road socio-economic conditions throughout the century, based on the second marker baseline scenario from the Shared Socioeconomic Pathways (SSP2, Riahi et al., 2017). It also assumes that climate, energy and land use policies that are currently ratified are implemented (cut-off date 1 July 2019).

The **NDC-plus** scenario builds further upon the CurPol scenario and assumes that the conditional NDCs (both unconditional and conditional NDC actions) as submitted by April 2020 are implemented by 2030. After 2030, the scenario reflects continuation of effort (see below).

5.4.2.2 Bridge scenario

The **Bridge** scenario builds upon the CurPol scenario and assumes that certain good practice policies, which have shown to be effective in some countries (Fekete et al., 2021; Kriegler et al., 2018; Roelfsema et al., 2018), will be implemented globally from 2020 until 2030 (Table S5.1 1 in Supplementary Data lists the good practice policies while Table S5.1 2 gives an overview of their implementation in models, with the implemented shares ranging from 44% to 94%). After 2030, the *Bridge* scenario transitions to a 2 °C scenario following a cost-effective pathway (see below). The set of policies was defined in dialogue with national model teams, granting a more realistic scenario narrative (for more details, see the Supplementary Information, S5). This was done in multiple rounds. First, national modelling teams responded to the proposed good practice policies (based on literature), considering whether these policies could be realistically implemented in their countries and, if not, what other target levels or years would be feasible. These teams cover Australia, Brazil, Canada, China, EU, India, Indonesia, Japan, Republic of Korea, Russia, United States; i.e. approximately 75% of global emissions. Second, the policy list was adjusted to differentiate country groups, regarding the timing and stringency of the targets.

Third, some national models ran the refined scenarios and provided feedback, upon which the list was further refined. As such, we eventually defined two country groups (high-income and middle-/low-income), and in some cases three (adding Other, with different definition per measure), which were found to offer enough differentiation to be nationally relevant while still adhering to a common set of policy measures. Finally, all national and global model teams ran the agreed set of scenarios.

5.4.2.2.1 Country differentiation of good practice policies

A distinction is made between low/medium income and high-income countries in terms of timing and stringency of good practice policy targets. The AFOLU sector's measures are differentiated mostly in terms of stringency, not timing, considering the current differences in efficiency between high- and lower-income countries. Afforestation rates have a more specific country differentiation, based on NDC ambition. Energy supply measures are rather similar between countries as these are already more widespread, with the exception of coal phase-out, where low-income countries would need more time. Measures in the buildings sector are differentiated in terms of timing (overall energy intensity of buildings and oil boilers) as well as stringency (efficiency of appliances and renovation rate) given the different starting points and future service demand in country groups. For industry, the CCS measure was differentiated in timing only, as the development of the technology has a global nature, but its implementation may encounter different institutional barriers between higher and lower income countries. For adipic acid production, no differentiation was applied as significant emissions reductions are already technically possible. For F-gases, the differentiation is in line with the Kigali Agreement. Transport measures were not differentiated for aviation due to its global nature, but vehicle measures were assumed to be less stringent in low-income countries given different starting points. Given the more abundant use of landfilling in lower income countries, reductions in methane emissions from waste were assumed to be smaller than in high-income countries.

5.4.2.2.2 Carbon pricing

Finally, as opposed to Fekete et al. (2021), carbon pricing is included as good practice policy, although it may be considered as a top-down policy of different nature than the other policies. Carbon pricing and emission trading schemes have been successfully implemented in various countries. Furthermore, previous work (Kriegler et al., 2018) highlights that good practice regulatory policies should be considered as complements to pricing-based approaches. In the simulations, the carbon price applies to all gases and sectors, hence represents an idealized view of carbon pricing schemes. It does not take the highest carbon price currently observed as starting point, but rather an approach in which countries were divided in three tiers with different carbon price levels and timelines to be most relevant to the countries represented here, and to better reflect the current status of pricing measures such as ETS(ICAP, 2021). As a variant and to analyse the effect of this measure, some models ran an additional scenario excluding the carbon price measure (see Figure S5.2.7).

5.4.2.3 Post-2030 assumptions

The *Bridge* scenario follows the good practice policies until 2030, after which the scenario transitions smoothly to the 2 °C scenario by remaining within the carbon budget consistent with the 2 °C target (1000 $GtCO_2$ for 2011-2100). This was implemented via a carbon price, with the scenario converging from the regionally differentiated 2030 carbon prices as prescribed to a global carbon price in 2050 that is in line with the 2 °C carbon budget. It is assumed that the gradual implementation of climate policy in the 2020-2030 period can build up enough momentum (and technology development) to move to a more comprehensive climate policy after 2030. The **2 °C (2Deg2020** and **2Deg2030)** scenarios assume that an average temperature increase of 2 °C without overshooting is reached by 2100 in a cost-effective way (starting from 2020 in *2Deg2020* and from 2030 in *2Deg2030*). National modelling teams used a carbon budget derived from the global carbon budget of 1,000 Gt CO_2 in the period 2011-2100 (including 2011 emissions), as done in CD-LINKS <https://www.cd-links.org/> (Roelfsema et al., 2020). This global carbon budget represents a 66% probability of keeping global warming below 2 °C. Carbon budgets have been revised since the CD-LINKS project in such a way that 1,000 Gt is even more stringent than previously. Cumulative CO_2 emissions in the 2 °C scenarios (*2Deg2020, 2Deg2030,* and *Bridge*) are not all exactly 1000 Gt, but range from 788 Gt CO_2 to 1540 Gt CO_2 (2011-2100), which is still within the range considered to be in line with 2 °C.

For the CurPol and NDC-plus scenarios, a continuation of efforts after the target year was assumed. This was implemented by extrapolating the equivalent carbon price in 2030, using the GDP growth rate of the different regions up to 2050. The equivalent carbon price represents the value of carbon that would yield the same emissions reduction as the NDC policies in a region. If a region has a carbon price of zero while implementing the NDC in 2030, a minimum carbon price of 1 $/$tCO_2$ in 2030 was assumed. If a region has a negative carbon price in 2030, the trajectory resulting from 1 $/$tCO_2$ was offset to the model's 2030 starting point. For land use, a carbon price ceiling of $200/$tCO_2$ was applied.

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5

Author contributions

H.v.S. coordinated the analysis, wrote the paper, and created the figures; T.V. did the analysis for the costs section; all authors contributed to the definition of the good practice policy package, the analysis, and article review. C.B., E.K., A.M., and others in the REMIND(MAgPIE) team developed the scenarios for the REMIND-MAgPIE model; R.S., L.B.B., and others in the COFFEE team developed the scenarios for the COFFEE model; P.F. developed the scenarios for the PROMETHEUS model; K.R., B.v.R., G.U., O.F. developed the scenarios for the MESSAGEix-GLOBIOM team; D.S.H., K.O., S.F. developed the scenarios for the AIM team; M.H., M.R., D.v.V., M.d.E., **H.v.S.** developed the scenarios for the IMAGE model; L.D., L.A.R., M.T. developed the scenarios for the WITCH model; J.D., K.K. developed the scenarios for the POLES model; N.G., S.M., A.K. developed the scenarios for the TIAM-Grantham model; G.I. developed the scenarios for the GCAM-USA model (presented elsewhere) and served as national expert.

6

Analysing interactions among Sustainable Development Goals with Integrated Assessment Models

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Abstract

In 2015, the Sustainable Development Goals (SDGs) were adopted. The integrated policies needed to achieve all goals in parallel require knowledge on their interactions. Integrated Assessment Models (IAMs) represent many human–environment interactions and can inform policymakers about the synergies and trade-offs of meeting multiple goals simultaneously. We investigate the suitability of IAMs to perform such analyses by comparing key interactions identified by experts with their current representation in models, including planned developments. This allows us to discuss how IAMs can contribute to achieving policy coherence and to stimulate discussions on future research. The analysis shows that IAMs cover SDGs related to sustainable resource use and the Earth system well. Goals related to human development and good governance are less well represented – and might be more difficult for these models to fully capture. Therefore, better representation of heterogeneity, using different types of models and linking different disciplines will be needed.

Keywords

Sustainable development goals, Integrated assessment, Synergies, Trade-offs, Policy coherence

Highlights

- Interactions between all 17 SDGs were identified in an expert survey, and compared with coverage of these processes by IAMs.
- 13 SDGs can (partly) be quantified by IAMs; goals related to human development and good governance are not well represented.
- IAMs mainly cover interactions within and between the 'Efficient and sustainable resource use' and 'Earth system' clusters.
- A better representation of heterogeneity, policy instruments and scales is needed to inform policy coherence for the SDGs.
- Cooperation in multi-model frameworks and outside models with other disciplines is needed to address the full SDG agenda.

6.1 Introduction

6.1.1 The 2030 agenda

With the approval of the Sustainable Development Goals (SDGs) in autumn 2015, the United Nations adopted an ambitious agenda to tackle several grand challenges of the 21st century simultaneously. This includes ending hunger and eradicating poverty while also protecting the environment through actions such as limiting the pace of climate change and protecting marine and terrestrial biodiversity (United Nations, 2015). This agenda is expressed in the form of 17 SDGs that have been broken down into 169 specific targets. A key aspect of the SDGs is 'achieving sustainable development in its three dimensions – economic, social and environmental – in a balanced and integrated manner' (United Nations, 2015). However, the understanding of interactions among the policies targeting different SDGs presents a gap in the knowledge (Weitz et al., 2018). Several studies have developed frameworks to examine the interactions among the SDGs, each with a different classification scheme (Coopman et al., 2016; International Council for Science, 2016; Nilsson et al., 2016; Singh et al., 2018; Weitz et al., 2018). While Nilsson et al. (2016) emphasised the need for case studies to identify interactions, the ex-ante identification of possible interactions using a global forward-looking model-based analysis is a prerequisite. Such analyses can quantify the effort required to reach the targets and can identify the interactions among the targets in terms of synergies and trade-offs (Cameron et al., 2016; Collste et al., 2017). Examples of such interactions include the competing claims for land between bioenergy production to prevent climate change and food production to reduce hunger (Humpenöder et al., 2018; Popp et al., 2011), and the possible synergy between climate policy and reducing air pollution (Braspenning Radu et al., 2016). A recent study by the International Council for Science (ICSU, 2017) called for approaches and tools to support assessments of the nature and strength of interactions to help design implementation strategies.

Thus far, no comprehensive review has explored the possible interactions among the SDGs at a global scale (in a 17 by 17 matrix), which the ICSU (2017) report called for. At the same time, some studies have used one or more SDGs as a starting point to study interactions with other SDGs (Dickson et al., 2010; Fuso Nerini et al., 2018; Wood et al., 2018). Some have looked at interactions in a specific country (Weitz et al., 2018). Pradhan et al. (2017) and Pollitt et al. (2010) are the closest to a comprehensive review. Pradhan et al. (2017) systematically analysed the correlations between SDG indicators in a historical time series across the 227 countries for which data was available. Though they provided insights on potential interactions among the SDGs, they were not able to distinguish between the direct causal relations and the correlations because of a confounding third factor. Pollitt et al. (2010) examined the links between macroeconomic perspectives and sustainable development and reviewed their representation in models, focusing mostly on macroeconomic models in the process.

6.1.2 Integrated Assessment Models

Integrated Assessment Models (IAMs) offer an integrated perspective on complex human–environment interactions and can thus contribute to an assessment of the strategies to achieve multiple SDGs simultaneously. Originally, they were used to study integrated energy, land, and climate change mitigation pathways, but have since been developed further with expanded sets of interactions across sectors and systems (Riahi et al., 2017; van Vuuren et al., 2011). Here, we assess the extent to which these models can perform wider analyses of the SDGs. IAMs have already been used systematically to study interactions between climate change mitigation and other societal priorities (GEA, 2012; Iyer et al., 2018; van Vuuren et al., 2015; von Stechow et al., 2015), including air pollution, health (Fullman et al., 2017; Sellers & Ebi, 2018), energy (McCollum et al., 2011; von Stechow et al., 2016), food (Obersteiner et al., 2016) and water security, and biodiversity. They have done so either by incorporating these processes in the models themselves, or by linking different models, modules, or tools. IAMs have used model comparison exercises to spur development in new areas. For example, in EMF21, models collaborated to add non-CO_2 gases to the analysis. Several recent and planned model innovations can also help develop a systemic understanding of the interactions among the SDGs across different dimensions of sustainability.

IAMs come in many forms. They have a diverse range of objectives, scopes, methods, spatial and temporal dimensions, sectoral and technology representations, solution method, and anticipation (simulation or foresight). The analysis here centres on models that focus on climate change mitigation and processes (in contrast to IAMs engaging in cost-benefit analysis), but within this set, the models included span the entire spectrum of the literature for the attributes mentioned. Some notable models that are not included here have covered the SDGs more extensively, namely iSDG (Millennium Institute, 2017), International Futures (Hughes, 2019), and Earth 3 (Randers et al., 2018).

6.1.3 Overview of this study

The objective of this paper is to analyse current practices and planned model developments in order to show how IAMs, originally developed to study interactions among energy, the economy, climate, and land, can contribute to an analysis of a wider pool of SDGs and the development of integrated policies. We first aim to understand the key interactions through experts who have tacit knowledge on how SDGs are interconnected. Next, we compare this learning with current and future representations of both the SDG targets and their interactions in well-established IAMs. We complement these results by performing a computer-aided synthesis of the IAM literature related to SDGs to better understand how IAM results have been used to discuss interactions among SDGs in the past. The model survey and literature synthesis aim to capture the tacit knowledge of what is modelled, either endogenously or through coherent assumptions, and to what extent it has been used to study interactions among SDGs. Capitalising on the results from these three complementary perspectives, we discuss the opportunities for IAMs to inform policy discussions and help identify gaps, which, in turn, can contribute to setting priorities for further research and identifying areas for collaboration. When compared to Pollitt et al. (2010), the new element in our work is this combination of the two surveys of both SDG experts and IAM modellers. As Pollitt et al. (2010) predated the SDGs, and IAMs have developed strongly towards broader system boundaries since then, there is a need for an update with respect to an overview of the representation of SDGs.

We established **information on key interactions** by asking a group of experts on one or more SDGs (e.g. poverty) about the existing interactions (see Methods). The survey aimed at identifying interactions among the SDGs at the goal-level, which work in various directions and even change over time. Therefore, we used only the scores for the strength of the interactions and not the scores for the direction.

To assess the suitability of the models to represent the interactions among the SDGs, we approached IAM modelling teams participating in the Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing (CD-LINKS) project (CD-LINKS, 2018). The models included here are AIM-CGE (Fujimori et al., 2017), China TIMES (Chen et al., 2016), DNE21+ (Akimoto et al., 2010), GCAM (Calvin et al., 2017), GEM-E3 (Capros et al., 2014), IMAGE (van Vuuren et al., 2017), IPAC (Jiang et al., 2016), PRIMES (Capros et al., 2014), REMIND-MAgPIE (Kriegler et al., 2017), MESSAGE-Brazil (Nogueira et al., 2014), MESSAGE-GLOBIOM (Fricko et al., 2017), and WITCH (Emmerling et al., 2016). These models represent the state of the art of integration of SDGs in their frameworks, and include leading IAMs used in climate assessments such as those prepared by the IPCC (Clarke et al., 2014) and the shared socio-economic pathways (SSP) scenarios (Riahi et al., 2017), ecosystem assessments such as the Millennium Ecosystem Assessment (Carpenter et al., 2005) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2016), and other integrated assessments such as the Global Environment Outlook (GEO, 2012), Global Energy Assessment (GEA, 2012), and The World in 2050 (TWI2050, 2018). The survey comprised six questions (see Methods for the full text of the questions) related to the current model representation of individual SDGs; the planned model representation of individual SDGs; important interactions among the SDGs (in a 17x17 matrix); currently modelled interactions among the SDGs; interactions planned to be modelled; and interactions that are conceivable to be modelled in the future. For brevity, the SDG expert survey on key interactions is referred to in the following sections as the *expert survey*, while the model assessment is referred to as the *model survey* (while noting that modellers are also experts).

For the computer-aided synthesis of the existing literature, we sent a request to the Integrated Assessment Modelling Consortium (IAMC, 2018) mailing list and requested an overview of the key SDG-related references for each model, which we extended with key references from the CD-LINKS (2018), EMF27 (2018), LIMITS (2011), and PATHWAYS (2018) projects (see also Methods). We applied text mining methods to full text publications to analyse the interactions among the SDGs that have been studied in the literature. As IAMs are diverse, the results below should not be interpreted as a precise mapping of everything that the entire IAM community has to offer on the SDGs. Rather, it aims to present a general overview of SDG clusters that IAMs can and cannot speak to, in order to help identify areas for further model development and collaboration with other disciplines.

6.2 Results

We separated the SDGs into four clusters to ease the discussion of results (see also e.g. Lucas et al., 2016; United Nations, 2014). This clustering is only used to simplify the presentation and discussion of our findings and does not represent any hierarchy. We acknowledge that several SDGs also have elements that can fall into other clusters. The clustering followed in this study pertains to the structure of most IAM frameworks, as the aim of this paper is to show how the IAMs deal with the SDGs (see Figure 6.1 and Figure S6.2.1): efficient and sustainable resource use (SDGs 2, 6, 7, 12); Earth system (SDGs 13, 14, 15); human development goals (SDGs 1, 3, 4, 5, 8, 10); and good governance and infrastructure (SDGs 9, 11, 16, 17) (in Figure 6.1: yellow for human development goals; green for resource use; blue for Earth system; and red for governance and infrastructure). More detailed results of the surveys and the literature synthesis and an overview of the model representation of individual SDGs are presented in the Supplementary Information.

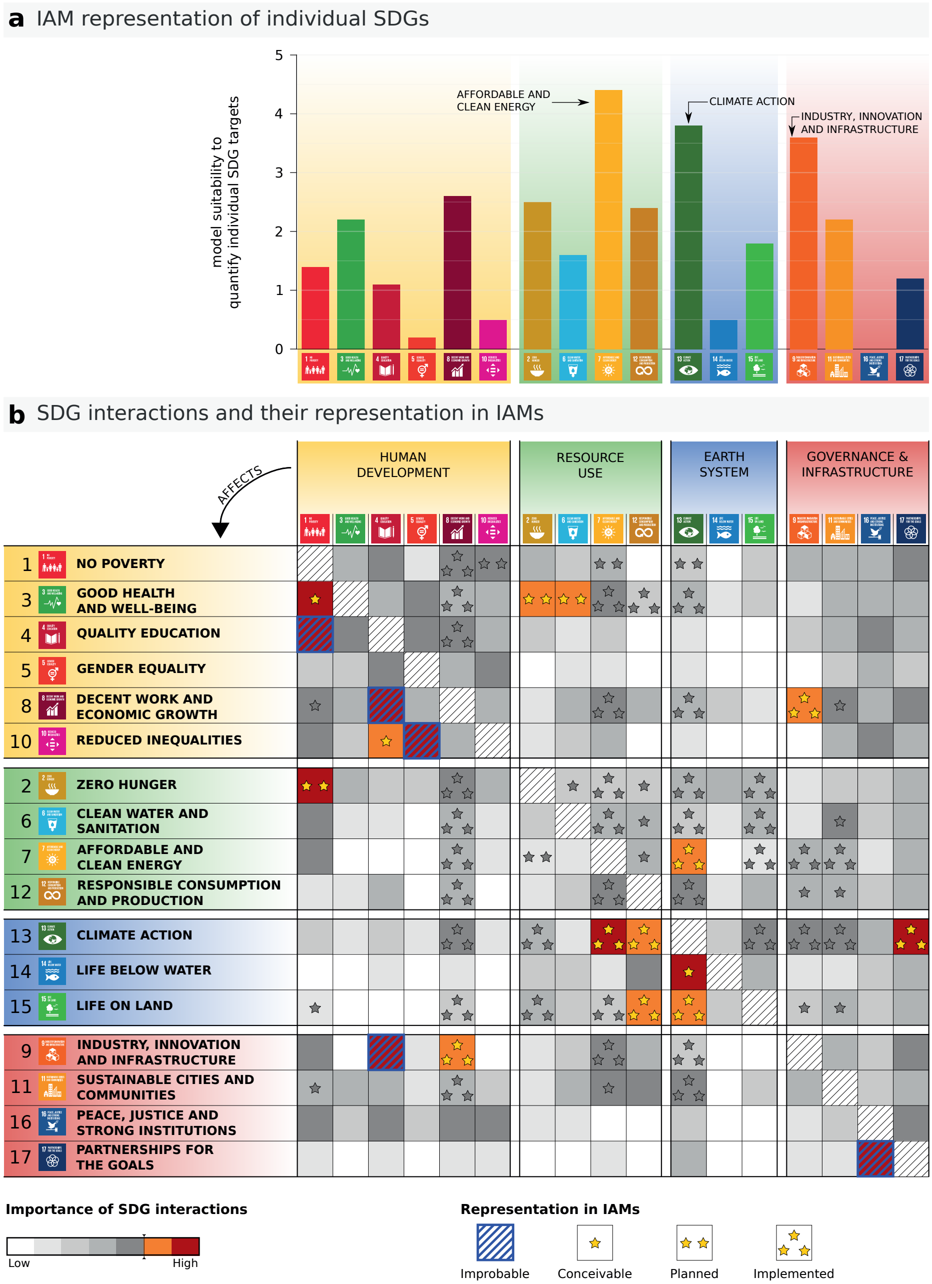

Figure 6.1: The representation of SDGs by IAMs. (A): Bar height represents the average score for individual target coverage from the *model survey* (Table 6.1). (B): SDG interactions and coverage by IAM models according to the *expert* and *model surveys* (the SDG in the column impacts the SDG in the row). The strength dimension of SDG interactions is indicated by grey shading: the darkest shade of grey represents average scores near 3 (strong interactions), while

white represents no interactions. The representation of IAMs following the *model survey* is indicated by asterisks. ***: currently in IAMs, **: planned development, and * conceivable to be represented in the future. Finally, orange cells indicate the highest agreement between the importance of interactions and potential model representation, while blue coloured cells show the most notable important interactions without model representation. Interactions that are marked as currently represented are endogenous, with various levels of process detail. Future modelling of the SDG interactions that have remained unrepresented thus far can be achieved as a part of a consistent set of exogenous assumptions such as, for example, the impact of quality education on reducing poverty.

6.2.1 Key interactions in and with the human development cluster

According to the *expert survey*, key interactions (dark grey and orange in Figure 6.1b) exist across all SDG clusters, but lie especially within the human development cluster, between the human development and resource use clusters (specifically the effects of economic growth and reducing poverty on other goals), and in the Earth system cluster. Experts noted that the strength and direction of the interactions often depend on the policy instruments and their implementation (see Table S6.3.1).[16]

6.2.2 IAMs can be expanded to deal with other social goals

6.2.2.1 Representation of individual SDGs: 13 at least partly quantified

Figure 6.1 also includes the self-assessment of IAM modelers on the ability of their models to represent individual SDGs and their interactions. First, we assessed how many of the 169 targets included in the SDGs can be quantified by indicators that either already exist or are planned to be used in the future (see Figure 6.1a and Table 6.1). It shows that many SDGs can at least be partly quantified by IAMs, while some are clearly not well covered in these models. The latter most notably relate to (gender) inequalities (SDGs 5 and 10, although some indicators can be found in the literature), education (SDG 4, although the International Futures model (Hughes, 2019) has made progress in this area), and peace (SDG 16), and to some extent also cities (SDG 11) and marine life (SDG 14). Well-covered SDGs are in the 'Efficient and sustainable resource use' and 'Earth system' clusters, concerning climate (SDG 13), energy (SDG 7), land use (SDGs 2 and 15), and water (SDG 6). SDGs relating to 'Human development goals' and 'Good governance and infrastructure' are generally more difficult for IAMs to quantify fully (but see 56), especially for indicators on institutions and the existence of policies and legal frameworks (see also C. Allen et al., 2016).

16 For a comparison between the *expert survey* and the empirical analysis by Pradhan et al. (2017), see Supplementary Information Figure S6.2.2. See Table S6.3.1 and Figure S6.2.4 for disaggregated results on important interactions according to both the *model* and *expert surveys*.

6.2.2.2 Interactions among SDGs prevailing currently in models: resource use and earth system clusters

The asterisks show whether IAMs can represent crucial interactions among different SDGs (as pairs) based on current model versions (three asterisks in Figure 6.1b, with two indicating planned developments) or whether these interactions are conceivable to be represented in the models in the future (one star in Figure 6.1b). These currently represented interactions are found mostly in and between the resource use and Earth system clusters because broad coverage is necessary for the representation of climate and energy, and IAMs have developed to cover processes beyond climate change. The agreement between IAM representation (three stars) and key interactions is the highest (dark orange cells) for the effect of economic growth on all SDG clusters, the effect of energy on health and climate, the effect of consumption and production on climate and life on land, the effect of climate on other resource use and Earth system SDGs, and the effect of governance SDGs on economic growth and climate. It is important to note that some SDG interactions are fully endogenous (e.g. between access to clean energy and climate action), while others are rather part of a consistent set of exogenous assumptions as a component of a scenario narrative (e.g. between education and economic growth (Kc & Lutz, 2017).

The interactions best represented in IAMs (i.e. receiving the highest average scores in the *model survey*) were checked in great detail with the comments provided in the *expert survey*, to assess whether the representations of interactions in the IAMs correspond with the processes described by the experts[17] on the associated SDGs. The four interactions with the highest scores for model representation are energy affecting climate, climate affecting energy, economic growth affecting climate, and climate affecting life on land. Processes highlighted by experts generally agree with model representations of these interactions, although the experts mentioned detailed dynamics that are not always covered by the models, such as how access to clean cooking reduces demand for biomass (see Table 6.2 for a mapping of expert-defined processes and model representations for these highest ranked interactions, and Table S6.3.1 for all comments on interactions from the *expert survey*). The experts' comments highlight the need to develop IAMs further and to use them in combination with other tools and approaches.

17 These SDG experts were not necessarily aware of or connected to the IAMs

Table 6.1: Average scores (0–5) for model suitability to quantify individual SDG targets, and key indicators. Modelers were asked to assign a score between 0 and 5 to each SDG, based on the ability of their model to quantify individual targets, and provide key indicators (see also Table S6.3.3). GINI: Gini coefficient representing income distribution (inequality); DALY: disability-adjusted life years; MSA: mean species abundance.

	All models	Key indicators
SDG 1	1.4	Per capita / household consumption, food/energy expenditure of households, people living below poverty line, GINI
SDG 3	2.2	Air pollution related mortality/air quality, DALY, health expenditure
SDG 4	1.1	Enrolment ratios and educational attainment, education expenditure
SDG 5	0.2	-
SDG 8	2.6	GDP(/growth), consumption, investment, economic structure, sector value added, employment, labour wages, food/water/steel/cement/energy efficiency
SDG 10	0.5	GINI, private consumption, labour share of GDP
SDG 2	2.5	Undernourishment, food availability/consumption per capita, food prices/expenditure, people at risk of hunger, agricultural productivity
SDG 6	1.6	Population with access to safe drinking water/sanitation, wastewater treatment, water stress, water used for energy, water prices, irrigation water withdrawal
SDG 7	4.4	People without access to electricity/relying on solid fuels/ traditional biomass use, energy prices for consumers, share of renewable energy, energy intensity
SDG 12	2.4	Energy (renewable/fossil) resource estimates/utilization, recycling rates, labour/capital/material/energy productivities, material consumption, food waste/consumption
SDG 13	3.8	NDC and policy implementation, climate forcing indicators, adaptation costs/investments/damages, residual damage, heating/cooling demand, planting dates, and variety change
SDG 14	0.5	Ocean acidification, fertilizer use/losses, adaptation capacity of coastal areas, fisheries as % of GDP, Nitrogen cycle indicators, and MSA in aquatic ecosystems
SDG 15	1.8	Land use/cover area, forest/deforested/terrestrial ecosystems area, area under sustainable forest management, nitrogen losses agriculture, terrestrial acidification, MSA/wilderness/species richness indicators, reforestation/protection targets
SDG 9	3.6	Transport/industry energy demand, manufacturing value added/employment, CO_2 emissions per sector/per value added, travel demand
SDG 11	2.2	Travel demand/per capita, transport energy use, waste/wastewater volumes, air pollutant emissions, urbanisation rate

Table 6.1: *Continued.*

	All models	Key indicators
SDG 16	0.0	-
SDG 17	1.2	GDP per capita, economic structure, private/public consumption, investments, sector value added, exports, taxes as a % of GDP, import duties per product, share of exports of developing countries in global exports by sector, and average tariffs faced by developing countries

Table 6.2: Model representation of the highest-ranked currently covered interactions compared with expert-identified processes.

From SDG → to SDG	Model representation	Experts
7 → 13	Increased access to renewable energy/cleaner energy/higher energy efficiency: lower GHG emission factors and lower energy use → reduced greenhouse gas emissions (mitigation side of SDG 13)	*Access to clean cooking reduces the demand for biomass and thereby decreases related global GHG emissions (SDG 13). Improved biomass stoves reduce biofuel demand. Gaseous and liquid fuels are more efficient and therefore reduce CO_2 emissions. Electric cooking can lower emissions significantly because of the improvement in efficiency and, if generated with renewables, CO_2 neutral.*
13 → 7	Climate change mitigation policies (carbon pricing, taxes and subsidies, renewable energy targets, efficiency targets, standards, etc.) → increase in renewable energy deployment and efficiency measures. Possible negative effects of climate policy (via fuel prices) on energy access	*Climate mitigation action (SDG 13) can be used to accelerate the transition by using climate or international emissions trading to finance renewable energy development in developing countries. Technology development, for example, the global renewable energy revolution in countries like Germany and China has pushed down prices, making them more competitive with fossil fuels in generating electricity in developing countries.*
8 → 13	GDP is one of the main drivers of energy demand, resource demand, land use, and therefore GHG emissions. GDP growth increases funding capabilities to invest in climate action	

Table 6.2: *Continued.*

From SDG → to SDG	Model representation	Experts
13 → 15	CO_2 concentration, temperature, and precipitation in land-use models affect vegetation growth (natural, food, and bioenergy crops). Climate change is included as a driver for the decrease in biodiversity. Bioenergy with CCS (BECCS) and afforestation/reforestation as carbon removal technologies affect land use	*The health of the planet and planetary ecosystems depend on a stable climate. Without reducing the concentrations of GHGs in the atmosphere, the systems that currently support life on earth may be jeopardized by climatic instability. Addressing this is essential for the implementation of Agenda 2030. Ecologically, climate change impacts marine life and terrestrial biodiversity. Slowing down climate change impacts will benefit natural habitats by only marginally changing their climate regimes. However, if 'renewables' from the land sector are not carefully considered in this energy transition - climate mitigation actions like BECCS can have highly negative impacts.*

6.2.2.3 SDG interactions planned to be modelled: increasing coverage of human development

In addition to resource use and Earth system clusters that are currently modelled, model developments in the planning stages include interactions between resource use and human development goals, while interactions that are conceivable to be modelled further include governance and infrastructure goals, most notably regarding cities. Interactions planned to be covered generally show overlap in scores between the *expert* and *model surveys* (orange cells in Figure 6.1), with poverty affecting hunger, hunger affecting health, and clean water affecting health being assigned the highest scores in both surveys, followed by inequalities affecting poverty, energy affecting poverty, and climate affecting poverty. This suggests that these planned model developments are supported by experts. With lighter grey in Figure 6.1 (i.e. deemed less important by experts) but still representing the existing interactions, the same holds for the planned development of hunger affecting energy.

6.2.2.4 Potential for model development

It is perhaps more important to identify what has not been modelled rather than to identify what has. Looking at the overlap between existing interactions (grey) and interactions deemed conceivable to be modelled in the future (one star) in Figure 6.1, the potential for IAMs to improve representation of important SDG interactions in the future seems to lie in the human development and resource use clusters. These are the effects of addressing poverty on health and economic growth, of (renewable) energy on cities, of education on inequalities, of climate action on oceans, and of cities on water and economic growth. Interactions that are deemed most important without current, planned, or conceivable IAM coverage (blue hatched cells in Figure 6.1) mostly lie in the human development cluster, despite planned developments and potential for further improvements. These interactions include poverty affecting education, education affecting economic growth and industry, gender equality affecting inequalities, and peace affecting partnerships for the goals.

6.2.2.5 SDG interactions at various levels

SDG experts in the *expert survey* were asked about the scale of the problems and solutions pertaining to the SDGs (see Table S6.3.2), illustrating that SDG interactions can be both global and local. Broadly speaking, the problem dimension of most SDGs was identified as global (with exceptions, e.g. SDG 10), while the solution dimension was more often found to be local (with climate and oceans being a notable exception, being global and transboundary in nature). The 'Means of Implementation' targets were mostly classified as global. A few were classified as transboundary, whereas only one was classified as local (Target 7b). Most experts noted that solutions at multiple scales would be necessary for most SDGs. This may be difficult to implement in models, meaning that modellers still need to decide what solutions should be endogenously represented in the models.

6.2.3 Model assessment: synthesis of literature confirms model survey

We compared the results of the *model survey* with the findings drawn from a synthesis of the IAM literature. This helped identify which of the SDGs were jointly discussed in the literature. We used topic modelling (Blei, 2012), a machine learning method in natural language processing, to automatically identify the possible interlinkages among different SDGs across 383 papers from the available IAM literature on SDGs (see Figure 6.2). In Figure 6.2, topics (inner ring) were endogenously detected by our topic model. Each topic on the inner ring is related to a particular SDG in the outer ring of the graph (see Methods).[18]

18 See the methodology section and the SI for a complete presentation and discussion of the results, and see Figure 6.3 for a comparison between results from the content analysis and from the model survey.

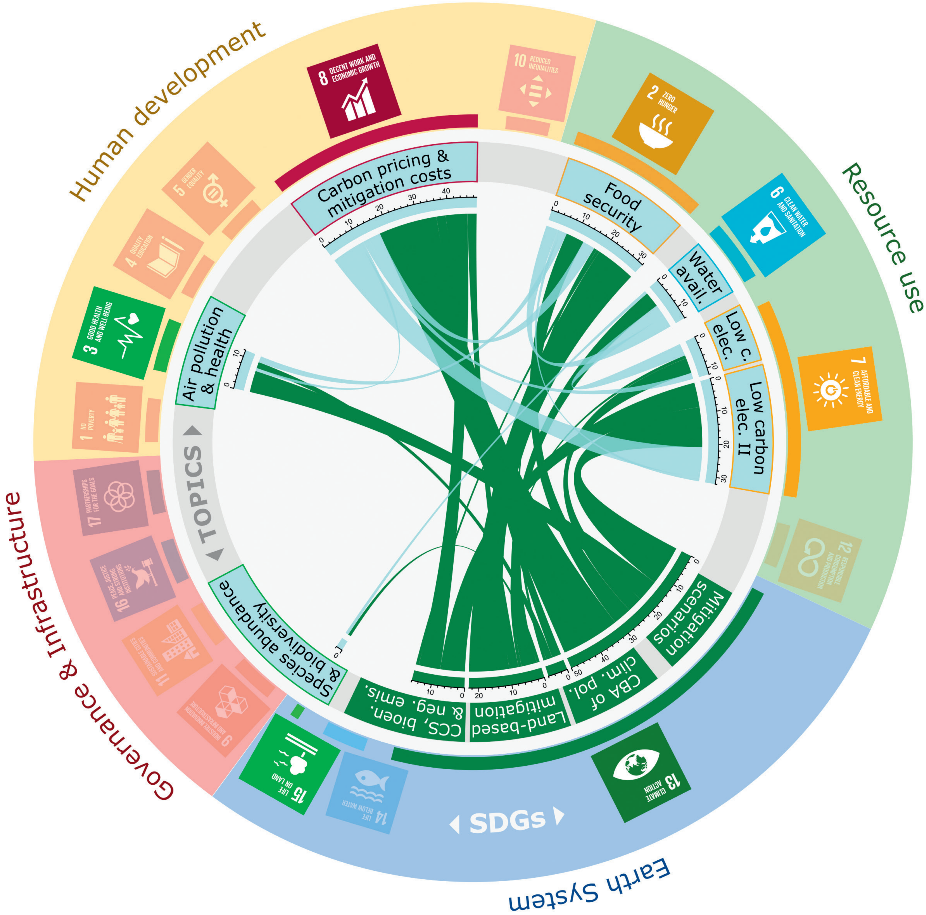

Figure 6.2: SDG interactions in the IAM literature. Linkages among the topics in the literature (inner circle) have been uncovered endogenously using topic modelling. Topics are manually allocated to SDGs (outer circle). Chord width is proportional to the number of documents that simultaneously feature two topics. Climate topics are in green while non-climate ones are in light blue. Water avail.: Water availability; Low c. elec.: low-carbon electricity; CBA of clim. pol.: cost-benefit analysis of climate policy; CCS: carbon capture and storage; bioen.: bioenergy; neg. emis.: negative emissions.

Topic modeling: number of documents

	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17	Total
SDG1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG2	0	0	2	0	0	4	1	4	0	0	0	0	21	0	0	0	0	**32**
SDG3	0	0	0	0	0	0	0	1	0	0	0	0	9	0	0	0	0	**10**
SDG4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG6	0	0	0	0	0	0	4	0	0	0	0	0	5	0	1	0	0	**10**
SDG7	0	0	0	0	0	0	0	12	0	0	0	0	**27**	0	0	0	0	**39**
SDG8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
SDG14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
SDG17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Total	**0**	**0**	**2**	**0**	**0**	**4**	**5**	**17**	**0**	**0**	**0**	**0**	**62**	**0**	**2**	**0**	**0**	**92**

Model survey: average score for current representation

	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
SDG1	0.0	0.3	0.2	0.3	0.0	0.1	0.5	1.1	0.7	0.3	0.0	0.7	0.6	0.0	0.2	0.0	0.7
SDG2	0.5	0.0	0.7	0.3	0.0	0.8	1.3	1.9	0.5	0.3	0.0	0.4	1.3	0.0	1.6	0.0	0.5
SDG3	0.2	0.6	0.0	0.2	0.0	0.8	1.8	1.5	0.5	0.3	0.6	1.0	1.6	0.0	0.5	0.0	0.5
SDG4	0.4	0.2	0.2	0.0	0.0	0.0	0.2	1.1	0.2	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.5
SDG5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SDG6	0.7	0.8	0.2	0.1	0.0	0.0	1.3	1.3	0.3	0.0	0.0	0.7	1.6	0.0	0.7	0.0	0.0
SDG7	0.3	0.9	0.3	0.1	0.0	0.8	0.0	1.9	1.7	0.3	1.0	0.9	**2.7**	0.0	1.1	0.0	0.9
SDG8	0.5	0.0	0.5	0.2	0.0	0.3	1.0	0.0	1.6	0.7	0.2	0.9	1.5	0.0	0.0	0.0	0.8
SDG9	0.1	0.4	0.0	0.0	0.0	0.5	1.3	1.6	0.0	0.7	0.4	0.9	1.4	0.0	0.7	0.0	0.8
SDG10	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
SDG11	0.1	0.0	0.0	0.0	0.0	0.1	0.7	1.1	0.4	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.5
SDG12	0.1	0.5	0.0	0.0	0.0	0.4	1.6	1.4	0.9	0.3	0.4	0.0	1.3	0.0	0.9	0.0	0.3
SDG13	0.1	1.0	0.5	0.0	0.0	0.9	**2.8**	2.3	1.9	0.0	1.6	1.8	0.0	0.0	1.8	0.0	1.2
SDG14	0.0	0.6	0.0	0.0	0.0	0.0	0.8	0.8	0.0	0.0	0.0	0.0	0.8	0.0	0.4	0.0	0.0
SDG15	0.4	1.6	0.0	0.1	0.0	0.3	1.6	1.7	0.4	0.0	0.1	1.2	2.1	0.0	0.0	0.3	0.3
SDG16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SDG17	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.7	0.5	0.2	0.0	0.2	0.3	0.0	0.0	0.0	0.0

Model representation of individual SDGs	Model representation of SDG interactions		Human development						Resource use				Earth system			Governance			
			1 No poverty	3 Health	4 Education	5 Gender equality	8 Work & economic growth	10 Inequalities	2 Zero hunger	6 Clean water	7 Energy	12 Consumption & production	13 Climate action	14 Life below water	15 Life on land	9 Industry, innovation, infrastructure	11 Cities	16 Peace	17 Institutions
SDG1	Human development	1 No poverty					***	**			**		**						
SDG3		3 Health	*				*** 1		** 2	**	***	***	*** 9						
SDG4		4 Education					***												
SDG5		5 Gender equality																	
SDG8		8 Work & economic growt	*	1					4		** 12		** 32			***	*		
SDG10		10 Inequalities			*														
SDG2	Resource use	2 Zero hunger	**	2			*** 4			* 4	*** 1	*	*** 21		***				
SDG6		6 Clean water					***		4		*** 4	*	*** 5		1		*		
SDG7		7 Energy					** 12		** 1	4		*	** 27		***	***	***		
SDG12		12 Consumption&producti					***				***		***			*	*		
SDG13	Earth system	13 Climate action		9			** 32		*** 21	5	** 27	***			*** 1	***	***		***
SDG14		14 Life below water											*						
SDG15		15 Life on land	*				***		***	1	***	***	*** 1			*	*		
SDG9	Governance	9 Industry, innovation, infr					***				***		***						
SDG11		11 Cities	*				***				*		***						
SDG16		16 Peace																	
SDG17		17 Institutions																	

Figure 6.3: Comparison between topic modelling results (number of papers discussing two SDGs) and *model survey* average scores for the current representation of interactions among the SDGs. Overlap can be found in all cells filled with numbers in the topic modelling overview (first matrix) corresponding to above 0 average scores in the *model survey* (second matrix). The largest number of documents corresponds to the cell with the second highest score in the *model survey* (SDG 8 – SDG 13). Interactions indicated by survey respondents not found in topic modelling relate to SDG 12 – SDG 13, SDG 2 – SDG 15, SDG 7 – SDG 15, SDG 12 – SDG 15, and with SDGs in the governance cluster. As the topics were assigned uniquely to one SDG, SDG 12 is included in the topics falling under the other SDGs, thus not showing up separately.

The existing IAM literature focuses mostly on the interlinkages among 7 out of 17 SDGs, confirming the self-assessment of IAM modelers in the *model survey*. Almost all interlinkages involve the climate SDG (SDG 13) because climate change is a central theme of the analysed literature. In contrast, there are very few linkages among the non-climate SDGs alone. Most of these include linkages within and between the human development and resource use clusters (e.g. SDGs 7 and 8). Some interlinkages are not represented at all because they are only covered by a small number of studies and thus cannot be detected by our topic model. We believe that this is actually a feature of the analysis focusing on community practice as it only identifies interlinkages with a certain level of maturity without human bias.

As revealed by the results from the *model survey*, the most prominent interlinkages concern topics that have been of long-standing interest to the integrated assessment community, such as the link between climate stabilisation and transformations towards clean and affordable energy systems (Akashi et al., 2014; Luderer et al., 2014; Portugal-Pereira et al., 2016; Sano et al., 2014; van Vliet et al., 2014) or linkages to economic growth (Bibas & Méjean, 2014; Hamdi-Cherif & Waisman, 2016; Kriegler et al., 2014a; Leimbach et al., 2010; Li et al., 2017; Luderer et al., 2012; Reilly et al., 2012; van Vuuren et al., 2009). Large bodies of literature feature SDG interactions of medium importance according to experts. These discuss, for instance, the linkage between land-based mitigation options (SDG 13), in particular, bioenergy, and aspects around land competition and food security (SDG 2) (Hasegawa et al., 2015; Hayashi et al., 2015; Lotze-Campen et al., 2010; Lotze-Campen et al., 2014; Riahi et al., 2007; Valin et al., 2013), as well as water availability/security (SDG 6) (Bonsch et al., 2016; Bonsch et al., 2015; Gerbens-Leenes et al., 2009; Havlík et al., 2011; Lotze-Campen et al., 2010). Conversely, only a few studies have analysed biodiversity impacts (SDG 15) of land-based mitigation (SDG 13) (Eitelberg et al., 2016), an interaction that has been deemed as important according to the *expert survey*. Finally, some studies have examined the air pollution implications (SDG 3) of alternate climate mitigation pathways (SDG 13) (Bollen et al., 2009; Braspenning Radu et al., 2016; Rafaj et al., 2013a; Rafaj et al., 2013b; Smith & Mizrahi, 2013), even though health impacts have been studied directly only in recent times (West et al., 2013).

6.3 Conclusions and discussion

6.3.1 Conclusions

With the adoption of both the SDGs and the Paris Agreement, a great challenge and opportunity lies ahead for IAMs. IAMs appear capable of adapting and of including more interactions among the SDGS. The SDGs now call for further model development towards integrated sustainable development pathways (SDPs), maximising synergies and minimising trade-offs, in order to ensure policy coherence. Such SDPs should cover a more comprehensive range of SDGs and their targets and indicators, while specifically considering interactions among them (e.g. between eliminating poverty and hunger, which is an interaction that is set to be included in some of the models that participated in the *model survey*).

Forward-looking, model-based analyses of interactions are critical for informing such integrated SDPs. They supplement case studies that can only cover combinations of policies that have been implemented in the past. These pathways are important not only for assessing potential future developments and consequences but also for informing policymakers on achieving SDPs, based on a systemic understanding of human–environment interactions.

The objective of this article is to show how IAMs can contribute to the analysis of all 17 SDGs and the development of integrated policies. **We find that 3 SDGs are well-covered and 10 can at least partly be quantified by IAMs, while 4 are clearly not well covered in these models.** Areas identified for model development include oceans, consumption and production patterns, cities (in relation to public transport and buildings, including e.g. compactness/polycentrism), inequalities (especially for national models and CGEs), health (in relation to food, air pollution, climate change, and life below water and on land), poverty, and, to some extent, education (on an aggregated level, and possibly through coupling with specialised education models).

Key interactions among SDGs according to the *expert survey* were found within the human development cluster, between the human development and resource clusters, and with the Earth system cluster. Addressing many of them but with a slightly different focus because of their original design, **IAMs mainly cover interactions within and between the 'Efficient and sustainable resource use' and 'Earth system' clusters**. However, they have expanded to other fields, covering the 'Good governance and infrastructure' and 'Human development' clusters to some extent. The strength of IAMs lies in their ability to provide a global picture, highlighting the differences between regions and including displacement effects, but also between, for instance, cities and rural areas. **Planned developments include increased coverage of the human development cluster**, with interactions that have been deemed important by experts but are currently not (well) represented by the existing models. Model development is possible in some cases, but other tools may be more appropriate in other cases. Although gaps in the representation of SDG targets, indicators, processes, and interactions exist, IAMs provide a good starting point for more comprehensive SDG assessments. **IAMs have proven capable of expanding their applicability and of assessing interactions between sectors and regions** (Riahi et al., 2017).

6.3.2 Discussion: IAM research agenda

Looking at the relevant, known, and conceivable relationships among the SDGs, we identified areas for model development while recognising that not all models need to cover all aspects and interactions. IAMs are heterogeneous. Some lend themselves better to the study of certain SDGs, whereas others are better suited for other SDGs. One limitation of the analysis is in the number of models surveyed. This limitation implies that results apply to mitigation- and process-focused IAMs, although the synthesis of the literature helped broaden the scope. As these models represent the state of the art, the findings are relevant for identifying areas for future research and for describing how current IAMs can be used in the analysis of SDGs. The resource use and human development clusters have the potential to improve the models further. This includes the effects of addressing poverty on health and economic growth (possibly through model coupling), of (renewable) energy on cities (possibly through modules or model coupling), of education on inequalities (possibly through model coupling), of climate action on oceans (possibly through model extensions), and of cities on water and economic growth (possibly through model extensions). Model development can also include a component on improving current relationships because many IAM indicators related to SDG targets are currently based on either exogenous inputs or endogenous outputs without feedbacks ('impact indicators'), thus representing one-directional relationships. Here, a distinction can be made between 1) tracking SDG progress, for which improving the representation of SDG indicators is necessary, and 2) solutions, for which IAMs may need to improve the representation of processes relevant for the SDG indicator and the interaction dynamics. Combining models that cover a selection of these aspects can help present a broad overview. An example of this approach is the integration of life cycle assessment methods with IAMs. Doing so allows a more systematic and comprehensive analysis of the interactions between the SDGs in the resource and Earth system clusters. After the survey presented here was conducted, substantial progress was made in this area (e.g. Arvesen et al., 2018; Mendoza Beltran et al., 2020).

Going beyond studying how the SDGs are affected by climate policies is important. Evaluating the impact of achieving the human development goals on climate, ecosystems, and resource usage can be a good starting point.

In addition to interactions among the policy domains, interactions among different geographical scales should also be considered (Bijl et al., 2018). As Weitz et al. (2018) and Moyer et al. (2019) indicated, ultimately SDG targets will have to be interpreted in specific settings with appropriate formulations of the targets considering the national circumstances in question (political, economic, and social contexts). The SDG *expert survey* confirmed that SDG targets speak to multiple scales in both the problem and solution dimensions. Besides better coverage of SDG targets and their interactions, sufficient temporal and spatial resolution is necessary to assess the potential strategies for reaching the SDGs (see Table S6.3.2). Allen et al. (2016) suggested that models would be most useful for the SDGs if they have a long time horizon, support analysis at the national scale (with linkages to global feedbacks), have broad sectoral coverage (supporting analysis of interlinkages across goals), and are able to simulate the transformations required for achieving the SDGs. The IAMs assessed here generally have these abilities, but the granularity is limited for several SDG-relevant aspects. The incorporation of detailed policy instruments in models is an important step in simulating the required transformations. In CD-LINKS, models have started to implement individual policy measures and targets in G20 countries in the scenarios that were developed under the project (CD-LINKS, 2017). However, it is necessary to enhance model capabilities in this area. While the resolution of individual models can be increased (e.g. Li et al., 2018; Vernon et al., 2018), interactions among models focusing on different scales seems useful as global relationships are not necessarily the same at the local level. National and global models will need to exchange information, for example, through harmonised future storylines such as the Shared Socioeconomic Pathways (SSPs, Riahi et al., 2017) and the exchange of information on national policies and political circumstances and global boundary conditions such as carbon budgets, as was done in the COMMIT[19] and CD-LINKS[20] projects, for instance. Global models will be necessary to fully capture global SDG processes, while national IAMs and other tools and models are necessary for higher spatial and temporal resolution, for example, for assessing energy access targets (C. Allen et al., 2016). It is necessary to go beyond scale and move away from averages towards explicit modelling of heterogeneity as many SDGs are distributional issues, especially human development goals (see e.g. Rao et al., 2017). This could be done endogenously, or by building more detailed modules and linking them to the integrated assessment framework.

6.3.3 Discussion: cooperation and interdisciplinarity

Although many gaps can be closed by integrating more SDG dimensions in IAMs, full endogenisation of all interactions is not possible (e.g. because of numerical limitations or lack of clear-cut dynamics) and is probably not desired in some cases. In such cases, linking different disciplines through exogenous assumptions and a common narrative is an alternative option. This approach was formalised and put into operation as part of the SSPs (O'Neill et al., 2017; Riahi et al., 2017). This holds true especially for targets related to the institutional and social dimensions of the SDGs that are often crucial for enabling other SDGs. IAMs will need to cooperate more closely with social sciences, as understanding biophysical processes is no longer sufficient while studying SDGs (e.g. demography, governance, and poverty research). This could, however, increase intrinsic uncertainty in projections, thus necessitating the careful communication

19 https://themasites.pbl.nl/commit/

20 https://www.cd-links.org/

of results. Whereas using a consistent set of exogenous assumptions rather than endogenisation cannot fully capture feedbacks, it can be a good starting point. Closer cooperation within the IAM community can contribute to closing gaps, for example, by applying different IAMs, each according to their strengths, in one framework (as, for example, already done in the development of the SSPs, with each model detailing one storyline such as the one for SSP1). Future research can examine the overview of how interactions are modelled with experts on associated SDGs (such as those in the *expert survey*), given the importance of uncovering the mechanisms underlying the interactions identified.

As Figure 6.1 (blue hatched cells) showed, many interactions that were deemed important are neither covered by IAMs nor conceivable to be represented in the future. These include the effects of, for example, SDGs related to human development and governance and infrastructure on many other SDGs. However, these interactions can still be covered to some extent, for example, in more abstract ways or, most importantly, by linking with other tools and communities. Such an approach relates to the modular operation of IAMs. Looking at the effect of other SDGs on each cluster highlights the potential for studying how human development goals affect each other, as well as resource use and Earth system SDGs. Future research can focus on these interactions and expand the analysis by explicitly identifying and empirically testing the causal links underpinning the interactions classified in the *expert survey*.

Multi-model frameworks can help fill some of the gaps related to both scale and topic. Soft-linking to other more qualified models can also be a good starting point, possibly even moving to integrated assessment frameworks that include these different models. Such multi-model frameworks can help capture multi-sectoral dynamics that are not endogenous to the models themselves. As decision-support tools, these frameworks can provide information at finer spatial and temporal resolutions while maintaining consistency with global boundary conditions (e.g. CD-LINKS, 2017; Harrison et al., 2016; Kraucunas et al., 2015; Lotze-Campen et al., 2018). Beyond modelling, however, IAMs will need to be combined with empirical research to bring in the local context and experience pertaining to strategies that work in different settings, as IAMs cannot and probably should not even try to represent everything. Although empirical research on interactions has been going on, for example, in climate impact studies, a major shift is necessary to help translate IAM results into concrete policy recommendations.

6.3.4 Policy implications

IAMs have already informed global and national policy on climate change mitigation, both through IPCC assessments and, for example, with individual model applications such as the International Futures (Hughes, 2019) and iSDG (Millennium Institute, 2017) models and several national energy system models (COMMIT, 2018). These tools can promote policy coherence for the SDGs, by structuring complexity, exploring uncertainties pertaining to the impact of policies with scenarios, and reconciling contested views through common narratives, including by bringing different ministries together. They can help track dynamics, including trickle-down effects of various policy targets and instruments, and second-order interactions, to help policymakers identify and minimise trade-offs while maximising synergies.

6.4 Methods

6.4.1 SDG expert survey

Expert consultation is useful in investigating interactions among the SDGs, because experts can appraise causality, that is, the processes underlying the observed and identified synergies and trade-offs, which correlation analyses would not be able to provide. It is also complementary to the literature review, indicating the relevant relations that are not covered in the literature. The SDG experts were identified and selected through the following process:

1. Subject experts involved in the Elsevier study on sustainability science (Elsevier, 2015) were chosen first.

Gaps in the coverage of SDGs were filled with the following sources:

2. Experts who drafted the UN Global Sustainable Development Report (2019);
3. All those who were invited to attend the meetings of the 'The World in 2050' project regardless of whether they attended the meetings;
4. Authors of the ICSU/ISSC review of the SDG targets (ICSU & ISSC, 2015);
5. Members of the professional IISD SDG mailing list (listserv).

The survey was piloted with a small subset of the target group to ensure that the questions were clear. After this, each expert in groups 1 to 4 was contacted individually via email. The aim of the survey was explained. They were invited to provide suggestions for additional experts that we could contact (snowball sampling technique). A total of 20 experts participated in the survey (19% of the 105 contacted, see S6.1.1 Expert survey on interactions among SDGs for an overview of the number of experts per SDG), conducted from 2 November 2017 to 14 March 2018. For group 5, the same email was sent to the mailing list, but with a different hyperlink to a copy of the survey (conducted between 27 November 2017 and 14 March 2018), so responses could be tracked separately. For this group, additional questions pertaining to the respondents' backgrounds and areas of expertise were added (see S6.1.1 Expert survey on interactions among SDGs) in order to filter responses of this self-selected group (given that they were invited through an anonymous email list rather than approached individually). To be included in the matrix, experts had to have a selfassigned score of above 6 for level of knowledge on the topic (i.e. 7–10), resulting in 30 useful responses from group 5, additional to the 20 responses from groups 1 through 4, that is, 50 in all. Except for SDG 5, all SDGs were covered at least once, but the distribution was skewed towards SDGs 7, 11, 15, and 17.

Two types of biases can be distinguished in expert elicitations: motivational (related to personal interests and circumstances) and cognitive (related to heuristics, and originating from the incorrect processing of information) biases (Baddeley et al., 2004). The former can be limited by framing questions appropriately and asking for an honest response. The latter are more difficult to control but were considered as playing a minor role in this survey. For example, the *availability, anchoring, and adjustment* and *representativeness* heuristics were expected not to play a role, as the probability of events did not have to be assessed. Asking the experts to use a given framework to score the interactions ensured standardised responses (the seven-point typology by Nilsson et al. (2016), which does not measure the strength of interactions but only classifies them as follows: -3 for cancelling, -2 for counteracting, -1 for constraining, 0 for consistent, +1 for enabling, +2 for reinforcing, and +3 for indivisible, International Council for Science, 2017). *Overconfidence* is more likely to affect the results, although the framework for scoring interactions consisted of qualitative descriptions of each score, which enabled the mapping of each interaction to the most appropriate description rather than merely assigning numbers. Structured protocols for expert elicitation can also help reduce biases further. However, they are generally aimed at addressing questions with probabilistic or quantitative responses and in-person meetings, such as the IDEA protocol as described by Hemming et al. (2017), which do not apply to this study.

The survey was administered online for geographical flexibility and cost-effectiveness, and to provide respondents with the option to take the survey anytime (including pausing and continuing later). It consisted of four question groups that were aimed at eliciting standardised results and included ‘no answer’ options to avoid forced choices. Future research can consider applying the Delphi method (Gordon, 1994), in which experts can react to information from and explanations offered by other experts in a number of iterations. This would refine and enable the analysis of uncertainty in expert judgement.

Experts were asked to fill in only information that pertained to the areas of their expertise and at the level of the SDGs. Some respondents raised concerns saying that the scores at the SDG level were meaningless because the interactions among targets vary and result in the co-existence of synergies and trade-offs at the SDG level. Therefore, the sign (positive or negative) was not used. Wherever possible, respondents were asked to specify target-level interactions.

6.4.1.1 Survey questions

1. Which SDG best covers your field of expertise? (Broader interpretation of SDG than the strict formulation of goal and targets allowed, and please specify interpretation of SDG13).
2. How would you like to answer the next question? 1) Fill in one matrix at once, both for how your SDG affects other SDGs and how it is affected by others or 2) In two separate questions, one for how your SDG affects other SGs, one for how your SDG is affected by others
    a. Could you please indicate how the SDG that covers your field of expertise interacts with other SDGs? Please do so in the following way: - Use the column to indicate how your SDG affects other SDGs, i.e. the effect of your SDG in the column on the SDGs in the rows - Use the row to indicate how your SDG is affected by other SDGs, i.e. the influence of SDGs in the columns on your SDG in the row. As such, you will only fill one row and one column of the matrix. In filling in the matrix, please score the interactions, using the ICSU framework see picture below; (International Council for Science, 2017). I.e. 3 indivisible, 2 reinforcing, 1 enabling, 0 consistent, -1 constraining, -2 counteracting, -3 cancelling. Please use N/A for no interaction between the two SDGs, and unclear if there is an interaction, but the direction is not clear. As this question only allows numerical input, both N/A and unclear are separate columns/rows. Source: ICSU (click picture to enlarge). If you can, please specify target-level interactions in the next question.
        i. Optional comments
    b. Could you please indicate how the SDG that covers your field of expertise interacts with other SDGs? Could you please score the interactions, using the ICSU framework (see picture below)? I.e. +3 indivisible, +2 reinforcing, +1 enabling, 0 consistent, -1 constraining, -2 counteracting, -3 cancelling. Please use N/A for no interaction between the two SDGs, and unclear if there is an interaction, but the direction is not clear. Source: ICSU (click picture to enlarge). In this part, please assign scores only for how your SDG is affected by other SDGs (i.e. the influence of SDGs mentioned in the columns on your SDG). If you can, please specify which targets are affected in the next question.
        i. Optional comments
    c. Could you please indicate how the SDG that covers your field of expertise interacts with other SDGs? Could you please score the interactions, using the ICSU framework (see picture below)? I.e. +3 indivisible, +2 reinforcing, +1 enabling, 0 consistent, -1 constraining, -2 counteracting, -3 cancelling. Please use N/A for no interaction between the two SDGs, and unclear if there is an interaction, but the direction is not clear. Source: ICSU (click picture to enlarge). In this part, please assign scores

only for how your SDG affects other SDGs (i.e. the influence of your SDG on the SDGs mentioned in the rows). If you can, please specify which targets are affected in the next question.

i. Optional comments

3. Looking at the individual SDG for your field of expertise, would you describe it as a local, transboundary or global issue?
   a. Problem
   b. Solution
4. Further comments; please leave your e-mail address if you are interested in the outcomes.

6.4.1.2 Processing of results

Figure S6.2.3 colour codes the interactions based only on the *expert survey* in which combined scores of 0 are grey and scores between 1 and 3 move from lighter to darker blue, while the scores between -1 and -3 move from lighter to darker red. Multiple responses in one cell of the interaction matrix were combined with the mode wherever possible (i.e. most occurring score, being -3, -2, -1, 0, 1, 2, or 3), and maximum wherever it was not possible. For Figure 6.1, individual responses from the SDG *expert survey*, after removing the sign (i.e. -2 was recorded as 2) were combined with individual responses from the *model survey* question on the 'importance' of interactions, by averaging them with equal weighting of all individual responses. This score aggregation was necessary for the integration of all the experts' responses into the same question in two different surveys.

6.4.2 Model survey on representation of SDGs and interactions among SDGs

The survey was conducted among modellers who participated in the CD-LINKS project. The CD-LINKS project analyses the interplay between climate action and development to inform the design of complementary climate–development policies. It is, thus, well suited for the objective of this study.

The interpretation of SDG targets and indicators deserves attention while studying the representation of SDGs in IAMs. We have adhered to the SDG indicators that were formulated by the inter-agency expert group on SDG indicators (IAEG-SDG, 2017) as far as possible, but also included other IAM indicators that were thought of as representing the SDG targets well. This is especially true for SDG 13 (climate action), which focuses on resilience, climate strategies, and education, and refers to the UNFCCC. The IAEG-SDG indicators for this goal (mostly 'number of countries that have/adopt… policies') can generally not be modelled by IAMs per se, but IAMs do report many other highly relevant climate-related indicators. A broader interpretation of SDG targets and indicators is necessary to reflect the physical linkages included in IAMs, beyond the 'political' linkages among the SDGs (see also Le Blanc, 2015). Indirect or second-order interactions were not considered. Internal links (e.g. from SDG 2.4 to SDG 2.1) were excluded from the analysis in order to focus on interactions among the SDG areas. The same holds true for targets that are in some way a sub-target or element of another (umbrella) target (e.g. 6.2, access to sanitation, and 7.1, access to energy, can be considered elements of 1.4, access to basic services): these 'links' were excluded from the analysis, but they represent policy coherence thinking within the SDGs. The so-called 'Means of implementation' (a, b, c sub-targets) were also excluded from the analysis. SDG 17 was included, but it can be considered a 'means of implementation' and is difficult to measure. SDG 17 is, however, part of the rationale for this study, highlighting the importance of policy coherence for sustainable development. China TIMES and IPAC were only included in the assessment of the representation of individual SDG targets and not in the assessment of interactions, as that part of the survey was not filled in completely.

6.4.2.1 Survey questions

1. *Model representation of individual SDGs (now):* Please indicate the suitability of your model to represent a certain SDG by a score of 0 (not suitable) to 5 (very suitable). Also indicate maximum 5 key indicators that your model could provide for that particular SDG.
2. *Model representation of individual SDGs (planned):* Same as previous sheet but include planned model development.
3. *Important interactions:* We would like you to assess the importance of the interactions between different SDGs. Clearly, these interactions can go in different directions. Therefore, please assume that the rows indicate the target SDGs and the interaction thus indicates how important the other SDGs are for achieving the row. We would like you to assess the importance of the interactions between different SDGs. Clearly, these interactions can go in different directions. Therefore, in answering, do not restrict yourself to only those interactions that can be modelled: the idea is to score all possible, important, interactions. We would like you to score the linkages on a scale of 0 (no or very little impact) until 3 (strong impact). Not necessary to fill in the 0 values (no number is assumed to be zero).
4. Modelled *interactions (now):* Please fill in the interactions between the different SDGs as represented by your model. Indicate each link by scores 0 (not represented) to 3 (plays a key role in the model). If possible, please specify the modelled interactions at the target-target level (e.g. SDG 7.2–6.3).
5. *Modelled interactions (planned):* Same as previous sheet but include planned model development.
6. *Modelled interactions (conceivable)*: Please fill in the interactions between SDGs that are conceivable to be modelled by IAMs, i.e. score the interactions identified in step 1 for representation in IAMs in general.

6.4.2.2 Processing of results

Scores were averaged across all the models for each question. As personality or cultural biases may have entered while assigning levels to represent the SDGs adequately in the models, teams were asked to map their 0–5 scores onto a scale with descriptions for normalisation (see SI), although all model teams used the full 0–5 range. Based on the mapping, original scores for two models were revised before averaging (see SI). Three stars were assigned to Figure 6.1 when the average score in question 4 was at least 1, two were assigned when the average score in question 5 was at least 1, and one was assigned when the average score in question 6 was at least 1. For the colours in Figure 6.1, individual scores of question 3 were combined with individual scores from the SDG *expert survey* (see above). The SI also shows a table with colours assigned based only on the *model survey*, where average scores below 1 were left blank and average scores between 1 and 3 were colour coded from lighter to darker orange.

6.4.3 Synthesis of literature: topic modelling

We applied topic modelling to identify well-established interlinkages among different SDGs in the available IAM literature. Topic modelling refers to a suite of algorithms that aim to unravel the latent thematic structure of a large and unstructured collection of documents (Blei, 2012). The idea here is to discover this thematic structure, link the identified themes or topics to SDGs where appropriate, and analyse the co-occurrence of SDG-related topics in documents. By doing so, we can obtain a bird's eye view of the interlinkages that have been substantively discussed in the literature so far. Our methodology proceeded in three steps:

1. Identifying the literature base;
2. Discovering the latent thematic structure of the identified literature; and
3. Linking topics/themes to SDGs.

These steps will be discussed below.

6.4.3.1 STEP 1: identifying the relevant literature

To generate meaningful results, it is crucial for our literature base to be broadly representative of the studies on integrated assessment modelling. For this study, integrated assessment modelling has been defined as any model describing key processes in the interactions between human development and the natural environment. Different types of models were developed with varying levels of detail and focus areas. These models are all included here.

We developed a dedicated literature identification strategy with two major components. The first component relied on expert surveys. Within the CD-LINKS project consortium, we asked all 17 modelling teams to provide comprehensive reference lists attesting to their past activities related to SDG themes. Of the 17 teams, 12 responded. We also asked all members of the Integrated Assessment Modelling Consortium (IAMC)—the major community organising initiative within integrated assessment—to provide lists of publications for their respective models as well, and 9 teams responded. The second component involved adding the remaining publications from major model inter-comparison exercises, namely EMF-27 (2018), PATHWAYS, CD-LINKS, and LIMITS.

We collected 429 documents in all. Of these, we were able to obtain the full text versions of 402 documents. We discarded model documentations (15) and protected pdf files (4) from the sample, because our text extraction tool could not read them. We ended up with 383 documents for our analysis: 299 peer-reviewed articles and 84 working papers, reports, book chapters, and theses. Our sample does not cover the entire integrated assessment literature because of 1) the differences in responses across teams, and 2) better coverage of more recent publications. To the best of our knowledge, this is the most comprehensive review of the IAM literature related to SDGs to date.

The sample is broadly representative of the literature because of the comprehensive involvement of the integrated assessment community. For the sake of validation, we compared the results from topic modelling with the independent model expert evaluation of the existing modelling capabilities for SDG interlinkages. Within the limits of topic modelling (interlinkages of individual pioneering studies cannot be identified, see below), this comparison confirms the results from our topic model and provides a two-way validation of our results.

6.4.3.2 STEP 2: topic modelling

Several additional preliminary steps are necessary before applying topic modelling. First, we extracted the entire text from the 383 documents that served as our text corpus for the analysis that followed. We filtered out sections containing irrelevant information for our assessment, such as references and appendices. We processed our literature corpus by stemming and removing punctuations, numbers, and stop words. The result was used to generate a document-term matrix that comprised the term frequencies in the documents. We used the popular Term Frequency-Inverse Document Frequency (TF-IDF) term-weighting scheme to ensure that common words were filtered out of the corpus. This statistic combines the measures of term-frequency with inverse-document-frequency to give more weight to terms occurring frequently over a small number of documents and less weight to terms occurring in several or all documents or to terms that occur fewer times in a document. This procedure can also be seen as a means to remove noise.

Next, we applied topic modelling to uncover the latent thematic structure of our text corpus. Topic modelling proceeds on the assumption that words systematically co-occur within certain documents, and that repeated co-occurrence indicates a shared semantic structure across the corpus (Blei, 2012). We used Non-negative Matrix Factorisation (NMF), which is an unsupervised machine learning algorithm (Lee & Seung, 1999; Lee & Seung, 2001) that has been used in a number of previous scientific studies to identify topics in corpora (Arora et al., 2012; Belford et al., 2018; Du et al., 2017; O'Callaghan et al., 2015). NMF factors the document-term matrix into a document-topic matrix and a topic-term matrix. The document-topic matrix provides a measure of topic prominence in documents whereas the topic-term matrix provides a description of topics by ranking the terms associated with them. As the number of topics needs to be specified exogenously, we ran NMF with different numbers of topics (i.e. 10, 12, 14, 16, 18, 20, 25, 35, 40, 50, and 60). The resulting allocations of documents and terms to topics were then manually and independently analysed by multiple people. We found that 14 topics provided a meaningful synthesis and classification of the literature and covered a broad spectrum of themes while minimising the number of topics with little additional information (i.e. overfitting).

6.4.3.3 STEP 3: linking topics/themes to SDGs

We characterised each topic based on the key features revealed through a study of high-scoring documents and their most prominent keywords. The results are presented in Table 6.3. Topics at the top of the table have a higher marginal distribution and are more frequent in the integrated assessment literature. A more comprehensive discussion of results can be found in the SI. Next, we manually matched the topics to the SDGs. Matches can occur more generally at a goal-level or more specifically at a target-level. We reviewed documents that scored highly on a particular topic and compared them with the relevant SDGs and targets. For example, the topic on mitigation scenarios (1) deals with mitigation strategies and emissions reduction. It contains many documents that deal with climate change mitigation in line with the international climate goals. However, it does not relate to any of the more specific targets. We therefore matched it at the goal level. The topic on food security (4), on the other hand, directly relates to different targets under SDG 2, and to related indicators such as the ones on agricultural productivity (2.3) or sustainable food production (2.4). Of the 14 topics, 3 did not relate to any SDG (3, 11, 12).

Table 6.3: 14 topics synthesising the content of the available IAM literature. For each topic, the manually allocated SDG and the top 5 stemmed keywords are provided. The marginal topic distribution is a measure of the importance of a topic across the literature.

ID	Topic name	Stemmed keywords	Marginal topic distribution	SDG
1	Mitigation scenarios	emiss, reduct, scenario, mitig, cost	17.46	13 – target*
2	Carbon pricing and mitigation costs	price, carbon, scenario, sector, product	16.51	13 – target
3	Sustainable transitions and governance	transit, govern, actor, social, sustain	14.25	None
4	Food security	food, crop, scenario, product, yield	12.27	2 – target**
5	CCS, bioenergy, and negative emissions	CCS, scenario, fulltech, technolog, bioenergi	11.01	13 – goal
6	Land-based mitigation	land, bioenergy, crop, forest, product	10.11	13 – goal
7	Low-carbon electricity	plant, power, brazilian, brazil, csp	10.09	7 – target
8	Air pollution and health	pollut, air, emiss, aerosol, forc	9.34	3 – target
9	Water availability and consumption	water, irrig, withdraw, cool, river	9.22	6 – target
10	Low-carbon electricity II	nuclear, technolog, electr, power, wind	9.12	7 – target
11	Energy security	secur, oil, scenario, indic, divers	7.65	None
12	SSP scenario framework	ssps, scenario, rcp, narrat, socioecono	7.34	None
13	CBA of climate policies	Damage, cost, adapt, mitig, dice	7.00	13 – goal
14	Species abundance and biodiversity	speci, dispers, biodiverse, msa, migrat	4.04	15 – target

Finally, we identified documents that substantially deal with SDG interlinkages. We assumed that such a substantial interlinkage occurs if a paper deals with two topics that relate to two different SDGs and the related topic scores pass a certain global threshold. To do so, we asked multiple team members to assess the topic quality in papers at different thresholds. We identified this threshold at a topic score of 0.1. We then removed the interlinkages between topics within the same SDG.

We do not claim that our topics cover the SDGs comprehensively. The coverage differs considerably in terms of the number of relevant topics for a particular SDG (see Figure 6.2), but equally in terms of the relevance of an individual topic for a particular SDG. Through the text, we interpret our results very carefully. Any link identified is seen as evidence for research that is relevant to some aspect of the respective interlinkages. We leave it to the other components of this paper to qualify them in very concrete terms. We also acknowledge that we only find interlinkages in fields in which the literature has already begun to mature. Pioneering studies that deal with new interlinkages will not be identified by this procedure. Yet, we see this as a feature of our analysis here as it shows the areas of substantive research alone.

Based on the stemmed keywords belonging to each topic (ordered by importance) and a thorough look at the documents pertaining to the topics, the topics were manually associated with the SDGs and targets (see Table 6.3). Of the 14 topics, only 11 were associated with an SDG target or goal.

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Author contributions

H.v.S. designed, distributed, and analysed both surveys, collected inputs for the literature review, and designed the paper. D.v.V. contributed to paper design and analysis of survey results. M.H. contributed to the *model survey*. V.K. contributed to the design of the SDG *expert survey*. K.R. contributed to paper design and *expert survey* distribution. J.M. contributed to the literature review. J.H. performed the literature review and formatted the figures in the main text. A.P. and G.L. contributed to the *model survey*. All authors participated in writing the paper.

7

Summary and conclusions

This chapter serves two purposes: summarising the thesis and adding some discussion and conclusions. Chapters 7.1 and 7.2 summarise the Introduction (Chapter 1), Chapter 7.3 summarises the main findings with the conclusions from Chapters 2 through 6, and Chapter 7.4 offers a discussion and recommendations for research and policy.

7.1 Introduction and research questions

7.1.1 Paris Agreement and Global Stocktake

Parties to the Paris Agreement agreed to limit global warming to 'well below' 2 °C relative to pre-industrial levels, and strive to limit it further to 1.5 °C; to reach a peak in global greenhouse gas emissions as soon as possible, and achieve a 'balance' between anthropogenic sources and sinks of greenhouse gases in the second half of the century. Policies, however, need to be implemented at the national level. Parties were asked to submit their self-determined mitigation targets in so-called Intended Nationally Determined Contributions (INDCs). Upon ratification of the Agreement, an INDC would become a Nationally Determined Contribution (NDC). However, the Parties foresaw that such voluntary pledges were not likely to lead to the global emission levels in line with the goals of the Paris Agreement. Therefore, they also agreed on processes to regularly take stock of the aggregate effect of individual NDCs and ensure ambition levels would be raised over time: the Global Stocktake (GST) and ratchet mechanism, with a trial run in 2018: the Talanoa Dialogue. It centred around three overarching questions: where are we, where do we want to go, and how do we get there?

7.1.2 Emissions gap

Many researchers (Roelfsema et al., 2020; Rogelj et al., 2016) have observed a gap between emission levels needed to stay on a pathway in line with the 2 °C and 1.5 °C goals of the Paris Agreement and global emission levels expected as a result of full implementation of the NDCs. This **total emissions gap** can be further broken down into two distinct gaps (Figure 7.1): the **ambition gap**, i.e. the difference between emissions promised by countries in their NDCs and those in line with the well-below 2 °C and 1.5 °C targets, and the **implementation gap**, i.e. the difference between emissions expected under currently implemented climate policies and those needed to achieve the NDCs (a new dimension introduced by Roelfsema et al. (2020) and used in this thesis). While the 'ambition gap' has received plenty of attention, the 'implementation gap' is the one to focus on in this crucial decade for climate action. Put differently, the focus should be broadened: not only the Talanoa Dialogue question 'where do we want to go?', but also 'how do we get there?'. For setting targets ('where do we want to go?'), Integrated Assessment Models (IAMs) have proved useful (J. Rogelj et al., 2018; van Beek et al., 2020). With their increasing sectoral, spatial and temporal granularity, they can also inform the 'how' – with a detailed analysis of mitigation pathways.

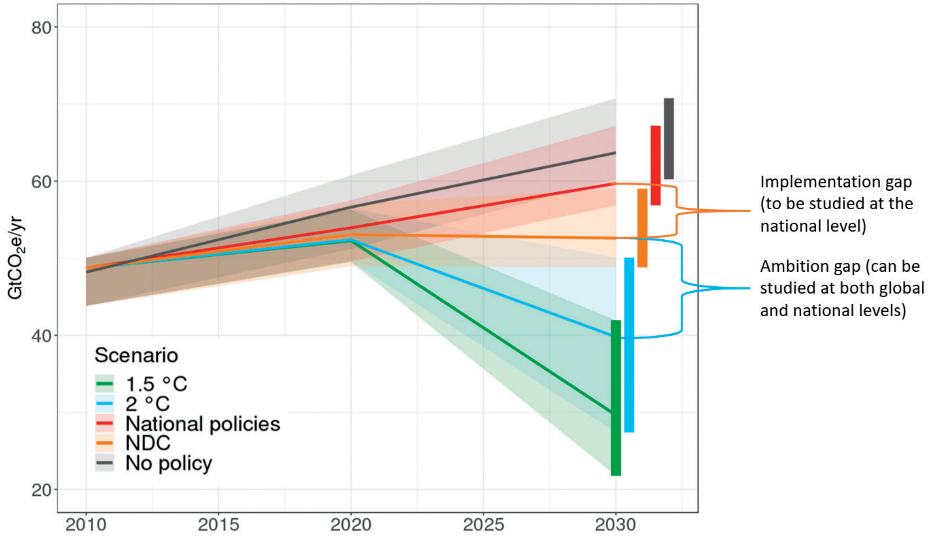

Figure 7.1: The global emissions gap (COMMIT & CD-LINKS, 2018), which can be broken down into an ambition gap and an implementation gap (included for illustration, as it needs to be studied at the national level).

7.1.3 Model-based analysis

IAMs are computational models to assess complex, long-term interactions between humans and their environment for a better understanding of global environmental problems. Broadly speaking, two types of IAMs can be distinguished: high-resolution or process-based IAMs, and cost-benefit IAMs. This thesis uses the process-based models. These IAMs disaggregate the world in multiple regions, which can either be single-country or multi-country. The IAMs that divide the world in more than one region are called global IAMs here, while those that focus on a country are called national IAMs[21]. IAMs are not meant to produce predictions; instead, they can help explore uncertain futures through scenarios (Riahi et al., 2017; van Vuuren et al., 2011). Such scenarios are plausible descriptions of how socio-economic, technological and environmental trends may develop. As a world government does not exist, implementation of the Paris Agreement's goals will need to happen at the national and other levels. Therefore, countries will need information that is tailored to their circumstances. National and sectoral models can be used to study national mitigation pathways with high granularity (Fragkos et al., 2021b; Schaeffer et al., 2020b).

21 Not all national models are IAMs: some focus, for example, on the energy system.

However, the application of national models in isolation will not be able to shed light on whether these pathways are in line with the global mitigation goals. In addition, analytical capacity differs strongly between countries. However, for negotiations, a joint information base is crucial to focus discussions on opinions rather than on (disputed) facts or numbers. That is why global IAMs have been applied in conjunction with national IAMs or energy system models in projects such as CD-LINKS (McCollum et al., 2018; Roelfsema et al., 2020; Schaeffer et al., 2020a; Schaeffer et al., 2020b; van den Berg et al., 2020), COMMIT (Fragkos et al., 2021b; van Soest et al., 2021), and ENGAGE. Global models provide the boundary conditions, such as cost-optimal national carbon budgets that globally are in line with a 1.5 °C or 2 °C goals, biomass availability, or energy prices (Hof et al., 2020), which national models can use as a constraint for their mitigation pathways.

7.2 Aim of the thesis and research questions

Considerable analysis has been conducted on the emissions gap and scenarios that limit global warming to well below 2 °C and 1.5 °C, both at the global and national levels. Still, critical questions remain. These are partly related to the emerging work on the linkages between global and national models and the new phase of international climate policy after the Paris Agreement. This new phase means that the focus is mostly on how to reach net-zero emissions and on which concrete policies to implement in the next one to two decades. At the same time, the transitions in the energy and land systems needed to meet the Paris goals need to be combined with the Sustainable Development Goals to maximise synergies and minimise trade-offs. We focus on these critical issues, leading to the following research questions, inspired by the Talanoa Dialogue. Even though the last question is key, the others are also needed for a comprehensive answer.

1. **Where are we?**
    a. *How large are the global ambition and implementation gaps?*
    b. *How large are the national ambition gaps?*
2. **Where do we want to go?**
    a. *When can countries achieve net-zero greenhouse gas emissions?*
3. **How do we get there?**
    a. *How can the global ambition gap be bridged?*
    b. *If we want to use the SDGs to inform increased national mitigation ambition, are IAMs fit for the purpose of studying the interactions between climate action and broader sustainable development?*

7.3 Main findings of the thesis

7.3.1 Where are we?

7.3.1.1 How large are the global ambition and implementation gaps?

Chapter 2 showed that, collectively, currently implemented climate policies are projected to lead to global emissions levels of almost 60 GtCO_2eq by 2030. Ambitions, as pledged in the NDCs, would bring that down to approximately 50 GtCO_2eq. The current policies scenario includes the current climate and energy policies of major emitting countries, such as the assumed implementation of renewable energy share or capacity targets, power plant standards, fuel efficiency standards for cars, and carbon prices. The NDC scenarios start from emission levels in 2020 resulting from current policies and 2020 pledges, and 2030 emission levels resulting from the full implementation of the NDCs. Implementation of NDCs is projected to result in a peak in global GHG emissions in 2030 at 50 GtCO_2eq. This is a reduction of 14% to 15% compared to the current policies scenario, but still an increase of 5% on 2010 levels.

There is a considerable gap between the implementation and ambition levels and optimal pathways in line with the Paris Agreement. A cost-optimal pathway that limits global warming to 2 °C, shows global 2030 emissions of approximately 40 GtCO_2eq, a reduction of 20% on 2010 levels (Figure 7.2). As such, roughly half of the *emissions gap* is formed by the *implementation gap*, while the other half consists of the *ambition gap*. Therefore, closing both parts of the *emissions gap* is crucial to keep the Paris Agreement's climate goals within reach. That means that *ambitions* need to be strengthened and, at the same time, policies need to be *implemented* to meet those ambitions.

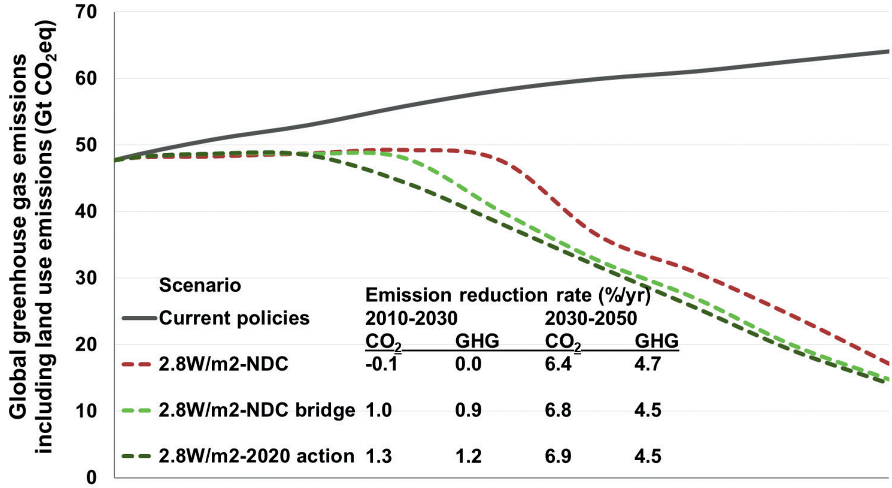

Figure 7.2: Global GHG emissions ($GtCO_2eq$/year) between 2010 and 2050, including CO_2 emissions from land use, under the current policies scenario (*solid line*), and the 2.8 W/m^2 scenarios (*2.8 W/m ^{2} -NDC*, *2.8 W/m ^{2} -NDC bridge* and *2.8 W/m ^{2} -2020 action*; *dashed lines*)

7.3.1.2 How large are the national ambition gaps?

Chapter 3 showed that the NDCs of almost all countries are projected to result in higher emissions than emission levels of cost-optimal 2 °C scenarios. Still, some countries have fairly ambitious NDCs. The NDCs of China, India, Japan, the Russian Federation, and Turkey, for example, are projected to result in emissions levels above those consistent with 2 °C. For Russia and Turkey, the emission projections of the NDCs are even above the baseline projections. The NDC projections for China and India are surrounded by uncertainties, driven by uncertain GDP projections. In contrast, the NDCs of Brazil, Canada, the EU, Mexico (conditional target), the Republic of Korea, and the USA would be relatively close to cost-optimal 2 °C scenarios, where 'close' is defined as less than 10 percentage point difference (Figure 7.3). At the global level, however, the sum of emission reductions projected to result from the implementation of the NDCs falls short of the reductions required in the cost-optimal 2 °C pathway.

Limiting global temperature increase to below 2 °C implies a substantial reduction of the cumulative CO_2 emissions (carbon budget) between 2010 and 2100 for each country. The national carbon budgets between 2010 and 2100 showed on average a 79% reduction between the baseline and the mitigation scenario, with the largest reductions projected for Brazil (95%) and Canada (91%) and the smallest for South Korea (52%). After full implementation of the NDCs, the world would be left with approximately 40% of the carbon budget for 2 °C for the rest of the century. Under the mitigation scenario, most countries' greenhouse gas emissions are projected to peak before 2025. Only Brazil, China, Mexico and Turkey have projected NDC peak years later than the model peak years for the mitigation scenario.

There are considerable differences between models. These may relate to either the model itself (e.g. type, structure and definitions, see Chapter 1.4) or the scenario implementation. For example, regional definitions may differ across models. Also, the representation of national specificities and policies differs. Other sources of model differences include projected baseline developments and land-use emissions (notably for Brazil).

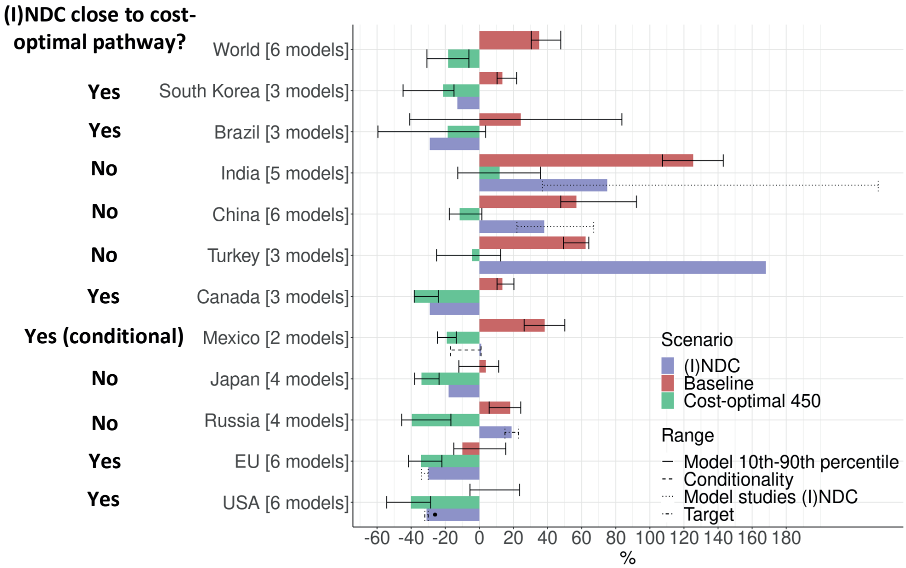

Figure 7.3: Kyoto gas emissions in 2030 projected by models for baseline and cost-optimal 450 ppm CO_2eq scenarios, compared to NDCs[22]. Total emissions are shown relative to 2010 (%, with positive numbers indicating emission increase). The number of models per country is indicated. *Filled bars* for baseline and cost-optimal 450 ppm CO_2eq show the median value across models; *error bars* show the 10th to 90th percentile range of the model results ('*Model 10th–90th percentile*'). For regions covered by less than three models, the range (minimum–maximum) is shown. *Filled bars* for NDC show the central estimate from Den Elzen et al. (2016), error bars the range. NDC ranges are of three types: range in the reduction target mentioned in the NDCs themselves ('*Target*'; Russia, USA), range resulting from unconditional and conditional targets ('*Conditionality*'; Mexico; *filled bar* shows the unconditional target; *error bar* shows the effect of moving to the conditional target) and range resulting from various model studies analysed in UNEP (2015) ('*Model Studies (I)NDC*'; India, China). For the USA, the NDC range consists of both '*Target*' (error bar, based on den Elzen et al., 2016) and '*Model Studies (I)NDC*' (filled circle, based on Emmerling et al., 2016). The *column on the left* shows whether a country's NDC is close to the cost-optimal 450 ppm CO_2eq projection, where 'close' is defined as less than 10 percentage point difference

7.3.2 Where do we want to go?

7.3.2.1 When can countries achieve net-zero greenhouse gas emissions?

More stringent emission reduction targets will be needed to close the *ambition gap*. Chapter 4 showed when 10 major emitting countries reach net-zero greenhouse gas emissions (hereafter: phase-out year, phase-out of greenhouse gas emissions) in

22 Numbers may be outdated, as they are based on the analysis published in 2017. Many countries have submitted new NDCs, often with more stringent emissions reduction targets, since then.

cost-optimal scenarios to help answer the question *Where do we want to go?* In those scenarios, the global average phase-out year for total greenhouse gas emissions is around 2070 for 1.5 °C and around 2090 for 2 °C, assuming that options for Carbon Dioxide Removal (CDR) are available (which will also be needed after the phase-out year). For CO_2 only, these dates are roughly 20 years earlier. Brazil, the United States, and Japan reach net-zero greenhouse gas emissions earlier than the global average in the cost-optimal scenarios (Figure 7.4). For Brazil, the difference with the global average generally is more than 20 years, while for the USA, the difference is around 10 years. In contrast, India and Indonesia typically have a phase-out year later than the global average (with an approximately 10 years difference). China, the EU, and Russia have phase-out years typically near the global average. The remaining five countries show a mixed picture: results vary across sources of emissions and temperature targets. For example, a country in which land use is a source of emissions (e.g., Indonesia) will see a later phase-out of total CO_2 emissions than of fossil CO_2 only, whereas the reverse is true for countries in which land use forms a sink (e.g. Canada).

When countries can reach net-zero greenhouse gas emissions according to cost-optimal scenarios is a different question than when they can in reality. For one thing, many countries have now set or announced official net-zero targets, often as part of their long-term, low-emission development strategy or long-term strategy (LTS) under the Paris Agreement. The targets set so far are in line with the cost-optimal phase-out years for 1.5 °C and 2 °C. However, the global division of mitigation effort is not likely to be cost-optimal; in reality, questions around equity will play a role. Therefore, countries may choose either an earlier net-zero target year than strictly required under cost-optimal scenarios (such as the European Union has done) or request financial aid to phase out greenhouse gas emissions earlier than deemed fair (such as India). These differences between countries relate to their mitigation potentials, notably the potential to realise negative emissions through afforestation or (BE)CCS[23]. The current situation also plays a role: for example, a higher current share of non-CO_2 emissions, which are more difficult to eliminate, would result in a later phase-out year.

More methodological factors further play a role, notably the allocation of negative emissions (accounting) and land-use data. Clear definitions and political agreement will be needed on these issues to produce meaningful outcomes for the global stocktake.

23 Direct Air Capture (DAC) was not (yet) included in the models.

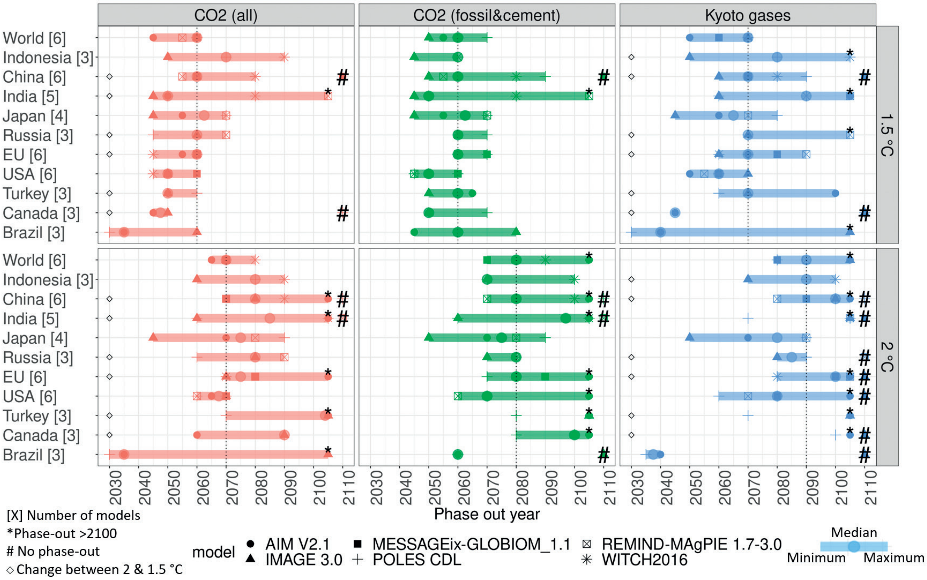

Figure 7.4: Year when projected emissions reach net-zero, per country (number of models representing that country between brackets), for 2 °C and 1.5 °C scenarios, for CO_2 emissions, CO_2 emissions from fossil fuels and cement (energy and industrial processes), and total GHG emissions (Kyoto Gases, including land-use emissions). Individual models are indicated by symbols, whereas the bars show the minimum–maximum range (enlarged circles: model median). In some cases, individual models show a phase-out after 2100 in the extrapolated data (indicated by an asterisk) or no phase-out at all (#). Diamonds plotted at the 2030 mark indicate a change between the 2 °C and 1.5 °C scenarios in terms of a country reaching net-zero earlier than, similar to, or later than the global average. Vertical dotted lines indicate the global average phase-out year.

7.3.3 How do we get there?

It is possible to close the ambition gap to a large extent by 2030 and fully by 2050, enabling meeting the 2 °C goal in the long run. This is shown by the theoretical *NDC-Bridge* scenario introduced in Chapter 2 (Figure 7.2) and the more concrete *Bridge* scenario discussed in Chapter 5 (Figure 7.5). Acting early is cheaper than delay and increases the chances of success by allowing for a smoother transition.

There are different elements to closing the *emissions gap*. Here, we study two: 1) analysing a concrete set of measures that can be implemented in the short term, showing potential for strengthening NDC *ambition* and 2) using the SDGs to inform increased *ambition*. However, an intermediate step is needed for the latter: if we want to use the SDGs to shape ambition, are IAMs the right tools?

7.3.3.1 How can the ambition gap be bridged?

To close the *ambition gap*, climate targets will need to be strengthened, while at the same time *implementing* climate policies to meet those targets. For that purpose, Chapter 2 presented a stylised Bridge scenario. Its additional emission reductions in the energy system were achieved by a combination of enhancing efficiency and scaling down the use of fossil fuels while increasing deployment of low-carbon energy sources. Scaling down fossil fuel use was a result of no investments in new coal power plants after 2025 and early retirement of existing capacity to phase out unabated coal between 2030 and 2060[24]. Chapter 5 presented a more refined Bridge scenario based on a concrete set of measures, so-called good practice policies, which can be implemented until 2030. These measures and their differentiated targets across high- and low-income countries were based on successful examples in countries and interaction with national experts. As such, they comprise a relevant and feasible list of options for all sectors (agriculture, land-use, energy supply, buildings, industry, transport, waste, other). For example, to increase the share of non-fossil in new vehicle sales to 50% by 2030 in high-income countries, 25% by 2025 in China, and 25% by 2030 in low-income countries.

When combined with comprehensive carbon pricing after 2030, such a Bridge scenario would close the global *ambition gap* between NDCs and cost-optimal 2 °C scenarios by two-thirds by 2030 (a median 7.2 $GtCO_2eq$ reduction of the 11.8 $GtCO_2eq$ gap) and fully by 2050 (Figure 7.5)**.** In the absence of immediate, all-encompassing and ambitious climate policy measures, successful implementation of good practice policies can not only put the world on track to a 2 °C-compatible pathway, but it would also be cheaper than delay. Also, the stylized Bridge scenario showed that enhancing the ambition level of NDCs before 2030 can allow for a smoother energy system transition, with lower annual emission reduction rates, more time to phase out unabated fossil fuels, and lower total mitigation costs.

24 In IEA's net zero scenario, this happens by 2040 - IEA. (2021). *Net Zero by 2050*. IEA. Paris https://www.iea.org/reports/net-zero-by-2050.

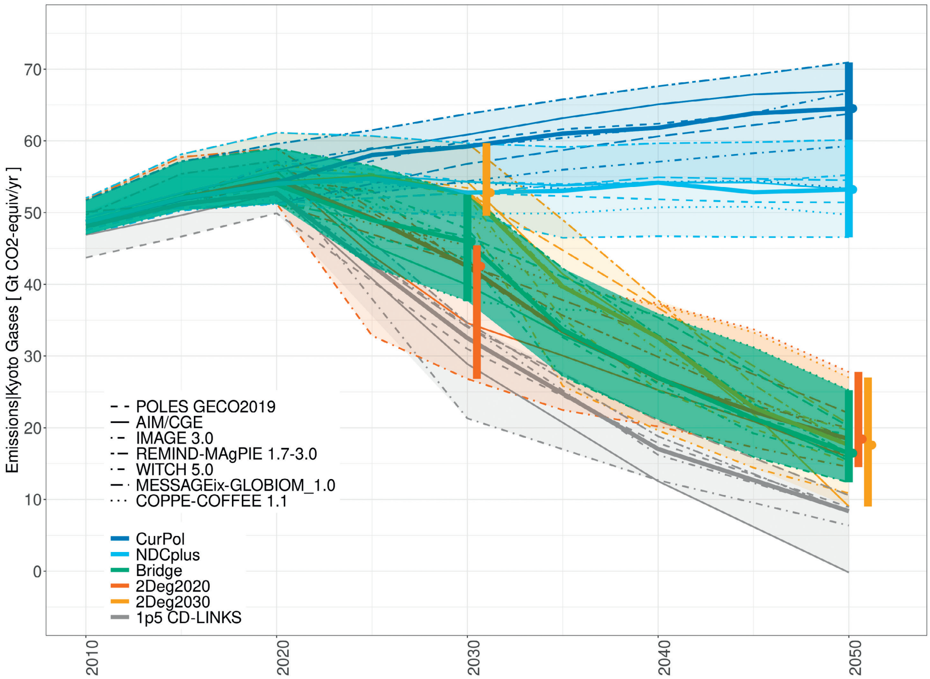

Figure 7.5: Global GHG emissions (Gt CO_2eq/year) between 2010 and 2050, as projected by the global models. Vertical bars: model range in 2050. Circles: model median in 2050. Thick solid lines: median. Grey: 1.5 °C scenarios from the IPCC SR1.5 database are included for comparison (a selection was made to cover the same models as represented here, with the most similar scenario set-up, i.e. the 1.5 °C scenarios developed in the CD-LINKS project). Projections for the Bridge scenario without the carbon tax measure are shown in Figure S5.2.7, NDCplus variant NDC_2050convergence in Figure S5.2.8, and 2050 – 2100 in Figure S5.2.9.

7.3.3.2 If we want to use the SDGs to inform increased national mitigation ambition, are IAMs fit for the purpose of studying the interactions between climate action and broader sustainable development?

The analysis in Chapter 6 showed that IAMs cover SDGs related to sustainable resource use and the Earth system well. Goals related to human development and good governance are less well represented – and might be more difficult for these models to fully capture. According to the expert survey, key interactions among SDGs were found within the human development cluster, between the human development and resource clusters, and with the Earth system cluster. Addressing many of them but with a slightly different focus because of their original design, IAMs mainly cover interactions within and between the ‘Efficient and sustainable resource use'[25] and 'Earth system' clusters (Figure 7.6). However, they have expanded to other fields, covering the 'Good governance and infrastructure' and 'Human development' clusters. The strength of IAMs lies in their ability to provide a global picture, highlighting the differences between regions and including displacement effects, but also between, for instance, cities and rural areas. Planned developments include increased coverage of the human development cluster, with interactions that have been deemed important by experts but are currently not (well) represented by the existing models. Model development is possible in some cases, but other tools may be more appropriate in other cases. Therefore, better representation of heterogeneity, using different models, and linking different disciplines will be needed.

Although gaps in the representation of SDG targets, indicators, processes, and interactions exist, IAMs provide a good starting point for more comprehensive SDG assessments. IAMs have proven capable of expanding their applicability and of assessing interactions between sectors and regions. As such, they can be used to inform closing the *ambition gap* through the SDGs. As a first step, the *Bridge* scenario presented in Chapter 5 showed notable co-benefits: emissions of air pollutants such as black carbon, carbon monoxide, nitrogen oxides, organic carbon, sulphur, and volatile organic compounds are projected to decrease, compared to the NDC scenario. More generally, Dagnachew et al. (2021) found significantly more synergies between mitigation measures and other SDGs than trade-offs in all world regions, highlighting the potential to ratchet up ambitions. Increasing the share of renewable electricity, for example, showed the most synergies with other SDGs, but technology choice matters. Complementary policies may limit potential trade-offs; for example, to shield the poor. Given IAM coverage of the effects of SDGs 2 (zero hunger), 7 (affordable and clean energy), 8 (decent work and economic growth), 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities), 12 (responsible consumption and production), and 15 (life on land) on SDG 13 (climate action), future work could, for example, look into how providing energy access through low-carbon energy sources may simultaneously stimulate climate ambition (e.g. Dagnachew et al., 2018).

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25 Including SDGs 2, 6, 7, and 12, i.e. not only covering energy resources but also e.g. water, food, metals, and materials – See for an example of coverage of the latter in an IAM: Deetman, S., de Boer, H. S., Van Engelenburg, M., van der Voet, E., & van Vuuren, D. P. (2021). Projected material requirements for the global electricity infrastructure – generation, transmission and storage. *Resources, Conservation and Recycling*, *164*, 105200. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.105200 .

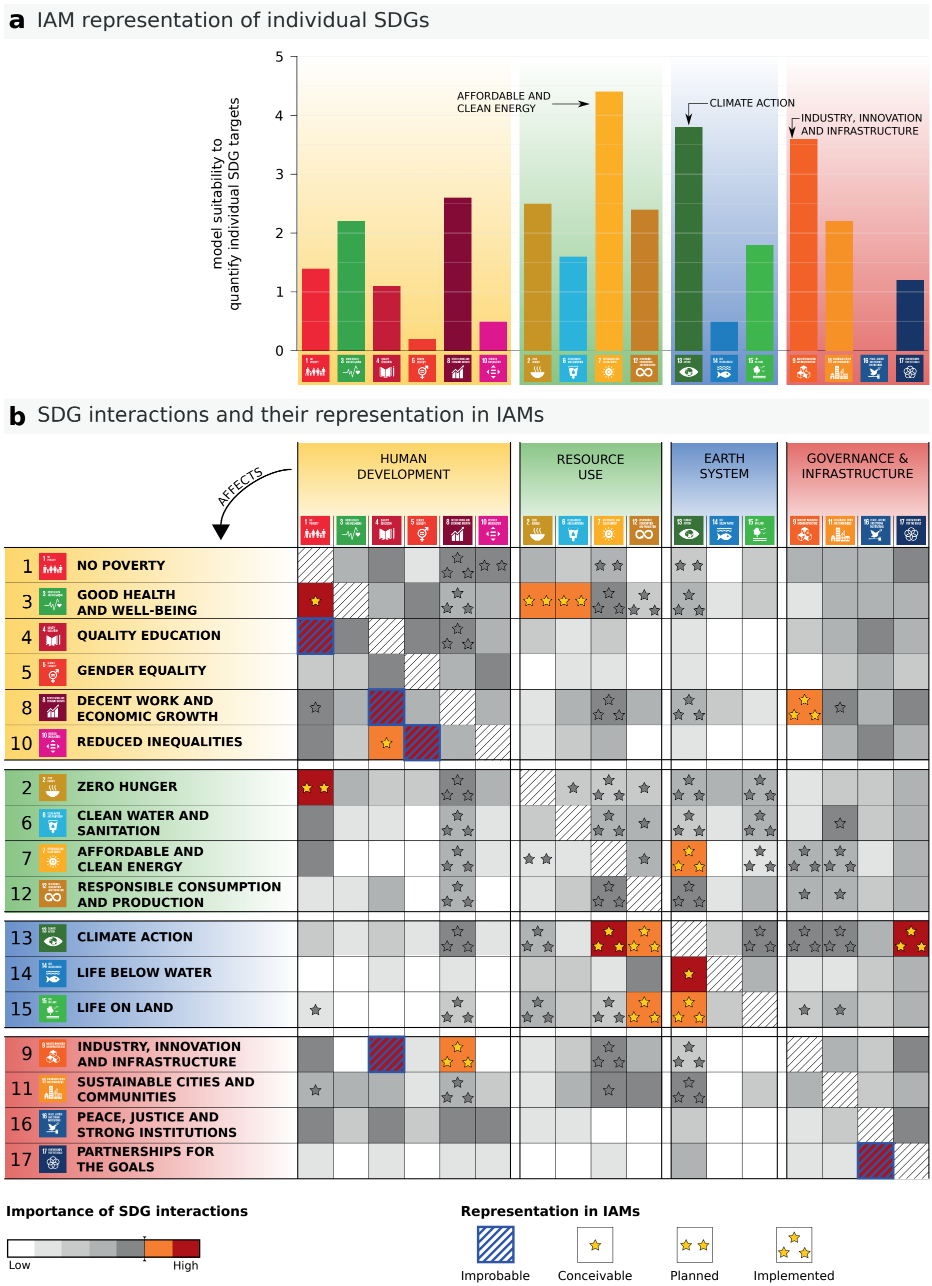

Figure 7.6: The representation of SDGs by IAMs. (A): Bar height represents the average score for individual target coverage from the *model survey* (Table 6.1). (B): SDG interactions and coverage by IAM models according to the *expert* and *model surveys* (the SDG in the column impacts the SDG in the row). The strength dimension of SDG interactions is indicated by grey shading: the darkest shade of grey represents average scores near 3 (strong interactions), while white

represents no interactions. Asterisks indicate the representation of IAMs following the model survey. ***: currently in IAMs, **: planned development, and * conceivable to be represented in the future. Finally, orange cells indicate the highest agreement between the importance of interactions and potential model representation, while blue coloured cells show the most notable important interactions without model representation. Interactions that are marked as currently represented are endogenous, with various levels of process detail. Future modelling of the SDG interactions that have remained unrepresented thus far can be achieved as a part of a consistent set of exogenous assumptions such as, for example, the impact of quality education on reducing poverty.

7.4 Policy and research recommendations

7.4.1 Research recommendations

The recommendations for future research can be classified along two main lines: more details within the IAMs, and more collaboration and interaction with other tools and disciplines.

7.4.1.1 More detailed modelling

Important aspects of model improvement are the regional disaggregation of models and the representation of policies. Modelling all countries individually would not be practical, but covering at least the, say 20, largest emitters individually (together accounting for roughly 80% of global greenhouse gas emissions) would certainly be useful for informing climate policy. That includes redefining the European Union region, which in many models resembles Europe more than EU28 (let alone EU27). In CD-LINKS, models have started to implement individual policy measures and targets in G20 countries in the scenarios that were developed under the project. However, given the fast developments in climate policy worldwide, it is necessary to enhance model capabilities in this area. IAMs will need to continuously work on their coverage of targets, measures, and instruments to stay relevant. Model developments are needed to ensure leverage points (policy measures and instruments) in all parts of the model, i.e. in all sectors and on multiple scales. Regional definitions may need to be updated based on new political developments; for example, a better representation of the EU27. Next to coverage of all relevant major emitting countries, coverage of non-state actors (cities and companies) will be important.

More detailed modelling will need to be accompanied by timeliness to maximise relevance. Related to the coverage of policy instruments is the cut-off date applied to policies and NDC targets to be considered in the analysis. A cut-off date is a prerequisite for models to run policy scenarios, but it implies that the scenarios are likely to be outdated by the time of publication. Standardisation of the scenario update process would help ensure timely publication of up-to-date scenarios and easy incorporation of marginal changes. This process has already started with the modelling protocol and documentation, but it can be further refined and, to some

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extent, automated. Another element of timeliness is to what extent short-term developments—the COVID-19 pandemic being a prime example—can and should be incorporated in scenario development. IAMs may not always be suited to answer policy questions about the effect of crises, but a deliberate reflection on how to deal with such questions is needed when thinking about relevance.

Next to a more detailed analysis of policy instruments, net-zero emissions targets will require attention. In addition to the factors we studied, future work could analyse a few other factors that would affect national differences in phase-out years: metrics other than Global Warming Potentials (GWPs) to compare the contribution of different greenhouse gases, consumption-based vs production-based emissions accounting, and the effect of different model assumptions on available mitigation options per sector, determining how fast each sector can reduce emissions. For robustness, it would be better to use a richer set of models and countries. With such an enlarged dataset, a PCA (as applied in Chapter 4) would be more meaningful. Alternatively, one could dive into the results of one model and tease out underlying dynamics. A comparison of scenario results with countries' submitted long-term strategies would further be useful: on the one hand, to identify additional mitigation potential for these strategies and, on the other hand, to make the scenarios better reflect political realities.

Finally, areas for model improvement can be distilled from the SDG surveys, recognising that not all models need to cover all aspects and interactions. For one thing, going beyond studying how the SDGs are affected by climate policies is important. Evaluating the impact of achieving the human development goals on climate, ecosystems, and resource usage (in the broadest sense) can be a good starting point. As such, no-regret areas for increased climate ambition may be identified. To do so properly, models may need to develop further to include the effects of addressing poverty on health and economic growth (possibly through model coupling), of (renewable) energy on cities (possibly through modules or model coupling), of education on inequalities (possibly through model coupling), of climate action on oceans (possibly through model extensions), and of cities on water and economic growth (possibly through model extensions). Model development can also improve current relationships because many IAM indicators related to SDG targets are currently based on either exogenous inputs or endogenous outputs without feedback ('impact indicators'), thus representing one-directional relationships. Here, a distinction can be made between 1) tracking SDG progress, for which improving the representation of SDG indicators is necessary, and 2) solutions, for which IAMs may need to improve the representation of processes relevant for the SDG indicator and the interaction dynamics. In addition to interactions among the policy domains, interactions among different geographical scales should also be considered. Sufficient temporal and spatial resolution is necessary to assess the potential strategies for reaching the SDGs. It is, furthermore, necessary to go beyond scale and move away from averages towards explicit modelling of heterogeneity as many SDGs are distributional issues, especially human development goals. This could be done endogenously or by building more detailed modules and linking them to the integrated assessment framework.

7.4.1.2 Collaboration

Next to model-internal developments, collaboration with other models, methods and disciplines will be needed for a comprehensive answer to the question 'how do we get there?'.

First of all, although the national results of global IAMs are a helpful addition to the literature, **the interaction between national and global models will need to be continued and strengthened.** Although mutual learning has occurred, focus so far has been mostly on providing global boundary conditions (often in the form of carbon budgets) from global models to national models. Next steps would be to strengthen the two-way interaction, with some clear areas where national models can provide information to global models, for example: feasibility of scenarios and specific solutions, national resource potentials, national targets and policies, political priorities, especially in areas other than climate policy, and historical (inventory) data. Next to the interaction between national and global models, links to bottom-up analyses may help to integrate more sectoral detail.

Model collaboration is also needed on the SDGs. Although many gaps can be closed by integrating more SDG dimensions in IAMs, full endogenisation of all interactions is not possible and is probably not desired in some cases. In such cases, linking different disciplines through exogenous assumptions and a common narrative (such as the SSPs) is an alternative option. This holds true especially for targets related to the institutional and social dimensions of the SDGs that are often crucial for enabling other SDGs. Closer cooperation within the IAM community can contribute to closing gaps. Soft-linking to other more qualified models can be a good starting point, possibly even moving to integrated assessment frameworks that include these different models. Such multi-model frameworks can help capture multi-sectoral dynamics that are not endogenous to the models themselves. As decision-support tools, these frameworks can provide information at finer spatial and temporal resolutions while maintaining consistency with global boundary conditions.

IAMs will further need to cooperate more closely with social sciences, especially in relation to questions of feasibility and on the SDGs. IAMs will need to be combined with empirical research to bring in the local context and experience pertaining to strategies that work in different settings, as IAMs cannot and probably should not even try to represent everything. A major effort is necessary to help translate IAM results into concrete policy recommendations. For example, a comparison of scenario results with countries' submitted long-term strategies would be useful: on the one hand, to identify additional mitigation potential for these strategies and, on the other hand, to make the scenarios better reflect political realities. That is also where social sciences could add value to this work: guide the social acceptance and practical implementation of net-zero targets, with an understanding of relevant actors and their motivations. At the same time, questions of global justice and distributional effects of climate policy will need to be considered (Fragkos et al., 2021a; Ohlendorf et al., 2021). Focusing on feasibility (Jewell & Cherp, 2020) of the scenarios will be an important next step: first, with an assessment of feasibility of existing scenarios, followed by design of scenarios that consider feasibility dimensions. Ongoing work in the ENGAGE project will form a decent basis, where two concepts are being developed and tested. One can help evaluate feasibility of scenarios by comparing projections to historical precedents, while the other one defines boundary conditions based on a multi-dimensional feasibility approach, which can inform the next step of designing scenarios that consider feasibility from the start.

7.4.2 Policy recommendations

We aimed to bridge the *emissions gap*, not only by exploring concrete measures to close the gap, but also methodologically, by using IAMs to inform national policymaking. We broke down the emissions gap into an *ambition gap* between NDCs and 2 °C and 1.5 °C (which can be studied both globally and nationally), and an *implementation gap* between currently implemented climate policies and NDCs (which can be best studied nationally). Both parts of the gap will need to be closed if we are to meet the global mitigation goals of the Paris Agreement.

7.4.2.1 Ambition and implementation gaps

To close the *ambition gap*, net-zero emission targets could be, if fully implemented, an important step in the right direction to meet the climate goals of the Paris Agreement. They will need to account for national circumstances, such as different mitigation potentials, and be clear on their scope. To simultaneously close the *implementation gap*, they will need to be accompanied by measures to start implementing them in the shorter term, including clarity on how they relate to 2030 targets (NDCs). The SDGs may help to close the remaining gap, by informing countries on potential areas for enhanced ambition where synergies with other development priorities may be found. This will require further study.

To close the *implementation gap*, additional climate policies will need to be adopted and existing ones strengthened in the short term (this decade). The *Bridge* scenario developed here contains a set of concrete and nationally relevant measures that can be implemented now, as they were based on existing technologies and policies that some countries have already adopted.

The findings result in a number of policy recommendations, which can be classified as related to either target setting or implementation of policy measures.

7.4.2.2 Targets

In addition to the well-known recommendation that NDC targets will need to be strengthened, **net-zero targets would benefit from clarification** in the following areas. First of all, they will need to clearly specify their scope in terms of greenhouse gas emissions and sectoral coverage, as well as whether they are intended to be achieved domestically or to what extent ITMOs are planned to be used. Secondly, explicit mention of the land-use data and assumptions on continuation of land sinks used would help resolve discrepancies with scientific inventories. Thirdly, any assumptions on the use and accounting of BECCS need to be specified to uncover potential competing claims on resources and double counting. Fourthly, the formulation of the net-zero target should be accompanied by a view on equity, as different perspectives lead to different phase-out years. Finally, special attention is needed for enhancing the capacity to realise negative emissions. In addition, their relation to shorter term targets, such as enshrined in NDCs, is important.

NDCs will need to be aligned with net-zero emission or other long-term targets. Net-zero targets present a helpful long-term vision and may help closing the ambition gap in 2050, but they will be difficult to achieve if not combined with a view of what needs to happen in the shorter term. That includes not just a 2030 emissions reduction target that enables meeting the net-zero target, but also a target year for peaking emissions (if not already achieved), and consideration of the reduction pathway between 2030 and the net-zero emission target year. Linear emission reductions may become more difficult to achieve when mitigation options are exhausted.

Policy-makers should not simply use the results presented here to set national targets. Scenario outcomes should be used with care: for example, a model average emission reduction target for an aggregated region or sector should not be applied directly to all that region's or sector's sub-elements (e.g. countries or companies). Not just because these are averages (or medians) of a full range of scenarios by different models leading to the same temperature outcome, but also because most of these scenarios are cost-optimal, i.e. do not account for equity principles. In addition, these scenarios do not explicitly account for questions of responsibility (e.g. consumer versus producer), nor do they fully capture model uncertainty (that is, one scenario by one model does not show that model's inherent uncertainty). Additionally, model uncertainty is not representative of the full uncertainty range. Therefore, national models and other tools and scientific disciplines will need to be applied as well, to fully incorporate relevant domestic circumstances and uncertainties. The national target setting can further be informed by studies on co-benefits, which suggest a significant share of mitigation costs could be covered by accounting for air quality and other co-benefits, making additional domestic mitigation more attractive.

7.4.2.3 Policy measures

The 'implementation gap' is the one to focus on in this crucial decade for climate action. As the implementation gap makes up roughly half of the total emissions gap, and preparation and implementation of climate policies takes time, major efforts are needed across countries to start closing the implementation gap. While existing policies can be strengthened, new policies may also need to be introduced, especially in sectors with lower policy coverage.

The *Bridge* scenario presented in Chapter 5 showed that it would be better to start with a package of non-cost-optimal measures, and prepare the ground for comprehensive carbon pricing, than wait; not just in terms of chances of success in limiting global warming, but also in terms of policy costs. Such measures would include, across all sectors: in transportation, the introduction of electric and other low-carbon vehicles, improving fuel efficiency, and improving energy efficiency of aviation; in buildings, improving energy efficiency of appliances, improving final energy intensity of new buildings, no new installations of oil boilers, and renovation of existing buildings; in industry, application of CCS, improving final energy efficiency, and reducing N_2O emissions from adipic acid production; in energy supply, phasing out unabated coal power plants, increasing the share of renewable energy in electricity, coal mine methane emissions recovery, and reducing venting and flaring of methane and CO_2; in AFOLU, application of anaerobic digesters for manure treatment, increasing nitrogen use efficiency, selective breeding, increasing afforestation and reforestation, and stopping deforestation; as well as reducing methane emissions from waste, reducing F-gas emissions, and carbon pricing.

On the use of IAMs in policy assessments, IAMs have already informed global and national policy on climate change mitigation, both through IPCC assessments and with individual model applications. These tools can promote policy coherence for the SDGs, by structuring complexity, exploring uncertainties pertaining to the impact of policies with scenarios, and reconciling contested views through common narratives, including by bringing different ministries together. They can help track dynamics, including trickle-down effects of various policy targets and instruments, and second-order interactions, to help policymakers identify and minimise trade-offs while maximising synergies.

8

Samenvatting en conclusies

Dit hoofdstuk dient twee doelen: samenvatten van het proefschrift en het bieden van een discussie en conclusies. Hoofdstukken 8.1 en 8.2 vatten de introductie (Hoofdstuk 1) samen, Hoofdstuk 8.3 vat de belangrijkste bevindingen samen met de conclusies van Hoofdstuk 2 tot en met 6, en Hoofdstuk 8.4 biedt een discussie en aanbevelingen voor onderzoek en beleid.

8.1 Introductie en onderzoeksvragen

8.1.1 Het Parijsakkoord en de *Global Stocktake*

Partijen in het Parijsakkoord zijn overeengekomen om de opwarming van de aarde te beperken tot ‘ruim onder’ 2 °C ten opzichte van het pre-industriële niveau, en ernaar te streven de opwarming te beperken tot 1,5 °C, om zo snel mogelijk een maximum te bereiken in de uitstoot van broeikasgassen, en om in de tweede helft van de eeuw een ‘balans’ te bereiken tussen antropogene uitstoot en opname van broeikasgassen door zogeheten *sinks*.

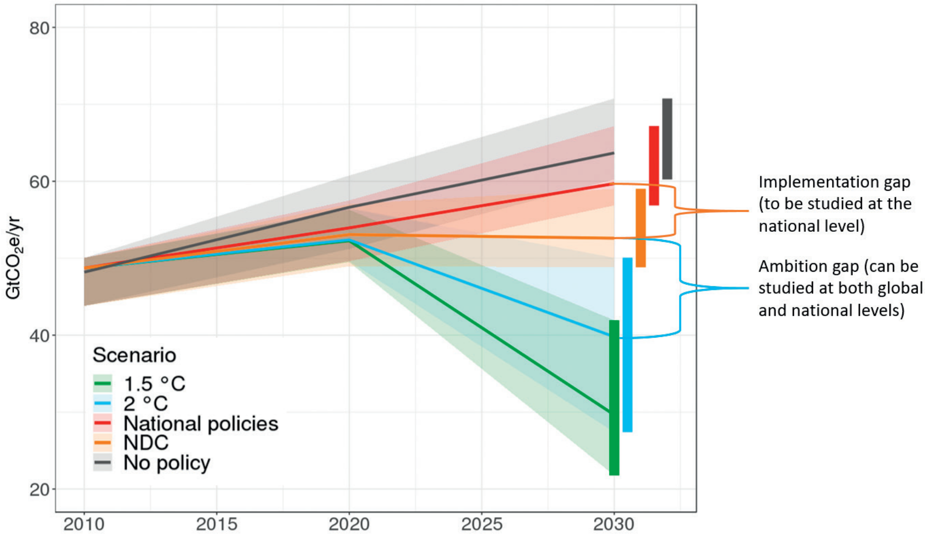
Beleid zal echter op het niveau van landen geïmplementeerd moeten worden. Partijen moesten daarom hun zelfbepaalde mitigatiedoelen indienen, de zogeheten *Intended Nationally Determined Contributions* (INDC’s). Na ratificatie van het Parijsakkoord werd een INDC een *Nationally Determined Contribution* (NDC). Partijen voorzagen al dat zulke vrijwillige beloftes bij elkaar opgeteld waarschijnlijk niet tot de emissieniveaus zouden leiden die overeenkomen met de doelstellingen van het Parijsakkoord. Daarom spraken ze ook een proces af om regelmatig te inventariseren wat het totale effect van de individuele NDC’s is en ervoor te zorgen dat de ambitieniveaus in de loop van de tijd zouden worden verhoogd: de *Global Stocktake* (GST)[26] en het ambitiemechanisme (de zogeheten *ratchet*, een tandwielconstructie die één kant op draait). In 2018 vond een informele test daarvan plaats: de zogeheten Talanoa-dialoog. Die draaide om drie overkoepelende vragen: waar staan we, waar willen we heen en hoe komen we daar?

8.1.2 Emissiekloof

Onderzoekers (Roelfsema et al., 2020; Rogelj et al., 2016) wijzen op de kloof tussen emissieniveaus die nodig zijn om op een pad richting 2 °C en 1,5 °C te blijven en de mondiale emissies die naar verwachting bereikt worden als de NDC’s volledig geïmplementeerd worden. Die **totale emissiekloof** kan verder worden onderverdeeld (Figuur 8. 1) in de **ambitiekloof**, het verschil tussen emissieniveaus als gevolg van de NDC’s en niveaus die overeenkomen met 2 °C en 1,5 °C, en de **implementatiekloof**, het verschil tussen emissieniveaus als gevolg van daadwerkelijk geïmplementeerd klimaatbeleid en niveaus die overeenkomen met de NDC’s. Deze implementatiekloof

26 Niet vertaald omdat het internationaal beleidsjargon is geworden. Hetzelfde geldt voor NDC’s en verderop SDG’s.

is een nieuwe dimensie die door Roelfsema et al. (2020) geïntroduceerd is en hier gebruikt wordt. Tot dusver is de aandacht vooral uitgegaan naar de ambitiekloof, maar in dit cruciale decennium voor het klimaatbeleid verdient de implementatiekloof extra aandacht. Anders gezegd, de focus moet worden verbreed: niet alleen de vraag uit de Talanoa-dialoog 'waar willen we heen?', maar ook, uit datzelfde proces, 'hoe komen we daar?' Voor het stellen van doelen ('waar willen we heen?') zijn, onder andere, *Integrated Assessment*-modellen (IAM's)[27] geraadpleegd (Rogelj et al., 2018; van Beek et al., 2020). Met hun toenemende sectorale, ruimtelijke en temporele resolutie kunnen ze ook de 'hoe'-vraag informeren, met een gedetailleerde analyse van mitigatiepaden.



Figuur 8.1: De mondiale emissiekloof (COMMIT & CD-LINKS, 2018), die onderverdeeld kan worden in een ambitiekloof en een implementatiekloof (alleen toegevoegd voor illustratiedoeleinden, omdat dit op het niveau van landen of samenwerkende landen zoals de EU bestudeerd moet worden).

8.1.3 Modelanalyse

IAM's zijn rekenmodellen om complexe interacties tussen mensen en hun leefomgeving te bestuderen voor een beter begrip van mondiale milieuproblemen. In grote lijnen kunnen twee soorten IAM's worden onderscheiden: IAM's met hoge resolutie of procesgebaseerde IAM's, en kosten-baten-IAM's. Dit proefschrift maakt gebruik van procesgebaseerde modellen. Deze IAM's splitsen de wereld op in meerdere regio's, die bestaan uit één land of meerdere landen. De IAM's die de wereld

27 Niet vertaald omdat het een naam is.

in meer dan één regio verdelen worden hier mondiale IAM's genoemd en de IAM's die zich op één land richten nationale IAM's[28]. IAM's zijn niet bedoeld om voorspellingen te doen; wel kunnen ze helpen bij het verkennen van onzekere toekomsten door middel van scenario's (Riahi et al., 2017; van Vuuren et al., 2011). Scenario's zijn plausibele beschrijvingen van hoe sociaaleconomische, technologische en milieutrends zich zouden kunnen ontwikkelen. Aangezien er geen wereldregering bestaat, zal de uitvoering van de doelstellingen van het Parijsakkoord op het niveau van landen en andere schaalniveaus moeten plaatsvinden. Daarom zullen landen informatie nodig hebben die is afgestemd op hun omstandigheden. Nationale en sectorale modellen kunnen worden gebruikt om nationale mitigatiepaden met hoge resolutie te bestuderen (Fragkos et al., 2021b; Schaeffer et al., 2020b). Het afzonderlijk toepassen van nationale modellen zal echter geen antwoord kunnen geven op de vraag of deze paden in overeenstemming zijn met de mondiale mitigatiedoelstellingen. Daarnaast verschilt het analytisch vermogen sterk tussen landen. Voor onderhandelingen is een gedeelde informatiebasis echter cruciaal om discussies te richten op daadwerkelijke meningsverschillen en niet in discussies over feiten of cijfers terecht te komen. Daarom zijn mondiale IAM's toegepast in combinatie met nationale IAM's of energiesysteemmodellen in projecten zoals CD-LINKS (McCollum et al., 2018; Roelfsema et al., 2020; Schaeffer et al., 2020a; Schaeffer et al., 2020b; van den Berg et al., 2020), COMMIT (Fragkos et al., 2021b; van Soest et al., 2021) en ENGAGE. Mondiale modellen bieden de randvoorwaarden, zoals kostenoptimale nationale koolstofbudgetten die wereldwijd in lijn zijn met 1,5 °C of 2 °C, beschikbaarheid van bijvoorbeeld biomassa of energieprijzen (Hof et al., 2020), die nationale modellen kunnen gebruiken als randvoorwaarden voor hun mitigatiepaden.

8.2 Doel van het proefschrift en onderzoeksvragen

Tal van analyses hebben de emissiekloof en scenario's die de opwarming van de aarde beperken tot ruim onder de 2 °C en 1,5 °C bestudeerd, zowel op mondiaal niveau als op het niveau van landen. Toch zijn er nog belangrijke vragen. Deze hebben deels te maken met de toenemende interacties tussen mondiale en nationale modellen en de nieuwe fase van het internationale klimaatbeleid sinds het Parijsakkoord. Deze nieuwe fase betekent dat de focus vooral ligt op het bereiken van netto-nuluitstoot en op welk concreet beleid in de komende een tot twee decennia moet worden geïmplementeerd. Tegelijkertijd moeten de transities in de energie- en landsystemen die nodig zijn om de doelstellingen van Parijs te halen, worden gecombineerd met de *Sustainable Development Goals* (SDG's) om synergiën te maximaliseren en afruilen te minimaliseren. We richten ons op deze belangrijke vraagstukken, wat leidt tot

28 Niet alle nationale modellen zijn IAM's: sommige concentreren zich bijvoorbeeld op het energiesysteem.

de volgende onderzoeksvragen, geïnspireerd door de Talanoa-dialoog. Hoewel de laatste vraag cruciaal is, zijn de andere vragen ook nodig voor een volledig antwoord.

1. **Waar zijn we?**
   a. *Hoe groot zijn de mondiale ambitie- en implementatiekloven?*
   b. *Hoe groot zijn de nationale ambitiekloven?*
2. **Waar willen we heen?**
   a. *Wanneer kunnen landen netto-nul-uitstoot van broeikasgassen bereiken?*
3. **Hoe komen we daar?**
   a. *Hoe kan de mondiale ambitiekloof worden overbrugd?*
   b. *Als we de SDG's willen gebruiken om landen te informeren over hoe ze hun mitigatieambitie kunnen verhogen, zijn IAM's dan geschikt om de interacties tussen klimaatbeleid en bredere duurzame ontwikkeling te bestuderen?*

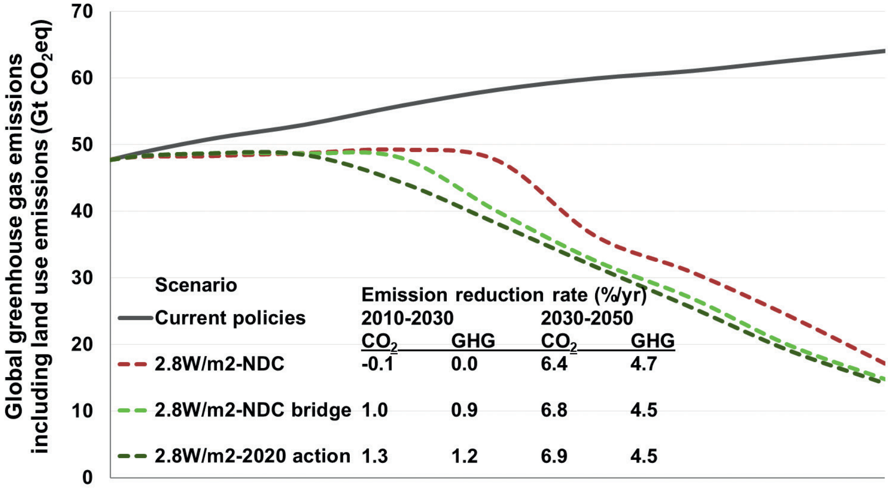
8.3 Belangrijkste bevindingen van dit proefschrift

8.3.1 Waar zijn we?

8.3.1.1 Hoe groot zijn de mondiale ambitie- en implementatiekloven?

Hoofdstuk 2 heeft laten zien dat het huidige geïmplementeerde klimaatbeleid gezamenlijk naar verwachting zal leiden tot wereldwijde emissieniveaus van bijna 60 $GtCO_2eq$ in 2030. Ambities zoals beloofd in de NDC's zouden dat terugbrengen tot ongeveer 50 $GtCO_2eq$. Het huidig-beleidsscenario omvat het huidige klimaat- en energiebeleid van de belangrijkste uitstotende landen, zoals de (veronderstelde implementatie van) doelstellingen voor het aandeel of de capaciteit van hernieuwbare energie, normen voor elektriciteitscentrales, brandstofefficiëntienormen voor auto's en koolstofprijzen. De NDC-scenario's gaan uit van emissieniveaus in 2020 als gevolg van het huidige beleid en beloftes voor het jaar 2020, en emissieniveaus in 2030 als gevolg van de volledige implementatie van de NDC's. De implementatie van NDC's zal naar verwachting resulteren in een piek in de wereldwijde broeikasgasemissies van 50 $GtCO_2eq$ in 2030. Dit is een vermindering van 14% tot 15% in vergelijking met het huidig-beleidsscenario, maar nog steeds een stijging van 5% ten opzichte van het niveau van 2010.

Er is een aanzienlijke kloof tussen de verwachte emissieniveaus als gevolg van de huidige ambities en beleidsimplementatie, en optimale paden die in lijn zijn met het Parijsakkoord. Een kostenoptimaal pad voor 2 °C heeft een mondiaal emissieniveau van ongeveer 40 $GtCO_2eq$ in 2030, een afname van 20% ten opzichte van 2010-niveaus (Figuur 8. 2). Ruwweg de helft van de emissiekloof wordt dus gevormd door de *implementatiekloof* en de andere helft door de *ambitiekloof*. Het dichten van beide delen van de *emissiekloof* is daarom cruciaal om de klimaatdoelstellingen van het Parijsakkoord binnen bereik te houden. Dat betekent dat ambities moeten worden versterkt en tegelijkertijd beleid moet worden gevoerd om die ambities waar te maken.



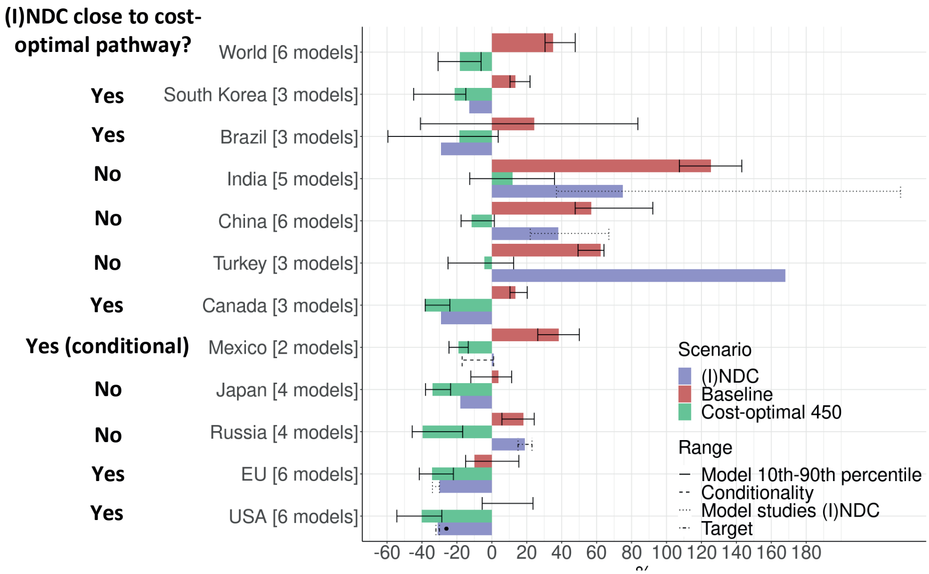
Figuur 8.2: Mondiale broeikasgasemissies (GtCO_2eq/jaar) van 2010 tot en met 2050, inclusief CO_2-emissies door landgebruik, in het huidig-beleidsscenario (doorgetrokken lijn), en de 2,8 W/m^2-scenario's (*2.8 W/m ^{2}-NDC*, *2.8 W/m ^{2}-NDC bridge* en *2.8 W/m ^{2}-2020 action*; *gestreepte lijnen*)

8.3.1.2 Hoe groot zijn de nationale ambitiekloven?

Hoofdstuk 3 heeft laten zien dat de NDC's van bijna alle landen naar verwachting zullen resulteren in hogere emissies dan emissieniveaus van kostenoptimale 2 °C-scenario's. Toch hebben sommige landen vrij ambitieuze NDC's. De NDC's van bijvoorbeeld China, India, Japan, Rusland en Turkije zullen naar verwachting resulteren in emissieniveaus die hoger zijn dan die van 2 °C. Voor Rusland en Turkije liggen de emissieprojecties van de NDC's zelfs boven de referentieprojecties. De NDC-projecties voor China en India zijn omgeven door onzekerheden, gedreven door onzekere BBP-projecties. Daarentegen liggen de NDC's van Brazilië, Canada, de EU, Mexico (het voorwaardelijke doel), Zuid-Korea en de VS relatief dicht bij de emissieniveaus van 2 °C-scenario's (minder dan 10 procentpunt verschil, Figuur 8. 3). Op mondiaal niveau blijft de som van de emissiereducties die naar verwachting het gevolg zijn van de implementatie van de NDC's echter achter bij de reducties die het kostenoptimale 2 °C-pad laat zien.

Het beperken van de mondiale temperatuurstijging tot onder de 2 °C impliceert een substantiële reductie van de cumulatieve CO_2-emissies (koolstofbudget) tussen 2010 en 2100 voor elk land. De nationale koolstofbudgetten tussen 2010 en 2100 lieten een reductie van gemiddeld 79% zien tussen het referentiescenario en het mitigatiescenario, met de grootste reducties voor Brazilië (95%) en Canada (91%) en de kleinste voor Zuid-Korea (52%). Na volledige implementatie van de NDC's zou de wereld voor de rest van de eeuw met ongeveer 40% van het koolstofbudget voor 2 °C overblijven. Volgens het mitigatiescenario zal de uitstoot van broeikasgassen van de meeste landen naar verwachting vóór 2025 pieken. Alleen Brazilië, China, Mexico en Turkije bereiken naar verwachting de emissiepiek later in hun NDC dan in de mitigatiescenario's van de modellen.

Er zijn grote verschillen tussen de modellen. Deze kunnen voortkomen uit het model zelf (bijvoorbeeld type, structuur en definities, zie Hoofdstuk 1.4) of de implementatie van het scenario. De indeling van regio's kan bijvoorbeeld verschillen tussen modellen. Ook de vertegenwoordiging van specifieke nationale kenmerken in de modellen en van beleid verschilt. Andere bronnen van modelverschillen zijn onder meer verwachte ontwikkelingen in het referentiescenario en emissies door landgebruik (met name voor Brazilië).



Figuur 8.3: Totale broeikasgasemissies in 2030, projecties door modellen voor referentiescenario's en kostenoptimale 450 ppm CO_2eq-scenario's, in vergelijking met de NDC's[29]. De totale emissies zijn weergegeven ten opzichte van 2010 (%, waarbij positieve cijfers een emissietoename aangeven). Het aantal modellen per land is aangegeven. Gevulde staven voor *baseline* en kostenoptimaal 450 ppm CO_2-eq tonen de mediaan over alle modellen; foutbalken tonen het 10e tot 90e percentiel van de modelresultaten (*Model 10th-90th percentile*). Voor regio's die door minder dan drie modellen worden gemodelleerd, wordt de volledige bandbreedte (minimum-maximum) weergegeven. Gevulde staven voor NDC tonen de centrale schatting van Den Elzen et al. (2016), foutbalken de bandbreedte. NDC-bandbreedtes zijn van drie typen: bandbreedte in de reductiedoelstelling die in de NDC's zelf wordt genoemd (*Target*; Rusland, VS), bandbreedte als gevolg van onvoorwaardelijke en voorwaardelijke doelen (*Conditionality*; Mexico; gevulde balk toont het onvoorwaardelijke doel; foutbalk toont het effect van het voorwaardelijke doel) en bandbreedte als resultaat van verschillende modelstudies die zijn geanalyseerd in UNEP (2015) (*Model Studies (I)NDC*; India, China). Voor de VS bestaat de NDC-bandbreedte uit zowel *Target* (foutbalk, gebaseerd op den Elzen et al., 2016) als *Model Studies (I)NDC* (gevulde cirkel, gebaseerd op Emmerling et al., 2016). De linkerkolom laat zien of de NDC van een land dicht bij de kostenoptimale 450 ppm CO_2-eq-projectie ligt, waarbij 'dichtbij' wordt gedefinieerd als een verschil van minder dan 10 procentpunt.

29 Cijfers zijn mogelijk verouderd, omdat ze gebaseerd zijn op de analyse die in 2017 is gepubliceerd. Veel landen hebben sindsdien nieuwe NDC's ingediend, vaak met ambitieuzere emissiereductiedoelstellingen.

8.3.2 Waar willen we heen?

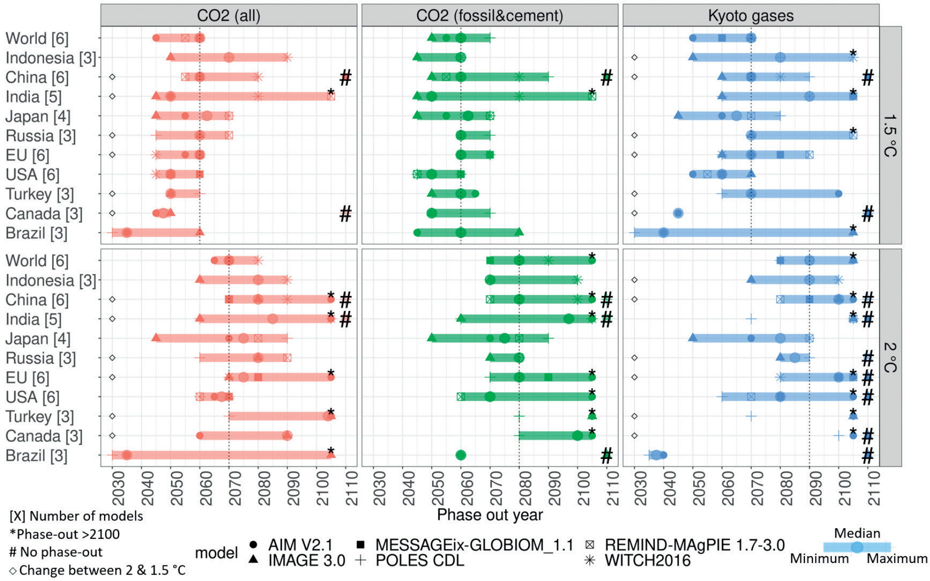
8.3.2.1 Wanneer kunnen landen netto-nul-uitstoot van broeikasgassen bereiken?

Sterkere emissiereductiedoelstellingen zijn nodig om de ambitiekloof te dichten. Hoofdstuk 4 heeft laten zien wanneer 10 grote uitstotende landen in kostenoptimale scenario's netto-nul-uitstoot van broeikasgassen bereiken (hierna uitfaseringsjaar genoemd: uitfasering van de uitstoot van broeikasgassen), om de vraag 'waar willen we heen?' te helpen beantwoorden. In die scenario's ligt het wereldwijd gemiddelde uitfaseringsjaar voor de totale uitstoot van broeikasgassen rond 2070 voor 1,5 °C en rond 2090 voor 2 °C, ervan uitgaande dat er opties voor CO_2-verwijdering beschikbaar zijn. Deze zullen ook nodig zijn na het uitfaseringsjaar. Voor alleen CO_2 liggen deze jaren ongeveer 20 jaar eerder. Brazilië, de Verenigde Staten en Japan bereiken in de kostenoptimale scenario's eerder netto-nul-uitstoot van broeikasgassen dan het wereldgemiddelde (Figuur 8. 4). Voor Brazilië is het verschil met het wereldgemiddelde over het algemeen meer dan 20 jaar, terwijl het verschil voor de VS rond de 10 jaar is. Daarentegen hebben India en Indonesië in de meeste scenario's een later uitfaseringsjaar dan het wereldgemiddelde (met een verschil van ongeveer 10 jaar). China, de EU en Rusland hebben uitfaseringsjaren die doorgaans in de buurt van het wereldgemiddelde liggen. De overige vijf landen laten een gemengd beeld zien: de resultaten variëren met emissiebronnen en temperatuurdoelstellingen. Zo zal een land waar landgebruik een bron van emissies is (bijvoorbeeld Indonesië) de totale CO_2-emissies later uitfaseren dan alleen fossiele CO_2, terwijl het omgekeerde geldt voor landen waar landgebruik een *sink* vormt (zoals Canada).

Wanneer landen volgens kostenoptimale scenario's netto-nul-uitstoot van broeikasgassen kunnen bereiken, is een andere vraag dan wanneer ze dat in werkelijkheid kunnen. Om te beginnen hebben veel landen nu officiële netto-nul-emissiedoelstellingen vastgesteld of aangekondigd, vaak als onderdeel van hun langetermijnstrategie in het kader van het Parijsakkoord. De tot nu toe gestelde doelen zijn in lijn met de kostenoptimale uitfaseringsjaren voor 1,5 °C en 2 °C. Het is echter niet waarschijnlijk dat de wereldwijde verdeling van de mitigatie-inspanningen kostenoptimaal is; in werkelijkheid zullen vragen rond rechtvaardigheid een rol spelen. Daarom kunnen landen ofwel kiezen voor een streefjaar voor netto-nul-uitstoot dat eerder ligt dan wat kostenoptimale scenario's laten zien (zoals de Europese Unie heeft gedaan), ofwel om financiële steun vragen om de broeikasgasuitstoot eerder uit te faseren dan als eerlijk wordt beschouwd (zoals India). Verschillen tussen landen hebben betrekking op hun mitigatiepotentieel, met name het potentieel om negatieve emissies te realiseren door (her)bebossing of (BE)CCS[30]. Ook speelt de huidige situatie een rol: zo resulteert een hoger huidig aandeel niet-CO_2-emissies, die moeilijker te elimineren zijn, in een later uitfaseringsjaar.

30 Direct Air Capture (DAC) zat (nog) niet in de modellen.

Verder spelen meer methodologische factoren een rol, met name de allocatie (boekhoudkundige toerekening) van negatieve emissies en landgebruiksdata. Duidelijke definities en politieke overeenstemming over deze kwesties zijn nodig om zinvolle resultaten voor de *global stocktake* te produceren.



Figuur 8.4: Jaar waarin de geprojecteerde emissies netto nul bereiken, per land (aantal modellen die dat land modelleren tussen haakjes), voor scenario's voor 2 °C en 1,5°C, voor CO_2-emissies, CO_2-emissies van fossiele brandstoffen en cement (energie en industriële processen), en totale BKG-emissies (Kyoto-gassen, inclusief emissies door landgebruik). Individuele modellen worden aangegeven met symbolen, terwijl de balken de bandbreedte (minimum-maximum) aangeven (vergrote cirkels: modelmediaan). In sommige gevallen tonen individuele modellen een uitfasering na 2100 in de geëxtrapoleerde projecties (aangegeven met een asterisk) of helemaal geen uitfasering (#). Ruitjes die bij 2030 zijn geplot, duiden op een verandering tussen de scenario's voor 2 ° C en 1,5 ° C in termen van een land dat eerder dan, vergelijkbaar met of later dan het wereldgemiddelde netto-nul bereikt. Verticale stippellijnen geven het wereldwijd gemiddelde uitfaseringsjaar aan.

8.3.3 Hoe komen we daar?

Het is mogelijk om de ambitiekloof grotendeels in 2030 en volledig in 2050 te dichten, zodat de 2 °C-doelstelling op de langere termijn kan worden gehaald. Dit blijkt uit het theoretische *NDC-Bridge*-scenario geïntroduceerd in Hoofdstuk 2 (Figuur 8. 2) en het meer concrete *Bridge*-scenario besproken in Hoofdstuk 5 (Figuur 8. 5). Vroeg ingrijpen is goedkoper dan uitstel en vergroot de kans op succes door een soepelere transitie mogelijk te maken.

Er zijn verschillende manieren om de emissiekloof te dichten. Hier bestuderen we er twee: 1) een concrete set maatregelen op korte termijn implementeren, waarmee de ambitie in NDC's aangescherpt zou kunnen worden, en 2) de SDG's gebruiken om de ambitie te verhogen. Voor de laatste optie is echter een tussenstap nodig: als we de SDG's willen gebruiken om ambitie vorm te geven, zijn IAM's dan de juiste tools?

8.3.3.1 Hoe kan de mondiale ambitiekloof worden overbrugd?

Om de ambitiekloof te dichten zullen emissiereductiedoelen versterkt moeten worden, terwijl tegelijkertijd klimaatbeleid geïmplementeerd wordt om die doelen te halen. Daartoe presenteerde Hoofdstuk 2 een gestileerd *Bridge*-scenario. De extra emissiereducties in het energiesysteem werden daarin bereikt door een combinatie van efficiëntieverbetering, vermindering van het gebruik van fossiele brandstoffen en toenemende inzet van koolstofarme energiebronnen. Het gebruik van fossiele brandstoffen nam als volgt af: geen investeringen in nieuwe kolencentrales na 2025 en vervroegde afschrijving van bestaande capaciteit om het gebruik van steenkool zonder CCS tussen 2030 en 2060 uit te faseren[31]. Hoofdstuk 5 presenteerde een meer verfijnd *Bridge*-scenario op basis van een concrete set maatregelen, zogenaamde *good practice policies*, die tot 2030 kunnen worden geïmplementeerd. Deze maatregelen en hun gedifferentieerde doelstellingen voor rijkere en armere landen waren gebaseerd op succesvolle voorbeelden in landen en interactie met nationale experts. Zo vormen ze een relevante en haalbare lijst van opties voor alle sectoren (landbouw, landgebruik, energievoorziening, gebouwen, industrie, transport, afval, overig). Een voorbeeld is het verhogen van het aandeel van niet-fossiele voertuigen in de verkoop van nieuwe voertuigen naar 50% in 2030 in landen met een hoog inkomen, naar 25% in 2025 in China en naar 25% in 2030 in landen met lage inkomens.

In combinatie met een alomvattende koolstofprijs na 2030 dicht een dergelijk *Bridge*-scenario de mondiale ambitiekloof tussen NDC's en kostenoptimale 2 °C-scenario's in 2030 met tweederde (een reductie van 7.2 GtCO_2eq, tegenover een kloof van 11.8 GtCO_2eq, modelmediaan) en in 2050 volledig (Figuur 8. 5). Bij gebrek aan onmiddellijke, allesomvattende en ambitieuze klimaatmaatregelen, kan een succesvolle implementatie van *good practice* beleidsmaatregelen de wereld niet alleen op weg helpen naar een traject dat compatibel is met 2 °C, maar het zou ook goedkoper zijn dan uitstel. Het gestileerde *Bridge*-scenario toonde ook aan dat het verhogen van het ambitieniveau van NDC's vóór 2030 kan zorgen voor een soepelere energietransitie, met lagere jaarlijkse emissiereductiesnelheden, meer tijd om het gebruik van fossiele brandstoffen zonder CCS uit te faseren en lagere totale mitigatiekosten.

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31 In IEA's *net-zero*-scenario gebeurt dit in 2040 - IEA. (2021). *Net Zero by 2050*. IEA. Paris https://www.iea.org/reports/net-zero-by-2050.

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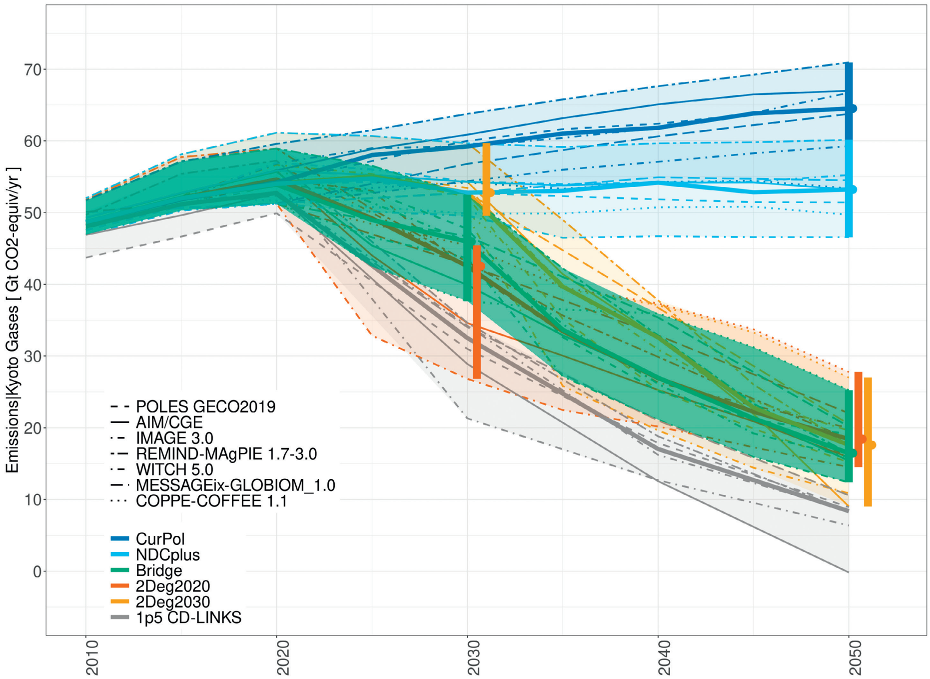


Figuur 8.5: mondiale broeikasgasemissies (Gt CO_2eq/jaar) van 2010 tot en met 2050, projecties van mondiale modellen. Verticale balken: bandbreedte over alle modellen in 2050. Cirkels: modelmediaan in 2050. Dikke ononderbroken lijnen: mediaan. Grijs: 1,5 °C-scenario's uit de IPCC SR1.5-database zijn ter vergelijking opgenomen (er is gekozen voor dezelfde modellen als hier weergegeven, met de meest vergelijkbare scenario-aannames, d.w.z. de 1,5 °C-scenario's ontwikkeld in het CD -LINKS-project). Projecties voor het *Bridge*-scenario zonder de koolstofprijsmaatregel zijn weergegeven in Figure S5.2.7, NDCplus variant NDC_2050convergence in Figure S5.2.8, en 2050 – 2100 in Figure S5.2.9.

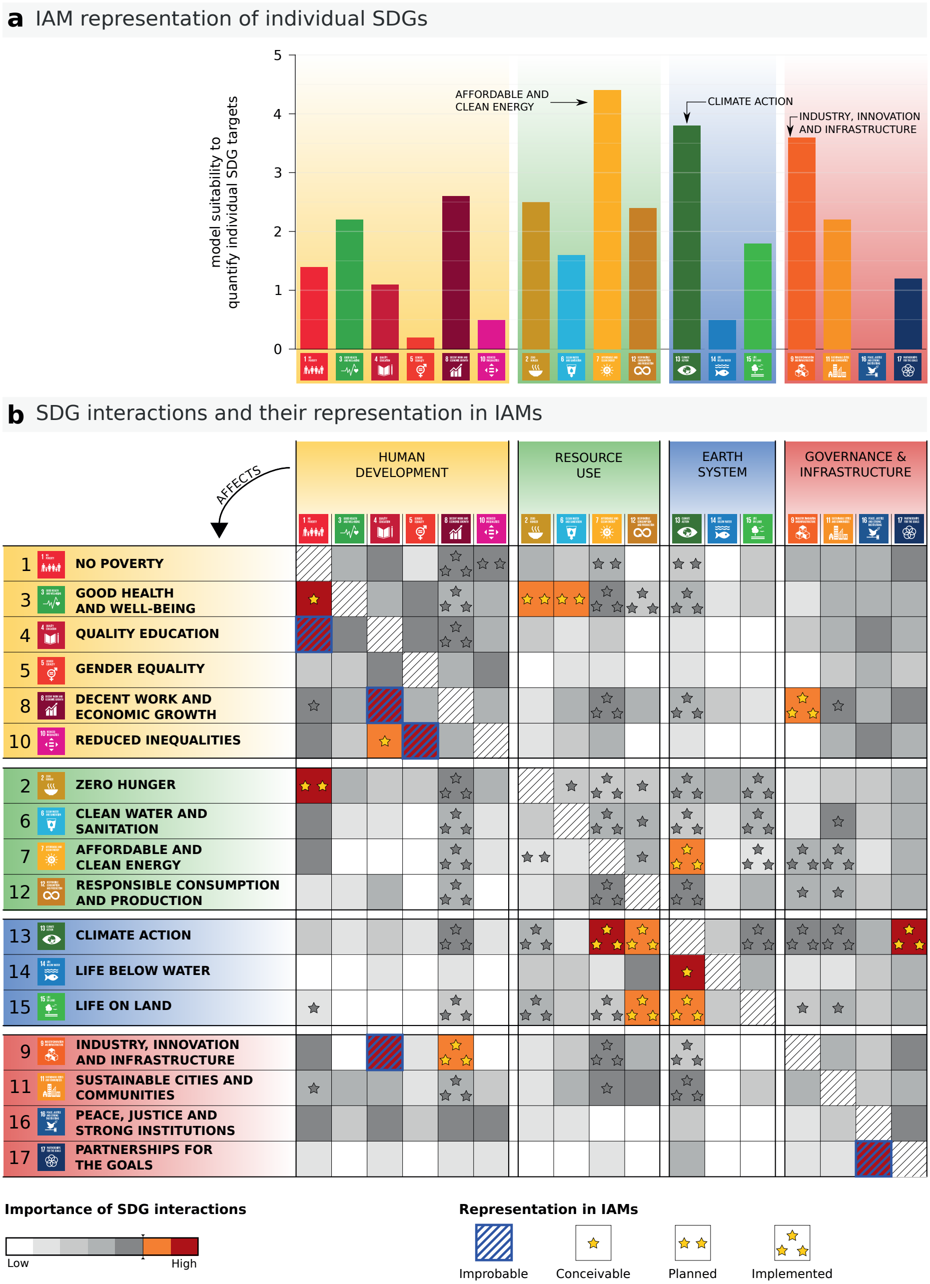
8.3.3.2 Als we de SDG's willen gebruiken om landen te informeren over hoe ze hun mitigatieambitie kunnen verhogen, zijn IAM's dan geschikt om de interacties tussen klimaatbeleid en bredere duurzame ontwikkeling te bestuderen?

De analyse in Hoofdstuk 6 heeft laten zien dat IAM's de SDG's met betrekking tot duurzaam gebruik van hulpbronnen en het aardsysteem goed meenemen. Doelen met betrekking tot menselijke ontwikkeling en goed bestuur zijn minder goed vertegenwoordigd - en kunnen voor deze modellen moeilijker zijn om volledig mee te nemen. Volgens de expertenquête bevinden belangrijke interacties tussen SDG's zich binnen het cluster menselijke ontwikkeling, tussen de clusters menselijke ontwikkeling en hulpbronnen, en met het cluster aardsysteem. Vele daarvan worden door IAM's meegenomen, zij het met verschillende aandachtspunten vanwege de historie van deze modellen; met name de interacties binnen en tussen de clusters

‘Efficiënt en duurzaam hulpbronnengebruik’[32] en ‘aardsysteem’ (Figuur 8.6). De modellen zijn echter uitgebreid naar andere gebieden, waaronder elementen uit de clusters ‘Goed bestuur en infrastructuur’ en ‘Menselijke ontwikkeling’. De kracht van IAM’s ligt in hun vermogen om een mondiaal beeld te geven, de verschillen tussen regio’s te benadrukken en verplaatsingseffecten mee te nemen, maar ook de verschillen tussen bijvoorbeeld steden en plattelandsgebieden te laten zien. Geplande ontwikkelingen omvatten een betere vertegenwoordiging van het cluster menselijke ontwikkeling, met interacties die door experts als belangrijk worden beschouwd, maar die momenteel niet (goed) worden meegenomen door de bestaande modellen. In sommige gevallen is modelontwikkeling mogelijk, maar in andere gevallen kunnen andere analyses geschikter zijn. Daarom zal een betere representatie van heterogeniteit, het gebruik van verschillende modellen en het koppelen van verschillende disciplines nodig zijn.

Hoewel er lacunes bestaan in de vertegenwoordiging van SDG-doelen, -indicatoren, -processen en - interacties, bieden IAM’s een goed startpunt voor uitgebreidere SDG-studies. IAM’s hebben bewezen in staat te zijn hun toepasbaarheid te vergroten en interacties tussen sectoren en regio’s te analyseren. Daarom zouden ze ook gebruikt kunnen worden om te bestuderen of de SDG’s mogelijkheden bieden om de ambitiekloof te dichten. Als eerste stap daarin liet het *Bridge*-scenario uit Hoofdstuk 5 belangrijke nevenvoordelen zien: de emissies van luchtverontreinigende stoffen zoals roet, koolmonoxide, stikstofoxiden, organische koolstof, zwavel en vluchtige organische stoffen zullen naar verwachting afnemen in vergelijking met het NDC-scenario. Dagnachew et al. (2021) vonden significant meer synergiën tussen mitigatiemaatregelen en andere SDG’s dan afruilen (*trade-offs*) in alle wereldregio’s, wat het potentieel benadrukt om ambities te verhogen. Zo liet het vergroten van het aandeel hernieuwbare elektriciteit de meeste synergiën zien met andere SDG’s, maar technologiekeuze is daarin wel belangrijk. Flankerend beleid kan potentiële afruilen beperken; bijvoorbeeld om de armen te beschermen. Gezien de IAM-vertegenwoordiging van de effecten van SDG’s 2 (geen honger), 7 (betaalbare en schone energie), 8 (fatsoenlijk werk en economische groei), 9 (industrie, innovatie en infrastructuur), 11 (duurzame steden en gemeenschappen), 12 (verantwoorde consumptie en productie), en 15 (leven op het land) op SDG 13 (klimaatactie), zou in de toekomst bijvoorbeeld kunnen worden onderzocht hoe het bieden van toegang tot energie via koolstofarme energiebronnen tegelijkertijd meer klimaatambitie kan stimuleren (e.g. Dagnachew et al., 2018).

32 Dit cluster omvat SDG’s 2, 6, 7, en 12, dus niet alleen energiebronnen maar ook hulpbronnen als water, voedsel en metalen, en materialen – Zie voor een voorbeeld van hoe dat laatste in een IAM wordt meegenomen: Deetman, S., de Boer, H. S., Van Engelenburg, M., van der Voet, E., & van Vuuren, D. P. (2021). Projected material requirements for the global electricity infrastructure – generation, transmission and storage. *Resources, Conservation and Recycling*, *164*, 105200. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.105200 .



Figuur 8.6: De vertegenwoordiging van SDG's door IAM's. (A): De staafhoogte geeft de gemiddelde score voor dekking van individuele doelen uit de modelenquête weer (Table 6.1). (B): SDG-interacties en vertegenwoordiging door IAM's volgens de expert- en modelenquêtes (de SDG in de kolom heeft invloed op de SDG in de rij). De sterkte-dimensie van SDG-interacties wordt aangegeven door grijstinten: de donkerste grijstint staat voor gemiddelde scores in

de buurt van 3 (sterke interacties), terwijl wit geen interacties vertegenwoordigt. Sterretjes geven de representatie van IAM's aan volgens het modelonderzoek. ***: momenteel in IAM's, **: geplande ontwikkeling, en * denkbaar om in de toekomst te worden gemodelleerd. Ten slotte geven oranje cellen de hoogste overeenkomst aan tussen het belang van interacties en mogelijke modelrepresentatie, terwijl blauw gekleurde cellen de meest opvallende belangrijke interacties laten zien zonder modelrepresentatie. Interacties die zijn gemarkeerd als momenteel in IAM's zijn endogeen, met verschillende niveaus van procesdetails. Toekomstige modellering van de SDG-interacties die tot nu toe niet zijn meegenomen kan worden bereikt als onderdeel van een consistente set van exogene aannames, zoals de impact van kwaliteitsonderwijs op het verminderen van armoede.

8.4 Aanbevelingen voor onderzoek en beleid

8.4.1 Aanbevelingen voor verder onderzoek

De aanbevelingen voor toekomstig onderzoek kunnen in twee hoofdlijnen worden ingedeeld: meer details binnen de IAM's en meer samenwerking en interactie met andere tools en disciplines.

8.4.1.1 Meer gedetailleerde modellering

Belangrijke aspecten van modelverbetering zijn de regionale uitsplitsing van modellen en de representatie van beleid. Het zou niet praktisch zijn om alle landen afzonderlijk te modelleren, maar het zou zeker nuttig zijn om ten minste de, zeg 20, grootste uitstoters (samen goed voor ongeveer 80% van de wereldwijde uitstoot van broeikasgassen) afzonderlijk te vertegenwoordigen voor het adviseren van het klimaatbeleid. Dat betekent ook het herdefiniëren van de regio 'Europese Unie', die in veel modellen eerder als Europa dan als EU28 (laat staan EU27) gezien kan worden. In CD-LINKS zijn modelleurs begonnen om individuele beleidsmaatregelen en doelen van G20-landen te implementeren in de scenario's die in het kader van het project zijn ontwikkeld. Gezien de snelle ontwikkelingen in het klimaatbeleid wereldwijd is het echter noodzakelijk om de modelcapaciteiten op dit gebied te vergroten. IAM's zullen continu moeten werken aan hun vertegenwoordiging van doelen, maatregelen en instrumenten om relevant te blijven. Modelontwikkelingen zijn nodig om sturingsmogelijkheden (beleidsmaatregelen en instrumenten) in alle onderdelen van het model op te nemen, dus in alle sectoren en op meerdere schaalniveaus. Regionale definities moeten mogelijk worden bijgewerkt op basis van nieuwe politieke ontwikkelingen; bijvoorbeeld een betere vertegenwoordiging van de EU27. Naast dekking van alle relevante grote uitstotende landen, zal vertegenwoordiging van niet-statelijke actoren (steden en bedrijven) belangrijk zijn.

Meer gedetailleerde modellering zal gepaard moeten gaan met tijdigheid om de relevantie te maximaliseren. Gerelateerd aan de wijze waarop beleidsinstrumenten in de modellen vertegenwoordigd zijn is de peildatum die wordt toegepast op het beleid en de NDC-doelen die in de analyse worden meegenomen. Een peildatum is een voorwaarde voor modellen om beleidsscenario's te draaien, maar een peildatum impliceert dat de scenario's op het moment van publicatie waarschijnlijk verouderd zijn. Standaardisering van het proces voor het bijwerken van scenario's zou bijdragen aan de tijdige publicatie van actuele scenario's en het gemakkelijk opnemen van marginale wijzigingen. Dit proces is al begonnen met het modelleringsprotocol en de documentatie, maar kan verder worden verfijnd en tot op zekere hoogte geautomatiseerd. Een ander element van tijdigheid is in hoeverre kortetermijnontwikkelingen—de COVID-19-pandemie is een goed voorbeeld—kunnen en moeten worden opgenomen in de ontwikkeling van scenario's. IAM's zijn misschien niet altijd geschikt om beleidsvragen over het effect van crises te beantwoorden, maar bij het nadenken over relevantie is een bewuste reflectie op hoe met dergelijke vragen om te gaan nodig.

Naast een meer gedetailleerde analyse van beleidsinstrumenten zullen doelstellingen voor netto-nul-emissies aandacht behoeven. Naast de factoren die we hebben bestudeerd, zou toekomstig werk een aantal andere factoren kunnen analyseren die van invloed kunnen zijn op verschillen in uitfaseringsjaren tussen landen. Het gaat dan onder meer om andere conversiefactoren dan *Global Warming Potentials* (GWP's) om de bijdrage van verschillende broeikasgassen te vergelijken, op verbruik gebaseerde versus op productie gebaseerde emissieboekhouding, en het effect van verschillende modelaannames over beschikbare mitigatie-opties per sector, die bepalen hoe snel elke sector emissies kan reduceren. Het zou voor de robuustheid beter zijn om een grotere set van modellen en landen te gebruiken. Met zo'n uitgebreide dataset zou een *Principal Component Analysis* (PCA) zoals toegepast in Hoofdstuk 4 zinvoller zijn. Als alternatief zou in de resultaten van één model gedoken kunnen worden om de onderliggende dynamiek bloot te leggen. Een vergelijking van scenarioresultaten met door landen ingediende langetermijnstrategieën zou verder nuttig zijn: aan de ene kant om extra mitigatiepotentieel voor deze strategieën te identificeren en, aan de andere kant, om de scenario's een betere afspiegeling te laten zijn van de politieke realiteit.

Ten slotte kunnen uit de SDG-enquêtes gebieden voor modelverbetering worden gedestilleerd, waarbij wordt erkend dat niet alle modellen alle aspecten en interacties hoeven te dekken. Om te beginnen is het belangrijk om verder te gaan dan alleen te onderzoeken hoe de SDG's worden beïnvloed door klimaatbeleid. Het evalueren van de impact van het bereiken van de menselijke ontwikkelingsdoelen op het klimaat, ecosystemen en het gebruik van hulpbronnen (in de ruimste zin) kan een goed uitgangspunt zijn. Als zodanig kunnen *no-regret*-gebieden voor verhoogde klimaatambitie worden geïdentificeerd (no-regret wil zeggen dat er geen negatieve of wellicht positieve effecten op andere SDG's zijn). Om dit goed te doen, moeten modellen mogelijk verder worden ontwikkeld om de effecten mee te nemen van armoedebestrijding op gezondheid en economische groei (mogelijk via modelkoppeling), van (hernieuwbare) energie op steden (mogelijk via modules of modelkoppeling), van onderwijs op ongelijkheden (mogelijk via modelkoppeling), van klimaatactie op oceanen (mogelijk via modeluitbreidingen), en van steden op water en economische groei (mogelijk via modeluitbreidingen). Modelontwikkeling kan ook de huidige vertegenwoordiging van interacties verbeteren, omdat veel IAM-indicatoren met betrekking tot SDG-doelen momenteel gebaseerd zijn op exogene invoer of endogene uitvoer zonder feedback ('impactindicatoren'), en dus eenrichtingsrelaties vertegenwoordigen. Hierbij kan onderscheid worden gemaakt tussen 1) het volgen van de SDG-voortgang, waarvoor een verbetering van de modellering van SDG-indicatoren nodig is, en 2) oplossingen, waarvoor IAM's mogelijk de vertegenwoordiging van processen die relevant zijn voor de SDG-indicator en de interactiedynamiek moeten verbeteren. Naast interacties tussen de beleidsdomeinen moet ook rekening worden gehouden met interacties tussen verschillende geografische schalen. Voldoende temporele en ruimtelijke resolutie is nodig om de mogelijke strategieën voor het bereiken van de SDG's te analyseren. Het is bovendien noodzakelijk om verder te gaan dan schaalniveaus en van gemiddelden naar expliciete modellering van heterogeniteit te gaan, aangezien veel SDG's verdelingskwesties zijn, met name menselijke ontwikkelingsdoelen. Dit kan endogeen gebeuren of door meer gedetailleerde modules te ontwikkelen en te koppelen aan het *integrated assessment*-raamwerk.

8.4.1.2 Samenwerking

Naast modelinterne ontwikkelingen zal samenwerking met andere modellen, methoden en disciplines nodig zijn voor een integraal antwoord op de vraag 'hoe komen we daar?'.

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Ten eerste, hoewel de nationale resultaten van mondiale IAM's een nuttige aanvulling op de literatuur zijn, **zal de interactie tussen nationale en mondiale modellen moeten worden voortgezet en versterkt.** Hoewel er wederzijds leren heeft plaatsgevonden, is de focus tot nu toe vooral gericht geweest op het bieden van mondiale randvoorwaarden (vaak in de vorm van koolstofbudgetten) door mondiale modellen aan nationale modellen. De volgende stappen zouden zijn om de wederzijdse interactie te versterken, met enkele duidelijke gebieden waar nationale modellen informatie kunnen verstrekken aan mondiale modellen, bijvoorbeeld: haalbaarheid van scenario's en specifieke oplossingen, potentieel van nationale hulpbronnen, nationale doelstellingen en beleid, politieke prioriteiten, vooral in andere terreinen dan klimaatbeleid, en historische data. Naast de interactie tussen nationale en mondiale modellen kan samenwerking met *bottom-up*-analyses helpen om meer sectorale details mee te nemen.

Ook rond de SDG's is modelsamenwerking nodig. Hoewel veel hiaten kunnen worden gedicht door meer SDG-dimensies in IAM's te integreren, is volledige endogenisering van alle interacties niet mogelijk en in sommige gevallen waarschijnlijk ook niet gewenst. In dergelijke gevallen is het koppelen van verschillende disciplines door middel van exogene aannames en een gemeenschappelijk narratief (zoals de *Shared Socioeconomic Pathways,* SSP's) een alternatieve optie. Dit geldt met name voor doelen die verband houden met de institutionele en sociale dimensies van de SDG's die vaak cruciaal zijn om het halen van andere SDG's mogelijk te maken. Nauwere samenwerking binnen de IAM-gemeenschap kan bijdragen aan het dichten van hiaten. *Soft-linking* naar andere, meer gekwalificeerde, modellen kan een goed uitgangspunt zijn, om uiteindelijk misschien zelfs naar een *integrated assessment*-raamwerk te gaan waarin deze verschillende modellen zijn opgenomen. Dergelijke multimodelraamwerken kunnen helpen om dynamieken tussen sectoren te beschrijven die niet endogeen zijn voor de modellen zelf. Als beslissingsondersteunende instrumenten kunnen deze raamwerken informatie verschaffen met hogere ruimtelijke en temporele resoluties, terwijl de consistentie met mondiale randvoorwaarden behouden blijft.

Verder zullen IAM's nauwer moeten samenwerken met sociale wetenschappen, vooral op het gebied van haalbaarheidsvragen en de SDG's. IAM's zullen moeten worden gecombineerd met empirisch onderzoek om de lokale context en ervaring met betrekking tot strategieën die in verschillende omgevingen werken mee te nemen, aangezien IAM's niet alles kunnen (en waarschijnlijk niet eens moeten proberen te) vertegenwoordigen. Er is een grote inspanning nodig om IAM-resultaten te helpen vertalen naar concrete beleidsaanbevelingen. Een vergelijking van scenarioresultaten met door landen ingediende langetermijnstrategieën zou bijvoorbeeld nuttig zijn: enerzijds om extra mitigatiepotentieel voor deze strategieën te identificeren en anderzijds om de scenario's beter af te stemmen op de politieke realiteit. Dat is ook waar sociale wetenschappen waarde kunnen toevoegen aan dit werk: het bestuderen van de maatschappelijke acceptatie en praktische implementatie van netto-nul-emissiedoelen, met begrip van relevante actoren en hun motivaties. Tegelijkertijd behoeven kwesties als rechtvaardigheid en verdelingseffecten van klimaatbeleid aandacht (Fragkos et al., 2021a; Ohlendorf et al., 2021). Het focussen op de praktische haalbaarheid (Jewell & Cherp, 2020) van de scenario's zal een belangrijke volgende stap zijn: eerst met een beoordeling van de haalbaarheid van bestaande scenario's, gevolgd door het ontwerpen van scenario's die rekening houden met verschillende dimensies van haalbaarheid. Doorlopend werk in het ENGAGE-project zal een goede basis vormen, waar twee concepten worden ontwikkeld. De ene kan de haalbaarheid van scenario's helpen evalueren door projecties te vergelijken met historische precedenten, terwijl de andere randvoorwaarden definieert op basis van een multidimensionale haalbaarheidsbenadering. Dit kan de volgende stap zijn bij het ontwerpen van scenario's die vanaf het begin rekening houden met de haalbaarheid.

8.4.2 Beleidsaanbevelingen

We hebben getracht de emissiekloof te overbruggen, niet alleen door concrete maatregelen te onderzoeken om de kloof te dichten, maar ook methodologisch, door (mondiale) IAM's te gebruiken om nationale beleidsvorming te informeren. We hebben de emissiekloof opgesplitst in een ambitiekloof tussen NDC's en 2 °C en 1,5 °C (die zowel wereldwijd als op landenniveau kan worden bestudeerd), en een implementatiekloof tussen het huidige geïmplementeerde klimaatbeleid en NDC's (die het best op landenniveau kan worden bestudeerd). Beide delen van de kloof zullen moeten worden gedicht als we de wereldwijde mitigatiedoelstellingen van het Parijsakkoord willen halen.

8.4.2.1 Ambitiekloof en implementatiekloof

Om de ambitiekloof te dichten, zouden netto-nul-emissiedoelstellingen, indien volledig geïmplementeerd, een belangrijke stap in de goede richting kunnen zijn om de klimaatdoelstellingen van het Parijsakkoord te halen. Ze zullen rekening moeten houden met nationale omstandigheden, zoals verschillende mitigatiemogelijkheden, en duidelijk moeten zijn over hun reikwijdte. Om tegelijkertijd de implementatiekloof te dichten zullen ze ook vergezeld moeten gaan van maatregelen om ze op kortere termijn te gaan implementeren, inclusief duidelijkheid over hoe ze zich verhouden tot 2030-doelen (NDC's). De SDG's kunnen helpen de resterende kloof te dichten door landen te informeren over mogelijke gebieden voor verhoogde ambitie waar synergiën met andere ontwikkelingsprioriteiten kunnen worden gevonden. Dit vereist nader onderzoek.

Om de implementatiekloof te dichten, zal op korte termijn (dit decennium) aanvullend klimaatbeleid moeten worden aangenomen en bestaand beleid moeten worden versterkt. Het hier ontwikkelde *Bridge*-scenario bevat een reeks concrete en nationaal relevante maatregelen die nu kunnen worden geïmplementeerd, omdat ze gebaseerd zijn op bestaande technologieën en beleidsmaatregelen die sommige landen al hebben aangenomen.

De bevindingen resulteren in een aantal beleidsaanbevelingen die gerelateerd zijn aan *ambitie* (het stellen van doelen, Hoofdstuk 8.4.2.2) en aan *implementatie* (het implementeren van beleidsmaatregelen, Hoofdstuk 8.4.2.3).

8.4.2.2 Doelen

Naast de bekende aanbeveling dat NDC-doelstellingen moeten worden aangescherpt, zouden **netto-nul-emissiedoelstellingen gebaat zijn bij verduidelijking** op de volgende gebieden. Allereerst moeten ze duidelijk hun reikwijdte specificeren in termen van broeikasgasemissies en sectorale dekking, evenals of ze bedoeld zijn om in eigen land te worden bereikt of in welke mate *Internationally Transferred Mitigation Outcomes* (ITMO's) zullen worden gebruikt. Ten tweede zou een expliciete vermelding van de gebruikte landgebruiksdata en aannames over de voortzetting van de *sinks* helpen om discrepanties met wetenschappelijke emissie-inventarisaties op te lossen. Ten derde zouden alle aannames over het gebruik en de boekhouding van BECCS moeten worden gespecificeerd om mogelijke concurrerende claims op hulpbronnen en dubbeltellingen aan het licht te brengen. Ten vierde dient de formulering van een netto-nul-emissiedoelstelling expliciet te maken op welke visie op rechtvaardigheid deze gebaseerd is, aangezien verschillende perspectieven tot verschillende uitfaseringsjaren leiden. Tot slot is bijzondere aandacht nodig voor het vergroten van het vermogen om negatieve emissies te realiseren. Daarnaast is de relatie tussen netto-nul-emissiedoelen en korteretermijndoelen, zoals vastgelegd in NDC's, belangrijk.

NDC's moeten worden afgestemd op netto-nul-emissie- of andere langetermijndoelen. Netto-nul-doelen bieden een nuttige langetermijnvisie en kunnen helpen de ambitiekloof in 2050 te dichten, maar ze zullen moeilijk te realiseren zijn als ze niet worden gecombineerd met een visie op wat er op kortere termijn moet gebeuren. Dat omvat niet alleen een emissiereductiedoelstelling voor 2030 die het mogelijk maakt om de netto-nul-emissiedoelstelling te halen, maar ook een streefjaar voor piekemissies (indien nog niet bereikt), en het reductietraject tussen 2030 en het streefjaar voor netto-nul-emissies. Lineaire emissiereducties kunnen moeilijker worden bereikt wanneer de mitigatiemogelijkheden zijn uitgeput.

Beleidsmakers kunnen de hier gepresenteerde resultaten niet zomaar gebruiken om nationale doelen vast te stellen. Scenario-uitkomsten moeten met zorg worden gebruikt: een modelgemiddelde emissiereductiedoelstelling voor een geaggregeerde regio of sector kan bijvoorbeeld niet rechtstreeks worden toegepast op alle sub-elementen van die regio of sector (bijvoorbeeld landen of bedrijven). Niet alleen omdat dit gemiddelden (of medianen) zijn van een waaier aan scenario's door verschillende modellen die tot dezelfde temperatuuruitkomst leiden, maar ook omdat de meeste van deze scenario's kostenoptimaal zijn, dat wil zeggen: geen rekening houden met rechtvaardigheid. Bovendien houden deze scenario's niet expliciet rekening met waar de verantwoordelijkheid ligt (bijvoorbeeld consument versus producent), en geven ze ook geen volledige weergave van modelonzekerheid (dat wil zeggen dat één scenario per model niet de inherente onzekerheid van dat model laat zien). Bovendien is de modelonzekerheid niet representatief voor het volledige onzekerheidsbereik. Nationale modellen en andere instrumenten en wetenschappelijke disciplines zullen daarom ook moeten worden toegepast om de relevante binnenlandse omstandigheden en onzekerheden volledig mee te nemen. De vaststelling van de nationale doelstellingen kan verder worden onderbouwd door studies over nevenvoordelen, die suggereren dat een aanzienlijk deel van de mitigatiekosten zou kunnen worden gedekt door rekening te houden met luchtkwaliteit en andere nevenvoordelen, waardoor aanvullende binnenlandse mitigatie aantrekkelijker wordt.

8.4.2.3 Beleidsmaatregelen

De 'implementatiekloof' is het deel om op te focussen in dit cruciale decennium voor klimaatactie. Aangezien de implementatiekloof ongeveer de helft van de totale emissiekloof uitmaakt, en de voorbereiding en uitvoering van klimaatbeleid tijd kost, zijn er grote inspanningen nodig in alle landen om de implementatiekloof te dichten. Hoewel bestaand beleid kan worden versterkt, moet mogelijk ook nieuw beleid worden ingevoerd, vooral in sectoren met minder beleid.

Het *Bridge*-scenario dat in Hoofdstuk 5 is gepresenteerd, liet zien dat het beter zou zijn om te beginnen met een pakket van niet-kostenoptimale maatregelen en zo de weg vrij te maken voor een alomvattende koolstofbeprijzing, dan om te wachten. Beter wil zeggen: niet alleen in termen van kans op succes bij het beperken van de opwarming van de aarde, maar ook in termen van beleidskosten. Dergelijke maatregelen voor alle sectoren omvatten bijvoorbeeld: in vervoer, de introductie van elektrische en andere koolstofarme voertuigen, verbetering van de brandstofefficiëntie en verbetering van de energie-efficiëntie van de luchtvaart; in gebouwen, verbetering van de energie-efficiëntie van apparaten, verbetering van de intensiteit van eindgebruik van energie van nieuwe gebouwen, geen nieuwe installaties van olieketels en renovatie van bestaande gebouwen; in de industrie, toepassing van CCS, verbetering van de efficiëntie van eindgebruik van energie en vermindering van N_2O-emissies door de productie van adipinezuur; op het gebied van energievoorziening, uitfasering van kolencentrales zonder CCS, verhoging van het aandeel van hernieuwbare energie in elektriciteit, terugwinning van methaanemissies uit kolenmijnen en vermindering van het affakkelen van methaan en CO_2; in landbouw en landgebruik, toepassing van anaerobe vergisters voor mestverwerking, verhoging van de efficiëntie van het stikstofgebruik, selectieve veredeling, toenemende bebossing en herbebossing en stoppen van ontbossing; evenals het verminderen van de methaanemissies uit afval, het verminderen van de uitstoot van F-gassen en koolstofprijzen.

Wat betreft het gebruik van IAM's in beleidsbeoordelingen, hebben IAM's al een rol gespeeld in het informeren van het wereldwijde en nationale klimaatbeleid, zowel via IPCC-*assessments* als met individuele modeltoepassingen. Deze tools kunnen beleidscoherentie voor de SDG's bevorderen door complexiteit te structureren, onzekerheden met betrekking tot de impact van beleid te onderzoeken met scenario's en omstreden standpunten te verzoenen door middel van gemeenschappelijke verhalen, onder meer door verschillende ministeries bij elkaar te brengen. Ze kunnen helpen bij het volgen van de dynamiek, waaronder keteneffecten van verschillende beleidsdoelen en -instrumenten, en tweede-orde-interacties, om beleidsmakers te helpen bij het identificeren en minimaliseren van afruilen, terwijl synergiën worden gemaximaliseerd.

Supplementary information

Section numbers in the Supplementary Information correspond with the chapter numbers used in this thesis. For example, S2 refers to the supplementary material for Chapter 2: Early Action on Paris Agreement Allows for More Time to Change Energy Systems.

S2 Early Action on Paris Agreement Allows for More Time to Change Energy Systems

S2.1 Supplementary text to section 2.2.1

S2.1.1 LULUCF emissions

To construct the final emission projections including emissions from LULUCF, IIASA provided the MAC curves for land use CO_2 emissions, using G4M (Böttcher et al., 2011; Kindermann et al., 2008), differentiating between activities (deforestation, afforestation, and forest management), as well as sources (biomass, soil, and dead organic matter). Only the activities deforestation and afforestation were considered in the final estimates of land use CO_2 emissions, and only emissions and removals related to biomass were incorporated. For most countries, IIASA's business-as-usual projections for this combination of activities and sources were used in the current policies scenario, after harmonisation to FAO (FAOSTAT, 2015). For some countries, updated projections to include current policies from den Elzen et al. (2015) and historical emissions from national communications were used instead. For the 2.8 W/m^2 scenarios, carbon prices resulting from FAIR projections were used to derive the additional reductions of land use CO_2 emissions in G4M. These additional LULUCF CO_2 emission reductions were subtracted from the harmonised BAU projections. In countries where further emission reductions would still be possible according to the *enhanced policy (bottom-up)* scenario as reported by den Elzen et al. (2015), these projections for LULUCF emissions were used instead (Turkey, Mexico, and India). The optimisation in FAIR was done with IMAGE land LULUCF emission pathways reflecting the expected effect of current policies and (I)NDCs on LULUCF emissions. Optimisation focused on energy and industry emissions, given uncertainties in land use emissions, but in the optimisation, an IMAGE land use emissions pathway consistent with 2°C and abatement costs including land use effects (more biomass use) was used. The IMAGE land LULUCF emission pathways started from higher 2010 emission levels (based on IPCC AR5) than the IIASA projections, but showed similar trends between 2010 and 2050. Differences in 2010 emission levels are largely explainable by different definitions of emissions and removals (Grassi and Dentener, 2015). The IMAGE land LULUCF CO_2 emissions were replaced by G4M emission levels after the optimisation. Increased biomass utilisation did not have a feedback on the LULUCF emissions and removals. Overall biomass utilisation in the 2.8 W/m^2 scenarios (Figure 2.3) was in line with G4M biomass potentials.

S2.1.2 Data sources

The main data sources behind the IMAGE model, relevant for this study, are:

1. SSP economic projections from OECD (Dellink et al., in press)
2. IEA Statistics and Data (IEA, 2015)
3. Enerdata Global Energy & CO_2 Data (Enerdata, 2016)
4. Survey of Energy Resources (World Energy Council, 2010)
5. The future of nuclear power - an interdisciplinary MIT study (MIT, 2003)
6. The potential role of hydrogen in energy systems with and without climate policy (van Ruijven et al., 2007)
7. Power and heat productions: plant developments and grid losses (Hendriks et al., 2004)
8. 1Assessment of the global fossil fuel reserves and resources for TIMER (Mulders et al., 2006)
9. Future bio-energy potential under various natural constraints (van Vuuren et al., 2009)
10. On the global and regional potential of renewable energy sources (Hoogwijk, 2004)

S2.2 Supplementary tables

Table S2.2.1: Overview of current policies and the reduction targets under 2020 pledges and 2025/2030 NDCs implemented in the scenarios. Assumptions on the achievement of 2020 pledges and inclusion of countries' pledges and NDCs within a model region are italicised

IMAGE region	Current policies	2020 pledge	2025 NDC	2030 NDC
Brazil	Forest code for the Amazon; renewable energy targets	36% - 39% below national BAU	37% below 2005	43% below 2005 (indicative target)
Canada	Fuel standard for light-duty vehicles and heavy-duty trucks; power plant standard	17% below 2005 *(12% from domestic action: current policies)*[*]		30% below 2005, excl. LULUCF
China	15% share of non-fossil fuels; renewable capacity targets for 2020 and 2030; CAFE standard (5 l/100 km by 2020); 10% ethanol blending mandate in selected provinces; subsidies for electric vehicles; forest area and stock volume increase	CO_2 /GDP -40–45% vs. 2005; 15% share of non-fossil fuel in primary energy consumption; increased forest coverage / stock volume		Peak CO_2 emissions around 2030; CO_2/GDP -60%-65% vs. 2005; 20% share of non-fossil fuels; increase forest stock volume
Eastern Africa	N.A.	N.A.		Ethiopia: 64% below BAU (conditional) Kenya: 30% below BAU (conditional) *SSP2 BAU minus effect of Ethiopia and Kenya NDCs*
India	Renewable energy targets (incl. 40% renewables in total power capacity by 2030); PAT scheme (reduce industrial energy consumption); Green India Mission (GIM).	GHG/GDP (except agriculture) -20–25% vs. 2005; 15% share of RES in electricity supply; wind and solar capacity targets		GHG/GDP -35%; 40% renewable energy in total power capacity; additional carbon sink of 2.5 to 3 Mt CO_2e (forest cover)

Table S2.2.1: *Continued.*

IMAGE region	Current policies	2020 pledge	2025 NDC	2030 NDC
Indonesia	Renewable energy target; 15% biofuels in transportation by 2025; Forestry/ agriculture/peatland policies	26% below national BAU		29% (unconditional) –41% (conditional) below BAU
Japan	13.5% renewable electricity by 2020, 20% by 2030; Transport: 16.8 km/l by 2015, 20.3 km/l by 2020	3.8% below 2005; 38 GW wind, 20 GW solar, 14 GW solar thermal capacity		25.4% below 2005 (excl. LULUCF); 20-22% nuclear, 22-24% renewables
Kazakhstan region	*2020 pledge + continuation of 2010-2020 trend toward 2030*	15% below 1992		15% below 1990
Korea (South Korea (SK) and North Korea)	SK: Renewable energy target; ETS (30% reduction below baseline by 2020)	SK: 30% below national BAU *(Korea region: policies leading to 3% above 2010 by 2020)* *		SK: 37% below BAU
Mekong region (incl. Singapore (SP))	N.A.	SP: 16% below BAU		SP: emission intensity 36% below 2005 *SSP2 BAU minus effect of Singapore pledge and NDC*
Mexico	Renewable electricity targets (Special Renewable Energy Programme); zero net emissions from land use change by 2020;	30% below national BAU *(current policies, leading to 9.5% above 2010 (excl. LULUCF) by 2020)* *		GHG incl. LULUCF -22% (unconditional) below national BAU (-36% conditional)
Middle East (including Israel, Jordan)	N.A.	Israel: 20% below BAU		Israel: 26% below 2005 Jordan: 1.5% below BAU (conditional: 14%) *SSP2 BAU minus effect of Israel pledge and Jordan NDC*

Table S2.2.1: *Continued.*

IMAGE region	Current policies	2020 pledge	2025 NDC	2030 NDC
Northern Africa	N.A.	N.A.		Morocco: 13% below BAU (conditional: 32%) *SSP2 BAU minus effect of Morocco NDC*
Oceania (Australia (AUS), New Zealand (NZ))	AUS: RES target (20% share in electricity supply); close 2000 MW brown-coal-fired power plants (replaced by gas); NZ: Not analysed	AUS: 5%-25% below 2000 *(policies leading to 5% below 2000 by 2020)* NZ: 10-20% below 1990		AUS: 26-28% below 2005 NZ: 30% below 2005.
Rest Central America	N.A.	Costa Rica: -16 Mt relative to BAU *SSP2 BAU minus effect of Costa Rica pledge*		
Rest South America	N.A.	Chile: -30 Mt relative to BAU		Colombia: 20% below BAU (conditional: 30%) Peru: 20% below BAU (conditional: 30%) *SSP2 BAU minus effect of Chile pledge and Colombia and Peru NDCs*
Rest Southern Africa	N.A.	N.A.		BAU
Russian Federation	2.5% to 4.5% renewable energy in the power sector by 2020	15-25% below 1990; 5% RES in electricity supply		25-30% below 1990

Table S2.2.1: *Continued.*

IMAGE region	Current policies	2020 pledge	2025 NDC	2030 NDC
South Africa	RES capacity target (25 GW 2030);	34% - 42% below national BAU *(policies leading to 19% above 2010 by 2020)*[*]; RES capacity target	Peak, Plateau and Decline scenario: 398 – 614 $MtCO_2eq$	Peak, Plateau and Decline scenario: 398 – 614 $MtCO_2eq$
Southern Asia	N.A.	N.A.		BAU
Turkey	*Current policies scenario + continuation of 2010-2020 trend toward 2030*	N.A.		21% below BAU
Ukraine region	N.A.	20% below 1990		40% below 1990
United States	Light-duty vehicles and heavy-duty trucks efficiency standards; biofuels in transport; 16% REN in electricity supply by 2020; carbon tax to realise 30% emission reduction in power sector between 2005 and 2030	17% below 2005; standards in transport, 14% share of RES in electricity supply	26-28% below 2005 (average 27%). Incl. LULUCF.	36-38% (linear interpolation to long-term target of -83% by 2050)
Western Africa	N.A.	N.A.	Congo: 48% below BAU (conditional)	Congo: 55% below BAU by 2035 *SSP2 BAU minus effect of Congo NDC*
Western + Central Europe	Fuel standard for new vehicles (95 g CO_2/km)	20% below 1990, 30% conditional *(current policies, leading to 25% below 1990 by 2020)*		40% below 1990 (excl. LULUCF)

[*] *For the NDC scenarios, we assumed partial implementation of the 2020 pledge.*

Table S2.2.2: Share of renewable energy sources and nuclear in primary energy use and in electricity production in 2030 and 2050, under the current policies scenario and the 2.8 W/m^2 scenarios (*2.8 W/m^2-NDC, 2.8 W/m^2-NDC bridge,* and *2.8 W/m^2- 2020 action*)

Share of renewables (including biomass) and nuclear in primary energy use	**Current policies**	**2.8 W/ m²-NDC**	**2.8 W/ m²-NDC bridge**	**2.8 W/ m²- 2020 action**
2030	18.5%	23.3%	26.4%	26.5%
2050	19.5%	46.7%	50.0%	50.7%
Share of renewables (including biomass) and nuclear in electricity production	**Current policies**	**2.8 W/ m²-NDC**	**2.8 W/ m²-NDC bridge**	**2.8 W/ m²- 2020 action**
2030	39.7%	50.7%	57.8%	57.1%
2050	37.4%	81.7%	82.0%	83.1%

S2.3 Supplementary figures

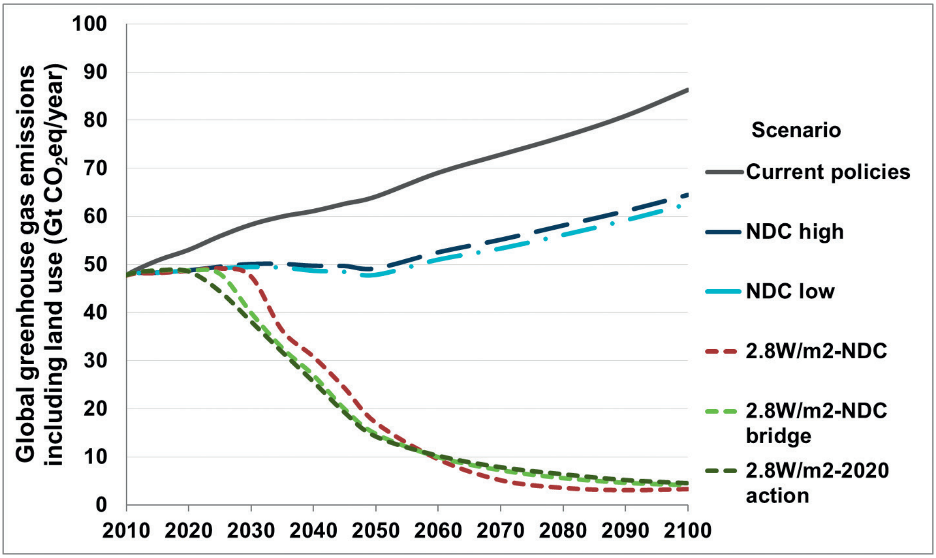

Figure S2.3.1: Global GHG emissions (Gt CO_2eq/year) between 2010 and 2100, including CO_2 emissions from land use, under the current policies scenario (solid line), *NDC high* and *NDC low* (long dashed lines), and the 2.8 W/m^2 scenarios (*2.8 W/m^2-NDC*, *2.8 W/m^2-NDC bridge* and *2.8 W/m^2-2020 action*; short dashed lines)

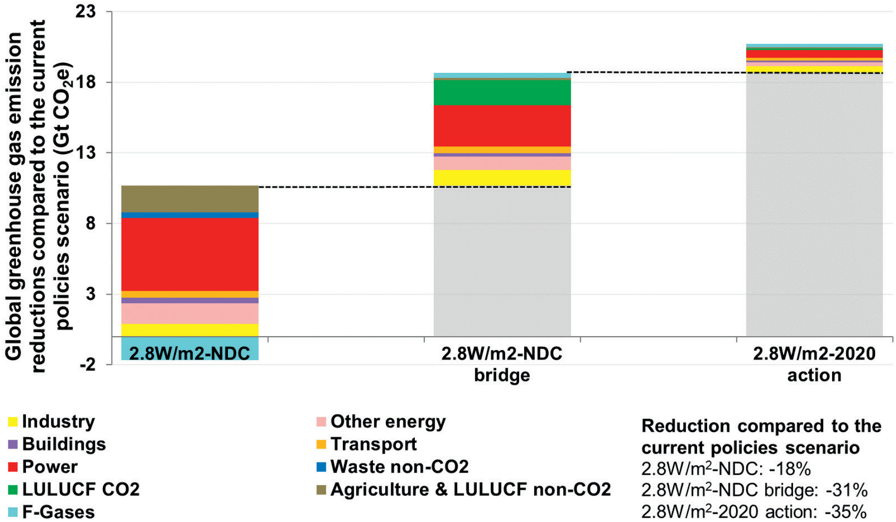

Figure S2.3.2: Differences in sectoral contributions to global emissions between the current policies scenario and 2.8 W/m^2 scenarios (*2.8 W/m^2-NDC*, *2.8 W/m^2-NDC bridge*, and *2.8W/m^2-2020 action*), 2030. Positive numbers indicate emission reductions in 2030, relative to the current policies scenario

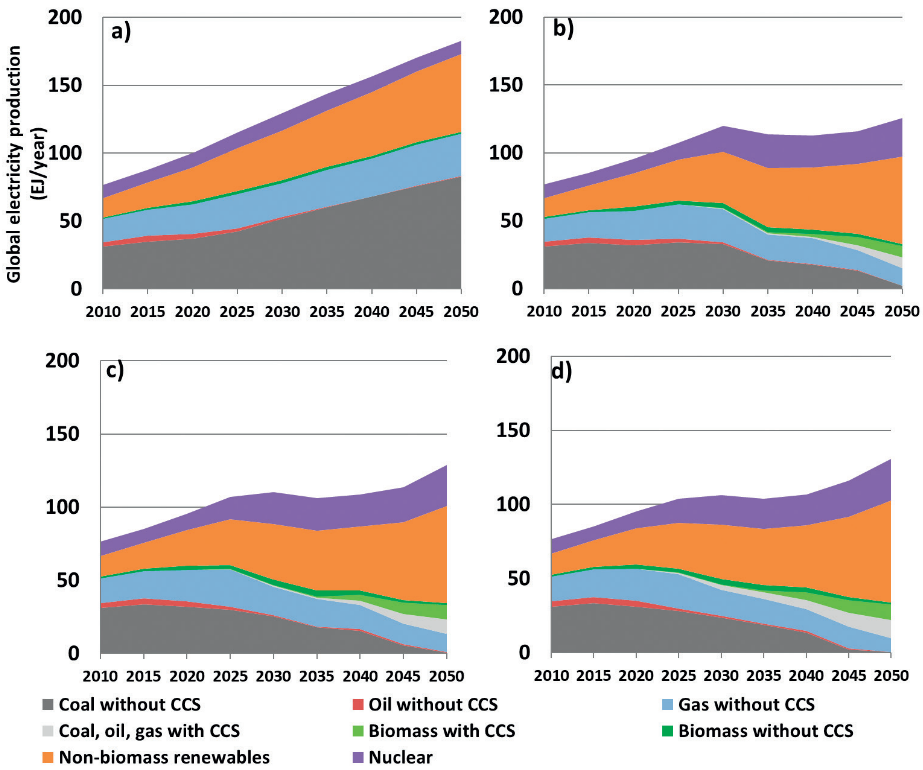

Figure S2.3.3: Global electricity production (EJ/year) between 2010 and 2050, per source, in the current policies scenario (a), *2.8 W/m²-NDC* scenario (b), *2.8 W/m²-NDC bridge* scenario (c), and *2.8 W/m²-2020 action* scenario (d)

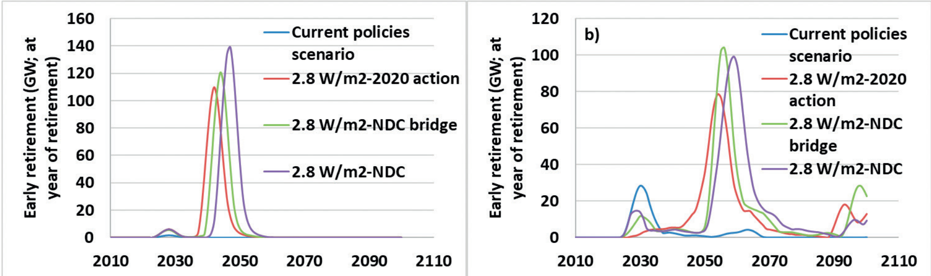

Figure S2.3.4: Early retirement (GW) at year of retirement for a) unabated coal-fired power plants and b) natural gas fired power plants, for the current policies scenario and 2.8 W/m² scenarios (*2.8 W/m²-NDC*, *2.8 W/m²-NDC bridge*, and *2.8W/m²-2020 action*)

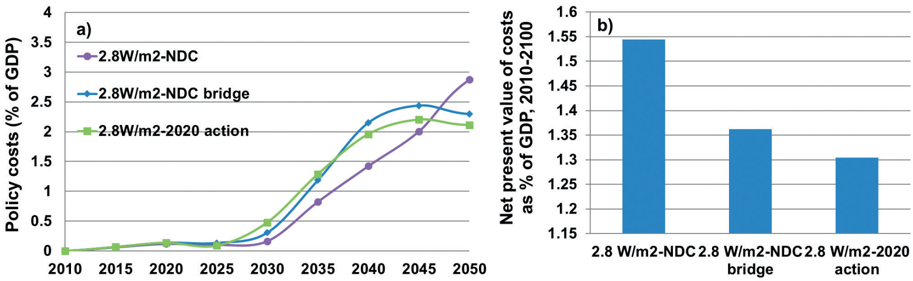

Figure S2.3.5: Global abatement costs (determined as area under MAC curve) of 2.8 W/m² scenarios relative to GDP, between 2010 and 2050 (a), and net present value of costs as % of GDP in the 2010–2100 period, with a 5% discount rate (b)

S2.4 Supplementary references

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S3 Low-emission pathways in 11 major economies: comparison of cost-optimal pathways and Paris climate proposals

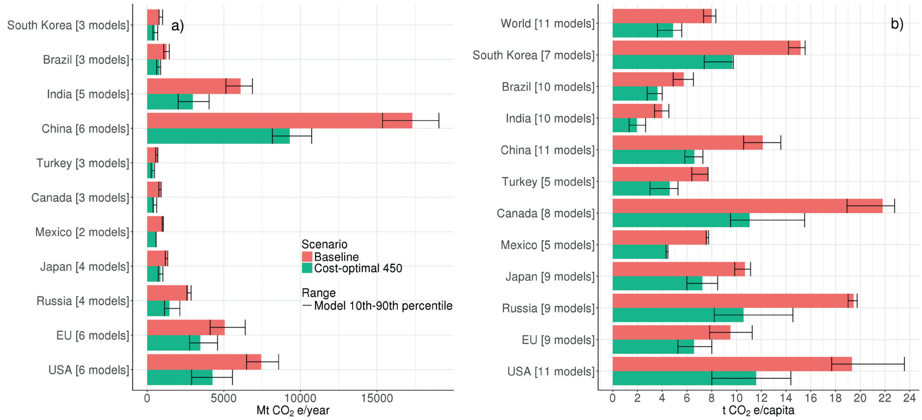


Figure S3.1: Kyoto gas emissions in 2030 projected by models for baseline and cost-optimal 450 ppm CO_2eq scenarios. The number of models per country is indicated (number may differ per variable because not all variables are reported by all models). Panel a): total emissions (MtCO_2eq), panel b): per capita emissions (tCO_2eq/capita). Filled bars show the median value across models, error bars show the 10^{th} to 90^{th} percentile range of the model results (‘Model 10^{th}-90^{th} percentile’). For regions covered by less than three models, only the range (minimum – maximum) is shown.

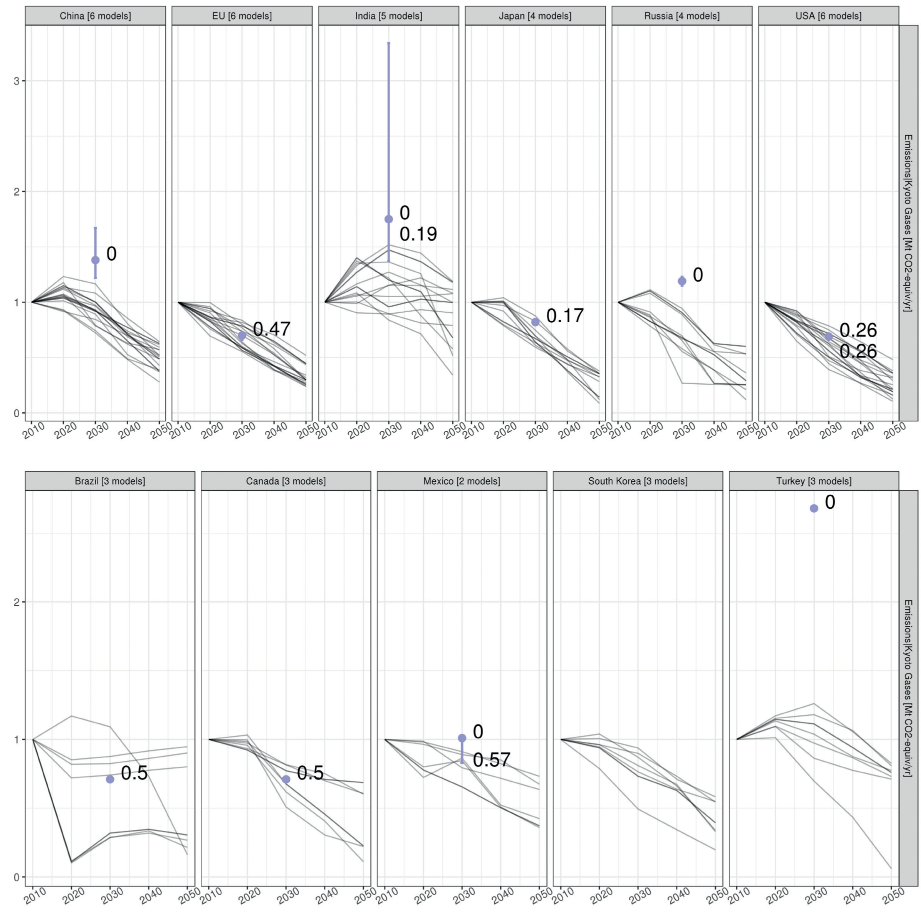


Figure S3.2: Kyoto gas emissions between 2010 and 2050 (indexed to 2010) projected by models for cost-optimal 450 ppm CO_2eq scenarios (lines), compared to (I)NDCs in 2030 (circles and vertical bars). Numbers denote what percentage of cost-optimal 450 ppm CO_2eq scenarios lie above the estimated (I)NDC emissions in 2030

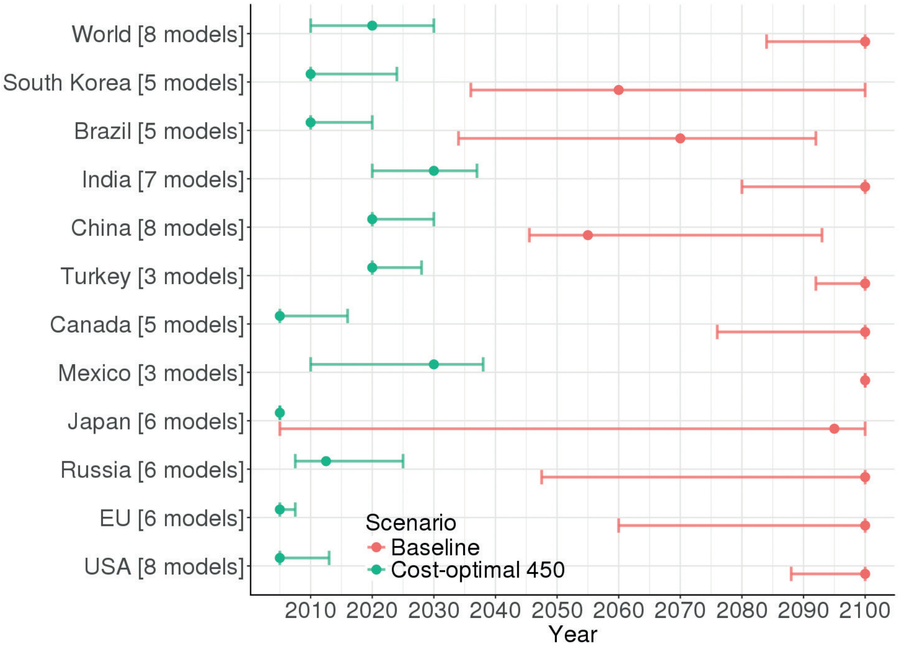


Figure S3.3: Regional peak years of CO_2 emissions for cost-optimal 450 ppm CO_2-eq and baseline scenarios. Dots give the median of the models, error bars give the 10th to 90th percentile ranges. The median results can be at the outer end of the range, for instance for OECD90.

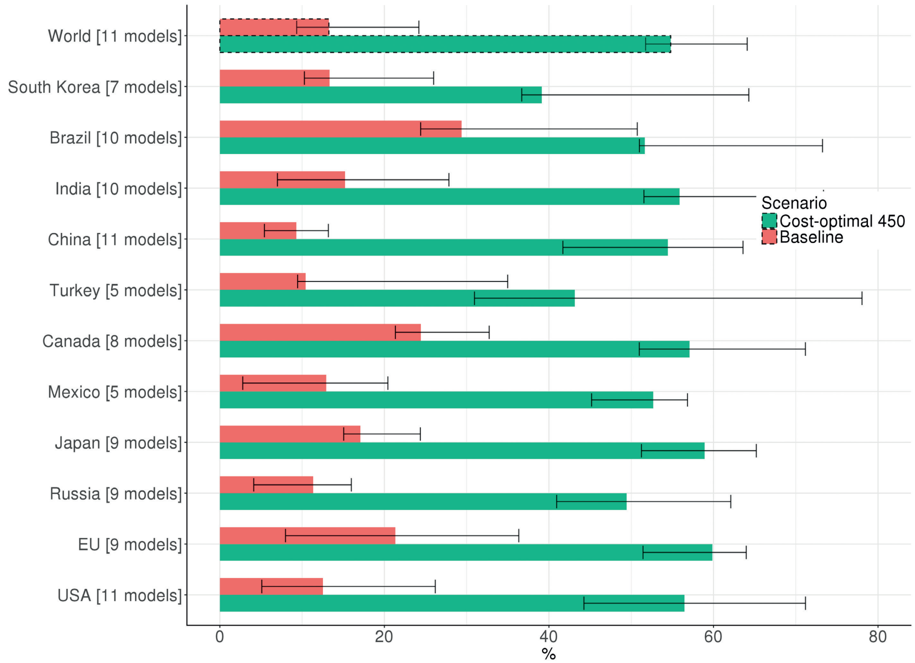


Figure S3.4: Share (%) of low-carbon primary energy sources (all energy sources except oil, coal and gas without carbon sequestration) in total primary energy supply in 2050, for cost-optimal 450 ppm CO_2eq and baseline scenarios. Filled bars represent the median, error bars give the 10^{th} to 90^{th} percentile ranges across models

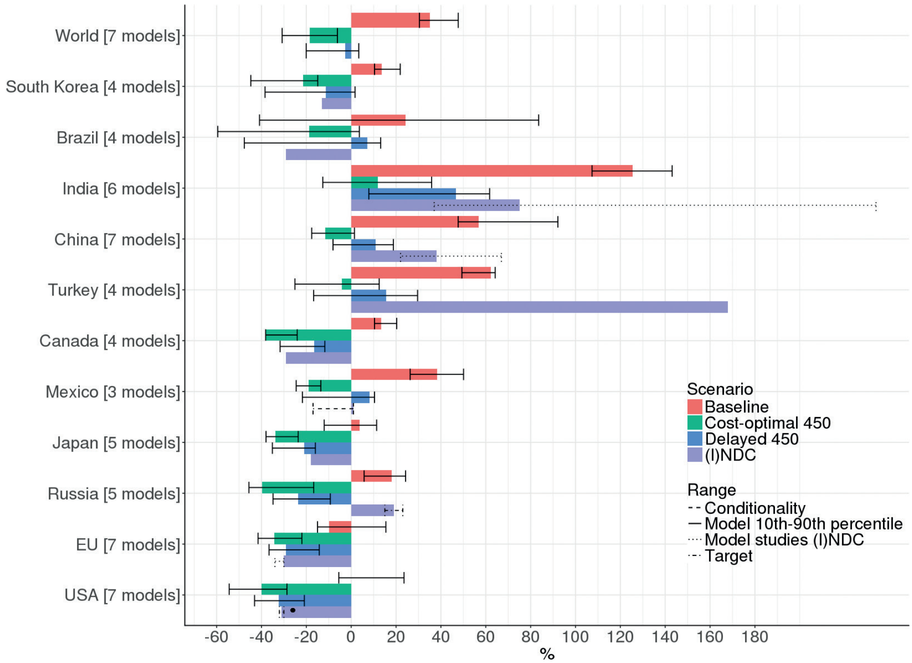
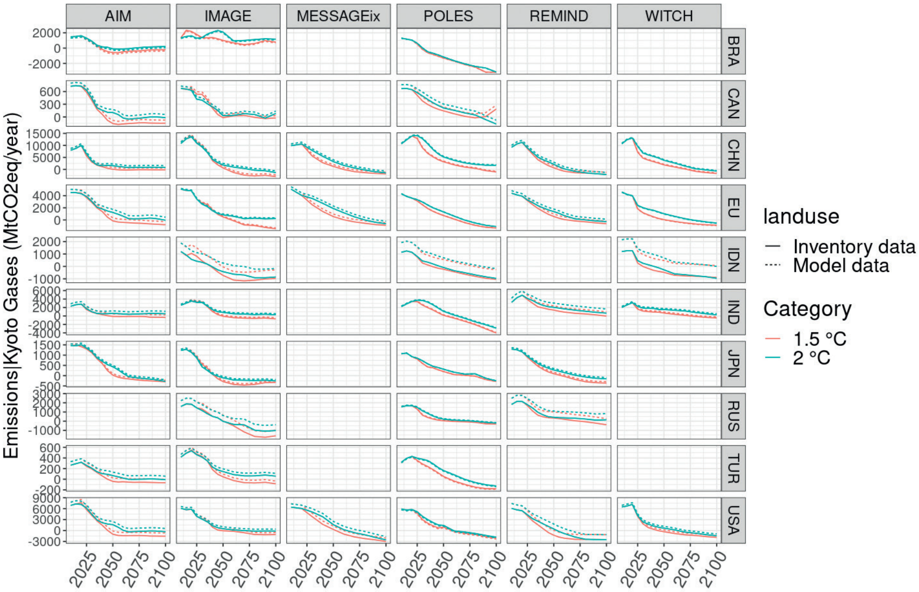


Figure S3.5: Kyoto gas emissions in 2030 projected by models for baseline, cost-optimal 450 ppm CO_2eq, and delayed 450 ppm CO_2eq scenarios, compared to (I)NDCs. Total emissions are shown with respect to 2010 (%, with positive numbers indicating emissions increase). The number of models per country is indicated. Filled bars for baseline, cost-optimal and delayed 450 ppm CO_2eq show the median value across models, error bars show the 10^{th} to 90^{th} percentile range of the model results ('Model 10^{th}-90^{th} percentile'). For regions covered by less than three models, the range (minimum – maximum) is shown. Filled bars for (I)NDC show the central estimate from Den Elzen et al. (2016), error bars the range. (I)NDC ranges are of three types: range in the reduction target mentioned in the (I)NDCs themselves ('Target'; Russia, USA); range resulting from unconditional and conditional targets ('Conditionality'; Mexico; filled bar shows the unconditional target, error bar shows the effect of moving to the conditional target); and range resulting from various model studies analysed in UNEP (2015) ('Model Studies (I)NDC'; India, China). For the USA, the (I)NDC range consists of both 'Target' (error bar, based on Den Elzen et al., 2016) and 'Model Studies (I)NDC' (filled circle, based on Emmerling et al., 2016).

S4 Net-zero emission targets for major emitting countries consistent with the Paris Agreement

S4.1 Supplementary Methods and Results: Emission pathways and the influence of definitions



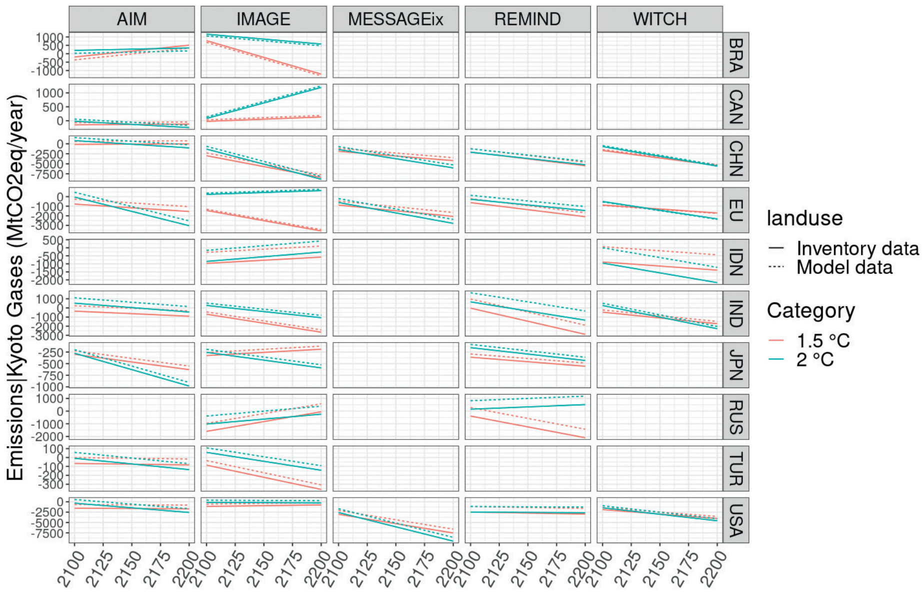


Figure S4.1.1: GHG emissions pathways when using model land-use change data versus when using inventory LULUCF data. GHG emissions pathways (MtCO_2eq per year) when using model land-use change (LUC) data (dotted lines) versus when using inventory LULUCF data (solid lines), in 1.5 °C (pink) and 2 °C (blue) scenarios, per model (horizontal panels) and country (vertical panels), for the time period 2010-2100 (upper graph) and the time period 2100-2200 (lower graph, extrapolation). For the solid lines, we calculated the difference between a model's 2010 LUC CO_2 emissions and the inventory's 2010 LULUCF CO_2 emissions (per country); subtracting that offset from the model LUC CO_2 projections (offset harmonisation method); adding the adjusted LULUCF CO_2 emissions projections to the model's projections for GHG emissions excluding LUC CO_2; and finally, calculating the phase-out year for the adjusted emission pathway. POLES was excluded from the lower graph as it does not show a significant difference between model data and inventory data.

Table S4.1.1: phase-out year of Kyoto GHG emissions with model LUC data versus inventory LULUCF data. NA: no phase-out

Model	Scenario	Country	Phase-out year with model LUC data	Phase-out year with inventory LULUCF data
IMAGE 3.0	1.5 °C	Canada	NA	2050
AIM V2.1	1.5 °C	China	NA	2055
IMAGE 3.0	1.5 °C	Mexico	NA	2060
IMAGE 3.0	2 °C	USA	NA	2070
POLES CDL	1.5 °C	Canada	NA	2080
IMAGE 3.0	2 °C	Canada	NA	2090
AIM V2.1	2 °C	India	NA	2154
IMAGE 3.0	2 °C	Brazil	NA	NA
POLES CDL	2 °C	China	NA	NA
IMAGE 3.0	2 °C	EU	NA	NA
IMAGE 3.0	2 °C	Mexico	NA	NA
REMIND-MAgPIE 1.7-3.0	2 °C	Russia	NA	NA

Historical LULUCF emissions data sources

For the selected Annex I countries (Canada, the European Union, Japan, the Russian Federation, Turkey and the USA), we used the GHG inventories submitted in 2019 to the UNFCCC (UNFCCC, 2019b). For historical emissions for non-Annex I Parties, the data was taken from the UNFCCC GHG databases (UNFCCC, 2019a), in which the GHG inventory data reported in most recent Biennial Update Reports (BURs) submitted to the UNFCCC were compiled. The sources are described in detail in Kuramochi et al. (2019) . National Inventory Reports (NIR) and National Communications (NC) were also used for some countries. For Brazil, the emissions inventory from Sistema de Estimativa de Emissões de Gases de Efeito Estufa (SEEG, 2018) was used.

Allocation of negative emissions from BECCS

Emissions|CO2|Allocation was used to calculate the phase-out year of CO_2 emissions when negative emissions are allocated, ex-post, to the biomass producer instead of the carbon-storing country. *Emissions|CO2|Allocation,* for country i (where w stands for world) and timestep t, was calculated as:

$$
\begin{aligned}
&Emissions|CO2|Allocation_{i,t} \\
&\quad = Emissions|CO2_{i,t} \\
&\quad + CCS|Biomass_{i,t} - (Agricultural\ Production|Energy_{i,t} \\
&\quad / \ Agricultrual\ Production|Energy_{w,t}) * CCS|Biomass_{w,t}
\end{aligned}
$$

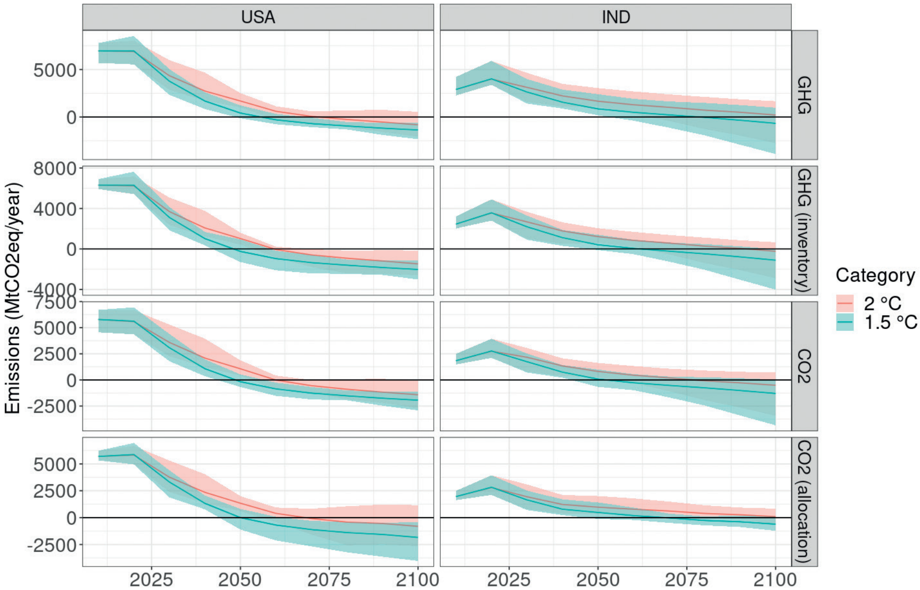


Figure S4.1.2: Emission pathways for the USA and India under the default and sensitivity cases. Emission pathways ($MtCO_2eq$) for a country with an early phase-out (USA) and a country with a late phase-out (India), for 2 °C and 1.5 °C scenarios, for the default case of total Kyoto GHG emissions ('GHG'), GHG emissions when using inventory LULUCF data ('GHG (inventory)'), CO_2 emissions ('CO_2'), and CO_2 emissions when allocating negative emissions from BECCS to the biomass producer ('CO_2 (allocation)'). Lines indicate model mean; funnels indicate the range (minimum – maximum).

S4.2 Supplementary Methods and Results: Multiple linear regression and Principal Component Analysis

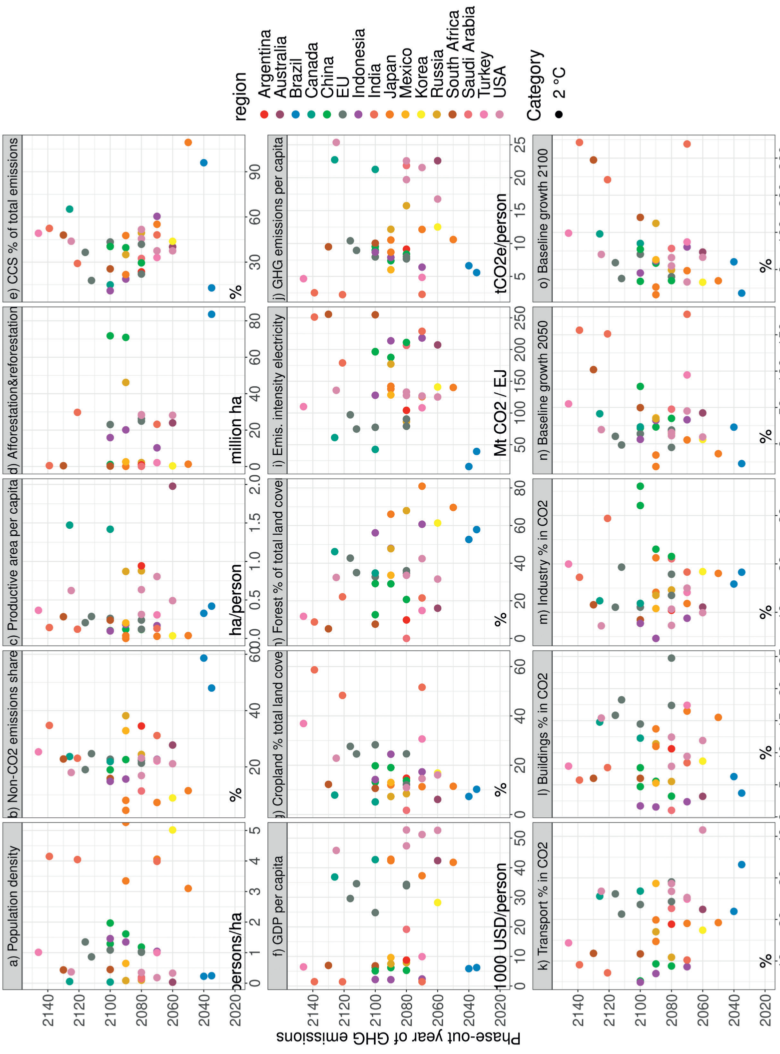
S4.2.1 Additional information on variables and scatter plots

Table S4.2.1: Variables used in multiple linear regression and principal component analysis, abbreviations used in text and figures, details of calculation and unit. Variables are grouped: grey – underlying driver, orange – current build-up of energy system and emissions (indication of hard-to-abate sectors) , light green – current indications of potential for negative emissions, dark green – future potential for negative emissions.

Variable	Abbreviation	Details	Unit
GDP per capita 2015	Gdpcap	**2015** value for GDP | MER / Population	1000 USD/ person
GHG emissions per capita 2015	Emiscap	**2015** value for Emissions | Kyoto Gases / Population	tCO_2e/ person
Growth of GHG emissions in baseline 2050	BaselineGHG2050	**2050** value for Emissions | Kyoto Gases (2050 – 2015) / 2015 *100	%
Growth of GHG emissions in baseline 2100	BaselineGHG2100	**2100** value for Emissions | Kyoto Gases (2100 – 2015) / 2015 *100	%
Transport share in total CO_2 emissions 2015	Transportshare	**2015** value for Emissions | CO2 | Energy | Demand | Transportation / Emissions | CO2	%
Buildings share in total CO_2 emissions 2015	Buildingshare	**2015** value for Emissions | CO2 | Energy | Demand | Residential and Commercial / Emissions | CO2	%
Industry share in total CO_2 emissions 2015	Industryshare	**2015** value for Emissions | CO2 | Energy | Demand | Industry / Emissions | CO2	%
Emissions intensity electricity sector 2015	Emisint	**2015** value for Emissions | CO2 | Energy | Supply | Electricity / Secondary Energy | Electricity	Mt CO_2 / EJ
Non-CO_2 share 2015	nonCO2share	**2015** value for (N_2O in CO_2eq + CH_4 in CO_2eq + F-gases in CO_2eq) / Kyoto Gases	%

Table S4.2.1: *Continued.*

Variable	Abbreviation	Details	Unit
Population density 2015	Density	**2015** value for Population / Land cover	Persons/ ha
Productive area per capita 2015	Prodcap	**2015** value for Land Cover | Cropland / Population	ha/ person
Cropland share of total land cover 2015	Cropshare	**2015** value for Land Cover | Cropland / Land Cover	%
Forest share of total land cover 2015	Forestshare	**2015** value for Land Cover | Forest / Land Cover	%
Carbon Sequestration|CCS 2050	CCSshare	**2050** value for Carbon Sequestration | CCS / abs(Kyoto Gas emissions + Carbon Sequestration | CCS)	%
Land Cover|Forest| Afforestation and Reforestation 2050	Afforestation	**2050** value for Land Cover | Forest | Afforestation and Reforestation	Million ha


a) Population density
b) Non-CO2 emissions share
c) Productive area per capita
d) Afforestation&reforestation
e) CCS % of total emissions
f) GDP per capita
g) Cropland % total land cove
h) Forest % of total land cove
i) Emis. intensity electricity
j) GHG emissions per capita
k) Transport % in CO2
l) Buildings % in CO2
m) Industry % in CO2
n) Baseline growth 2050
o) Baseline growth 2100
persons/ha
%
ha/person
million ha
1000 USD/person
Mt CO2 / EJ
tCO2e/person
Phase-out year of GHG emissions
region
Argentina
Australia
Brazil
Canada
China
EU
Indonesia
India
Japan
Mexico
Korea
Russia
South Africa
Saudi Arabia
Turkey
USA
Category
2 °C

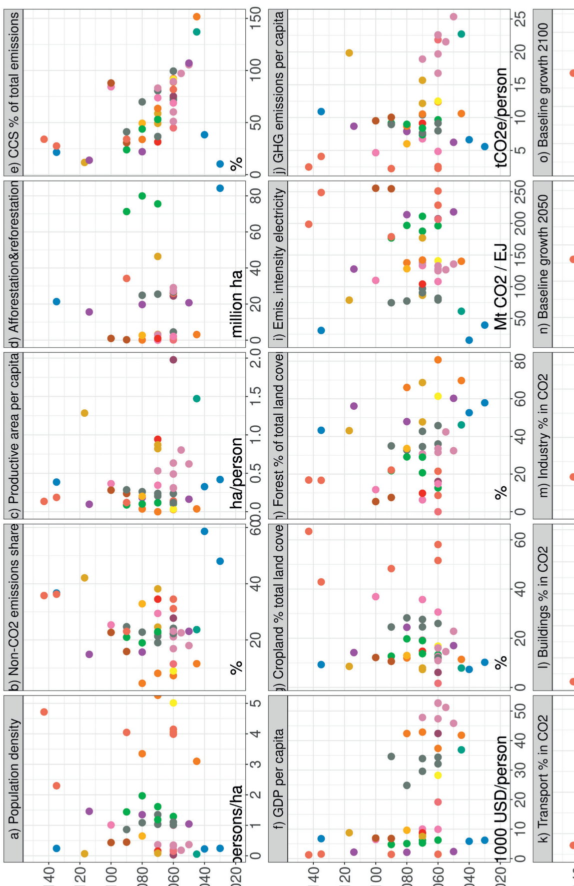


Figure S4.2.1: Phase-out years as function of explanatory variables. 15 explanatory variables versus phase-out years across all countries available in the dataset (colours, noting different model coverage per country), all models and the 2 °C scenario (upper graph) and 1.5 °C scenario (lower graph). See Table S4.2.1 for details of how the variables were calculated and their units.

S4.2.2 Methods: PCA

The dataset, consisting of projections by six models for 15 variables, for a number of countries (different per model), for both 1.5 °C and 2 °C scenarios, was further refined for the PCA:

- Only models with complete reporting (all 15 variables) were used. Missing land cover data for Japan by the REMIND model and missing afforestation data for AIM and REMIND meant REMIND and AIM had to be removed for the PCA to work.
- MESSAGE data for 2010 and 2020 were interpolated to get an estimate for 2015.
- Different subsets of the dataset described above were created for sensitivity analysis on the limited number of records (countries), consisting of:
  - All models (despite varying country coverage), both 1.5 °C and 2 °C scenarios, and ten countries;
  - All models, both 1.5 °C and 2 °C scenarios, 10 countries, but excluding those with no projected phase-out;
  - Model median (noting that for each country, a different number of models was available), both 1.5 °C and 2 °C scenarios, and 10 countries;
    - Model median, only 1.5 °C scenarios, and 10 countries;
    - Model median, only 2 °C scenarios, and 10 countries;
  - Only the POLES and IMAGE models (as both cover all 10 countries), both 1.5 °C and 2 °C scenarios, and 10 countries;
  - Only the POLES model, both 1.5 °C and 2 °C scenarios, and 16 countries (to increase the number of records; only POLES covers these 16 countries).
- For POLES, forest cover data for Saudi Arabia was set at 0 due to a reporting error.

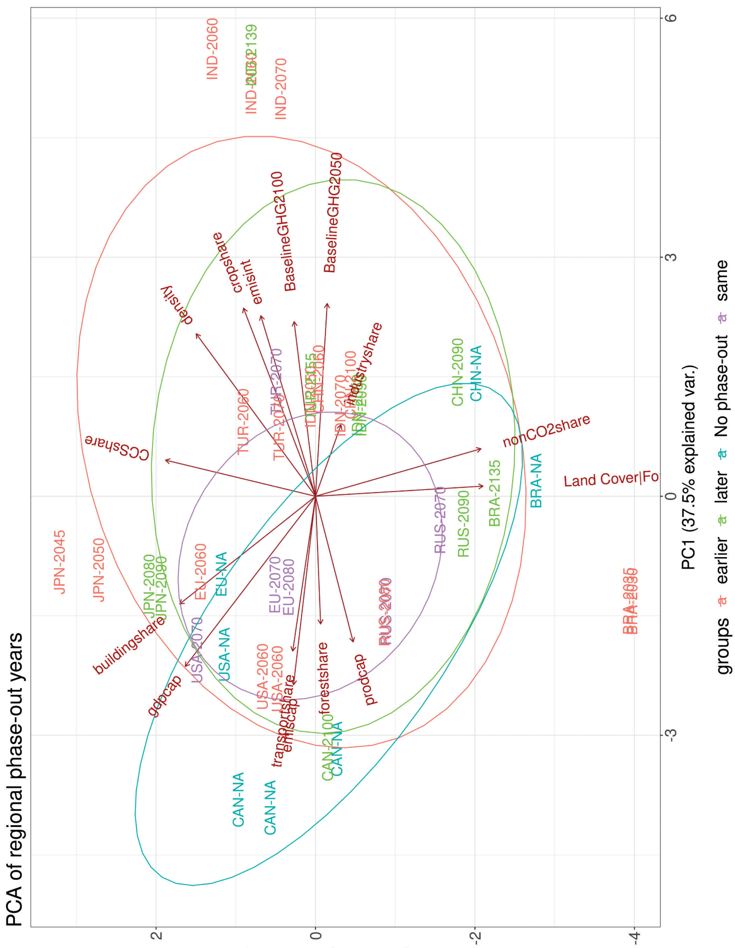
S4.2.3 Results: PCA

The scree plot (Figure S4.2.3) does not show a strong decline, so we only used the PCA for the corroboration of the results.

The first principal component explains 37% of the variance in national phase-out years. Its largest contributors are baseline growth, emissions per capita, emissions intensity of electricity, and the share of cropland area for biomass (Table S4.2.2). The second principal component explains 17% of the variance, and has the largest contributions from non-CO_2 emissions share, afforestation, CCS share, building sector emissions share, and GDP per capita. The third principal component explains another 13% of the variance, and the fourth 8%, for a cumulative proportion of explained variance of 75% for the first four principal components.

Applying the proportion of variance as weighting factor (i.e. absolute contribution of variable to PC1 times proportion of variance explained by PC1, plus absolute contribution of variable to PC2 times proportion of variance explained by PC2, etc.), resulted in the following top five explanatory variables: **productive area per capita,**

GDP per capita, buildings emissions share, transport emissions share, and emissions intensity of electricity. This list differs from the multiple linear regression results due to the different purposes, with PCA mainly aiming to explain the variance in the input data, by reducing redundancy in the dataset (correlated variables). The PCA was also performed on the other data subsets, for sensitivity analysis. The top five explanatory variables for each of these is shown in Table S4.2.3.


PCA of regional phase-out years
PC1 (37.5% explained var.)
PC2 (16.9% explained var.)
groups
earlier
later
No phase-out
same
BaselineGHG2100
BaselineGHG2050
cropshare
emisint
density
CCSshare
nonCO2share
Land Cover|Fo
industryshare
buildingshare
gdpcap
transportshare
emiscap
forestshare
prodcap
IND-2060
IND-2070
JPN-2045
JPN-2050
JPN-2080
JPN-2090
EU-2060
EU-NA
EU-2070
EU-2080
USA-NA
USA-2060
TUR-2060
TUR-2070
CHN-2090
CHN-NA
BRA-NA
BRA-2135
RUS-2070
RUS-2090
CAN-NA
CAN-2100

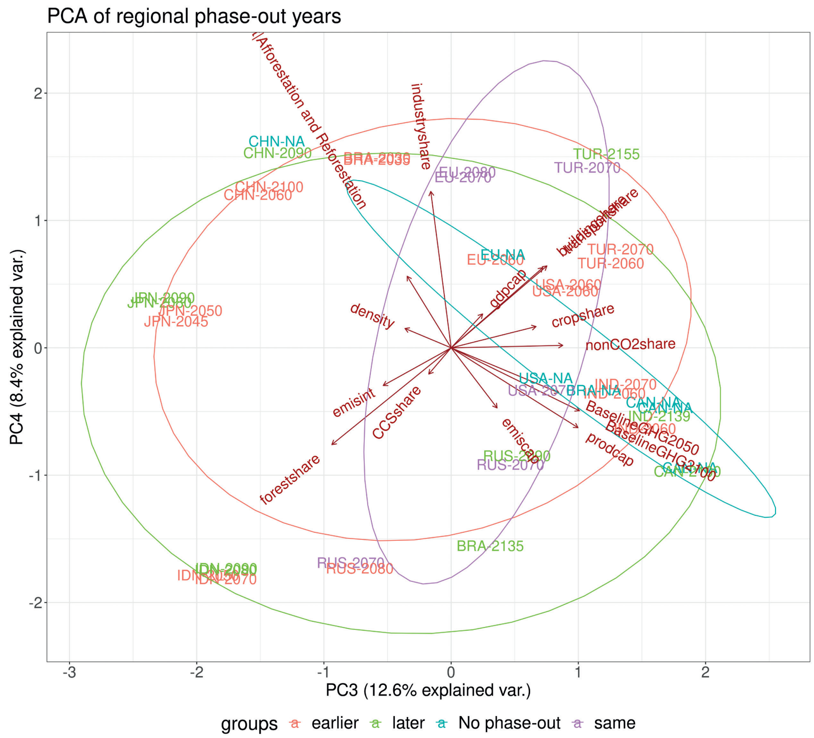


Figure S4.2.2: Principal Component Analysis of the national phase-out years of GHG emissions. Principal Component Analysis of the national phase-out years of GHG emissions, for both 1.5 °C and 2 °C scenarios by the POLES and IMAGE models. The upper graph shows PC1 and PC2, while the lower graph shows PC3 and PC4. Arrows indicate the contribution of each component to each PC (i.e., loading). Coloured circles group countries with a phase-out year before the global average (pink), similar to the global average (purple), later than the global average (green), and without a phase-out (blue). Individual countries are indicated by their three-letter codes plus phase-out year (multiple entries result from having two models and two scenarios).

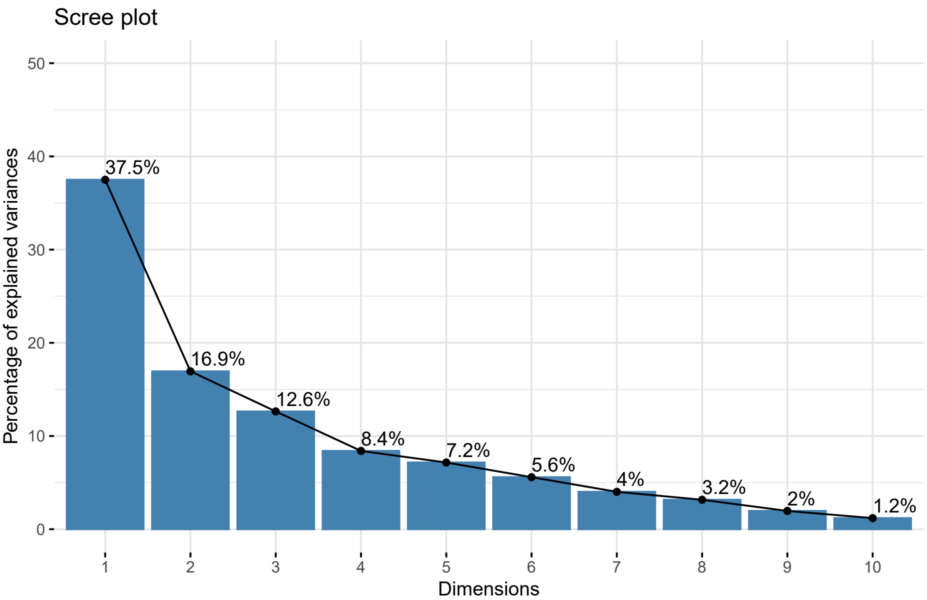


Figure S4.2.3: Scree plot for the PCA using the ‘IMAGE and POLES’ dataset.

Table S4.2.2: Contribution of each explanatory variable to the principal components (loadings), and summary statistics of the principal component analysis using the 'IMAGE and POLES' dataset.

Rotation	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15
Population density 2015	0.29	0.32	-0.14	0.07	-0.16	0.07	-0.02	0.54	-0.34	0.10	-0.09	0.06	-0.37	0.36	0.24
Non-CO_2 share 2015	0.09	-0.44	0.34	0.01	-0.06	0.45	0.07	-0.13	-0.29	0.22	0.46	-0.19	-0.16	0.21	-0.04
Productive area per capita 2015	-0.26	-0.10	0.39	-0.30	0.29	0.07	-0.11	0.29	0.18	0.36	-0.35	0.25	-0.27	0.05	-0.28
Carbon Sequestration|CCS 2050	0.02	-0.45	-0.13	0.27	-0.27	0.15	-0.58	0.23	0.29	-0.25	-0.19	-0.18	-0.09	0.03	-0.07
Land Cover|Forest| Afforestation and Reforestation 2050	0.07	0.40	-0.07	-0.10	0.20	0.67	-0.26	-0.40	-0.01	-0.20	-0.22	0.01	-0.14	-0.03	0.01
GDP per capita 2015	-0.31	0.35	0.10	0.13	-0.14	-0.11	-0.24	0.13	-0.36	-0.11	0.25	-0.18	-0.13	-0.27	-0.57
Cropland share of total land cover 2015	0.34	0.19	0.26	0.08	-0.23	-0.03	0.07	-0.10	0.07	0.35	-0.41	-0.53	0.27	0.08	-0.21
Forest share of total land cover 2015	-0.23	-0.01	-0.36	-0.36	-0.21	0.43	0.13	0.36	-0.02	0.12	0.05	-0.01	0.52	-0.01	-0.13
Emissions intensity electricity sector 2015	0.33	0.15	-0.21	-0.14	0.05	-0.16	-0.50	-0.14	0.22	0.39	0.41	0.23	0.13	0.20	-0.18
GHG emissions per capita 2015	-0.34	0.06	0.14	-0.22	0.31	-0.19	-0.36	0.04	-0.19	-0.11	0.03	-0.41	0.25	0.38	0.35
Transport share in total CO_2 emissions 2015	-0.28	0.06	0.29	0.30	-0.42	0.05	-0.20	-0.19	-0.22	0.16	-0.16	0.49	0.29	0.10	0.20
Buildings share in total CO_2 emissions 2015	-0.19	0.36	0.28	0.30	-0.03	0.18	0.17	0.20	0.62	-0.08	0.35	-0.07	0.02	0.18	0.10
Industry share in total CO_2 emissions 2015	0.13	-0.07	-0.06	0.58	0.61	0.14	-0.02	0.23	-0.18	0.12	-0.03	0.07	0.34	-0.11	-0.09
Growth of GHG emissions in baseline 2050	0.35	-0.03	0.33	-0.17	0.02	-0.04	0.06	0.10	-0.06	-0.59	-0.01	0.26	0.27	0.33	-0.34
Growth of GHG emissions in baseline 2100	0.31	0.06	0.39	-0.23	-0.04	0.06	-0.23	0.27	0.00	-0.03	0.14	0.01	0.12	-0.63	0.36

Table S4.2.2: *Continued.*

Summary	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15
Standard deviation	2.37	1.59	1.38	1.12	1.04	0.92	0.78	0.69	0.54	0.42	0.32	0.26	0.17	0.10	0.08
Proportion of variance	0.37	0.17	0.13	0.08	0.07	0.06	0.04	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00
Cumulative proportion	0.37	0.54	0.67	0.75	0.83	0.88	0.92	0.95	0.97	0.99	0.99	1.00	1.00	1.00	1.00

Table S4.2.3: Top five explanatory variables for each of the seven data subsets used in PCA.

Rank (weighted)	All models, 1.5 and 2 °C, 10 countries	All models, 1.5 and 2 °C, 10 countries, exclude ‘no phase-out’ countries	Only POLES and IMAGE, 1.5 and 2 °C, 10 countries	Only POLES, 1.5 and 2 °C, 20 countries	Model median, 1.5 and 2 °C, 10 countries	Model median, 1.5 °C, 10 countries	Model median, 2 °C, 10 countries
1	Transportshare	Transportshare	Prodcap	Density	BaselineGHG2100	Transportshare	emisint
2	BaselineGHG2100	Prodcap	GDPcap	emisint	Density	Density	BaselineGHG2100
3	Forestshare	Forestshare	Buildingshare	Emiscap	Transportshare	BaselineGHG2100	Buildingshare
4	GDPcap	Density	Transportshare	Prodcap	Cropshare	Cropshare	Prodcap
5	Prodcap	Cropshare	emisint	CCSshare	Prodcap	Forestshare	Cropshare

S4.2.4 Results: regression

Table S4.2.4: Results for the multiple linear regression, after trying all possible combinations of four, five, six or seven variables on the dataset containing both 1.5 °C and 2 °C scenarios, and selecting the one with highest R-squared (displayed here). Adjusted R-squared is also provided, as well as the variables.

	R-squared	**Adjusted R-squared**	**Variables**
Combination of 4	0.53	0.46	Afforestation CCSshare forestshare transportshare
Combination of 5	0.58	0.50	nonCO2share afforestation CCSshare gdpcap transportshare
Combination of 6	0.63	0.54	nonCO2share afforestation CCSshare gdpcap forestshare transportshare
Combination of 7	0.63	0.53	nonCO2share afforestation CCSshare gdpcap forestshare transportshare buildingshare

Table S4.2.5: Detailed results for the multiple linear regression, for the combinations of five and six variables. Weight and significance (p-value) per variable are provided.

Model: phase-out year versus	**R-squared**	**p-value**	**Variables**	**Weight [significance]**
Combination of 5 variables	**0.58**	0.0002	Afforestation NonCO2share CCSshare Gdpcap Transportshare	-16.3 [0.002] 15.5 [0.02] -18.7 [0.00004] 17.6 [0.05] -20.1 [0.007]
Combination of 6 variables	**0.63**	0.0001	Afforestation NonCO2share CCSshare GDPcap Transportshare Forestshare	-12.3 [0.02] 13.7 [0.03] -18.0 [0.00004] 20.9 [0.02] -22.6 [0.003] -6.5 [0.08]

Table S4.2.6: multiple linear regression results for 1.5 °C and 2 °C separately. Although higher R-squared may be obtained when using only 1.5 °C or only 2 °C scenarios, selecting only one scenario halves the number of records in the dataset, which was already relatively small, thereby decreasing the reliability of the results. In addition, one would want to be able to explain different phase-out years across countries and across all 'Paris-consistent' scenarios, not just for one specific scenario.

	1.5 °C				**2 °C**			
Model: phase-out year versus	**R-squared**	**p-value**	**Variables**	**p-value**	**R-squared**	**p-value**	**Variables**	**p-value**
Combination of 5 variables	**0.84**	0.0002	Density	0.004	**0.90**	0.0003	Baseline2100	0.0004
			Transport%	0.00008			Forestshare	0.0003
			CCSshare	0.0004			Afforestation	0.0002
			Gdpcap	0.0001			GDPcap	0.001
			Baseline2050	0.0008			Baseline2050	0.0003
Combination of 6 variables	**0.88**	0.0002	Density	0.01	**0.93**	0.0004	Afforestation	0.0001
			CCSshare	0.0009			CCSshare	0.11
			Gdpcap	0.0001			Gdpcap	0.001
			emisint	0.08			Forestshare	0.0009
			Transportshare	0.00003			BaselineGHG2050	0.0003
			BaselineGHG2050	0.0004			BaselineGHG2100	0.0003

S4.3 Supplementary Methods: Overview of models per country

Table S4.3.1: Overview of models and covered countries for total GHG emissions, after scenario selection, i.e. only including models with projections up to 2100. X indicates availability of both 1.5 °C and 2 °C scenarios.

Country	Number of models	AIM V2.1	IMAGE 3.0	MESSAGEix_ GLOBIOM_1.1	POLES CDL	REMIND-MAgPIE 1.7-3.0	WITCH2016
Brazil	3	X	X	-	X	-	-
Canada	3	X	X	-	X	-	-
China	6	X	X	X	X	X	X
EU	6	X	X	X [1]	X	X	X
India	6	X	X	-	X	X	X
Indonesia	3	-	X	-	X	-	X
Japan	4	X	X	-	X	X	-
Russia	3	-	X	-	X	X	-
Turkey	3	X	X	-	X	-	-
USA	6	X	X	X [2]	X	X	X
World	6	X	X	X	X	X	X

[1] *The EU-projections by the MESSAGE model were adjusted to exclude Turkey (by subtracting emissions projections for Turkey by the IMAGE model)*
[2] *USA projections by the MESSAGE model were adjusted to exclude Canada (based on IMAGE projections).*

S4.4 Supplementary Results: Additional indicators

Table S4.4.1: Peak year of total greenhouse gas (GHG) emissions, GHG emissions in 2030 and 2050 (relative to 2015), phase-out year of GHG emissions (as in Figure 4.1), and negative emissions in 2100, per country and for 2 °C and 1.5 °C scenarios. Median [minimum; maximum].

	Peak year of GHG emissions (-)		GHG emissions in 2030, relative to 2015 (%)		GHG emissions in 2050, relative to 2015 (%)		Phase-out year of GHG emissions (-)		Negative emissions in 2100 (Mt CO_2 / year)	
	2 °C	1.5 °C	2 °C	1.5 °C	2 °C	1.5 °C	2 °C	1.5 °C	2 °C	1.5 °C
Brazil	2020 [2005-2045]	2015 [2005-2020]	-33 [-99; -10]	-50 [-114; -42]	-52 [-201; 41]	-72 [-213; -59]	2037 [2035-2040]	2040 [2030-2135]	481 [262-692]	621 [230-713]
Canada	2005 [2005-2010]	2005 [2005-2010]	-36 [-37; -19]	-43 [-78; -16]	-60 [-88; -42]	-78 [-110; -69]	2113 [2100-2126]	2045 [2045-2045]	440 [307-664]	402 358-436]
China	2020 [2020-2025]	2020 [2020-2020]	-28 [-55; 4]	-45 [-61; -23]	-66 [-81; -48]	-82 [-91; -66]	2100 [2080-2186]	2070 [2060-2090]	2662 [656-4062]	2937 [491-4720]
EU	2005 [2005-2010]	2005 [2005-2010]	-28 [-52; -20]	-41 [-72; -32]	-65 [-81; -38]	-81 [-100; -75]	2100 [2080-2116]	2070 [2060-2090]	1687 [889-2505]	1605 [889-3141]
India	2020 [2020-2050]	2020 [2020-2020]	-12 [-51; 27]	-25 [-54; 8]	-53 [-67; 25]	-68 [-94; -19]	2130 [2070-2183]	2090 [2060-2143]	917 [686-6029]	1047 [542-5256]
Indonesia	2020 [2010-2020]	2020 [2010-2020]	-36 [-46; -27]	-48 [-71; -28]	-66 [-83; -44]	-73 [-102; -68]	2090 [2070-2100]	2080 [2050-2114]	776 [363-989]	622 [229-1104]
Japan	2005 [2005-2020]	2005 [2005-2015]	-36 [-63; -19]	-47 [-55; -24]	-70 [-103; -58]	-85 [-116; -77]	2080 [2050-2090]	2065 [2045-2080]	530 [209-1081]	475 [344-876]
Russia	2015 [2015-2020]	2015 [2015-2020]	-28 [-45; -21]	-57 [-79; -21]	-63 [-85; -23]	-74 [-94; -63]	2085 [2080-2090]	2070 [2070-2117]	812 [413-1647]	934 [610-2422]
Turkey	2020 [2020-2020]	2020 [2020-2020]	-13 [-29; -5]	-28 [-41; -11]	-60 [-64; -28]	-82 [-93; -51]	2146 [2070-2155]	2070 [2060-2100]	240 [232-258]	188 [151-338]
USA	2005 [2005-2020]	2005 [2005-2020]	-35 [-61; -16]	-46 [-68; -34]	-72 [-84; -51]	-90 [-102; -81]	2080 [2060-2125]	2060 [2050-2070]	2960 [2187-3902]	2951 [2292-5070]
World	2020 [2020-2020]	2020 [2010-2020]	-25 [-47; -12]	-37 [-61; -25]	-65 [-72; -35]	-82 [-100; -63]	2090 [2080-2156]	2070 [2050-2070]	24316 [14214-31214]	22439 [15959-31914]

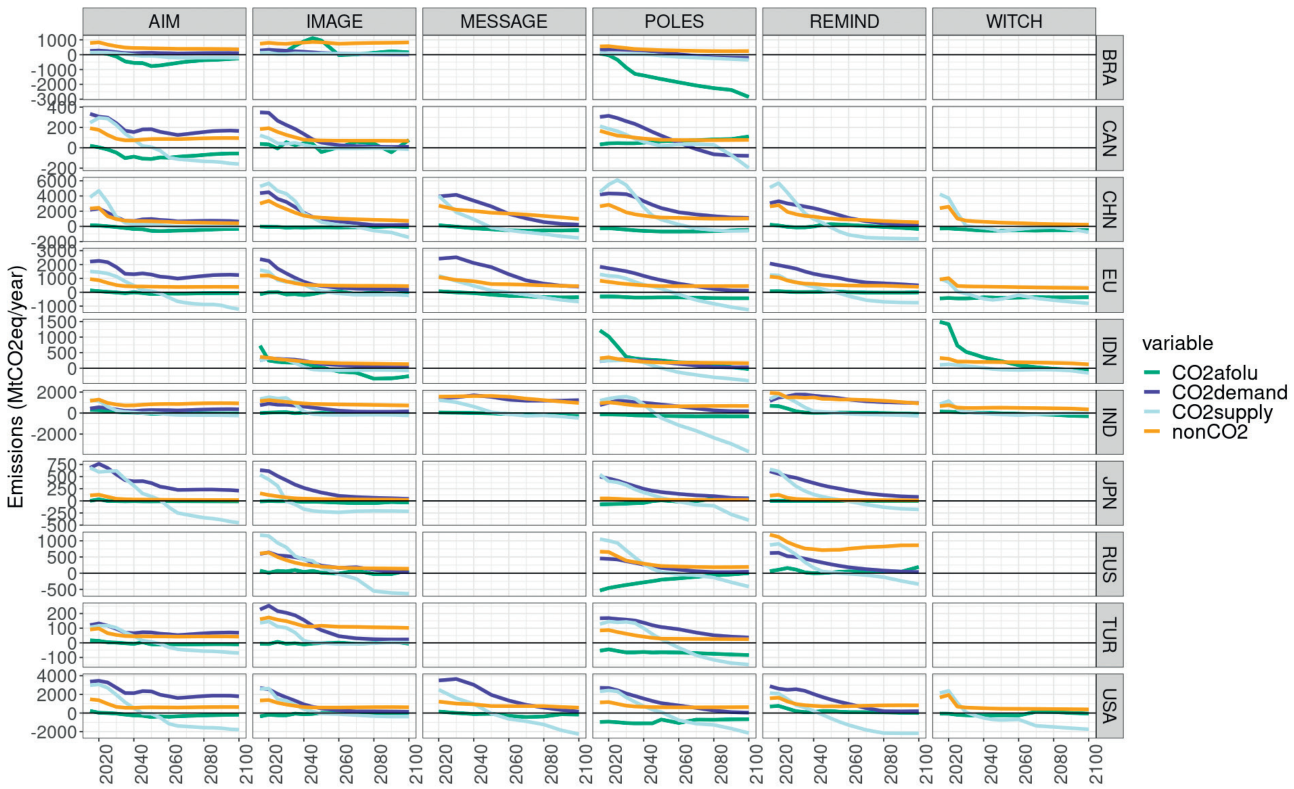


Figure S4.4.1: Emission pathways per model and region. Emission pathways per model and region, aggregated to: AFOLU CO_2 emissions, energy demand CO_2 emissions, energy supply CO_2 emissions, and non-CO_2 emissions. 2 °C scenario only.

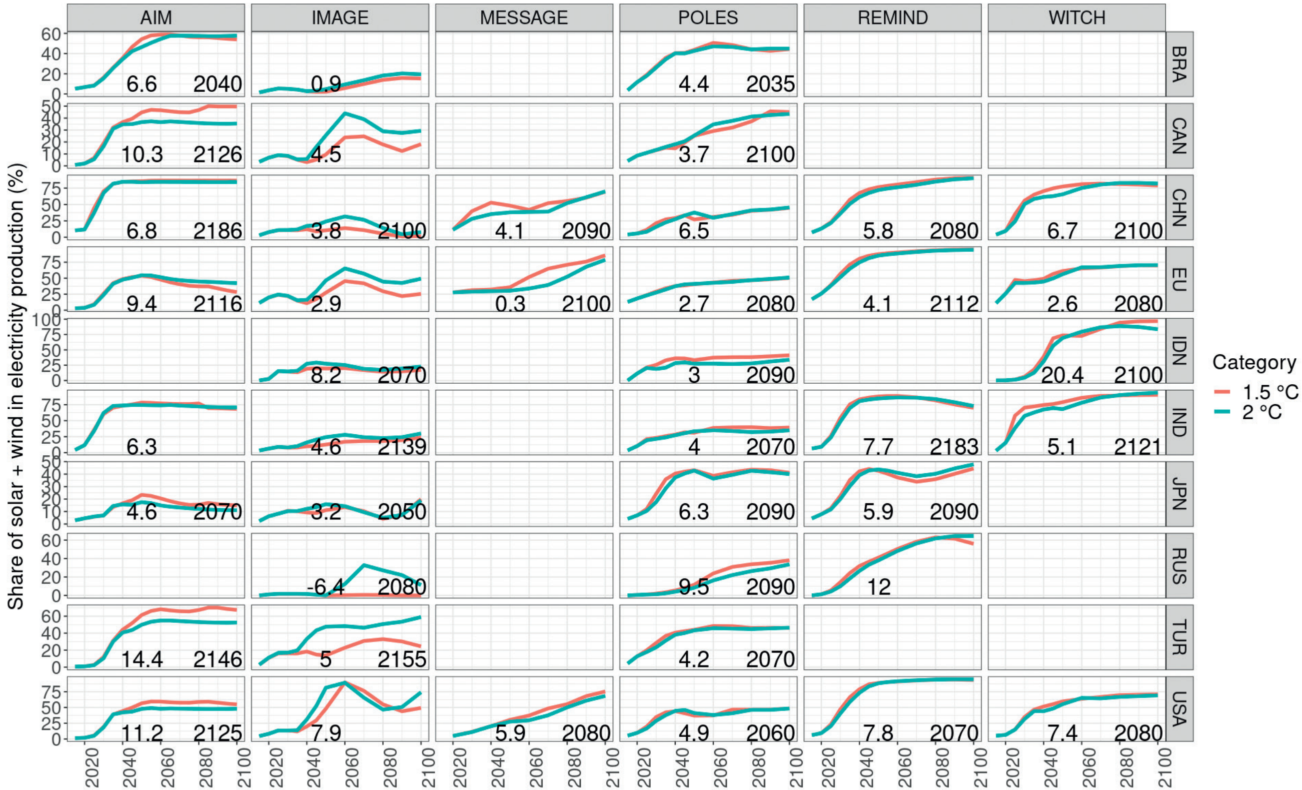


Figure S4.4.2: Share of solar and wind power in total electricity production. Share of solar and wind power in total electricity production (%), per model and region, for 1.5 °C and 2 °C scenarios. Numbers show the rate of change (as compound annual growth rate, % per year over 2020-2050) for the 2 °C scenario, as well as the year total GHG emissions reach net zero in the 2 °C scenario.

S4.5 Supplementary References

1. UNFCCC. *Greenhouse Gas Inventory Data - Detailed data by Party*, <http://di.unfccc.int/detailed_data_by_party> (2019).
2. UNFCCC. *GHG Profiles - Non-Annex I* <https://di.unfccc.int/ghg_profile_non_annex1> (2019).
3. Kuramochi, T. *et al.* Greenhouse gas mitigation scenarios for major emitting countries - Analysis of current climate policies and mitigation commitments: 2019 Update (NewClimate Institute, Cologne, Germany, 2019).
4. SEEG. *Total emissions*, <http://plataforma.seeg.eco.br/total_emission#> (2018).

S5 Global roll-out of comprehensive policy measures may aid in bridging emissions gap

S5.1 Supplementary Tables: implementation of good practice policies per model

The set of good practice policies was defined in dialogue with national model teams. In some cases, this process led to higher ambition than initially defined: for example, the target for the share of electric and hydrogen vehicles in new sales was brought forward by five years for China, and China was placed in the group of countries with highest assumed afforestation rates. In other cases, it led to a delay: for example, the target level for final energy intensity of buildings in the EU was adjusted, and for the USA, the carbon price was assumed to be introduced in 2025 rather than 2020.

Table S5.1.1: All good practice policies measures and their target values per country group. 2050 values only apply to the GPP scenario.

See sheet 'Supplementary Table 1' in file "Supplementary Information – Supplementary Data.xlsx" < https://static-content.springer.com/esm/art%3A10.1038%2Fs41467-021-26595-z/MediaObjects/41467_2021_26595_MOESM2_ESM.xlsx > or scan the QR-code below.

Table S5.1.2: Implementation of the good practice policies listed in Table S5.1 1, per model (percentages behind the model name indicate the share of the policies implemented, counting the orange and green cells, and excluding the proxy indicators)

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAg-PIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
1a	implemented	implemented	Included (non-CO_2 abatement factor)	agriculture policies not implemented		agriculture policies not implemented	implement-ed (exact numbers as in Kriegler et al. 2018)		Agricultural policies not implement-ed
1b	implemented	implemented	Included (non-CO_2 abatement factor)	agriculture policies not implemented			implement-ed (exact numbers as in Kriegler et al. 2018)		
2a	implemented	not imple-mented	Included (non-CO_2 abatement factor)	agriculture policies not implemented			implement-ed (exact numbers as in Kriegler et al. 2018)		
2b	implemented	not imple-mented	Included (non-CO_2 abatement factor)	agriculture policies not implemented			implement-ed (exact numbers as in Kriegler et al. 2018)		
22		not imple-mented	Included (non-CO_2 abatement factor)	agriculture policies not implemented					

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAgPIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
24a		Implemented	Included (non-CO_2 abatement factor)	agriculture policies not implemented					
24b		not implemented	Included (non-CO_2 abatement factor)	agriculture policies not implemented					
24c		not implemented	Included (non-CO_2 abatement factor)	agriculture policies not implemented					
3a	Adjusted the AEEI of buildings sector to match protocol value.	Implemented	Included (Make appliance Unit Energy Consumption (kWh per appliance) improve according to the rate of the protocol)	implemented by using the proxy values	Implemented	proxy implementation finalised	implemented by using the proxy values		Implemented

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAgPIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
3b	Adjusted the AEEI of buildings sector to match protocol value.	Implemented	Included (Make appliance Unit Energy Consumption (kWh per appliance) improve according to the rate of the protocol)	implemented by using the proxy values	Implemented	proxy implementation finalised	implemented by using the proxy values		Implemented
4a		Implemented by using the proxy values	Included (through the previous measure + transitioned to fully-LED lighting + Reduce heating and cooling intensity (kJ/m2/HDD or CDD) according to the protocol (This is an exogenous variable in the version of TIMER which was used) + the next measure)	implemented by using the proxy values	Implemented	implemented	implemented by using the proxy values		

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAg-PIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
4b		Implemented by using the proxy values	Included (through the previous measure + transitioned to fully-LED lighting + Reduce heating and cooling intensity (kJ/m2/HDD or CDD) according to the protocol (This is an exogenous variable in the version of TIMER which was used) + the next measure)	implemented by using the proxy values	Implemented	implemented	implemented by using the proxy values		
4c		-	-	implemented by using the proxy values	Implemented	implemented			
4d		-	-	implemented by using the proxy values	Implemented	implemented			

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAgPIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
5a		Implemented	Included (Deactivate coal and oil boilers for households. Only marginal capacity (existing capacity remains for their technical lifetime).)	implemented by using the proxy values	Implemented	Implemented			Implemented
5b		Implemented	Included (Deactivate coal and oil boilers for households. Only marginal capacity (existing capacity remains for their technical lifetime).)	implemented by using the proxy values	Implemented	Implemented			Implemented

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAg-PIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
6a		Not imple-mented	Included (through the appliance energy consumption improvement + transitioned to fully-LED lighting + Reduce heating and cooling intensity (kJ/m^2/HDD or CDD) according to the protocol (This is an exogenous variable in the version of TIMER which was used) + deactivation of coal and oil boilers for households)	implemented by using the proxy values	Implement-ed	Implemented	implemented by using the proxy values		Not Imple-mented

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAg-PIE (71%)	WITCH (68%)	TIAM-Grantham_ v3.2 (44%)
6b		Not imple-mented	Included (through the ap-pliance energy consumption improvement + transitioned to fully-LED lighting + Reduce heating and cooling intensity (kJ/ m2/HDD or CDD) according to the protocol (This is an exogenous variable in the version of TIMER which was used) + deactivation of coal and oil boilers for households)	implemented by using the proxy values	Implement-ed	Implemented	implemented by using the proxy values		Not Imple-mented
25		not imple-mented	-	implemented by using the proxy values	Implement-ed	implemented			Implement-ed
7	implemented	implemented	Included	implemented.	Implement-ed	implemented	implemented		Implement-ed

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAgPIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
8	implemented	implemented	Included (as no coal-fired power plant; 420 gCO_2/kWh)	implemented	Implemented	implemented	implemented		Implemented
9a	Adjusted the preference for renewables	implemented	Included (premium factors and forced capacity shares)	implemented	Implemented	implemented	implemented		Implemented
9b	Adjusted the preference for renewables	implemented	Included (premium factors and forced capacity shares)	implemented	Implemented	implemented	implemented		Implemented
10a	implemented	not implemented	Included (F-gas specific tax)	implemented			implemented		Not implemented (TIAM_Grantham not covering F-Gases in this analysis)

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAgPIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
10b	implemented	not implemented	Included (F-gas specific tax)	implemented			implemented		Not implemented (TIAM_Grantham not covering F-Gases in this analysis)
11	implemented	implemented	Included (non-CO_2 abatement factor)	implemented	Implemented				Not implemented
12a	implemented	implemented partially (% value not possible in all regions in 2030)	Included (non-CO_2 abatement factor)	not implemented due to model restriction					Not implemented
12b	implemented	implemented	Included (non-CO_2 abatement factor)	not implemented due to model restriction					Not implemented
26		implemented	Included (non-CO_2 abatement factor)						Implemented

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAgPIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
13a		implemented	-	implemented	Implemented	implemented	implemented (Approx. 200 $MtCO_2$ /year CCS in industry.)		Implemented
13b		implemented	-	implemented	Implemented				Implemented
14a	Adjusted the AEEI of industry sector to match protocol value.	not implemented	Included (added efficiency factor)	implemented by using the proxies		implemented	implemented by using the proxies		Implemented
14b	Adjusted the AEEI of industry sector to match protocol value.	not implemented	Included (added efficiency factor)			implemented	implemented by using the proxies		Implemented
15	implemented	not implemented	Included (non-CO_2 abatement factor)	implemented	Implemented				Not implemented

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAg-PIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
16		implemented	Included (ap-proximation, by reduced additional defor-estation)	not implemented			implemented (10 million ha/ year afforestation)		Not imple-mented
17		implemented	Included (ap-proximation, by reduced additional defor-estation)	not implemented			implemented (End natural forest loss;)		Not imple-mented
27		not imple-mented	-	not implemented					Not imple-mented
18a		implemented	Included (added efficiency factor)	implemented by using proxies	Implement-ed	implemented	implement-ed by using proxies		Implement-ed
18b		implemented	Included (added efficiency factor)	implemented by using proxies	Implement-ed	implemented	implement-ed by using proxies		Implement-ed
19a		implemented	Included (added efficiency factor)	implemented by using proxies	Implement-ed	Implemented by using proxies	implement-ed by using proxies		Implement-ed
19b		-	-	implemented by using proxies	Implement-ed	implemented	implement-ed by using proxies		Implement-ed

Table S5.1.2: *Continued.*

ID	AIM (56%)	COFFEE (65%)	IMAGE (94%)	MESSAGEix_GLOBIOM (74%)	POLES (62%)	PROMETHEUS (53%)	REMIND-MAgPIE (71%)	WITCH (68%)	TIAM-Grantham_v3.2 (44%)
19c	Adjusted AEEI in passenger transport to match final energy proxy values from IMAGE.	-	-	implemented by using proxies	Implemented	implemented	implemented by using proxies		Implemented
20		implemented. But we do also consider the sales of ethanol fuel cell vehicles	Included (by premium factors on vehicles)	implemented by using proxies	Implemented	implemented	implemented		Implemented
21a	implemented	not implemented	Included (non-CO_2 abatement factor)	implemented	Implemented				Not implemented
21b	implemented	not implemented	Included (non-CO_2 abatement factor)	implemented	Implemented				Not implemented

S5.2 Supplementary Figures

Figure S5.2.1: GHG emissions, relative to 2015 (%), per region (panel), for 2030 and 2050 (X-axis), for the CurPol, NDCplus, Bridge, 2Deg2020, and 2Deg2030 scenarios (colours). Bars indicate model median, symbols the individual model results. AUS: Australia, CAN: Canada, EU: European Union, JPN: Japan, USA: United States of America, BRA: Brazil, CHN: China, IDN: Indonesia, IND: India, ROK: Republic of Korea (South Korea), RUS: Russian Federation.

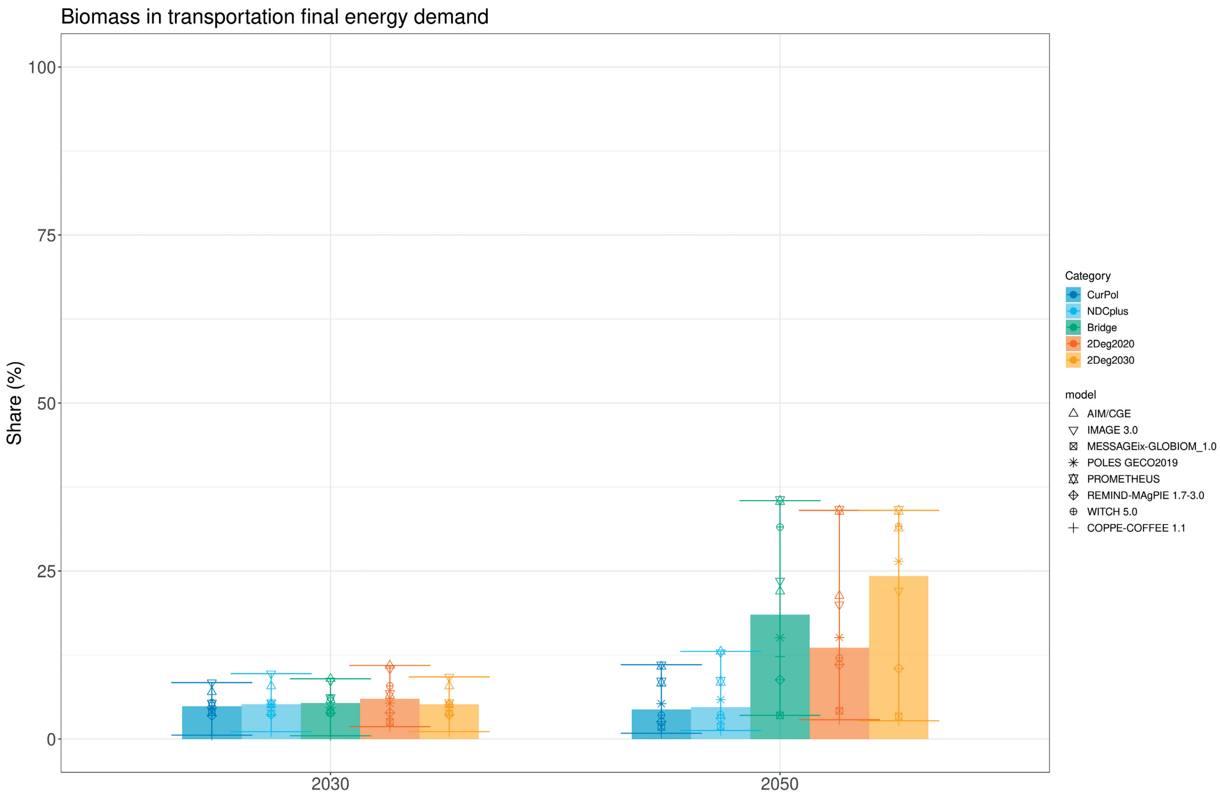


Figure S5.2.2: Projected changes in the share of liquid biomass in final energy demand of transportation (%), for 2030 and 2050, for the CurPol, NDCplus, Bridge, 2Deg2020, and 2Deg2030 scenarios. Bars show model median, error bars show the full range, and symbols show individual model results.

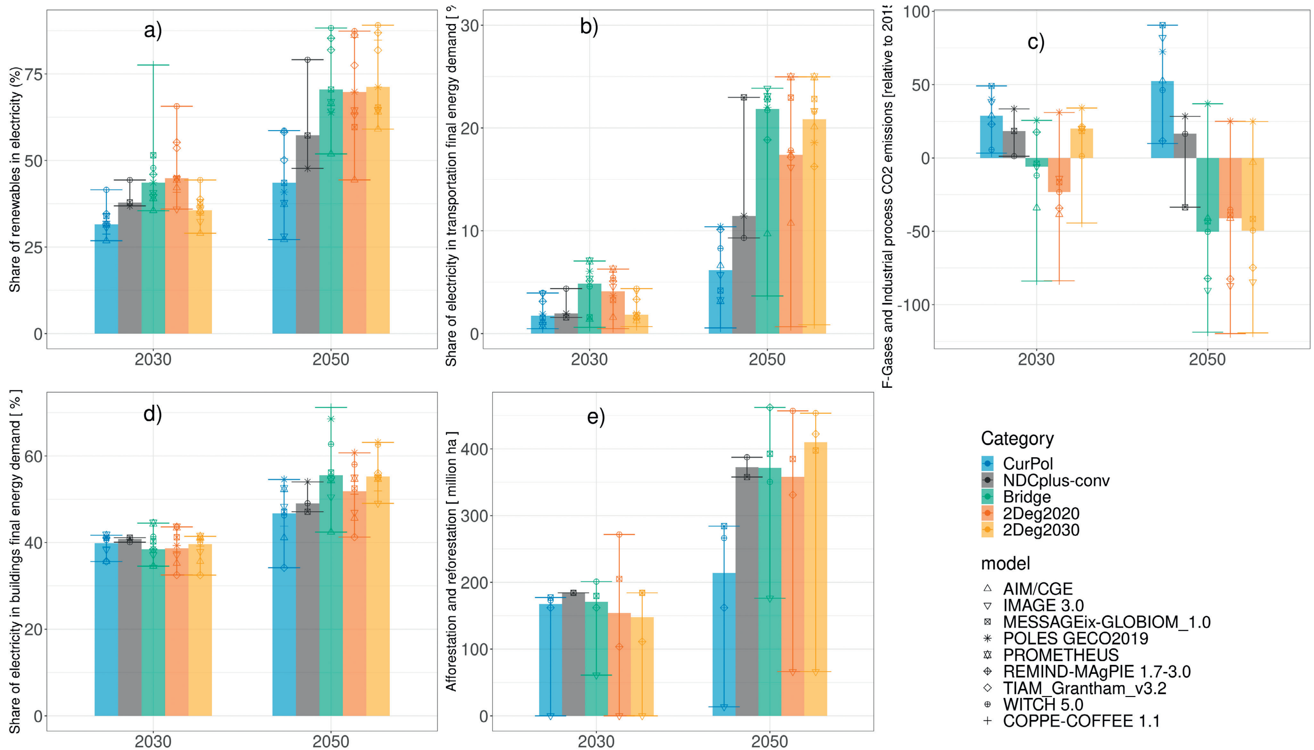


Figure S5.2.3: Projected changes in various indicators, for 2030 and 2050, for the CurPol, NDCplus-convergence, Bridge, 2Deg2020, and 2Deg2030 scenarios. Bars show model median, error bars show the full range, and symbols show individual model results. Panel a) share of renewables in electricity production (%), panel b) share of electricity in final energy demand of transportation (%), panel c) Emissions of F-gases and industrial process CO_2 emissions, relative to 2015 levels (%), panel d) share of electricity in final energy demand of buildings (%), panel e) total afforestation and reforestation (million ha).

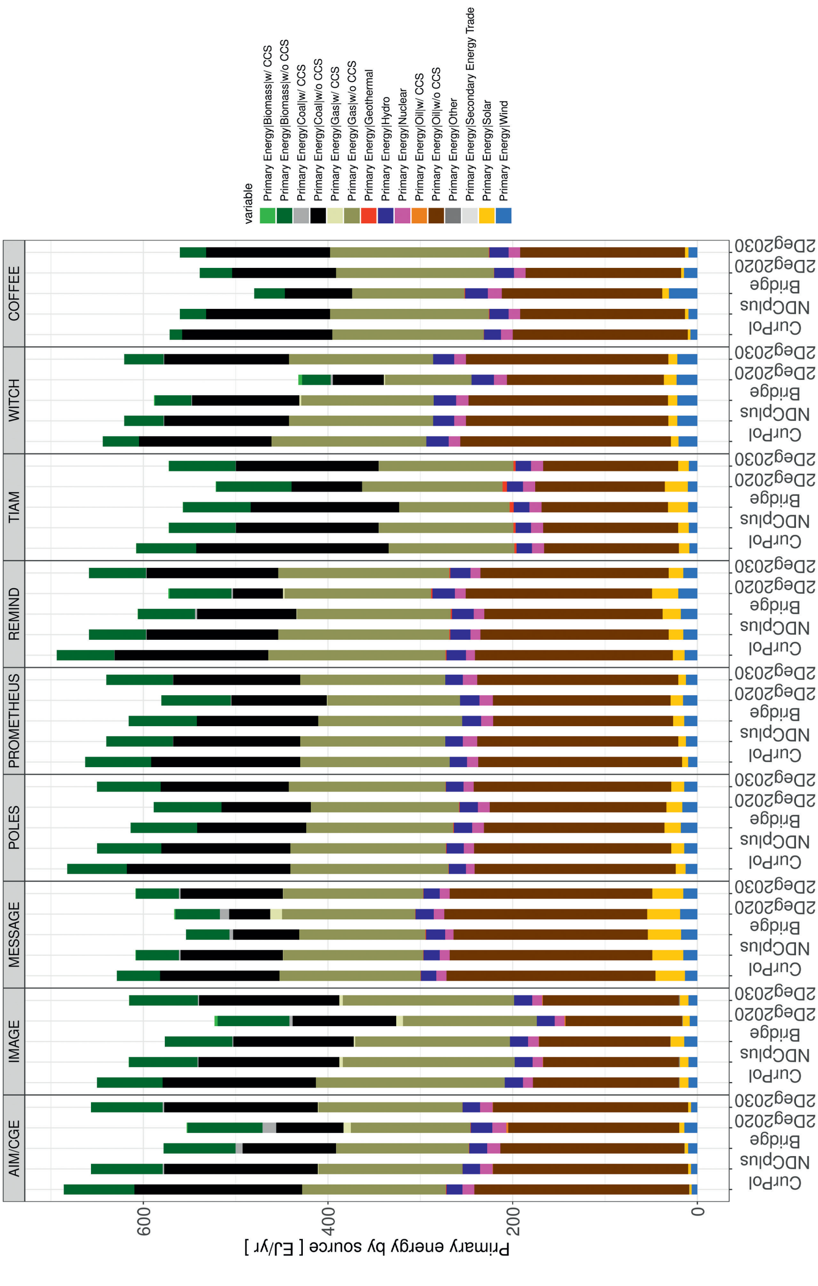
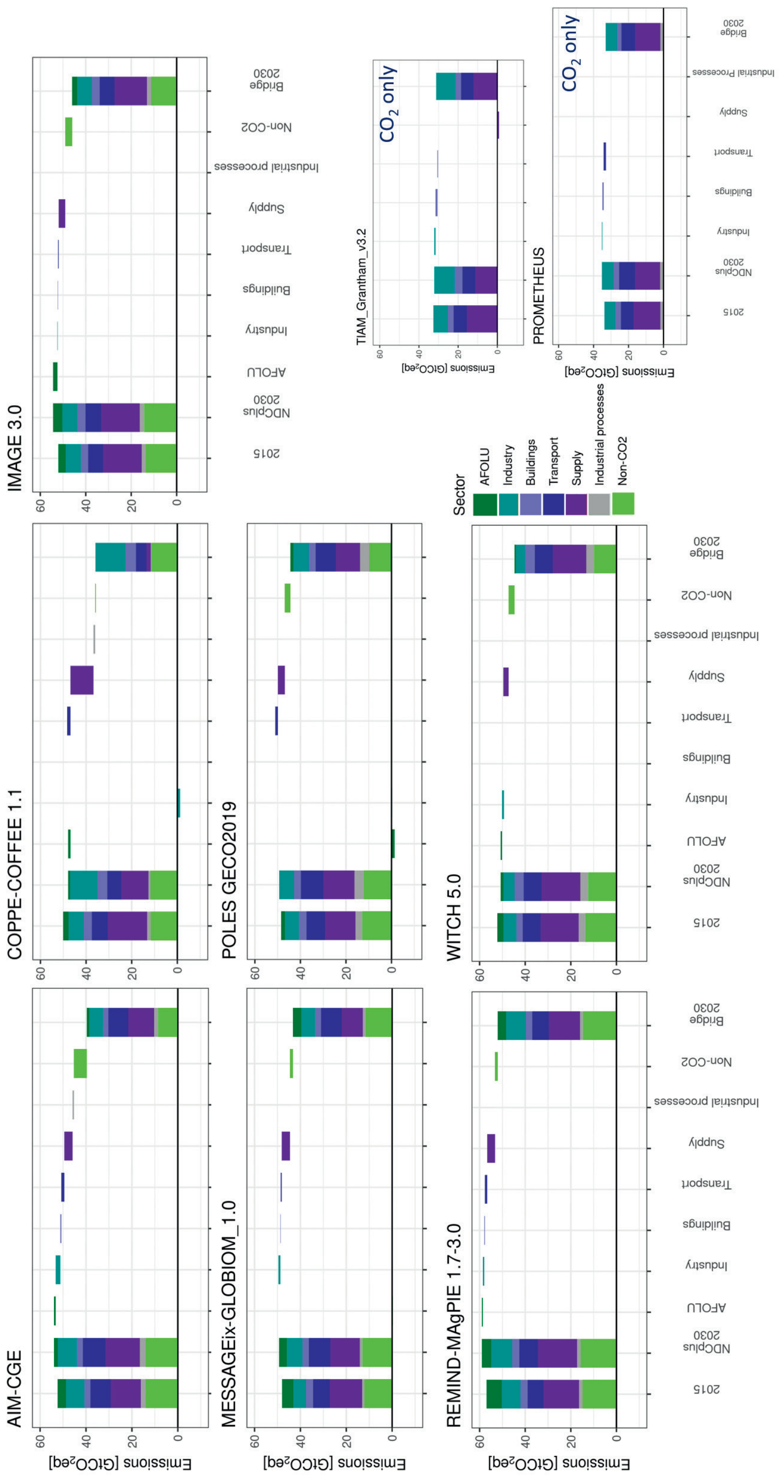


Figure S5.2.4: Primary energy production in 2030 by source, per model, for the CurPol, NDCplus, Bridge, 2Deg2020, and 2Deg2030 scenarios. w/: with, w/o: without. CCS: Carbon Capture and Storage.


AIM-CGE
COPPE-COFFEE 1.1
IMAGE 3.0
MESSAGEix-GLOBIOM_1.0
POLES GECO2019
TIAM_Grantham_v3.2
PROMETHEUS
REMIND-MAgPIE 1.7-3.0
WITCH 5.0
CO2 only
Emissions [GtCO2eq]
2015
NDCplus 2030
AFOLU
Industry
Buildings
Transport
Supply
Industrial processes
Non-CO2
Bridge 2030
Sector

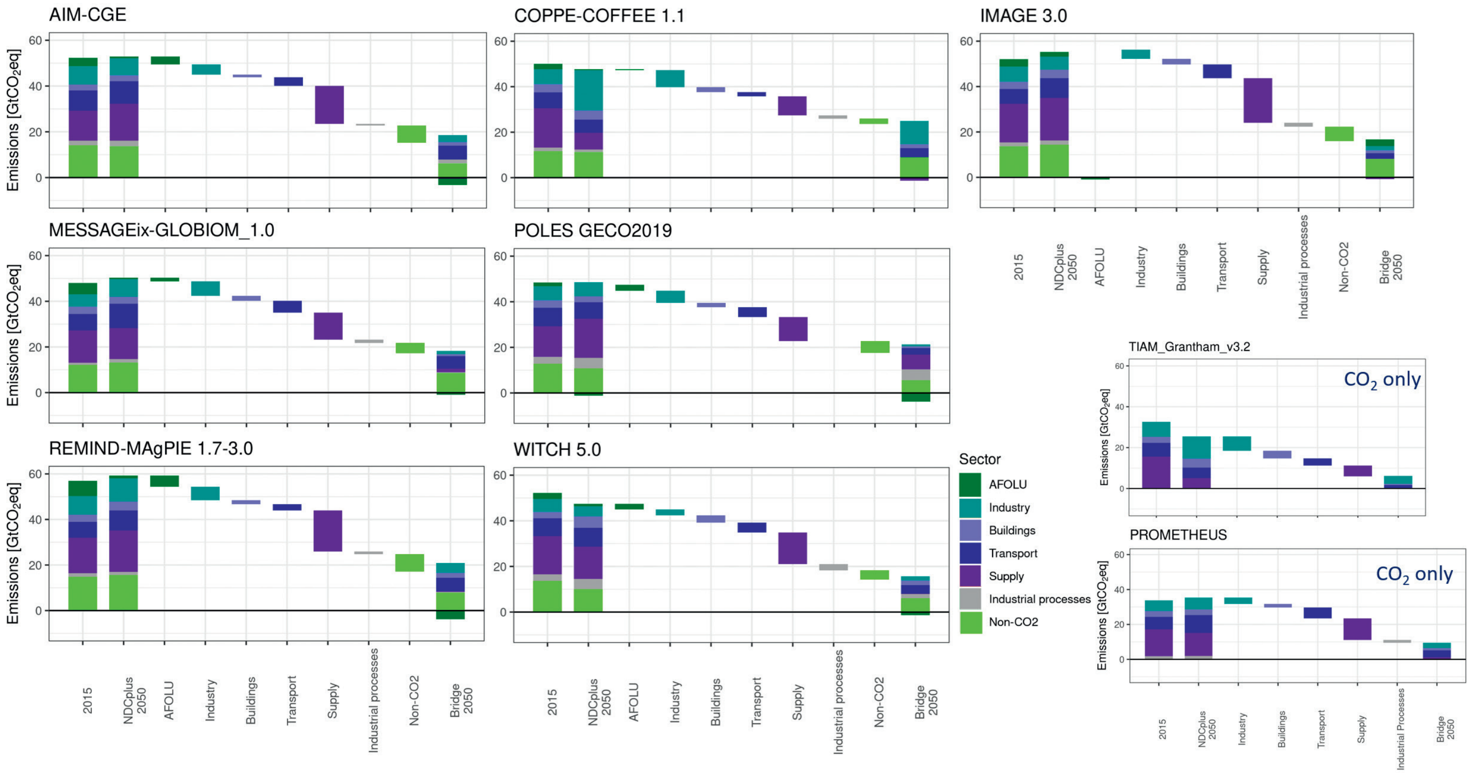


Figure S5.2.5: Contribution of each sector to emission reductions between the NDCplus and Bridge scenario (negative values denote an increase in emissions between NDCplus and Bridge). First bar: Emissions by sector in 2015. Second bar: emissions by sector in 2030 (upper graph) or 2050 (lower graph), under NDCplus. Third - ninth bar: emission reduction in energy supply, industry, buildings, transport, industrial processes, AFOLU, non-CO_2 emissions. Last bar: emissions by sector in 2030 (upper graph) or 2050 (lower graph), under Bridge. For TIAM and PROMETHEUS, only CO_2 emissions are shown.

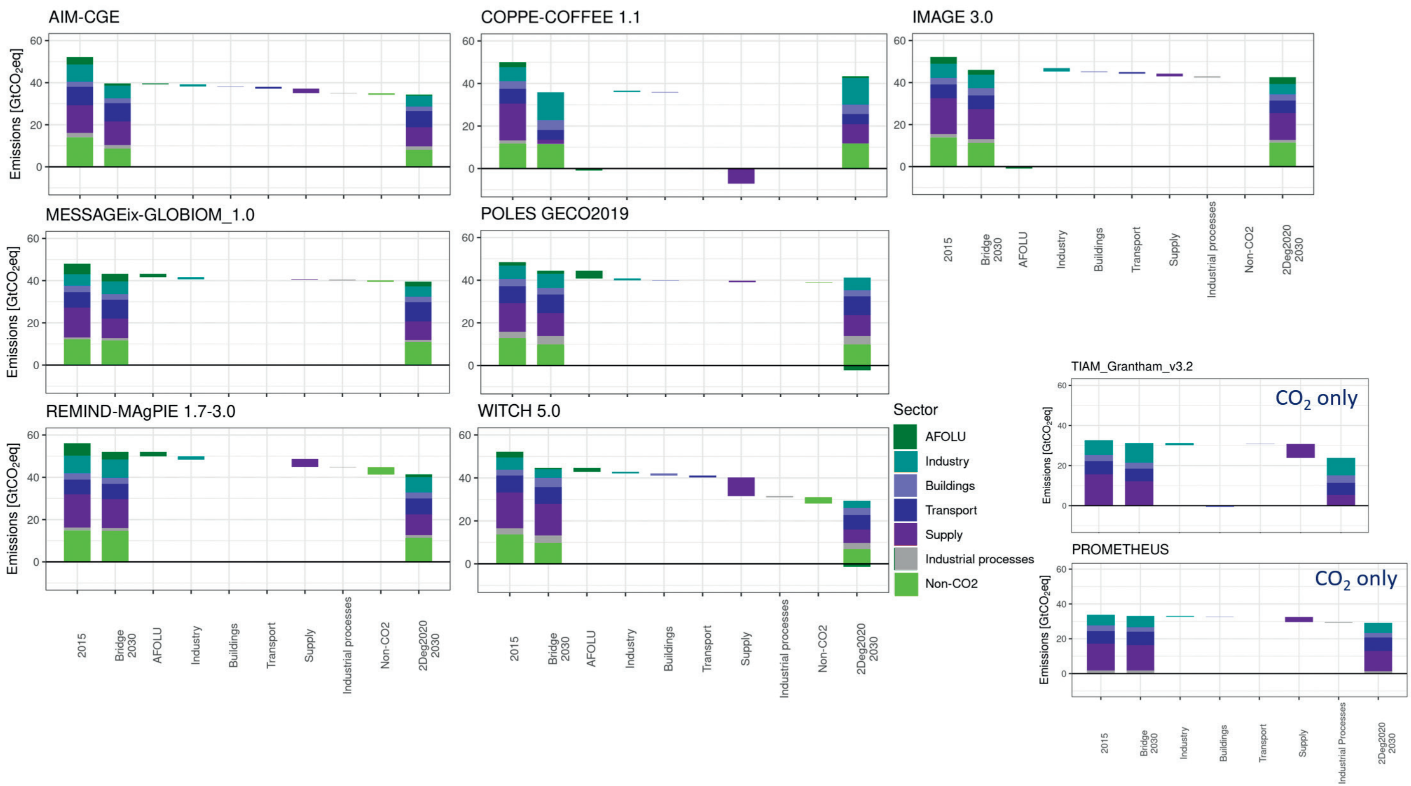


Figure S5.2.6: Contribution of each sector to emission reductions between the Bridge and 2Deg2020 scenarios (negative values denote an increase in emissions between Bridge and 2Deg2020). First bar: Emissions by sector in 2015. Second bar: emissions by sector in 2030, under Bridge. Third - ninth bar: emission reduction in energy supply, industry, buildings, transport, industrial processes, AFOLU, non-CO_2 emissions. Last bar: emissions by sector in 2030, under 2Deg2020. For TIAM and PROMETHEUS, only CO_2 emissions are shown.

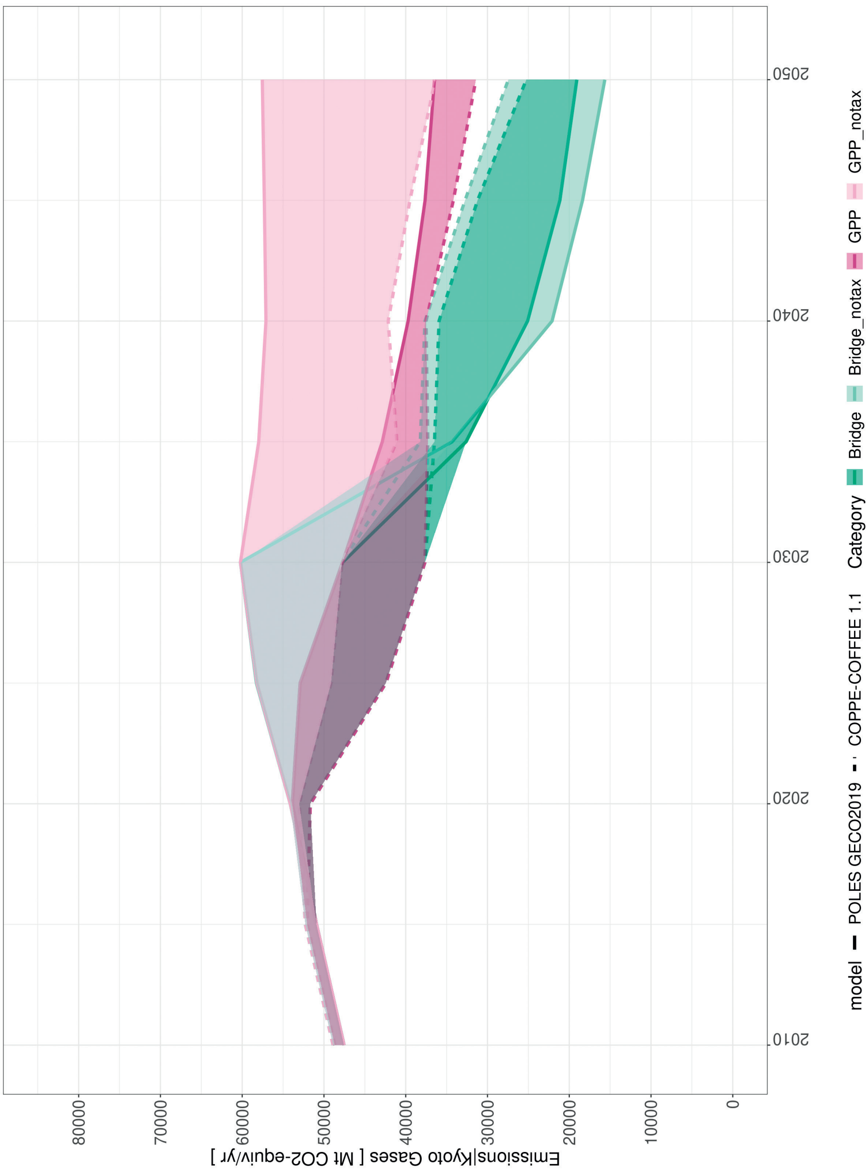


Figure S5.2.7: Global greenhouse gas emissions for the sensitivity cases of GPP and Bridge without the carbon tax measure (measure 7)

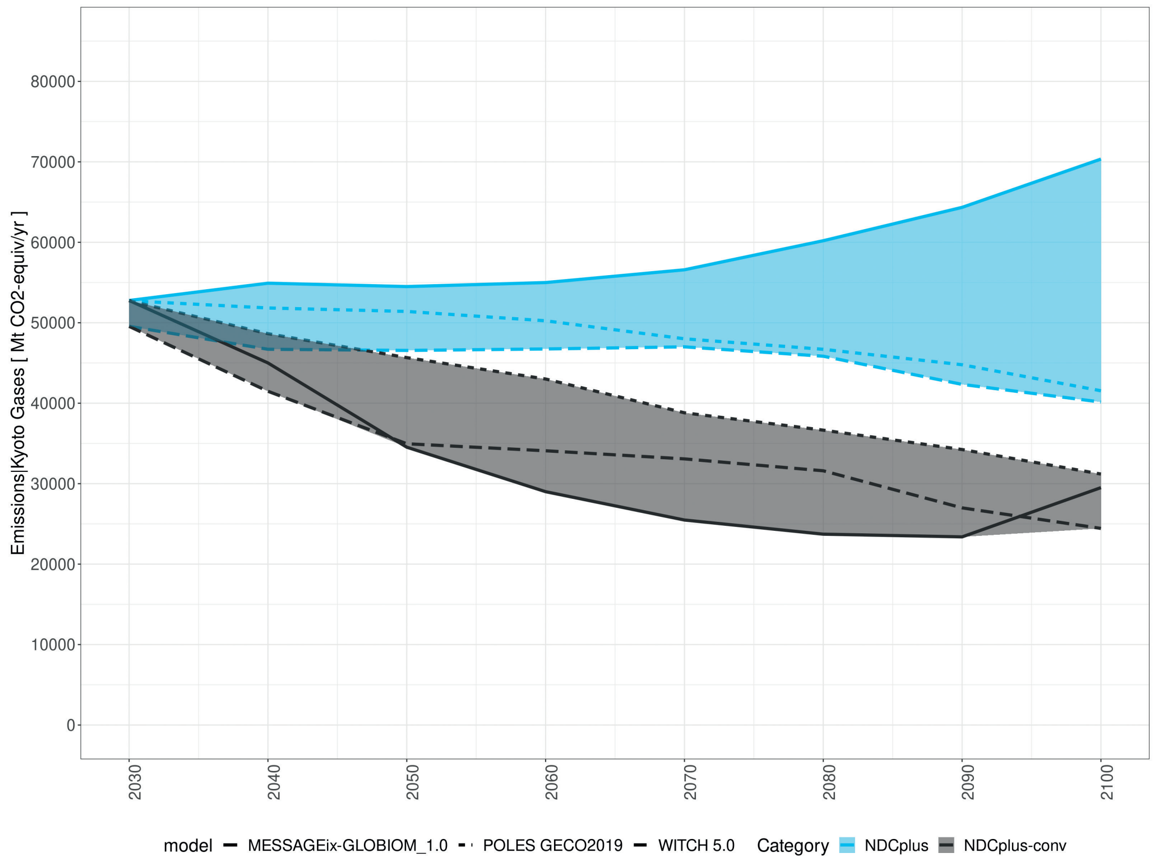


Figure S5.2.8: Global greenhouse gas emissions for the NDC variant NDC_2050convergence, as compared to the default NDCplus scenario

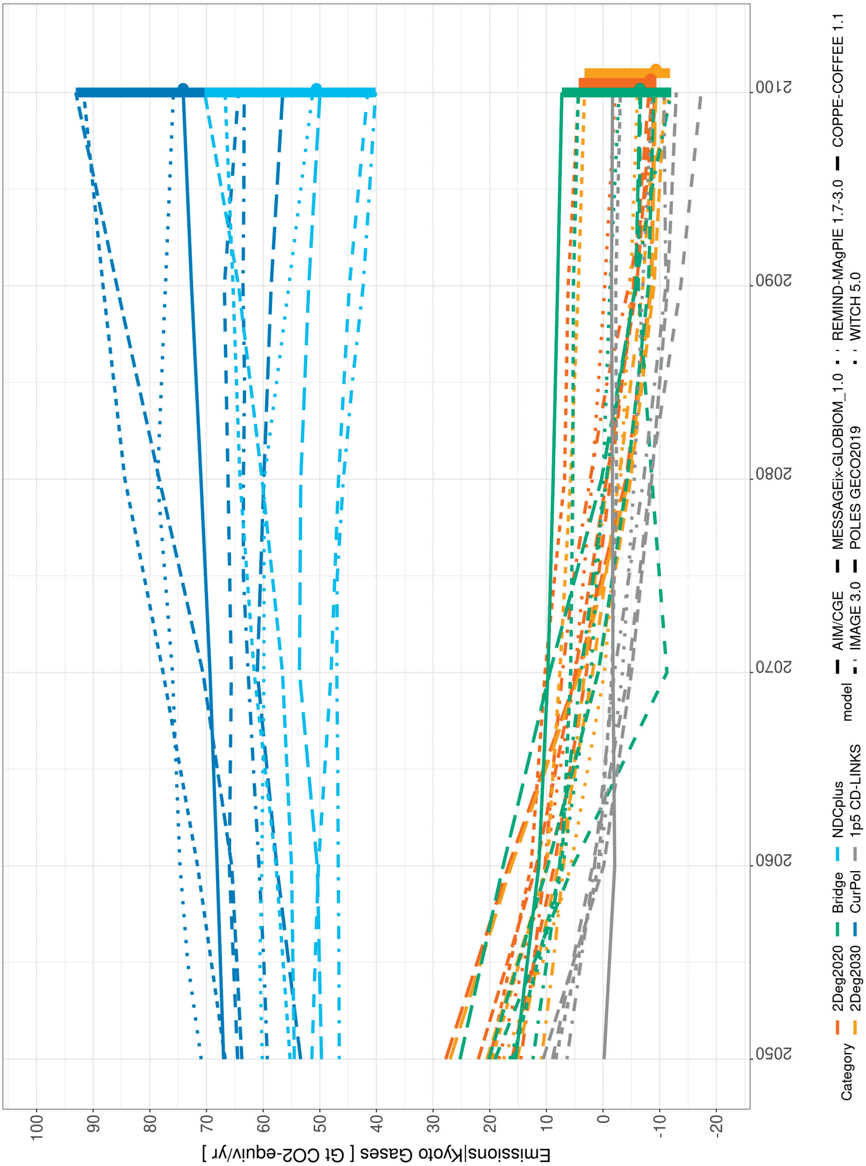


Figure S5.2.9: Global greenhouse gas emissions (Gt CO_2eq/year) between 2050 and 2100. Vertical bars: model range in 2100. Circles: model median in 2100.

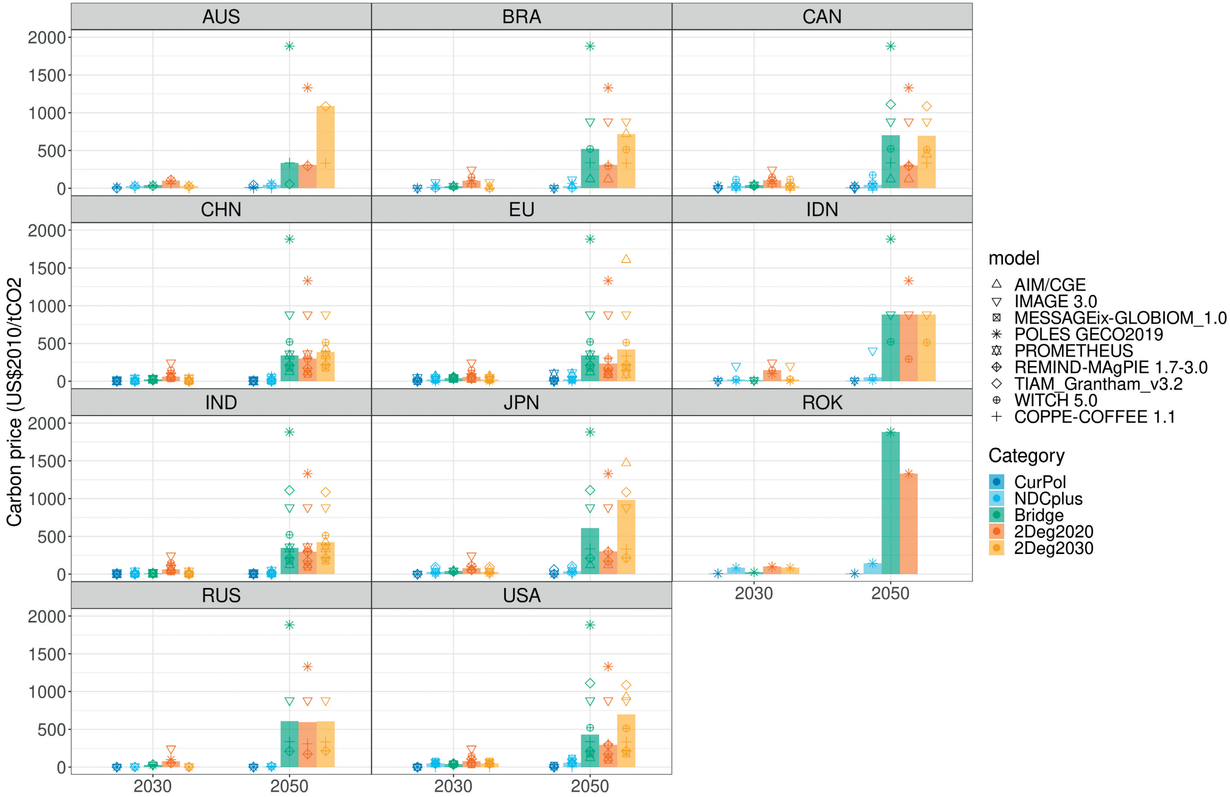
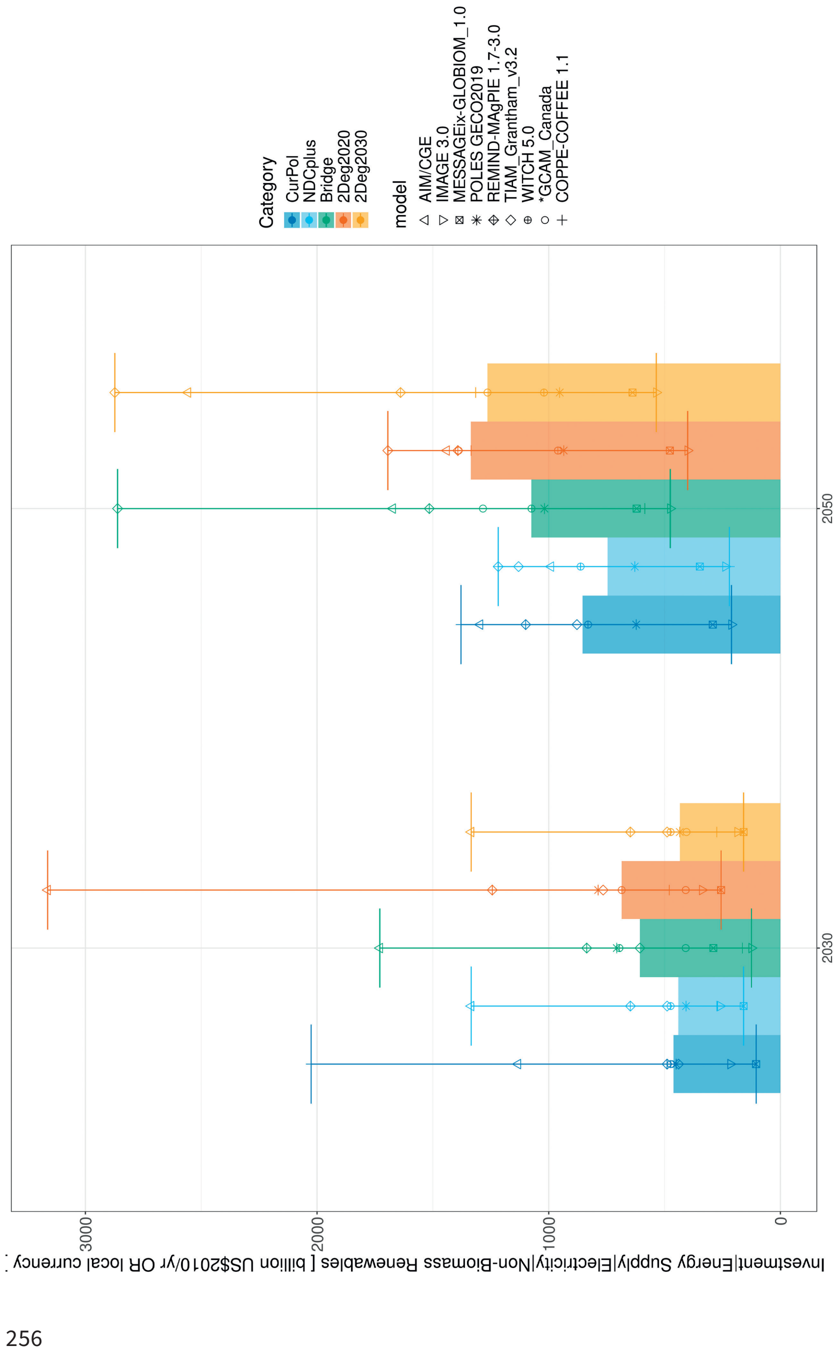


Figure S5.2.10: Regional carbon prices (US$2010/t$CO_2$) in 2030 and 2050, in the CurPol, NDCplus, Bridge, 2Deg2020, and 2Deg2030 scenarios. Bars: model median, symbols: individual models. AUS: Australia, BRA: Brazil, CAN: Canada, CHN: China, EU: European Union, IDN: Indonesia, IND: India, JPN: Japan, ROK: Republic of Korea (South Korea), RUS: Russian Federation, USA: United States of America.


Category
CurPol
NDCplus
Bridge
2Deg2020
2Deg2030
model
AIM/CGE
IMAGE 3.0
MESSAGEix-GLOBIOM_1.0
POLES GECO2019
REMIND-MAgPIE 1.7-3.0
TIAM_Grantham_v3.2
WITCH 5.0
*GCAM_Canada
COPPE-COFFEE 1.1
2050
2030
period
0
1000
2000
3000
Investment|Energy Supply|Electricity|Non-Biomass Renewables [billion US$2010/yr OR local currency]

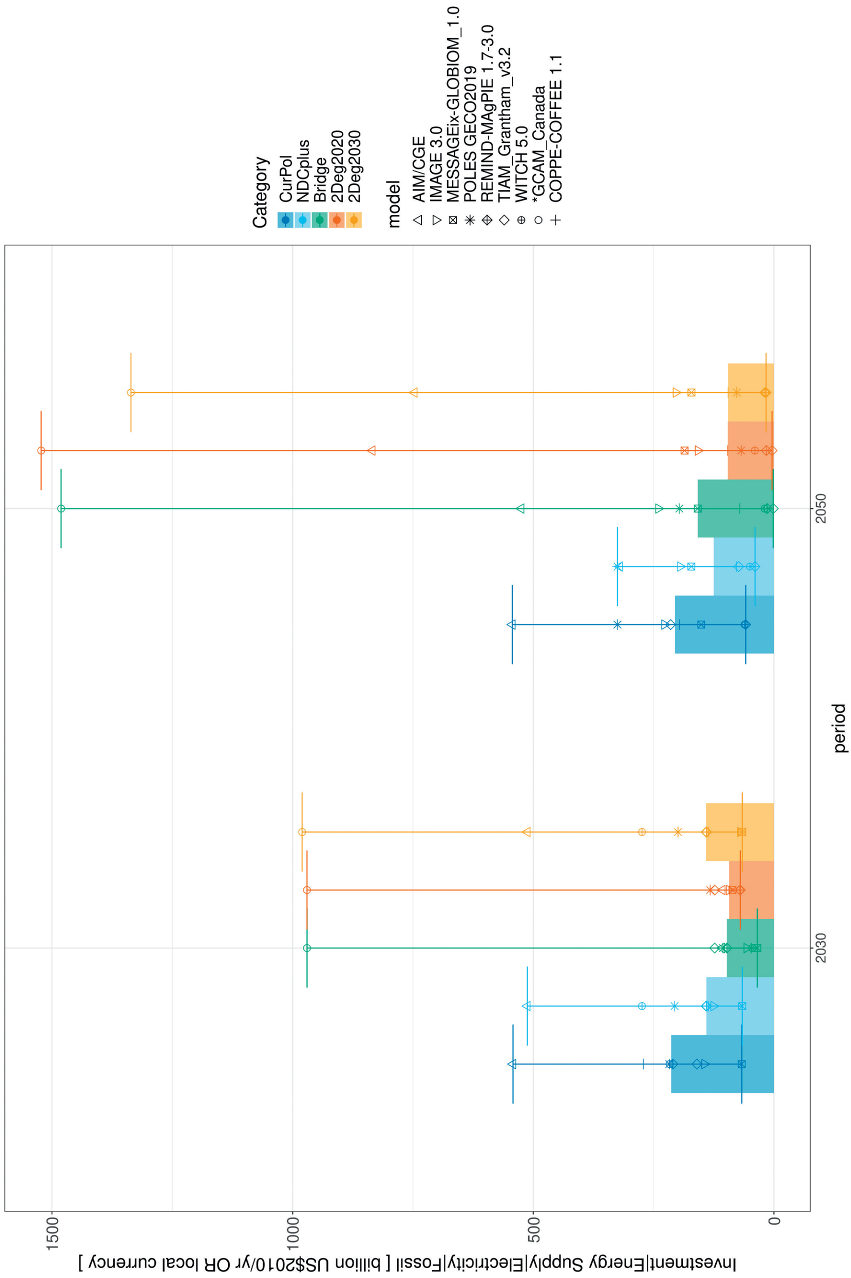


Figure S5.2.11: Investments in energy supply – electricity (billion US$2010 per year). Upper graph: non-biomass renewables, lower graph: fossil fuels. Bars show model median, error bars show the full range, and symbols show individual model results.

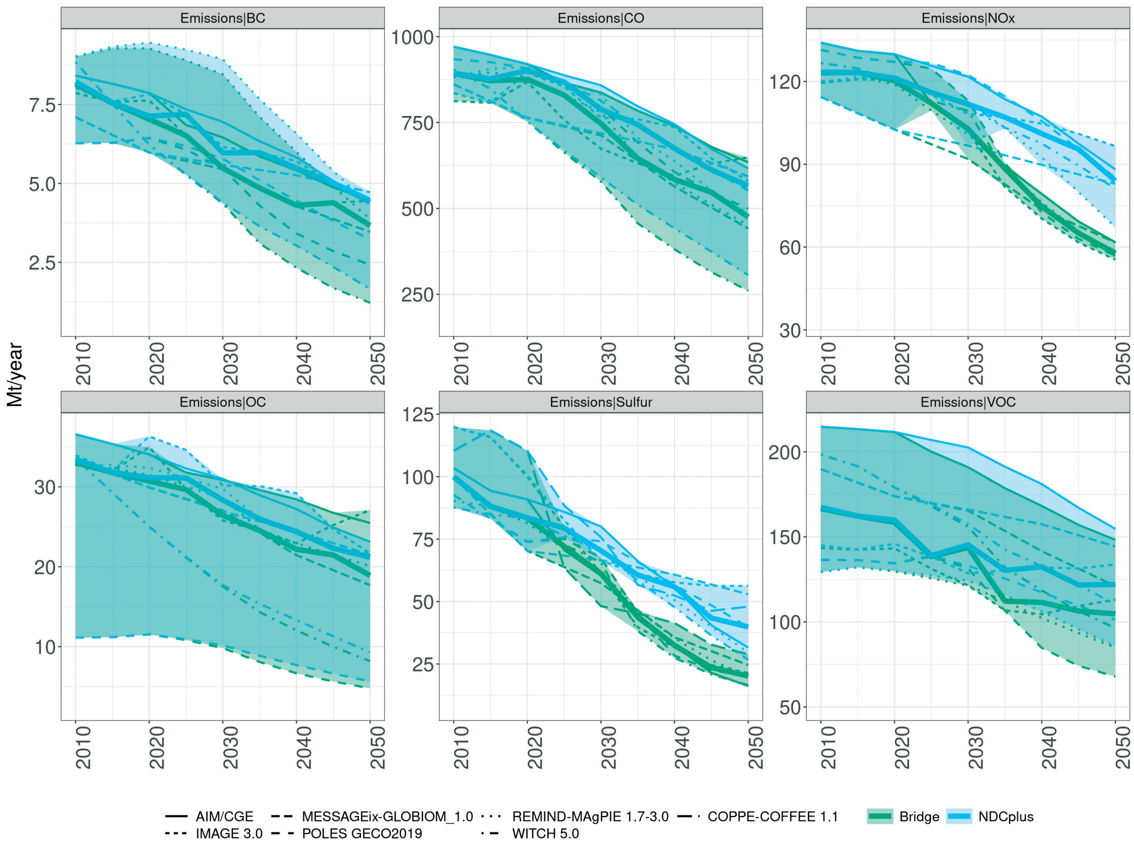


Figure S5.2.12: Air pollutant emissions (Mt/year) under the Bridge scenario, compared to NDCplus: black carbon (BC), carbon monoxide (CO), nitrogen oxides (NO_x), organic carbon (OC), sulphur, and volatile organic compounds (VOC).

S5.3 Supplementary Methods: COMMIT WP2&3 Scenarios for ratcheting up mitigation ambition

Protocol fourth round – 20 April 2020

S5.3.1 Introduction

In response to the global stocktake under the UNFCCC, scenarios will be developed that represent a ratcheted-up mitigation ambition level by Parties to the Paris agreement (hereafter: countries). The scenario suite described here consists of the following scenarios:

1. baseline,
2. current policy,
3. nationally determined contribution (NDC),
4. good practice policies,
5. bridging, and
6. 2 ˚C mitigation scenarios.

The good practice policies and bridging scenarios, which aim to bridge the gap between the ambition levels set out by countries and the required ambition levels to meet the mitigation goals agreed to in the Paris Agreement, are new, and most important. All other scenarios are added for comparison – and could be taken from earlier modelling exercises (although we require consistent model versions).

S5.3.2 Workflow and submission deadlines

Protocol development and scenario submission will take place in two rounds.

In **Round 1**, the national modelling teams got an opportunity to respond to the proposed policies as mentioned in the draft bridging scenario protocol (attached spreadsheet). PBL/PIK/COPPE gathered all comments and used them to construct the final bridging scenario protocol.

In **Round 2**, the final bridging scenario protocol will be distributed to both the national and global modelling teams. This will ensure that a common protocol is followed.

Please use this reporting template.

S5.3.3 Brief description of the scenarios

In line with the global stocktake, the ratcheting up mechanism has been applied in constructing the scenario protocol. This means that the scenarios build upon one another in terms of ambition and modelling assumptions. The Baseline scenario is the least ambitious and the 2 ˚C scenario is the most ambitious.

Table S5.3.1: Scenario descriptions

Scenario name	Scenario id	Builds upon	Novelty	National model implementation	Global model implementation
Baseline	BAU	None	None	Most likely socio-economic assumptions with no new climate policies after 2010	SSP2 scenario with no new climate policies after 2010
Current policy	CurPol	BAU	Possible update (new information available; old runs can be used)	As BAU scenario, but including implementation of current policies (cut-off date 1 July 2019)	As BAU scenario, but including climate policies based on CD-LINKS/ NewClimate/PBL policy database (cut-off date 1 July 2019)
NDC-plus	NDCplus Optional variants: NDC_2050convergence (global models) NDCMCS (national models)	CurPol	Update	As CurPol scenario including implementation of NDC until 2030, following the post-2030 extension guidelines thereafter	As CurPol scenario including implementation of NDCs, following the post-2030 extension guidelines thereafter
Good practice policies	GPP	CurPol	New	As CurPol scenario, including implementation of commonly defined good practice policies until 2050 – taking the value either for developed or for developing countries, and taking the more stringent of the CurPol and GPP values	As CurPol scenario, including implementation of commonly defined good practice policies until 2050 - distinguishing between developed and developing countries, and taking the more stringent of the CurPol and GPP values

Table S5.3.1: *Continued.*

Scenario name	**Scenario id**	**Builds upon**	**Novelty**	**National model implementation**	**Global model implementation**
Bridging	Bridge	GPP	New	As GPP scenario including implementation of good practice policies until 2030 to transition to the low carbon budget scenario (2Deg2030)	As GPP scenario including good practice policies until 2030, as identified by national teams, transitioning to the 2 °C scenario (2Deg2030)
2 ˚C 2020	2Deg2020	CurPol	None	As CurPol with the Implementation of a CD-LINKS carbon budget from 2020 (2020_low)	As CurPol with the implementation of a 2 ˚C / 2.6 Wm^{-2} climate target from 2020, represented by the CD-LINKS carbon budget: 1000 Gt CO_2 over 2011-2100, i.e. NPi2020_1000.
2 ˚C 2030	2Deg2030	NDCplus	None	As NDCplus with the implementation of a CD-LINKS carbon budget from 2030 (2030_low)	As NDCplus with the implementation of a 2 ˚C / 2.6 Wm^{-2} climate target from 2030, represented by the CD-LINKS carbon budget: 1000 Gt CO_2 over 2011-2100, i.e. INDC2030_1000

The **Baseline (BAU)** scenario should be a middle of the road socio-economic conditions scenario (preferably SSP2) throughout the century with no additional climate policy.

The **Current policy (CurPol)** scenario assumes the same socio-economic conditions as the BAU scenario. However, it also assumes that climate, energy and land use policies that are currently ratified are implemented (cut-off date 1 July 2019). For global models, this can be based on the updated CD-LINKS protocol. A new version is attached – please refer to the spreadsheet *Input-IAM-protocol_COMMIT_December2019.xlsx*, tab "Protocol CurPol numerical" (note that not all tabs were updated). Note that this update is optional: also the previous current policy scenario (CD-LINKS) could be submitted if needed, if based on the same model version.

The **NDC-plus (NDCplus)** scenario builds further upon the CurPol scenario and assumes that the NDCs are implemented by 2030. After 2030, the scenario should reflect continuation (but not strengthening) of effort (see S5.3.4.3 Post policy period for details). Specifically for China, please incorporate the 'peak' component of the NDC by ensuring that emissions do not increase above 2030 values.

Optional, additional scenario variants:

- ***NDC_2050convergence** - for global models only. In order to explore the implications of a scenario narrative "if the 2050 MCS in all countries become similarly stringent as the NDC targets of OECD countries for 2030", this scenario foresees a global convergence to a globally harmonized carbon price in 2050. See details under 'Post policy period'.*
- ***NDCMCS** - for national models only. For those countries that have submitted one to the UNFCCC, the MCS target for GHG emissions is implemented by 2050.*

The **Good practice policies (GPP)** scenario builds upon the CurPol scenario and assumes that certain good practice policies as defined in the spreadsheet, which have shown to be effective in some countries, will be implemented globally until **2050. For the list of policies to be implemented, see the spreadsheet *Bridging Scenario GPP list 20 April 2020.xlsx.*** That spreadsheet also contains tabs categorising countries in low / high income or other tiers. A distinction is made between low/medium income (columns K and L of the first tab) and high-income countries (columns I and J) in terms of timing and stringency (applied to all model regions). See also the fifth tab, 'Country categorisation', for a classification of all countries with their ISO codes: if the majority of countries in a region is classified as high income, the region can be considered high income (and vice versa for low/medium income). For some measures, we distinguish between three country tiers (columns M and N in the first tab, and see the third tab '7. CarbonPrice' and '16. Afforestation' for the country tiers applying to these measures).

- If CurPol is more stringent than GPP in certain sectors, take that value.

The **Bridging (Bridge)** scenario builds upon the GPP scenario. For the list of policies to be implemented until 2030, see the spreadsheet *Bridging Scenario GPP list 20 April 2020.xlsx.* After 2030, the Bridge scenario transitions to the 2 °C scenario (see Chapter 5).

The **2˚C (2Deg2020 and 2Deg2030)** scenarios assume that a radiative forcing target of 2.6 Wm^{-2} is reached by 2100 in a cost-effective way. National modelling teams can work with a carbon budget derived from the global carbon budget of 1000 Gt CO_2 in the period 2011-2100 (including 2011 emissions), as done in CD-LINKS (the '2020_low' budget for 2Deg 2020 and the '2030_low' budget for 2Deg 2030). Updated national carbon budget numbers for 2015-2050 are attached (*NationalCbudgetsCOMMIT.xlsx)*, including for the teams that did not participate in CD-LINKS, and distinguishing total CO_2 and only CO_2 from energy and industry for those models that do not represent land use. Global model teams can use the NPi2020_1000 (2Deg2020) and INDC2030_1000 (2Deg2030) scenarios.

S5.3.4 General specifications for all scenarios

S5.3.4.1 Naming

When uploading results to the IIASA database, scenario names as mentioned in the column Scenario id of Table S5.3.1 should be used with the extension of the version number, with _V4 for this round. That means: please submit the following scenarios, regardless of whether you have submitted in previous rounds:

- BAU_V4
- CurPol_V4
- NDCplus_V4
    - *NDC_2050convergence_V4*
    - *NDCMCS_V4*
- GPP_V4
- Bridge_V4
- 2Deg2020_V4
- 2Deg2030_V4

S5.3.4.2 Time horizon

Models are requested to report five-year intervals between 2000 and 2020 and 10-year intervals thereafter. Up to 2050 or 2100 based on model specifications. For models that do not have 5-year time steps, targets for e.g. 2035 should be implemented by the nearest (later) year, i.c. 2040. For base year values, use the provided 2015 value if needed.

S5.3.4.3 Post policy period

For the Current policy, NDC/MCS and Good Practice Policy scenarios, the ambition levels reached in the target year should remain at least constant throughout the rest of the century. This should be implemented by extrapolating the "equivalent" carbon price in 2030, using the GDP growth rate of regions. The equivalent carbon price represents the value of carbon that would yield in a region the same emissions reduction as the NDC policies. For most modelling teams this requires to run a set of (cost-optimal) sensitivity scenarios in order to derive the carbon price that would result in the same reductions as in the NDC cases. Importantly, if a region has a carbon price of zero while implementing the (I)NDC in 2030, please assume a minimum carbon price of 1 $/tCO_2$ in 2030 (= 8 $/tCO_2$ in 2100 with 3%/y GDP growth). If a region has a negative carbon price in 2030, offset the trajectory resulting from 1 $/tCO_2$ to your own 2030 starting point. For land use, a carbon price ceiling of $200/tCO_2$ should be applied.

Optional, additional scenario for global models: ***NDC_2050convergence***

In order to explore the implications of a scenario narrative "if the 2050 MCS in all countries become similarly stringent as the NDC targets of OECD countries for 2030", this scenario foresees a global convergence to a globally harmonized carbon price in 2050, at the level of the average carbon prices in OECD countries (which are increasing from 2030 onwards with regional GDP growth rates). <u>Exact calculation of carbon prices</u>: Initially, regional carbon prices after 2030 are taken from the NDC scenario where they are determined by applying the regional GDP growth rate to the effective carbon price in the region in 2030. The "global" carbon price for all years > 2030 is then calculated as the GDP-weighted average carbon price of OECD regions. The regional carbon prices of all regions are then updated to converge from the effective carbon price in the region in 2030 (as in the NDC scenario) to this global level until 2050 (linear increase from regional 2030 carbon price to 2050 global carbon price). They are equal to the global trajectory for all timesteps 2050 and beyond. Only OECD regions with carbon prices higher than the "global" trajectory should stick to their original carbon price trajectory (maximum operator).

S5.3.4.4 Regions

Apart from model specific regions, a mapping to the 5 RCP regions should be made by global models.

S5.3.4.5 Policy coverage in the model

If you are unable to implement the policy or target in the model, please adopt the provided proxy values instead. If that is not possible either, please indicate in the protocol spreadsheet which policies you were not able to capture. Proxy values are provided by IMAGE in the tab 'Indicators'.

For global sectors such as international aviation and shipping, measure 18 is included for aviation (no distinction between countries). For shipping, take the baseline trends (as no current policies are included for that sector).

S5.3.5 Detailed specifications of scenarios

S5.3.5.1 Updated CD-LINKS scenarios

To a large degree, the scenarios developed in the CD-LINKS project can be used. A mapping between the scenarios can be found in Table S5.3.2. The third column indicates the novelty of the scenario. The fourth indicates the corresponding CD-LINKS protocol that can be used as reference. The table shows that, with the exception of the good practice policies / bridging and NDC-plus scenario, the protocols from CD-LINKS can be used for all scenarios. Figure S5.3.1 gives an example of what the increasing ambition emission profiles might look like.

Table S5.3.2: Scenario mapping to CD-LINKS protocol

Scenario name	Scenario id	Novelty	Protocol (global / national models)
Baseline	BAU	**Update**	CD-LINKS NoPolicy / NoPOL
Current policy	CurPol	**Update**	CD-LINKS NPi / NPi
NDC-plus	NDCplus • *NDC_2050convergence* • *NDCMCS*	**Update**	New formulation (see this protocol)
Good practice policies	GPP	**New**	New (see spreadsheet)
Bridging	Bridge	**New**	New (see spreadsheet)
2 ˚C 2020	2Deg2020	**Update**	CD-LINKS NPi2020_1000 / NPi2020_low
2 ˚C 2030	2Deg2030	**Update**	CD-LINKS INDC2030i_1000 / INDC2030_low

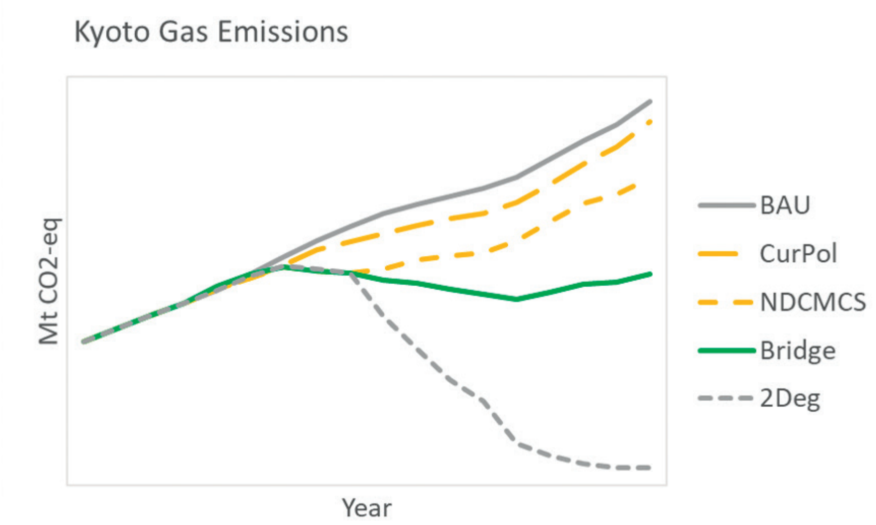


Figure S5.3.1: Example of emission profiles (note: the green 'Bridge scenario' actually represents the GPP scenario – the true Bridge scenario would be in between the green line and grey dashed line). The NDCMCS scenario is now optional (for national models) – instead, the NDCplus scenario would be more stringent than shown here.

S5.3.5.2 Good practice policies and Bridging scenarios

The list of policies to be implemented is given in the *Bridging Scenario GPP list 20 April 2020.xlsx* spreadsheet (they are based on previous studies as indicated in the sheet "underlying information", which marks as *Kriegler*[1], *Fekete*[2] *or Roelfsema*[3]*).* Note that these 'policies' are mostly physical measures, without the policy instruments to implement them (given that those are context dependent).

By 9 September, national teams should indicate, for every entry in the spreadsheet, whether they:

1. Believe these policies would be feasible to implement in their country as stated,
2. Are able to implement an adjusted form of the policy (e.g. lower ambition, later implementation year), or
3. Are not able to implement the policy as denoted or an adjusted form of the policy.

Furthermore, teams are encouraged to add optional policies that might apply to their national circumstances. The comments and suggestions have been stored in the tab 'Team comments'.

In the **good practice policies** scenario, the listed policies should be followed until 2030 and in many cases 2050. See ‘Post policy period’ for assumptions after the last target year.

In the **bridging** scenario, the listed policies should be followed until 2030, after which the scenario should transition smoothly to the 2 °C scenario by remaining within the carbon budget consistent with the 2 °C target (the 1000 $GtCO_2$ for 2011-2100 for global teams / 2030_low for national teams). This should be implemented via a carbon price: please converge from the regionally differentiated 2030 carbon prices listed in tab *7. CarbonPrice* in attached spreadsheet to a global carbon price in 2050 that is in line with the 2 °C carbon budget (in your model). If that implies the targets become infeasible, go for the latest convergence date possible that keeps the target in reach.

The above implies that the GPP and Bridge scenarios should follow the same pathway until 2030.

S5.4 Supplementary References

1 Kriegler, E. *et al.* Short term policies to keep the door open for Paris climate goals. *Environmental Research Letters* **13**, doi:10.1088/1748-9326/aac4f1 (2018).
2 Fekete, H. *et al.* A review of successful climate change mitigation policies in major emitting economies and the potential of global replication. *Renewable and Sustainable Energy Reviews* **137**, 110602, doi:https://doi.org/10.1016/j.rser.2020.110602 (2021).
3 Roelfsema, M. *et al.* Reducing global GHG emissions by replicating successful sector examples: the ‘good practice policies’ scenario. *Climate Policy* **18**, 1103-1113, doi:10.1080/14693062.2018.1481356 (2018).

S6 Analysing interactions among Sustainable Development Goals with Integrated Assessment Models

S6.1 Supplementary Materials

S6.1.1 Expert survey on interactions among SDGs

Extra questions for respondents from the IISD SDG mailing list:

1. *What is the highest level of education you have successfully completed?*

All respondents except one had at least a bachelor's degree. Of the responses we used, almost half had doctorate degrees. Among the remainder, we only discuss the responses we used.

2. *What is your current occupation title?*

Responses to this question were diverse.

3. *What best describes the type of organization you work for?*

A third of the respondents worked for non-profit organisations, while another third worked in research and education. The last group comprised government employees, employees of for-profit organisations, and self-employed and retired people.

4. *Please indicate how many years of professional or postgraduate experience you have in relation to the SDG that you selected in the first question. If you have no relevant experience, please enter '0'.*

Half the respondents had over 10 years of experience in their field of specialisation. The majority had at least seven years of experience.

5. *Please rate your knowledge on your SDG between 0 and 10: 0- No prior knowledge or understanding (e.g. you have never heard of this topic before). 1- Basic understanding, (e.g. have read a report, or news article, but have no direct or relevant experience). 5- Intermediate understanding (e.g. relevant experience gained through work, study , hobbies, or lay knowledge). 10- Specialist understanding (e.g. regularly collect data, prepare or sign off on reports, or provide advice on this topic)*

All respondents rated their knowledge with scores of 7 and above, with roughly each third assigning scores such as 8, 9, and 10. As many as 13 respondents rated their knowledge as 6 and below. Their results were no longer used.

6. Have you published technical or peer-reviewed reports on your SDG?

A total of 20 experts answered yes to this question.

a. Please provide an approximate number of peer-reviewed journal articles and technical reports.

Of the respondents, 3 had published more than 10 papers on their area of expertise. Half the respondents had published fewer than 3 papers. A total of 18 respondents had published fewer than 3 reports on their SDG, and 4 had published more than 10 reports on their SDG.

7. Are you a member of a committee or advisory panel relevant to your SDG?

Approximately half the respondents answered this question in the affirmative.

The number of respondents per SDG is listed below. Except SDG 5, each SDG was covered by at least one respondent. SDGs 7, 11, and 17 were covered by the largest number of respondents.

Number of respondents per SDG

SDG	Number of respondents (groups 1-4)	Number of respondents (group 5: IISD mailing list)	Number of respondents (group 5), filtered	Number of respondents (together)	Number of respondents (together), filtered
SDG 1	*0*	*3*	*2*	*3*	*2*
SDG 2	*0*	*1*	*1*	*1*	*1*
SDG 3	*2*	*2*	*1*	*4*	*3*
SDG 4	*1*	*5*	*1*	*6*	*2*
SDG 5	*0*	*0*	*0*	*0*	*0*
SDG 6	*1*	*2*	*2*	*3*	*3*
SDG 7	*3*	*4*	*3*	*7*	*6*
SDG 8	*0*	*4*	*2*	*4*	*2*
SDG 9	*1*	*0*	*0*	*1*	*1*
SDG 10	*1*	*0*	*0*	*1*	*1*
SDG 11	*3*	*4*	*4*	*7*	*7*
SDG 12	*0*	*3*	*3*	*3*	*3*
SDG 13	*0*	*3*	*3*	*3*	*3*
SDG 14	*1*	*0*	*0*	*1*	*1*
SDG 15	*3*	*4*	*2*	*7*	*5*
SDG 16	*1*	*4*	*2*	*5*	*3*
SDG 17	*2*	*4*	*4*	*6*	*6*
Various	*1*	-	-	*1*	*1*
Total	*20*	*43*	*30*	*63*	*50*
Response rate	*19%*	-	-	-	-

The *SDG expert survey* results indicated both stronger (darker colours) and a larger number of interactions as opposed to the *model survey* results (Figure S6.2.4). The *expert survey* shows extra interactions in the governance and infrastructure and human development clusters, as well as in the Earth system cluster, especially with oceans (SDG 14) and life on land (SDG 15).

An external validation of the question on existing interactions (as scored by modellers) with the literature (*2, 12, 26, 80,* and *92-95*) revealed that more interactions than those shown in the orange shading in Figure S6.2.4 are possible. These reports mentioned additional interactions, especially with gender equality (both the effect of gender equality on other SDGs and vice versa, with SDGs 5 and 12 ranking seventh as a pair in the trade-off top 10 by Pradhan et al. (2017)). The reports also highlighted the effects of SDGs 3 (health), 6 (water), 10 (inequalities), and 14 (oceans) on other goals in three different clusters, and of education (SDG 4) and peace (SDG 16) on resource use and Earth system SDGs. The impact of other SDGs on cities (SDG 11), oceans (SDG 14), peace (SDG 16), and partnerships (SDG 17) also came up in these reports. However, these areas are generally not well-covered by IAMs. Additional interactions also included SDGs 9 (innovation/infrastructure) and 12 (sustainable consumption and production), especially with goals in the human development cluster (the SDG pair 10–12 ranked first in the trade-off top 10 mentioned above). Finally, the effects of SDG 2 on SDG 12, of SDG 11 on SDGs 2 and 14, of SDG 13 (climate) on education (SDG 4) and gender equality (SDG 5), and of SDG 15 (life on land) on human development and governance and infrastructure SDGs were listed (with SDGs 10 and 15, as a pair, ranking sixth, and SDGs 4 and 15, as a pair, ranking tenth in Pradhan et al.'s (2017) trade-off top 10).

S6.1.2 External validation: Comparison with Pradhan et al. (2017) (Empirical correlation analysis)

Pradhan et al. (2017) provided the results of their empirical analysis in the form of a spreadsheet with COUNTNEG, COUNTZERO, and COUNTPOS representing the number of countries or indicators for which trade-offs (rho value less than -0.6), no relations (rho value between -0.6 and 0.6), and synergies (rho value greater than -0.6) were observed in indicator time series, respectively. PECNEG, PECZERO, and PECPOS represented similar information but in relative terms, respectively.

These results had to be translated to the same scale as that used in the matrices here (noting that the ICSU framework used here is qualitative, while Pradhan et al.'s results were quantitative). Interactions with percentage scores between 0 and 33 were assigned 1 or -1; between 33 and 66 were assigned 2 or -2; and between 66 and 100 were assigned 3 or -3 to represent that the higher the percentage, the 'stronger' the interaction. To combine both the trade-offs and synergies within one set of SDGs, the maximum among the transformed scores was taken after dropping the sign for the trade-off scores (the sign is not necessary while focusing on how strongly two SDGs are related). This very rough translation is meant for an initial qualitative comparison (see Figure S6.2.2) rather than a precise quantitative one, which is difficult given the different scopes of this analysis and the one by Pradhan et al. (2017). For example, the matrices in this paper have a direction component (i.e. the SDG in the column affects the SDG in the row), while the matrix resulting from the correlation analysis does not (ongoing work is investigating the underlying dynamics to identify the targets that drive other targets within the identified correlations). Therefore, the matrix based on

Pradhan et al. (2017) is diagonally symmetric. Despite these differences, comparisons of this sort are currently missing in the literature.

Notable differences between the empirical analysis and the expert survey include the effect of (and on) SDG 16, which is assessed as stronger in the expert survey than in the empirical analysis, while the effects of SDG 9 on SDGs 5, 10, and 15 and of SDG 2 on SDG 5 are assessed as stronger in the empirical analysis than in the expert survey.

Regional differences may be one reason for the differences between the results from the expert survey and the empirical analysis. Pradhan et al. (2017) found that SDGs have interacted differently in different countries. For example, SDGs 3 and 12 have had trade-offs in almost all countries but one. These regional differences are captured in the country-level empirical analysis while the SDG expert survey was conducted at the global level (noting that experts may have had various regions in mind while assigning scores). Another reason may be that the empirical analysis was about the past, and the experts may have filled in the survey with future achievements of SDG targets in mind.

S6.1.3 Model assessment: Individual SDGs

For more details on how the models represent the SDGs underlying the interactions reported in Figure 6.1, Table 6.1 presents the results of the survey question on the ability of the models to quantify individual targets. The overall picture that emerges is that four SDGs cannot be quantified or assessed directly with IAMs (average score below 1), mostly in the human development goals and governance and infrastructure clusters (most notably inequalities and peace, but also oceans). Three SDGs are well-covered by IAMs (average score above 3), in the efficient and sustainable resource use and Earth system clusters (energy, climate, and industry/innovation/infrastructure), and ten SDGs can partly be quantified in the IAMs (average score between 1 and 3) (Figure S6.2.1). Simulation and optimization models, however, differ in terms how they represent individual SDG targets.

These findings generally align with Allen et al. (2016), who found that SDGs 2, 6, 7, 8, 9, 13, and 17 were covered most, while SDGs 1, 3, 4, 5, 10, 11, 14, 15, and 16 were covered least. Although individual SDGs such as 1, 3, and 15 were found better covered in the set of models reviewed here, this study supports the main conclusion by Allen et al. (2016) that the social dimension is by far the least addressed. Similarly, Pollitt et al. (2010) found that 2 of the 10 sustainability themes, namely social inclusion and governance, were least covered in 60 integrated assessment tools, and that the endogenous representations of demographics and health was limited.

S6.1.4 Model assessment: Synthesis of literature

In this section, we provide additional results on topic modelling analysis. First, we describe the primary results of the topic model extensively by focusing on the topics, terms, and documents. Second, we analyse the results in light of SDG interactions in detail. After removing the documents that had topic scores lower than 0.1, the dataset contained 245 individual documents.

S6.1.4.1 Individual SDGs and topics

S6.1.4.1.1 SDGs and topics

The top 20 terms describing the 14 topics are presented in Table S6.3.4 with their scores. This shows that the first 5 terms in each topic already provide good descriptions. It is also important to note that although the two topics associated with SDG 7 (i.e. Topic 6 'Low-carbon electricity' and Topic 9 'Low-carbon electricity II') may initially appear similar, Topic 9 emphasises strongly on the role of nuclear technologies in energy transition pathways, whereas Topic 6 does not. This is why the term 'Japan' appears in the list of stemmed keywords.

S6.1.4.1.2 Number of documents per SDG and topic

Table S6.3.5 shows the number of individual documents associated with each topic and the associated SDG goal, whereas Table S6.3.6 shows the number of individual documents associated with each SDG. As expected, many documents are associated with climate mitigation (SDG 13, 149 documents) and energy transition (SDG 7, 54 documents). Topic 1 on 'Mitigation scenarios' is featured in 70 documents, whereas Topic 5 on land-based mitigation, Topic 7 on 'CCS, bioenergy and negative emissions', and Topic 13 on 'CBA of climate policies' are discussed in 37, 30, and 12 documents, respectively. The second topic, 'Carbon pricing and mitigation costs', has been discussed in 55 documents. 'Air pollution and health' (Topic 8) and 'Water availability and consumption' (topic 10) are peripheral topics that are discussed in 22 and 25 documents, respectively.

In the following sub-sections, we provide the list of documents associated with each topic and the SDG it pertains to.

Documents in topic 1: Mitigation scenarios (SDG 13)

ID	Publication	Score
1	Riahi 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	0.3938659
2	Fujimori et al. (2016) 'Implication of Paris Agreement in the context of long-term climate mitigation goals'. SPRINGERPLUS	0.3693782

ID	Publication	Score
3	Blanford et al. (2014) 'Harmonization vs. fragmentation: overview of climate policy scenarios in EMF27'. CLIMATIC CHANGE	0.3676366
4	Lucas et al. (2007) 'Long-term reduction potential of non-CO2 greenhouse gases'. ENVIRONMENTAL SCIENCE & POLICY	0.3487358
5	van Vuuren et al. (2016) 'Carbon budgets and energy transition pathways'. ENVIRONMENTAL RESEARCH LETTERS	0.3451435
6	Hof et al. (2016) 'The EU 40 % greenhouse gas emission reduction target by 2030 in perspective'. INTERNATIONAL ENVIRONMENTAL AGREEMENTS-POLITICS LAW AND ECONOMICS	0.3295609
7	Tavoni et al. (2012) 'The value of technology and of its evolution towards a low carbon economy'. CLIMATIC CHANGE	0.3288703
8	van Vliet et al. (2014) 'The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets'. CLIMATIC CHANGE	0.3188178
9	Kriegler et al. (2014) 'The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies'. CLIMATIC CHANGE	0.3177219
10	van Vuuren et al. (2013) 'If climate action becomes urgent: the importance of response times for various climate strategies'. CLIMATIC CHANGE	0.3128015
11	Hof et al. (2017) 'Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2 degrees C and 1.5 degrees C'. ENVIRONMENTAL SCIENCE & POLICY	0.3058376
12	Blanford et al. (2014) 'Trade-offs between mitigation costs and temperature change'. CLIMATIC CHANGE	0.2896471
13	Luderer et al. (2013) 'Economic mitigation challenges: how further delay closes the door for achieving climate targets'. ENVIRONMENTAL RESEARCH LETTERS	0.2818990
14	Rogelj et al. (2016) 'Paris Agreement climate proposals need a boost to keep warming well below 2 degrees C'. NATURE	0.2808022
15	Hof et al. (2015) 'Disentangling the ranges: climate policy scenarios for China and India'. REGIONAL ENVIRONMENTAL CHANGE	0.2750916
16	Liu et al. (2016) 'Temporal and spatial distribution of global mitigation cost: INDCs and equity'. ENVIRONMENTAL RESEARCH LETTERS	0.2732738

ID	Publication	Score
17	Zhu et al. (2014) 'Temperature control, emission abatement and costs: key EMF 27 results from Environment Canada's Integrated Assessment Model'. CLIMATIC CHANGE	0.2656851
18	Hoogwijk et al. (2009) 'Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials'. ENERGY POLICY	0.2627133
19	Kriegler et al. (2015) 'Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.2535161
20	Riahi et al. (2007) 'Scenarios of long-term socio-economic and environmental development under climate stabilization'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.2457646
21	Hasegawa et al. (2016) 'Land-Based Mitigation Strategies under the Mid-Term Carbon Reduction Targets in Indonesia'. SUSTAINABILITY	0.2434597
22	Jiang et al. (2013) 'China's role in attaining the global 2 degrees C target'. CLIMATE POLICY	0.2220488
23	Stevanovic et al. (2017) 'Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.2134305
24	Hamdi-Cherif et al. (2016) 'Global carbon pricing and the "Common But Differentiated Responsibilities": the case of China'. INTERNATIONAL ENVIRONMENTAL AGREEMENTS-POLITICS LAW AND ECONOMICS	0.2092312
25	Smith et al. (2013) 'Near-term climate mitigation by short-lived forcers'. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	0.2088765
26	Li et al. (2017) 'Aligning domestic policies with international coordination in a post-Paris global climate regime: A case for China'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.2033571
27	Akashi et al. (2014) 'Halving global GHG emissions by 2050 without depending on nuclear and CCS'. CLIMATIC CHANGE	0.1990518
28	Rogelj et al. (2014) 'Disentangling the effects of CO2 and short-lived climate forcer mitigation'. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	0.1982038
29	Lamb et al. (2015) 'Human development in a climate-constrained world: What the past says about the future'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.1956038

ID	Publication	Score
30	Martinez et al. (2015) 'Possible energy futures for Brazil and Latin America in conservative and stringent mitigation pathways up to 2050'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1912617
31	Luderer et al. (2012) 'On the regional distribution of mitigation costs in a global cap-and-trade regime'. CLIMATIC CHANGE	0.1903922
32	Fuss et al. (2016) 'Research priorities for negative emissions'. ENVIRONMENTAL RESEARCH LETTERS	0.1890835
33	Admiraal et al. (2016) 'Costs and benefits of differences in the timing of greenhouse gas emission reductions'. MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE	0.1755445
34	Borba et al. (2012) 'Energy-related climate change mitigation in Brazil: Potential, abatement costs and associated policies'. ENERGY POLICY	0.1713453
35	McJeon et al. (2014) 'Limited impact on decadal-scale climate change from increased use of natural gas'. NATURE	0.1690780
36	Rafaj et al. (2014) 'Changes in European greenhouse gas and air pollutant emissions 1960-2010: decomposition of determining factors'. CLIMATIC CHANGE	0.1674193
37	Capros et al. (2012) 'Model-based analysis of decarbonising the EU economy in the time horizon to 2050'. ENERGY STRATEGY REVIEWS	0.1570114
38	Lucas et al. (2013) 'Implications of the international reduction pledges on long-term energy system changes and costs in China and India'. ENERGY POLICY	0.1565457
39	Stehfest et al. (2009) 'Climate benefits of changing diet'. CLIMATIC CHANGE	0.1533490
40	Rafaj et al. (2013) 'Scenarios of global mercury emissions from anthropogenic sources'. ATMOSPHERIC ENVIRONMENT	0.1520446
41	Marcucci et al. (2015) 'Induced technological change in moderate and fragmented climate change mitigation regimes'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1485556
42	Radu et al. (2016) 'Exploring synergies between climate and air quality policies using long-term global and regional emission scenarios'. ATMOSPHERIC ENVIRONMENT	0.1479674
43	Valin et al. (2013) 'Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security?'. ENVIRONMENTAL RESEARCH LETTERS	0.1442222
44	Krey et al. (2014) 'Getting from here to there - energy technology transformation pathways in the EMF27 scenarios'. CLIMATIC CHANGE	0.1429283

ID	Publication	Score
45	Leimbach et al. (2010) 'Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R'. ENVIRONMENTAL MODELING & ASSESSMENT	0.1421548
46	Marcucci et al. (2017) 'The road to achieving the long-term Paris targets: energy transition and the role of direct air capture'. CLIMATIC CHANGE	0.1407283
47	Lanzi et al. (2012) 'Alternative approaches for levelling carbon prices in a world with fragmented carbon markets'. Energy Econ.	0.1377412
48	van Sluisveld et al. (2016) 'Exploring the implications of lifestyle change in 2 degrees C mitigation scenarios using the IMAGE integrated assessment model'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1367206
49	Kypreos et al. (2012) 'From the Copenhagen Accord to efficient technology protocols'. ENERGY POLICY	0.1357047
50	Portugal-Pereira et al. (2016) 'Overlooked impacts of electricity expansion optimisation modelling: The life cycle side of the story'. ENERGY	0.1355849
51	Cantore et al. (2012) 'Sustainability of the energy sector in the Mediterranean region'. ENERGY	0.1348135
52	Rafaj et al. (2013) 'Co-benefits of post-2012 global climate mitigation policies'. MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE	0.1340952
53	Frank et al. (2017) 'Reducing greenhouse gas emissions in agriculture without compromising food security?'. ENVIRONMENTAL RESEARCH LETTERS	0.1324923
54	Luderer et al. (2012) 'The economics of decarbonizing the energy system-results and insights from the RECIPE model intercomparison'. CLIMATIC CHANGE	0.1316240
55	Alcamo et al. (2003) 'Development and testing of the WaterGAP 2 global model of water use and availability'. HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	0.1292917
56	von Stechow et al. (2016) '2 degrees C and SDGs: united they stand, divided they fall?'. ENVIRONMENTAL RESEARCH LETTERS	0.1247781
57	Hamdi-Cherif et al. (2011) 'Sectoral targets for developing countries: combining 'common but differentiated responsibilities' with 'meaningful participation''. CLIMATE POLICY	0.1208526

ID	Publication	Score
58	Edelenbosch et al. (2017) 'Decomposing passenger transport futures: Comparing results of global integrated assessment models'. TRANSPORTATION RESEARCH PART D-TRANSPORT AND ENVIRONMENT	0.1202181
59	Calvin et al. (2014) 'Trade-offs of different land and bioenergy policies on the path to achieving climate targets'. CLIMATIC CHANGE	0.1201080
60	Capros et al. (2014) 'Description of models and scenarios used to assess European decarbonisation pathways'. ENERGY STRATEGY REVIEWS	0.1168060
61	Bollen et al. (2009) 'Local air pollution and global climate change: A combined cost-benefit analysis'. RESOURCE AND ENERGY ECONOMICS	0.1159243
62	Bertram et al. (2015) 'Complementing carbon prices with technology policies to keep climate targets within reach'. NATURE CLIMATE CHANGE	0.1131793
63	van Sluisveld et al. (2015) 'Comparing future patterns of energy system change in 2 degrees C scenarios with historically observed rates of change'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.1125654
64	Capros et al. (2014) 'European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis'. ENERGY STRATEGY REVIEWS	0.1122235
65	Sano et al. (2014) 'Impacts of different diffusion scenarios for mitigation technology options and of model representations regarding renewables intermittency on evaluations of CO2 emissions reductions'. CLIMATIC CHANGE	0.1118397
66	Daioglou et al. (2017) 'Greenhouse gas emission curves for advanced biofuel supply chains'. NATURE CLIMATE CHANGE	0.1084972
67	Hof et al. (2008) 'Analysing the costs and benefits of climate policy: Value judgements and scientific uncertainties'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.1045918
68	Fujimori et al. (2017) 'SSP3: AIM implementation of Shared Socioeconomic Pathways'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.1041757
69	Hof et al. (2010) 'Including adaptation costs and climate change damages in evaluating post-2012 burden-sharing regimes'. MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE	0.1036878

ID	Publication	Score
70	De Cian et al. (2016) 'Alleviating inequality in climate policy costs: an integrated perspective on mitigation, damage and adaptation'. ENVIRONMENTAL RESEARCH LETTERS	0.1015732

Documents in topic 2: Carbon pricing & mitigation costs (SDG 8)

ID	Publication	Score
1	Mathy et al. (2010) 'Climate policies in a second-best world-A case study on India'. ENERGY POLICY	0.4405947
2	Crassous et al. (2006) 'Endogenous structural change and climate targets modeling experiments with Imaclim-R'. ENERGY JOURNAL	0.4348473
3	Bibas et al. (2015) 'Energy efficiency policies and the timing of action: An assessment of climate mitigation costs'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.3974935
4	Paroussos et al. (2015) 'Assessment of carbon leakage through the industry channel: The EU perspective'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.3704346
5	Waisrnan et al. (2013) 'Monetary compensations in climate policy through the lens of a general equilibrium assessment: The case of oil-exporting countries'. ENERGY POLICY	0.3655442
6	Hamdi-Cherif et al. (2016) 'Global carbon pricing and the "Common But Differentiated Responsibilities": the case of China'. INTERNATIONAL ENVIRONMENTAL AGREEMENTS-POLITICS LAW AND ECONOMICS	0.3428139
7	Burniaux et al. (2013) 'Is there a case for carbon-based border tax adjustment? An applied general equilibrium analysis'. APPLIED ECONOMICS	0.3327507
8	Capros et al. (2015) 'The impact of hydrocarbon resources and GDP growth assumptions for the evolution of the EU energy system for the medium and long term'. ENERGY STRATEGY REVIEWS	0.3300517
9	Guivarch et al. (2012) 'Energy-GDP decoupling in a second best world-a case study on India'. CLIMATIC CHANGE	0.3253113
10	Lanzi et al. (2012) 'Alternative approaches for levelling carbon prices in a world with fragmented carbon markets'. Energy Econ.	0.3113032
11	Waisman et al. (2013) 'The transportation sector and low-carbon growth pathways: modelling urban, infrastructure, and spatial determinants of mobility'. CLIMATE POLICY	0.3105310

ID	Publication	Score
12	Hamdi-Cherif et al. (2011) ‘Sectoral targets for developing countries: combining ‘common but differentiated responsibilities’ with ‘meaningful participation’’. CLIMATE POLICY	0.2978154
13	Burniaux et al. (2014) ‘Greenhouse gases mitigation potential and economic efficiency of phasing-out fossil fuel subsidies’. Int. Econ.	0.2889022
14	Bibas et al. (2014) ‘Potential and limitations of bioenergy for low carbon transitions’. CLIMATIC CHANGE	0.2800122
15	Li et al. (2017) ‘Aligning domestic policies with international coordination in a post-Paris global climate regime: A case for China’. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.2686288
16	Bertram et al. (2015) ‘Complementing carbon prices with technology policies to keep climate targets within reach’. NATURE CLIMATE CHANGE	0.2627275
17	Capros et al. (2012) ‘Model-based analysis of decarbonising the EU economy in the time horizon to 2050’. ENERGY STRATEGY REVIEWS	0.2589065
18	Waisman et al. (2012) ‘Peak Oil profiles through the lens of a general equilibrium assessment’. ENERGY POLICY	0.2567076
19	Carl et al. (2016) ‘Tracking global carbon revenues: A survey of carbon taxes versus cap-and-trade in the real world’. ENERGY POLICY	0.2530894
20	Magne et al. (2014) ‘Global implications of joint fossil fuel subsidy reform and nuclear phase-out: an economic analysis’. CLIMATIC CHANGE	0.2452982
21	Bosetti et al. (2006) ‘The dynamics of carbon and energy intensity in a model of endogenous technical change’. ENERGY JOURNAL	0.2349726
22	Guivarch et al. (2011) ‘The costs of climate policies in a second-best world with labour market imperfections’. CLIMATE POLICY	0.2248528
23	Luderer et al. (2012) ‘On the regional distribution of mitigation costs in a global cap-and-trade regime’. CLIMATIC CHANGE	0.2236133
24	Chateau et al. (2013) ‘Economic and employment impacts of climate change mitigation policies in OECD: A general-equilibrium perspective’. Int. Econ.	0.2186417
25	Capros et al. (2014) ‘Description of models and scenarios used to assess European decarbonisation pathways’. ENERGY STRATEGY REVIEWS	0.2150271
26	Chaturvedi et al. (2014) ‘Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework’. CLIMATIC CHANGE	0.2127949

ID	Publication	Score
27	Broin et al. (2017) ‘Transport infrastructure costs in low-carbon pathways’. TRANSPORTATION RESEARCH PART D-TRANSPORT AND ENVIRONMENT	0.2056825
28	Capros et al. (2014) ‘European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis’. ENERGY STRATEGY REVIEWS	0.1914303
29	Kypreos et al. (2012) ‘From the Copenhagen Accord to efficient technology protocols’. ENERGY POLICY	0.1912607
30	Daioglou et al. (2012) ‘Model projections for household energy use in developing countries’. ENERGY	0.1905705
31	Bauer et al. (2015) ‘CO2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies’. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1840887
32	Daenzer et al. (2014) ‘Coal’s medium-run future under atmospheric greenhouse gas stabilization’. CLIMATIC CHANGE	0.1837423
33	Ekholm et al. (2010) ‘Determinants of household energy consumption in India’. ENERGY POLICY	0.1751425
34	Hoogwijk et al. (2009) ‘Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials’. ENERGY POLICY	0.1721575
35	Luderer et al. (2012) ‘The economics of decarbonizing the energy system-results and insights from the RECIPE model intercomparison’. CLIMATIC CHANGE	0.1696032
36	Edelenbosch et al. (2017) ‘Decomposing passenger transport futures: Comparing results of global integrated assessment models’. TRANSPORTATION RESEARCH PART D-TRANSPORT AND ENVIRONMENT	0.1692523
37	Kriegler et al. (2015) ‘Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy’. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1613626
38	von Lampe et al. (2014) ‘Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison’. AGRICULTURAL ECONOMICS	0.1538101
39	Vrontisi et al. (2016) ‘Economic impacts of EU clean air policies assessed in a CGE framework’. Environ. Sci. Policy	0.1518457
40	Leimbach et al. (2010) ‘Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R’. ENVIRONMENTAL MODELING & ASSESSMENT	0.1434590

ID	Publication	Score
41	Cantore et al. (2012) 'Sustainability of the energy sector in the Mediterranean region'. ENERGY	0.1401166
42	McCollum et al. (2014) 'Fossil resource and energy security dynamics in conventional and carbon-constrained worlds'. CLIMATIC CHANGE	0.1364986
43	Steckel et al. (2013) 'Development without energy? Assessing future scenarios of energy consumption in developing countries'. ECOLOGICAL ECONOMICS	0.1354254
44	Bowen et al. (2017) 'An 'equal effort' approach to assessing the North-South climate finance gap'. CLIMATE POLICY	0.1301788
45	McJeon et al. (2014) 'Limited impact on decadal-scale climate change from increased use of natural gas'. NATURE	0.1281585
46	Borba et al. (2012) 'Energy-related climate change mitigation in Brazil: Potential, abatement costs and associated policies'. ENERGY POLICY	0.1280553
47	Santarius et al. (2016) 'Rethinking climate and energy policies: New perspectives on the rebound phenomenon'. Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenom.	0.1250676
48	Hughes et al. (2012) 'Exploring Future Impacts of Environmental Constraints on Human Development'. SUSTAINABILITY	0.1232876
49	Kindermann et al. (2006) 'Predicting the deforestation-trend under different carbon-prices'. Carbon Balance Manage.	0.1188469
50	Moyer et al. (2012) 'ICTs: Do they contribute to increased carbon emissions?'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1179919
51	Hughes et al. (2005) 'Sustainable futures: policies for global development'. FUTURES	0.1091828
52	Reilly et al. (2012) 'Using Land To Mitigate Climate Change: Hitting the Target, Recognizing the Trade-offs'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.1091183
53	Lucas et al. (2013) 'Implications of the international reduction pledges on long-term energy system changes and costs in China and India'. ENERGY POLICY	0.1087007
54	Griffin et al. (2014) 'White Knights: will wind and solar come to the rescue of a looming capacity gap from nuclear phase-out or slow CCS start-up?'. CLIMATIC CHANGE	0.1066694
55	Yamamoto et al. (2014) 'Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model'. CLIMATIC CHANGE	0.1030822

Documents in topic 3: Sustainable transitions & governance (SDG NA)

ID	Publication	Score
1	Turnheim et al. (2015) 'Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.5564391
2	Geels et al. (2016) 'Bridging analytical approaches for low-carbon transitions'. NATURE CLIMATE CHANGE	0.5096017
3	Geels et al. (2015) 'A critical appraisal of Sustainable Consumption and Production research: The reformist, revolutionary and reconfiguration positions'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.4894098
4	Geels et al. (2014) 'Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective'. THEORY CULTURE & SOCIETY	0.4046475
5	Hughes et al. (2005) 'Sustainable futures: policies for global development'. FUTURES	0.3933367
6	Geels et al. (2016) 'The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014)'. RESEARCH POLICY	0.3827498
7	Rao et al. (2013) 'Better air for better health: Forging synergies in policies for energy access, climate change and air pollution'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.3716125
8	Hughes (2016) 'International Futures (IFs) and integrated, long-term forecasting of global transformations'. FUTURES	0.3678859
9	Nilsson et al. (2016) 'Governing the electric vehicle transition - Near term interventions to support a green energy economy'. APPLIED ENERGY	0.3652304
10	Ghisellini et al. (2016) 'A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems'. JOURNAL OF CLEANER PRODUCTION	0.3408102
11	van Vuuren et al. (2016) 'Horses for courses: analytical tools to explore planetary boundaries'. EARTH SYSTEM DYNAMICS	0.3391810
12	Hughes et al. (2012) 'Exploring Future Impacts of Environmental Constraints on Human Development'. SUSTAINABILITY	0.3358350
13	Jackson et al. (2003) 'Sustainability and the 'struggle for existence': The critical role of metaphor in society's metabolism'. ENVIRONMENTAL VALUES	0.2947243

ID	Publication	Score
14	Lamb et al. (2015) 'Human development in a climate-constrained world: What the past says about the future'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.2558135
15	Santarius et al. (2016) 'Rethinking climate and energy policies: New perspectives on the rebound phenomenon'. Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenom.	0.2344260
16	Hellweg et al. (2014) 'Emerging approaches, challenges and opportunities in life cycle assessment'. Science	0.2323181
17	Hughes et al. (2015) 'Opportunities and challenges of a world with negligible senescence'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.2211384
18	van Vuuren et al. (2015) 'Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.2133839
19	Pachauri (2017) 'Energy access and living standards: Some observations on recent trends'. Environ.Res.Lett.	0.2108921
20	Ahmad et al. (2017) 'Synergies and trade-offs between energy-efficient urbanization and health'. ENVIRONMENTAL RESEARCH LETTERS	0.1925468
21	Lucas et al. (2014) 'Integrating Biodiversity and Ecosystem Services in the Post-2015 Development Agenda: Goal Structure, Target Areas and Means of Implementation'. SUSTAINABILITY	0.1916806
22	Cherp et al. (2017) 'Comparing electricity transitions: A historical analysis of nuclear, wind and solar power in Germany and Japan'. ENERGY POLICY	0.1842793
23	Haas et al. (2015) 'How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005'. JOURNAL OF INDUSTRIAL ECOLOGY	0.1842220
24	Steckel et al. (2013) 'Development without energy? Assessing future scenarios of energy consumption in developing countries'. ECOLOGICAL ECONOMICS	0.1768166
25	von Stechow et al. (2016) '2 degrees C and SDGs: united they stand, divided they fall?'. ENVIRONMENTAL RESEARCH LETTERS	0.1674856
26	Burt (2016) 'Poverty eradication in fragile places: Prospects for harvesting the highest hanging fruit by 2030'. Stability	0.1545848
27	Arvesen et al. (2018) 'Deriving life cycle assessment coefficients for application in integrated assessment modelling'. ENVIRONMENTAL MODELLING & SOFTWARE	0.1512093

ID	Publication	Score
28	Yillia (2016) 'Water-Energy-Food nexus: framing the opportunities, challenges and synergies for implementing the SDGs'. Osterr. Wasser-Abfallwirtsch.	0.1503194
29	Jakob et al. (2016) 'Implications of climate change mitigation for sustainable development'. ENVIRONMENTAL RESEARCH LETTERS	0.1486320
30	Li et al. (2017) 'Aligning domestic policies with international coordination in a post-Paris global climate regime: A case for China'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1463299
31	Fuss et al. (2016) 'Research priorities for negative emissions'. ENVIRONMENTAL RESEARCH LETTERS	0.1446292
32	Gibon et al. (2015) 'A Methodology for Integrated, Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological Change'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.1323999
33	Birkmann et al. (2015) 'Scenarios for vulnerability: opportunities and constraints in the context of climate change and disaster risk'. CLIMATIC CHANGE	0.1320633
34	van Vuuren et al. (2013) 'If climate action becomes urgent: the importance of response times for various climate strategies'. CLIMATIC CHANGE	0.1301913
35	Singh et al. (2015) 'Material use for electricity generation with carbon dioxide capture and storage: Extending life cycle analysis indices for material accounting'. RESOURCES CONSERVATION AND RECYCLING	0.1283562
36	Amann et al. (2011) 'Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications'. ENVIRONMENTAL MODELLING & SOFTWARE	0.1278094
37	van Ruijven et al. (2011) 'Model projections for household energy use in India'. ENERGY POLICY	0.1218459
38	Guo et al. (2017) 'China's Green Lights Program: A review and assessment'. ENERGY POLICY	0.1204312
39	van Sluisveld et al. (2016) 'Exploring the implications of lifestyle change in 2 degrees C mitigation scenarios using the IMAGE integrated assessment model'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1128009
40	Bowen et al. (2017) 'An 'equal effort' approach to assessing the North-South climate finance gap'. CLIMATE POLICY	0.1103923
41	Bauer et al. (2015) 'CO2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1067401

ID	Publication	Score
42	Hanson et al. (2011) 'A global ranking of port cities with high exposure to climate extremes'. CLIMATIC CHANGE	0.1058413
43	Tavoni et al. (2012) 'The value of technology and of its evolution towards a low carbon economy'. CLIMATIC CHANGE	0.1009479
44	Phillips et al. (2006) 'Maximum entropy modeling of species geographic distributions'. ECOLOGICAL MODELLING	0.1005184

Documents in topic 4: Food security (SDG 2)

ID	Publication	Score
1	Biewald et al. (2015) 'The impact of climate change on costs of food and people exposed to hunger at subnational scale'. PIK Rep.	0.4656063
2	P et al. (1994) 'Potential impact of climate change on world food supply'.	0.4620741
3	Parry et al. (2004) 'Effects of climate change on global food production under SRES emissions and socio-economic scenarios'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.4285703
4	Mosnier et al. (2014) 'Global food markets, trade and the cost of climate change adaptation'. FOOD SECURITY	0.4285380
5	van Vuuren et al. (2017) 'A physically-based model of long-term food demand'. Global Environ. Change	0.3835643
6	Hasegawa et al. (2015) 'Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways'. ENVIRONMENTAL RESEARCH LETTERS	0.3766204
7	Hasegawa et al. (2015) 'Consequence of Climate Mitigation on the Risk of Hunger'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.3744581
8	Bodirsky et al. (2015) 'Global Food Demand Scenarios for the 21st Century'. PLOS ONE	0.3627900
9	Valin et al. (2014) 'The future of food demand: understanding differences in global economic models'. AGRICULTURAL ECONOMICS	0.3536469
10	Springmann et al. (2017) 'Mitigation potential and global health impacts from emissions pricing of food commodities'. NATURE CLIMATE CHANGE	0.3102451
11	Valin et al. (2013) 'Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security?'. ENVIRONMENTAL RESEARCH LETTERS	0.3027308
12	Nelson et al. (2014) 'Agriculture and climate change in global scenarios: why don't the models agree'. AGRICULTURAL ECONOMICS	0.2829471

ID	Publication	Score
13	von Lampe et al. (2014) 'Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison'. AGRICULTURAL ECONOMICS	0.2743959
14	Stevanovic et al. (2017) 'Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.2573604
15	Hasegawa et al. (2016) 'Economic implications of climate change impacts on human health through undernourishment'. CLIMATIC CHANGE	0.2526486
16	Alcamo et al. (2003) 'Development and testing of the WaterGAP 2 global model of water use and availability'. HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	0.2221348
17	Hayashi et al. (2015) 'Evaluation of global energy crop production potential up to 2100 under socioeconomic development and climate change scenarios'. Nihon Enerugi Gakkaishi	0.2221048
18	Frank et al. (2017) 'Reducing greenhouse gas emissions in agriculture without compromising food security?'. ENVIRONMENTAL RESEARCH LETTERS	0.2202126
19	Wiebe et al. (2015) 'Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios'. ENVIRONMENTAL RESEARCH LETTERS	0.2134203
20	van Vuuren et al. (2015) 'Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.2122283
21	Lotze-Campen et al. (2010) 'Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade'. ECOLOGICAL MODELLING	0.2047928
22	Damerau et al. (2016) 'Water saving potentials and possible trade-offs for future food and energy supply'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.2012745
23	Leclere et al. (2014) 'Climate change induced transformations of agricultural systems: insights from a global model'. ENVIRONMENTAL RESEARCH LETTERS	0.1840194
24	Schmitz et al. (2012) 'Trading more food: Implications for land use, greenhouse gas emissions, and the food system'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.1801767
25	Hughes et al. (2012) 'Exploring Future Impacts of Environmental Constraints on Human Development'. SUSTAINABILITY	0.1782667

ID	Publication	Score
26	Tabeau et al. (2017) 'REDD policy impacts on the agri-food sector and food security'. FOOD POLICY	0.1737080
27	Ishida et al. (2014) 'Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research'. ENVIRONMENTAL RESEARCH LETTERS	0.1664788
28	Gerbens-Leenes et al. (2009) 'The water footprint of bioenergy'. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	0.1621415
29	Stehfest et al. (2009) 'Climate benefits of changing diet'. CLIMATIC CHANGE	0.1483620
30	Daioglou et al. (2016) 'Projections of the availability and cost of residues from agriculture and forestry'. GLOBAL CHANGE BIOLOGY BIOENERGY	0.1459341
31	Riahi et al. (2007) 'Scenarios of long-term socio-economic and environmental development under climate stabilization'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1379745
32	Birkmann et al. (2015) 'Scenarios for vulnerability: opportunities and constraints in the context of climate change and disaster risk'. CLIMATIC CHANGE	0.1227872
33	Hughes et al. (2015) 'Opportunities and challenges of a world with negligible senescence'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1196964
34	Lotze-Campen et al. (2014) 'Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison'. AGRICULTURAL ECONOMICS	0.1165438
35	Hughes (2016) 'International Futures (IFs) and integrated, long-term forecasting of global transformations'. FUTURES	0.1164910
36	Hayashi et al. (2013) 'Global evaluation of the effects of agriculture and water management adaptations on the water-stressed population'. MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE	0.1090062
37	Burt (2016) 'Poverty eradication in fragile places: Prospects for harvesting the highest hanging fruit by 2030'. Stability	0.1063223
38	Chateau et al. (2013) 'Economic and employment impacts of climate change mitigation policies in OECD: A general-equilibrium perspective'. Int. Econ.	0.1022872
39	Jakob et al. (2016) 'Implications of climate change mitigation for sustainable development'. ENVIRONMENTAL RESEARCH LETTERS	0.1015544

ID	Publication	Score
40	Steckel et al. (2013) 'Development without energy? Assessing future scenarios of energy consumption in developing countries'. ECOLOGICAL ECONOMICS	0.1002793
41	Shindell et al. (2012) 'Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security'. SCIENCE	0.1000939

Documents in topic 5: Land-based mitigation (SDG 13)

ID	Publication	Score
1	Popp et al. (2011) 'The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system'. ENVIRONMENTAL RESEARCH LETTERS	0.4431075
2	Popp et al. (2014) 'Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options'. CLIMATIC CHANGE	0.4311718
3	Calvin et al. (2014) 'Trade-offs of different land and bioenergy policies on the path to achieving climate targets'. CLIMATIC CHANGE	0.4124053
4	Havlik et al. (2011) 'Global land-use implications of first and second generation biofuel targets'. ENERGY POLICY	0.3954961
5	Lotze-Campen et al. (2014) 'Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison'. AGRICULTURAL ECONOMICS	0.3829029
6	Eitelberg et al. (2016) 'Demand for biodiversity protection and carbon storage as drivers of global land change scenarios'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.3695548
7	Reilly et al. (2012) 'Using Land To Mitigate Climate Change: Hitting the Target, Recognizing the Trade-offs'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.3692755
8	Hasegawa et al. (2017) 'Global land-use allocation model linked to an integrated assessment model'. SCIENCE OF THE TOTAL ENVIRONMENT	0.3577156
9	Wise et al. (2014) 'Agriculture, land use, energy and carbon emission impacts of global biofuel mandates to mid-century'. APPLIED ENERGY	0.3554279
10	Popp et al. (2014) 'Land-use protection for climate change mitigation'. NATURE CLIMATE CHANGE	0.3511397
11	Wise et al. (2009) 'Implications of Limiting CO2 Concentrations for Land Use and Energy'. SCIENCE	0.3500405

ID	Publication	Score
12	Bonsch et al. (2016) 'Trade-offs between land and water requirements for large-scale bioenergy production'. GLOBAL CHANGE BIOLOGY BIOENERGY	0.3434707
13	Lotze-Campen et al. (2010) 'Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade'. ECOLOGICAL MODELLING	0.3377545
14	Daioglou et al. (2017) 'Greenhouse gas emission curves for advanced biofuel supply chains'. NATURE CLIMATE CHANGE	0.3224073
15	Hayashi et al. (2015) 'Evaluation of global energy crop production potential up to 2100 under socioeconomic development and climate change scenarios'. Nihon Enerugi Gakkaishi	0.2770343
16	Fujimori et al. (2014) 'Land use representation in a global CGE model for long-term simulation: CET vs. logit functions'. FOOD SECURITY	0.2717081
17	Humpenoder et al. (2014) 'Investigating afforestation and bioenergy CCS as climate change mitigation strategies'. ENVIRONMENTAL RESEARCH LETTERS	0.2707945
18	Tabeau et al. (2017) 'REDD policy impacts on the agri-food sector and food security'. FOOD POLICY	0.2565668
19	Kindermann et al. (2006) 'Predicting the deforestation-trend under different carbon-prices'. Carbon Balance Manage.	0.2375376
20	Rose et al. (2014) 'Bioenergy in energy transformation and climate management'. CLIMATIC CHANGE	0.2161143
21	Hasegawa et al. (2016) 'Land-Based Mitigation Strategies under the Mid-Term Carbon Reduction Targets in Indonesia'. SUSTAINABILITY	0.2015333
22	Valin et al. (2013) 'Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security?'. ENVIRONMENTAL RESEARCH LETTERS	0.1874671
23	Bonsch et al. (2015) 'Environmental flow provision: Implications for agricultural water and land-use at the global scale'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.1822769
24	Klein et al. (2014) 'The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE'. CLIMATIC CHANGE	0.1762648
25	Stehfest et al. (2009) 'Climate benefits of changing diet'. CLIMATIC CHANGE	0.1707641
26	Fuss et al. (2016) 'Research priorities for negative emissions'. ENVIRONMENTAL RESEARCH LETTERS	0.1457773
27	Schmitz et al. (2012) 'Trading more food: Implications for land use, greenhouse gas emissions, and the food system'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.1430192

ID	Publication	Score
28	Daioglou et al. (2016) 'Projections of the availability and cost of residues from agriculture and forestry'. GLOBAL CHANGE BIOLOGY BIOENERGY	0.1429421
29	Gerbens-Leenes et al. (2009) 'The water footprint of bioenergy'. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	0.1391066
30	Sands et al. (2014) 'Bio-electricity and land use in the Future Agricultural Resources Model (FARM)'. CLIMATIC CHANGE	0.1380834
31	Fujimori et al. (2016) 'Implication of Paris Agreement in the context of long-term climate mitigation goals'. SPRINGERPLUS	0.1347261
32	von Lampe et al. (2014) 'Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison'. AGRICULTURAL ECONOMICS	0.1302866
33	Leclere et al. (2014) 'Climate change induced transformations of agricultural systems: insights from a global model'. ENVIRONMENTAL RESEARCH LETTERS	0.1295455
34	Portugal-Pereira et al. (2015) 'Agricultural and agro-industrial residues-to-energy: Techno-economic and environmental assessment in Brazil'. BIOMASS & BIOENERGY	0.1294621
35	Mosnier et al. (2014) 'Modeling Impact of Development Trajectories and a Global Agreement on Reducing Emissions from Deforestation on Congo Basin Forests by 2030'. Environ. Resour. Econ.	0.1287953
36	Hasegawa et al. (2015) 'Consequence of Climate Mitigation on the Risk of Hunger'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.1284174
37	Stevanovic et al. (2017) 'Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.1126131

Documents in topic 6: Low carbon electricity (SDG 7)

ID	Publication	Score
1	Portugal-Pereira et al. (2016) 'Overlooked impacts of electricity expansion optimisation modelling: The life cycle side of the story'. ENERGY	0.5171628
2	Malagueta et al. (2013) 'Assessing incentive policies for integrating centralized solar power generation in the Brazilian electric power system'. ENERGY POLICY	0.5122155
3	Nogueira et al. (2014) 'Will thermal power plants with CCS play a role in Brazil's future electric power generation?'. INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL	0.5055793

ID	Publication	Score
4	Soria et al. (2015) ‘Hybrid concentrated solar power (CSP)-biomass plants in a semiarid region: A strategy for CSP deployment in Brazil’. ENERGY POLICY	0.4351786
5	Rochedo et al. (2016) ‘Carbon capture potential and costs in Brazil’. JOURNAL OF CLEANER PRODUCTION	0.4321089
6	Santos et al. (2017) ‘Scenarios for the future Brazilian power sector based on a multi criteria assessment’. JOURNAL OF CLEANER PRODUCTION	0.3849993
7	Lucena et al. (2016) ‘Climate policy scenarios in Brazil: A multi-model comparison for energy’. ENERGY ECONOMICS	0.3750867
8	Dale et al. (2013) ‘Modeling Future Life-Cycle Greenhouse Gas Emissions and Environmental Impacts of Electricity Supplies in Brazil’. ENERGIES	0.3549591
9	de Oliveira et al. (2016) ‘Critical technologies for sustainable energy development in Brazil: technological foresight based on scenario modelling’. JOURNAL OF CLEANER PRODUCTION	0.3449511
10	Portugal-Pereira et al. (2015) ‘Agricultural and agro-industrial residues-to-energy: Techno-economic and environmental assessment in Brazil’. BIOMASS & BIOENERGY	0.3422431
11	Singh et al. (2015) ‘Material use for electricity generation with carbon dioxide capture and storage: Extending life cycle analysis indices for material accounting’. RESOURCES CONSERVATION AND RECYCLING	0.3113814
12	Martinez et al. (2015) ‘Possible energy futures for Brazil and Latin America in conservative and stringent mitigation pathways up to 2050’. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.2952260
13	Gibon et al. (2015) ‘A Methodology for Integrated, Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological Change’. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.2795081
14	Arvesen et al. (2018) ‘Deriving life cycle assessment coefficients for application in integrated assessment modelling’. ENVIRONMENTAL MODELLING & SOFTWARE	0.2706650
15	Borba et al. (2012) ‘Energy-related climate change mitigation in Brazil: Potential, abatement costs and associated policies’. ENERGY POLICY	0.2589839
16	Zhang et al. (2014) ‘Water-Carbon Trade-off in China’s Coal Power Industry’. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.2383425
17	Meldrum et al. (2013) ‘Life cycle water use for electricity generation: a review and harmonization of literature estimates’. ENVIRONMENTAL RESEARCH LETTERS	0.2380425

ID	Publication	Score
18	Zhai et al. (2016) 'A Techno-Economic Assessment of Hybrid Cooling Systems for Coal and Natural-Gas-Fired Power Plants with and without Carbon Capture and Storage'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.2174338
19	Branco et al. (2011) 'Abatement costs of CO2 emissions in the Brazilian oil refining sector'. APPLIED ENERGY	0.1868907
20	Hoogwijk et al. (2007) 'Exploring the impact on cost and electricity production of high penetration levels of intermittent electricity in OECD Europe and the USA, results for wind energy'. Energy	0.1787418
21	Hellweg et al. (2014) 'Emerging approaches, challenges and opportunities in life cycle assessment'. Science	0.1762881
22	Sano et al. (2014) 'Impacts of different diffusion scenarios for mitigation technology options and of model representations regarding renewables intermittency on evaluations of CO2 emissions reductions'. CLIMATIC CHANGE	0.1424602
23	Davies et al. (2013) 'An integrated assessment of global and regional water demands for electricity generation to 2095'. ADVANCES IN WATER RESOURCES	0.1218942
24	McJeon et al. (2014) 'Limited impact on decadal-scale climate change from increased use of natural gas'. NATURE	0.1025174

Documents in topic 7: CCS, bioenergy & negative emissions (SDG 13)

ID	Publication	Score
1	Krey et al. (2014) 'Getting from here to there - energy technology transformation pathways in the EMF27 scenarios'. CLIMATIC CHANGE	0.5002369
2	Klein et al. (2014) 'The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE'. CLIMATIC CHANGE	0.4836734
3	McCollum et al. (2014) 'Transport electrification: A key element for energy system transformation and climate stabilization'. CLIMATIC CHANGE	0.4569658
4	Luderer et al. (2014) 'The role of renewable energy in climate stabilization: results from the EMF27 scenarios'. CLIMATIC CHANGE	0.4465020
5	Sugiyama et al. (2014) 'Energy efficiency potentials for global climate change mitigation'. CLIMATIC CHANGE	0.4167113
6	Rose et al. (2014) 'Bioenergy in energy transformation and climate management'. CLIMATIC CHANGE	0.3687987

ID	Publication	Score
7	Koelbl et al. (2014) ‘Uncertainty in Carbon Capture and Storage (CCS) deployment projections: a cross-model comparison exercise’. CLIMATIC CHANGE	0.3312319
8	McCollum et al. (2014) ‘Fossil resource and energy security dynamics in conventional and carbon-constrained worlds’. CLIMATIC CHANGE	0.2892547
9	Kanudia et al. (2014) ‘Effectiveness and efficiency of climate change mitigation in a technologically uncertain World’. CLIMATIC CHANGE	0.2818877
10	Popp et al. (2014) ‘Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options’. CLIMATIC CHANGE	0.2408785
11	Daenzer et al. (2014) ‘Coal’s medium-run future under atmospheric greenhouse gas stabilization’. CLIMATIC CHANGE	0.2288926
12	Yamamoto et al. (2014) ‘Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model’. CLIMATIC CHANGE	0.2269561
13	Bibas et al. (2014) ‘Potential and limitations of bioenergy for low carbon transitions’. CLIMATIC CHANGE	0.2266757
14	Kriegler et al. (2014) ‘The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies’. CLIMATIC CHANGE	0.2210923
15	van Vliet et al. (2014) ‘The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets’. CLIMATIC CHANGE	0.2143044
16	Tavoni et al. (2015) ‘Post-2020 climate agreements in the major economies assessed in the light of global models’. NATURE CLIMATE CHANGE	0.1875763
17	Chaturvedi et al. (2014) ‘Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework’. CLIMATIC CHANGE	0.1816857
18	Blanford et al. (2014) ‘Trade-offs between mitigation costs and temperature change’. CLIMATIC CHANGE	0.1779285
19	Sands et al. (2014) ‘Bio-electricity and land use in the Future Agricultural Resources Model (FARM)’. CLIMATIC CHANGE	0.1778104
20	Akashi et al. (2014) ‘Halving global GHG emissions by 2050 without depending on nuclear and CCS’. CLIMATIC CHANGE	0.1773236
21	Humpenoder et al. (2014) ‘Investigating afforestation and bioenergy CCS as climate change mitigation strategies’. ENVIRONMENTAL RESEARCH LETTERS	0.1718216

ID	Publication	Score
22	Riahi et al. (2007) 'Scenarios of long-term socio-economic and environmental development under climate stabilization'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1698435
23	Luderer et al. (2012) 'The economics of decarbonizing the energy system-results and insights from the RECIPE model intercomparison'. CLIMATIC CHANGE	0.1563028
24	Zhu et al. (2014) 'Temperature control, emission abatement and costs: key EMF 27 results from Environment Canada's Integrated Assessment Model'. CLIMATIC CHANGE	0.1437212
25	Popp et al. (2011) 'The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system'. ENVIRONMENTAL RESEARCH LETTERS	0.1312938
26	von Stechow et al. (2016) '2 degrees C and SDGs: united they stand, divided they fall?'. ENVIRONMENTAL RESEARCH LETTERS	0.1292042
27	Riahi 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	0.1203087
28	Luderer et al. (2013) 'Economic mitigation challenges: how further delay closes the door for achieving climate targets'. ENVIRONMENTAL RESEARCH LETTERS	0.1110650
29	Edelenbosch et al. (2017) 'Decomposing passenger transport futures: Comparing results of global integrated assessment models'. TRANSPORTATION RESEARCH PART D-TRANSPORT AND ENVIRONMENT	0.1076258
30	Fuss et al. (2016) 'Research priorities for negative emissions'. ENVIRONMENTAL RESEARCH LETTERS	0.1042773

Documents in topic 8: Air pollution & health (SDG 3)

ID	Publication	Score
1	Chuwah et al. (2013) 'Implications of alternative assumptions regarding future air pollution control in scenarios similar to the Representative Concentration Pathways'. ATMOSPHERIC ENVIRONMENT	0.5611604
2	Strefler et al. (2014) 'Can air pollutant controls change global warming?'. ENVIRONMENTAL SCIENCE & POLICY	0.5391149
3	Radu et al. (2016) 'Exploring synergies between climate and air quality policies using long-term global and regional emission scenarios'. ATMOSPHERIC ENVIRONMENT	0.4835880

ID	Publication	Score
4	Stohl et al. (2015) 'Evaluating the climate and air quality impacts of short-lived pollutants'. ATMOSPHERIC CHEMISTRY AND PHYSICS	0.4083110
5	Amann et al. (2011) 'Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications'. ENVIRONMENTAL MODELLING & SOFTWARE	0.4054063
6	McCollum et al. (2013) 'Climate policies can help resolve energy security and air pollution challenges'. CLIMATIC CHANGE	0.3833652
7	West et al. (2013) 'Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health'. NATURE CLIMATE CHANGE	0.3761201
8	Rafaj et al. (2013) 'Scenarios of global mercury emissions from anthropogenic sources'. ATMOSPHERIC ENVIRONMENT	0.3527291
9	Rao et al. (2017) 'Future air pollution in the Shared Socio-economic Pathways'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.3488007
10	Rafaj et al. (2013) 'Co-benefits of post-2012 global climate mitigation policies'. MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE	0.3356511
11	Rose et al. (2014) 'Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios'. CLIMATIC CHANGE	0.3148361
12	Shindell et al. (2012) 'Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security'. SCIENCE	0.3082939
13	Anenberg et al. (2012) 'Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls'. ENVIRONMENTAL HEALTH PERSPECTIVES	0.3025139
14	Vrontisi et al. (2016) 'Economic impacts of EU clean air policies assessed in a CGE framework'. Environ. Sci. Policy	0.2969364
15	Smith et al. (2013) 'Near-term climate mitigation by short-lived forcers'. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	0.2928804
16	Bollen et al. (2010) 'An integrated assessment of climate change, air pollution, and energy security policy'. ENERGY POLICY	0.2769447
17	Bollen et al. (2009) 'Local air pollution and global climate change: A combined cost-benefit analysis'. RESOURCE AND ENERGY ECONOMICS	0.2728078
18	Rogelj et al. (2014) 'Disentangling the effects of CO2 and short-lived climate forcer mitigation'. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	0.2612534

ID	Publication	Score
19	Bond et al. (2013) 'Bounding the role of black carbon in the climate system: A scientific assessment'. JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES	0.2500265
20	Rafaj et al. (2014) 'Changes in European greenhouse gas and air pollutant emissions 1960-2010: decomposition of determining factors'. CLIMATIC CHANGE	0.2436920
21	Meinshausen et al. (2011) 'Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6-Part 1: Model description and calibration'. ATMOSPHERIC CHEMISTRY AND PHYSICS	0.1403295
22	van Vuuren et al. (2015) 'Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1045529

Documents in topic 9: Low carbon electricity II (SDG 7)

ID	Publication	Score
1	Kim et al. (2014) 'Nuclear energy response in the EMF27 study'. CLIMATIC CHANGE	0.5202701
2	De Cian et al. (2014) 'Innovation benefits from nuclear phase-out: can they compensate the costs?'. CLIMATIC CHANGE	0.4748660
3	Griffin et al. (2014) 'White Knights: will wind and solar come to the rescue of a looming capacity gap from nuclear phase-out or slow CCS start-up?'. CLIMATIC CHANGE	0.4725525
4	Cherp et al. (2017) 'Comparing electricity transitions: A historical analysis of nuclear, wind and solar power in Germany and Japan'. ENERGY POLICY	0.3586312
5	Sano et al. (2014) 'Impacts of different diffusion scenarios for mitigation technology options and of model representations regarding renewables intermittency on evaluations of CO2 emissions reductions'. CLIMATIC CHANGE	0.3585430
6	Tavoni et al. (2015) 'Post-2020 climate agreements in the major economies assessed in the light of global models'. NATURE CLIMATE CHANGE	0.3466234
7	Kanudia et al. (2014) 'Effectiveness and efficiency of climate change mitigation in a technologically uncertain World'. CLIMATIC CHANGE	0.2919508
8	Zhou (2017) 'How much can nuclear energy do about global warming?'. Int J Global Energy Issues	0.2908003

ID	Publication	Score
9	Magne et al. (2014) ‘Global implications of joint fossil fuel subsidy reform and nuclear phase-out: an economic analysis’. CLIMATIC CHANGE	0.2733186
10	Marcucci et al. (2015) ‘Induced technological change in moderate and fragmented climate change mitigation regimes’. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.2546431
11	Hoogwijk et al. (2007) ‘Exploring the impact on cost and electricity production of high penetration levels of intermittent electricity in OECD Europe and the USA, results for wind energy’. Energy	0.2452609
12	Akashi et al. (2014) ‘Halving global GHG emissions by 2050 without depending on nuclear and CCS’. CLIMATIC CHANGE	0.2126858
13	Capros et al. (2014) ‘Description of models and scenarios used to assess European decarbonisation pathways’. ENERGY STRATEGY REVIEWS	0.2097127
14	Geels et al. (2016) ‘The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014)’. RESEARCH POLICY	0.2095384
15	Bosetti et al. (2006) ‘The dynamics of carbon and energy intensity in a model of endogenous technical change’. ENERGY JOURNAL	0.2060541
16	Capros et al. (2014) ‘European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis’. ENERGY STRATEGY REVIEWS	0.2010219
17	Luderer et al. (2014) ‘The role of renewable energy in climate stabilization: results from the EMF27 scenarios’. CLIMATIC CHANGE	0.1590026
18	Luderer et al. (2012) ‘The economics of decarbonizing the energy system-results and insights from the RECIPE model intercomparison’. CLIMATIC CHANGE	0.1547745
19	Kypreos et al. (2012) ‘From the Copenhagen Accord to efficient technology protocols’. ENERGY POLICY	0.1520220
20	Geels et al. (2014) ‘Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective’. THEORY CULTURE & SOCIETY	0.1451084
21	Bertram et al. (2015) ‘Complementing carbon prices with technology policies to keep climate targets within reach’. NATURE CLIMATE CHANGE	0.1387278
22	Yamamoto et al. (2014) ‘Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model’. CLIMATIC CHANGE	0.1314907

ID	Publication	Score
23	Capros et al. (2012) 'Model-based analysis of decarbonising the EU economy in the time horizon to 2050'. ENERGY STRATEGY REVIEWS	0.1273037
24	de Oliveira et al. (2016) 'Critical technologies for sustainable energy development in Brazil: technological foresight based on scenario modelling'. JOURNAL OF CLEANER PRODUCTION	0.1230871
25	van Vliet et al. (2014) 'The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets'. CLIMATIC CHANGE	0.1225878
26	Jakob et al. (2016) 'Implications of climate change mitigation for sustainable development'. ENVIRONMENTAL RESEARCH LETTERS	0.1181353
27	Jiang et al. (2013) 'China's role in attaining the global 2 degrees C target'. CLIMATE POLICY	0.1171955
28	Zhu et al. (2014) 'Temperature control, emission abatement and costs: key EMF 27 results from Environment Canada's Integrated Assessment Model'. CLIMATIC CHANGE	0.1078560
29	Santos et al. (2017) 'Scenarios for the future Brazilian power sector based on a multi criteria assessment'. JOURNAL OF CLEANER PRODUCTION	0.1059763
30	van Sluisveld et al. (2016) 'Exploring the implications of lifestyle change in 2 degrees C mitigation scenarios using the IMAGE integrated assessment model'. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	0.1048921

Documents in topic 10: Water availability and consumption (SDG 6)

ID	Publication	Score
1	Hayashi et al. (2013) 'Global evaluation of the effects of agriculture and water management adaptations on the water-stressed population'. MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE	0.4514460
2	Davies et al. (2013) 'An integrated assessment of global and regional water demands for electricity generation to 2095'. ADVANCES IN WATER RESOURCES	0.4385592
3	Hanasaki et al. (2013) 'A global water scarcity assessment under Shared Socio-economic Pathways - Part 2: Water availability and scarcity'. HYDROLOGY AND EARTH SYSTEM SCIENCES	0.4339684
4	Bijl et al. (2016) 'Long-term water demand for electricity, industry and households'. ENVIRONMENTAL SCIENCE & POLICY	0.4262101
5	Hanasaki et al. (2013) 'A global water scarcity assessment under Shared Socio-economic Pathways - Part 1: Water use'. HYDROLOGY AND EARTH SYSTEM SCIENCES	0.4190915

ID	Publication	Score
6	Alkemade et al. (2009) 'GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss'. ECOSYSTEMS	0.4068892
7	Fricko et al. (2016) 'Energy sector water use implications of a 2 degrees C climate policy'. ENVIRONMENTAL RESEARCH LETTERS	0.3994892
8	Yillia (2016) 'Water-Energy-Food nexus: framing the opportunities, challenges and synergies for implementing the SDGs'. Osterr. Wasser-Abfallwirtsch.	0.3871625
9	Sauer et al. (2010) 'Agriculture and resource availability in a changing world: The role of irrigation'. WATER RESOURCES RESEARCH	0.3764374
10	Jagermeyr et al. (2017) 'Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation'. NATURE COMMUNICATIONS	0.3699617
11	Bonsch et al. (2015) 'Environmental flow provision: Implications for agricultural water and land-use at the global scale'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.3667905
12	Damerau et al. (2016) 'Water saving potentials and possible trade-offs for future food and energy supply'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.3643950
13	Gerbens-Leenes et al. (2012) 'Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.3604839
14	Berger et al. (2015) 'Saving the Planet's Climate or Water Resources? The Trade-Off between Carbon and Water Footprints of European Biofuels'. SUSTAINABILITY	0.3482606
15	Arnell et al. (2011) 'The implications of climate policy for the impacts of climate change on global water resources'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.3255147
16	Meldrum et al. (2013) 'Life cycle water use for electricity generation: a review and harmonization of literature estimates'. ENVIRONMENTAL RESEARCH LETTERS	0.2938887
17	Hejazi et al. (2014) 'Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies'. HYDROLOGY AND EARTH SYSTEM SCIENCES	0.2907180
18	Fujimori et al. (2017) 'Projections of industrial water withdrawal under shared socioeconomic pathways and climate mitigation scenarios'. SUSTAINABILITY SCIENCE	0.2671130
19	Bonsch et al. (2016) 'Trade-offs between land and water requirements for large-scale bioenergy production'. GLOBAL CHANGE BIOLOGY BIOENERGY	0.2608083

ID	Publication	Score
20	Gerbens-Leenes et al. (2009) 'The water footprint of bioenergy'. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	0.2048137
21	Zhai et al. (2016) 'A Techno-Economic Assessment of Hybrid Cooling Systems for Coal and Natural-Gas-Fired Power Plants with and without Carbon Capture and Storage'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.1664470
22	Zhang et al. (2014) 'Water-Carbon Trade-off in China's Coal Power Industry'. ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.1417723
23	Janse et al. (2015) 'GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems'. ENVIRONMENTAL SCIENCE & POLICY	0.1262699
24	Lotze-Campen et al. (2010) 'Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade'. ECOLOGICAL MODELLING	0.1173901
25	Havlik et al. (2011) 'Global land-use implications of first and second generation biofuel targets'. ENERGY POLICY	0.1049804

Documents in topic 11: Energy security (SDG NA)

ID	Publication	Score
1	Jewell et al. (2014) 'Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices'. ENERGY POLICY	0.6045764
2	Kruyt et al. (2009) 'Indicators for energy security'. ENERGY POLICY	0.5280928
3	Cherp et al. (2014) 'The concept of energy security: Beyond the four As'. ENERGY POLICY	0.5118264
4	Cherp (2012) 'Defining energy security takes more than asking around'. ENERGY POLICY	0.4986060
5	Guivarch et al. (2016) 'Identifying the main uncertainty drivers of energy security in a low-carbon world: The case of Europe'. Energy Econ.	0.4369640
6	Oda et al. (2013) 'Analysis of CCS impact on Asian energy security'. Energy Procedia	0.4096086
7	Cherp et al. (2016) 'Global energy security under different climate policies, GDP growth rates and fossil resource availabilities'. CLIMATIC CHANGE	0.3512952
8	McCollum et al. (2014) 'Fossil resource and energy security dynamics in conventional and carbon-constrained worlds'. CLIMATIC CHANGE	0.2818927

ID	Publication	Score
9	Bollen et al. (2010) ‘An integrated assessment of climate change, air pollution, and energy security policy’. ENERGY POLICY	0.2813050
10	Waisman et al. (2012) ‘Peak Oil profiles through the lens of a general equilibrium assessment’. ENERGY POLICY	0.2324932
11	McCollum et al. (2013) ‘Climate policies can help resolve energy security and air pollution challenges’. CLIMATIC CHANGE	0.2225659
12	Alcamo et al. (2003) ‘Development and testing of the WaterGAP 2 global model of water use and availability’. HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	0.1750475
13	Jakob et al. (2016) ‘Implications of climate change mitigation for sustainable development’. ENVIRONMENTAL RESEARCH LETTERS	0.1662555
14	Birkmann et al. (2015) ‘Scenarios for vulnerability: opportunities and constraints in the context of climate change and disaster risk’. CLIMATIC CHANGE	0.1520324
15	von Stechow et al. (2016) ‘2 degrees C and SDGs: united they stand, divided they fall?’. ENVIRONMENTAL RESEARCH LETTERS	0.1236397
16	Waisrnan et al. (2013) ‘Monetary compensations in climate policy through the lens of a general equilibrium assessment: The case of oil-exporting countries’. ENERGY POLICY	0.1066683

Documents in topic 12: SSP scenario framework (SDG NA)

ID	Publication	Score
1	Fricko et al. (2017) ‘The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century’. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.5617178
2	Fujimori et al. (2017) ‘SSP3: AIM implementation of Shared Socioeconomic Pathways’. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.5376365
3	Kriegler et al. (2017) ‘Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century’. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.5311751
4	Bauer et al. (2017) ‘Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives’. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.5219394
5	van Vuuren et al. (2017) ‘Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm’. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.5041266

ID	Publication	Score
6	Rao et al. (2017) 'Future air pollution in the Shared Socio-economic Pathways'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.4124012
7	Wiebe et al. (2015) 'Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios'. ENVIRONMENTAL RESEARCH LETTERS	0.4076703
8	Fujimori et al. (2017) 'Projections of industrial water withdrawal under shared socioeconomic pathways and climate mitigation scenarios'. SUSTAINABILITY SCIENCE	0.3982459
9	Rozenberg et al. (2014) 'Building SSPs for climate policy analysis: a scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation'. CLIMATIC CHANGE	0.3513657
10	Hanasaki et al. (2013) 'A global water scarcity assessment under Shared Socio-economic Pathways - Part 1: Water use'. HYDROLOGY AND EARTH SYSTEM SCIENCES	0.3170938
11	Takakura et al. (2017) 'Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation'. ENVIRONMENTAL RESEARCH LETTERS	0.3147708
12	Ishida et al. (2014) 'Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research'. ENVIRONMENTAL RESEARCH LETTERS	0.2890380
13	Hof et al. (2017) 'Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2 degrees C and 1.5 degrees C'. ENVIRONMENTAL SCIENCE & POLICY	0.2697729
14	Hanasaki et al. (2013) 'A global water scarcity assessment under Shared Socio-economic Pathways - Part 2: Water availability and scarcity'. HYDROLOGY AND EARTH SYSTEM SCIENCES	0.2457890
15	Hasegawa et al. (2015) 'Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways'. ENVIRONMENTAL RESEARCH LETTERS	0.2038796
16	Guivarch et al. (2016) 'The diversity of socio-economic pathways and CO2 emissions scenarios: Insights from the investigation of a scenarios database'. ENVIRONMENTAL MODELLING & SOFTWARE	0.1996244
17	van Vuuren et al. (2017) 'A physically-based model of long-term food demand'. Global Environ. Change	0.1988279
18	Valin et al. (2014) 'The future of food demand: understanding differences in global economic models'. AGRICULTURAL ECONOMICS	0.1597111

ID	Publication	Score
19	von Lampe et al. (2014) 'Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison'. AGRICULTURAL ECONOMICS	0.1394184
20	Hasegawa et al. (2016) 'Economic implications of climate change impacts on human health through undernourishment'. CLIMATIC CHANGE	0.1185475

Documents in topic 13: CBA of climate policies (SDG 13)

ID	Publication	Score
1	Hof et al. (2009) 'The effect of different mitigation strategies on international financing of adaptation'. ENVIRONMENTAL SCIENCE & POLICY	0.6092099
2	de Bruin et al. (2009) 'AD-DICE: an implementation of adaptation in the DICE model'. CLIMATIC CHANGE	0.5835754
3	De Cian et al. (2016) 'Alleviating inequality in climate policy costs: an integrated perspective on mitigation, damage and adaptation'. ENVIRONMENTAL RESEARCH LETTERS	0.5801268
4	Admiraal et al. (2016) 'Costs and benefits of differences in the timing of greenhouse gas emission reductions'. MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE	0.4559236
5	Hof et al. (2008) 'Analysing the costs and benefits of climate policy: Value judgements and scientific uncertainties'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.4374462
6	Hof et al. (2010) 'Including adaptation costs and climate change damages in evaluating post-2012 burden-sharing regimes'. MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE	0.4267364
7	Bollen et al. (2009) 'Local air pollution and global climate change: A combined cost-benefit analysis'. RESOURCE AND ENERGY ECONOMICS	0.2060310
8	Luderer et al. (2012) 'On the regional distribution of mitigation costs in a global cap-and-trade regime'. CLIMATIC CHANGE	0.1880050
9	Daioglou et al. (2016) 'Projections of the availability and cost of residues from agriculture and forestry'. GLOBAL CHANGE BIOLOGY BIOENERGY	0.1256952
10	Bollen et al. (2010) 'An integrated assessment of climate change, air pollution, and energy security policy'. ENERGY POLICY	0.1183370
11	Ekholm et al. (2010) 'Determinants of household energy consumption in India'. ENERGY POLICY	0.1116654

ID	Publication	Score
12	Bowen et al. (2017) 'An 'equal effort' approach to assessing the North-South climate finance gap'. CLIMATE POLICY	0.1028700

Documents in topic 14: Species abundance & biodiversity (SDG 15)

ID	Publication	Score
1	Midgley et al. (2006) 'Migration rate limitations on climate change-induced range shifts in Cape Proteaceae'. DIVERSITY AND DISTRIBUTIONS	0.6910437
2	Bateman et al. (2013) 'Appropriateness of full-, partial- and no-dispersal scenarios in climate change impact modelling'. DIVERSITY AND DISTRIBUTIONS	0.6864999
3	Alkemade et al. (2011) 'Applying GLOBIO at different geographical levels'. Land Use, Climate Change and Biodiv. Modeling: Perspectives and Applic.	0.5061216
4	Janse et al. (2015) 'GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems'. ENVIRONMENTAL SCIENCE & POLICY	0.4207514
5	Phillips et al. (2006) 'Maximum entropy modeling of species geographic distributions'. ECOLOGICAL MODELLING	0.3555312
6	Lucas et al. (2014) 'Integrating Biodiversity and Ecosystem Services in the Post-2015 Development Agenda: Goal Structure, Target Areas and Means of Implementation'. SUSTAINABILITY	0.2355914
7	Guivarch et al. (2016) 'Identifying the main uncertainty drivers of energy security in a low-carbon world: The case of Europe'. Energy Econ.	0.1186624
8	Eitelberg et al. (2016) 'Demand for biodiversity protection and carbon storage as drivers of global land change scenarios'. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	0.1040189

S6.1.4.2 Studies featuring multiple SDGs

The topic modelling analysis allows us to detect when two or more SDGs are discussed jointly in documents. Across our list of documents, 110 featured binary interactions, 32 had ternary interactions, and 5 discussed 4 SDGs simultaneously (see Table S6.3.7, Figure S6.2.5, and Figure S6.2.6).

In this paper, we focus on binary SDG interactions. When more than two SDGs are jointly discussed in one document, we split the higher-level relationships and only account for the binary ones. Table S6.3.8 shows the relationships across the 147 unique documents that featured interactions among two or more SDGs. As expected, SDG 13, which covers 4 different topics, is the most jointly discussed SDG across the IAM literature. Scientific discussions between economic concerns (SDG 8) and climate action (SDG 13) feature prominently in 32 documents. These are closely followed by discussions between energy transition aspects (SDG 7) and climate action (SDG 13) (27 documents) and by discussions between food security (SDG 2) and climate action (SDG 13) (21 documents). Somehow climate action (SDG 13) is less discussed in the contexts of air pollution matters (SDG 3) (9 documents), water (SDG 6) (5 documents), and biodiversity issues (SDG 15) (1 document). SDG 7, which is related to energy transition questions and SDG 8, which is related to economics and mitigation costs feature together in 12 documents. Climate economics (SDG 8) is also discussed in the context of food security (SDG 2) (4 documents) and co-benefits from introducing air pollution measures (SDG 3) (2 documents). Discussions that are not related to either climate action (SDG 13), climate economics (SDG 8), or energy transition (SDG 7) are rare. Discussions between SDG 2 on food security and SDG 6 on water issues appear in four documents, and between SDGs 2 and 3 on air pollution appear in two documents. Similarly, biodiversity (SDG 15) and water issues (SDG 6) are discussed jointly in only one document.

S6.2 Supplementary Figures

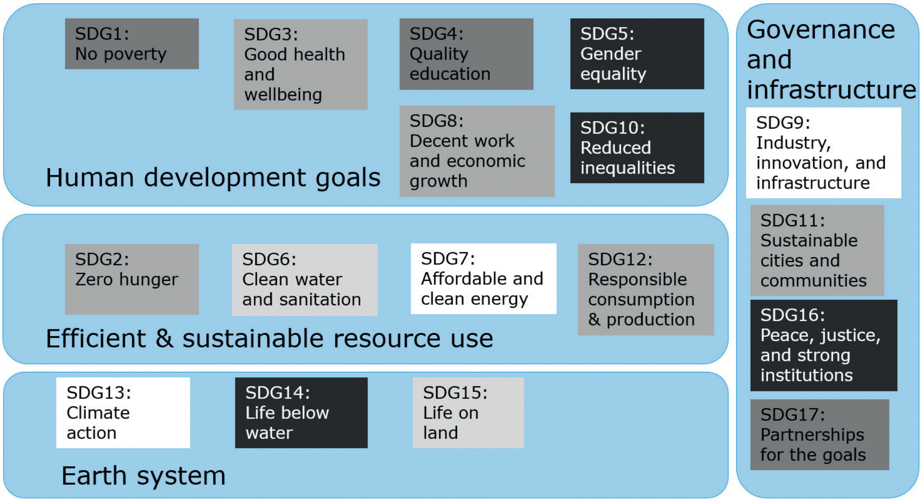
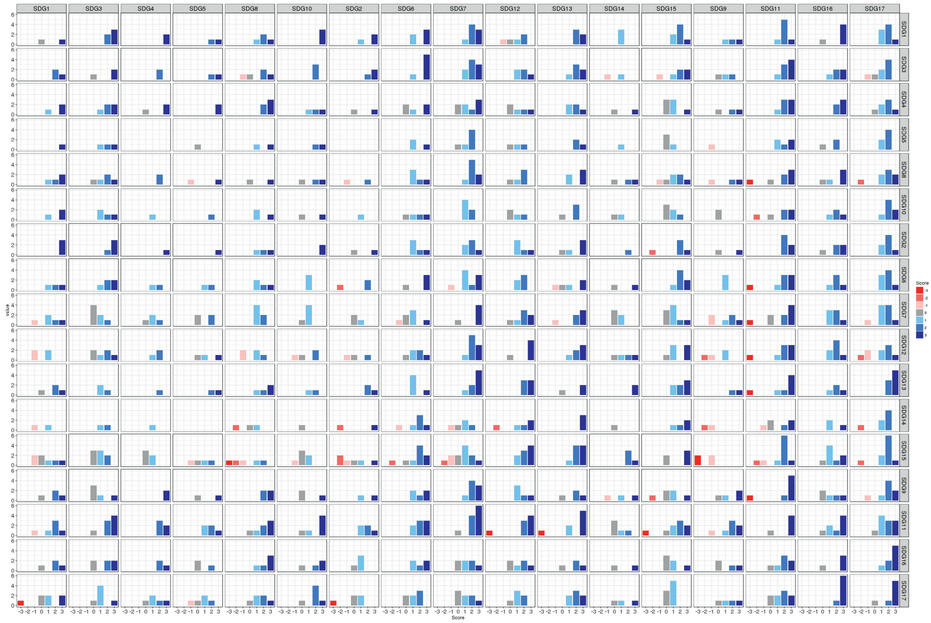


Figure S6.2.1: SDGs in an IAM framework. The shading indicates the overall coverage of SDGs by IAMs. The white boxes indicate that the SDG is well-covered and most of its underlying targets can be quantified by IAMs (average score above 3, SDGs 7, 9, and 13). The intermediate grey shading indicates average scores between 2 and 3 (SDGs 2, 3, 8, 11, and 12) and between 1.5 and 2 (SDGs 6 and 15). Dark grey indicates that the SDG can only partly be quantified (e.g. not all targets can be quantified or IAMs can only provide proxy indicators; average score between 1 and 1.5, SDGs 1, 4, and 17). Black indicates that the SDG is not well-covered by the IAMs (average score below 1, SDGs 5, 10, 14, and 16).

	Pradhan et al. 2017 (translation)	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
		No poverty	Zero hunger	Good health and wellbeing	Quality education	Gender equality	Clear water and sanitation	Affordable and Clean Energy	Decent work and economic growth	Industry, innovation and infrastructure	Reduced inequalities	Sustainable cities	Responsible consumption and production	Climate Action	Life below water	Life on land	Peace, justice, and strong intitutions	Partnerships
SDG1	No poverty	3	2	3	2	3	3	2	2	2	3	3	3	3	0	2	1	2
SDG2	Zero hunger	2	3	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2
SDG3	Good health and wellbeing	3	2	3	3	3	3	2	2	2	3	2	3	2	0	2	1	3
SDG4	Quality education	2	2	3	3	2	3	2	2	2	2	2	3	2	1	2	1	2
SDG5	Gender equality	3	2	3	2	2	3	2	2	2	3	2	2	2	1	2	0	2
SDG6	Clear water and sanitation	3	2	3	3	3	3	2	2	2	3	2	3	2	0	2	1	2
SDG7	Affordable and Clean Energy	2	2	2	2	2	2	2	2	2	2	2	2	2		2	1	2
SDG8	Decent work and economic growth	2	2	2	2	2	2	2	3	2	2	2	3	2	0	2	1	2
SDG9	Industry, innovation and infrastructure	2	2	2	2	2	2	2	2	2	2	2	2	1	0	2	1	2
SDG10	Reduced inequalities	3	2	3	2	3	3	2	2	2	3	2	3	2	0	2	2	2
SDG11	Sustainable cities	3	2	2	2	2	2	2	2	2	2	3	3	3	0	2	1	2
SDG12	Responsible consumption and production	3	2	3	3	2	3	2	3	2	3	3	3	3	0	3	3	2
SDG13	Climate Action	3	2	2	2	2	2	2	2	1	2	3	3	3	0	2	1	2
SDG14	Life below water	0	0	0	1	1	0		0	0	0	0	0	0		0		0
SDG15	Life on land	2	2	2	2	2	2	2	2	2	2	2	3	2	0	3	1	2
SDG16	Peace, justice, and strong intitutions	1	2	1	1	0	1	1	1	1	2	1	3	1		1	2	1
SDG17	Partnerships	2	2	3	2	2	2	2	2	2	2	2	2	2	0	2	1	3

	Expert survey	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
		No poverty	Zero hung	Good heal	Quality ed	Gender eq	Clear wate	Affordable	Decent wo	Industry, i	Reduced in	Sustainab	Responsib	Climate Ac	Life below	Life on lar	Peace, jus	Partnerships
SDG1	No poverty	3	3	3	3	3	3	3	3	3	3	2	2	3	1	2	3	3
SDG2	Zero hunger	3		3			3	3	3	3	3	2	2	3	2	2	3	2
SDG3	Good health and wellbeing	3	3	3	3	3	3	3	3	2	3	3	3	2	1	3	3	3
SDG4	Quality education	3	3	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3
SDG5	Gender equality	3		3			1	2	3	-1	3	3	2	3	1	1	2	2
SDG6	Clear water and sanitation	3	2	3	2	2	3	3	3	1	1	3	2	3	3	3	2	3
SDG7	Affordable and Clean Energy	3	1	2	2	2	3	3	2	3	1	3	3	3	1	3	3	2
SDG8	Decent work and economic growth	3	2	3	2	3	2	2	3	3	3	3	2	3	3	3	3	3
SDG9	Industry, innovation and infrastructure	3	3	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3
SDG10	Reduced inequalities	3	1	3	1	2	3	2	3	0	3	3	2	2	1	1	3	3
SDG11	Sustainable cities	3	2	3	3	3	3	3	3	3	3	3	3	3	2	3	3	3
SDG12	Responsible consumption and production	1	2	3	2	3	3	3	2	1	2	3	3	3	3	3	3	3
SDG13	Climate Action	3	3	2	2	3	3	3	3	3	2	3	3	3	3	3	3	3
SDG14	Life below water	1	3	2	1		2	1	1	-1	0	3	3	3		3	1	2
SDG15	Life on land	3	3	2	0	2	2	2	2	-1	1	3	3	3	2	3	3	3
SDG16	Peace, justice, and strong intitutions	3	1	3	2	0	3	3	3	2	3	3	3	3	3	3	3	3
SDG17	Partnerships	3	1	3	3	2	2	3	3	3	3	3	2	2	3	1	3	3

Figure S6.2.2: Comparison between empirical analysis by Pradhan et al. (2017) and the expert survey in this paper



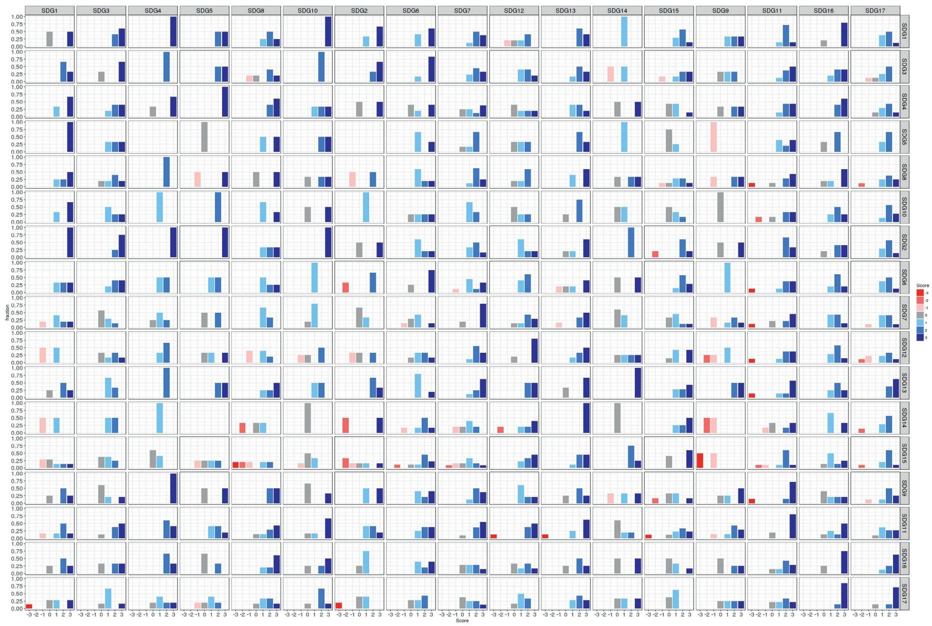


Figure S6.2.3: Counts for each score assigned in the expert survey. The number of times an interaction (each cell in the matrix using the same cluster order as in Figure 6.1) was assigned -3, -2, -1, 0, 1, 2, and 3 (using the ICSU framework for classifying interactions). The lower figure represents a fraction of the total number of responses in that cell. The negative scores (trade-offs) are in red, and the positive ones (synergies) are in blue.

Model representation of individual SDGs	Model representation of SDG interactions		Human development: 1 No poverty	Human development: 3 Health	Human development: 4 Education	Human development: 5 Gender equality	Human development: 8 Work & economic growth	Human development: 10 Inequalities	Resource use: 2 Zero hunger	Resource use: 6 Clean water	Resource use: 7 Energy	Resource use: 12 Consumption & production	Earth system: 13 Climate action	Earth system: 14 Life below water	Earth system: 15 Life on land	Governance & infrastructure: 9 Industry, innovation, infrastructure	Governance & infrastructure: 11 Cities	Governance & infrastructure: 16 Peace	Governance & infrastructure: 17 Institutions
SDG1	Human development	1 No poverty					***	**			**		**						
SDG3	Human development	3 Health	*				***		**	**	***	***	***						
SDG4	Human development	4 Education					***												
SDG5	Human development	5 Gender equality																	
SDG8	Human development	8 Work & economic growth	*								***		***			***	*		
SDG10	Human development	10 Inequalities			*														
SDG2	Resource use	2 Zero hunger	**				***			*	***	*	***		***				
SDG6	Resource use	6 Clean water					***				***	*	***				*		
SDG7	Resource use	7 Energy					***		**			*	***		***	***	***		
SDG12	Resource use	12 Consumption&productic					***				***		***			*	*		
SDG13	Earth system	13 Climate action					***		***		***	***			***	***	***		***
SDG14	Earth system	14 Life below water											*						
SDG15	Earth system	15 Life on land	*				***		***		***	***	***			*	*		
SDG9	Governance & infrastructure	9 Industry, innovation, infra					***				***		***						
SDG11	Governance & infrastructure	11 Cities	*				***				*		***						
SDG16	Governance & infrastructure	16 Peace																	
SDG17	Governance & infrastructure	17 Institutions																	

Model representation of individual SDGs	Model representation of SDG interactions		Human development						Resource use				Earth system			Governance & infrastructure			
			1 No poverty	3 Health	4 Education	5 Gender equality	8 Work & economic growth	10 Inequalities	2 Zero hunger	6 Clean water	7 Energy	12 Consumption & production	13 Climate action	14 Life below water	15 Life on land	9 Industry, innovation, infrastructure	11 Cities	16 Peace	17 Institutions
SDG1	Human development	1 No poverty					***	**			**		**						
SDG3		3 Health	*				***		**	**	***	***	***						
SDG4		4 Education					***												
SDG5		5 Gender equality																	
SDG8		8 Work & economic growth	*								***		***			***	*		
SDG10		10 Inequalities			*														
SDG2	Resource use	2 Zero hunger	**				***			*	***	*	***		***				
SDG6		6 Clean water					***				***	*	***				*		
SDG7		7 Energy					***		**			*	***		***	***	***		
SDG12		12 Consumption&productio					***				***		***			*	*		
SDG13	Earth system	13 Climate action					***		***		***	***			***	***	***		***
SDG14		14 Life below water											*						
SDG15		15 Life on land	*				***		***		***	***	***			*	*		
SDG9	Governance & infrastructure	9 Industry, innovation, infra					***				***		***						
SDG11		11 Cities	*				***				*		***						
SDG16		16 Peace																	
SDG17		17 Institutions																	

Model representation of individual SDGs	Model representation of SDG interactions		Human development						Resource use				Earth system			Governance & infrastructure			
			1 No poverty	3 Health	4 Education	5 Gender equality	8 Work & economic growth	10 Inequalities	2 Zero hunger	6 Clean water	7 Energy	12 Consumption & production	13 Climate action	14 Life below water	15 Life on land	9 Industry, innovation, infrastructure	11 Cities	16 Peace	17 Institutions
SDG1	Human development	1 No poverty					***	**			**		**						
SDG3		3 Health	*				***		**	**	***	***	***						
SDG4		4 Education					***												
SDG5		5 Gender equality																	
SDG8		8 Work & economic growth	*								***		***			***	*		
SDG10		10 Inequalities			*														
SDG2	Resource use	2 Zero hunger	**				***			*	***	*	***		***				
SDG6		6 Clean water					***				***	*	***				*		
SDG7		7 Energy					***		**			*	***		***	***	***		
SDG12		12 Consumption&productio					***				***		***			*	*		
SDG13	Earth system	13 Climate action					***		***		***	***			***	***	***		***
SDG14		14 Life below water											*						
SDG15		15 Life on land	*				***		***		***	***	***			*	*		
SDG9	Governance & infrastructure	9 Industry, innovation, infra					***				***		***						
SDG11		11 Cities	*				***				*		***						
SDG16		16 Peace																	
SDG17		17 Institutions																	

Figure S6.2.4: Comparison of individual matrices resulting from the model survey (upper table) and the SDG expert survey (lower tables). SDG interactions in IAMs, with the SDG in the column affecting the SDG in the row. ***: currently in IAMs, **: planned development, and * conceivable to be represented in the future. In the upper table (model survey only), orange shading indicates the average score for the 'importance' of the interaction in general. In the lower tables (model survey for stars, SDG expert survey for colours), blue shading indicates the score using the ICSU framework, with darkest blue representing a combined score of 3 and lighter shades representing scores of 2 and 1, grey representing 0 (no interaction), and darker shades of orange a score ranging from -1 to -3. In the last table, the sign was removed, that is, a score of -2 was presented as 2. In the first column in all tables, shading represents the average score for individual target coverage (Table 6.1).

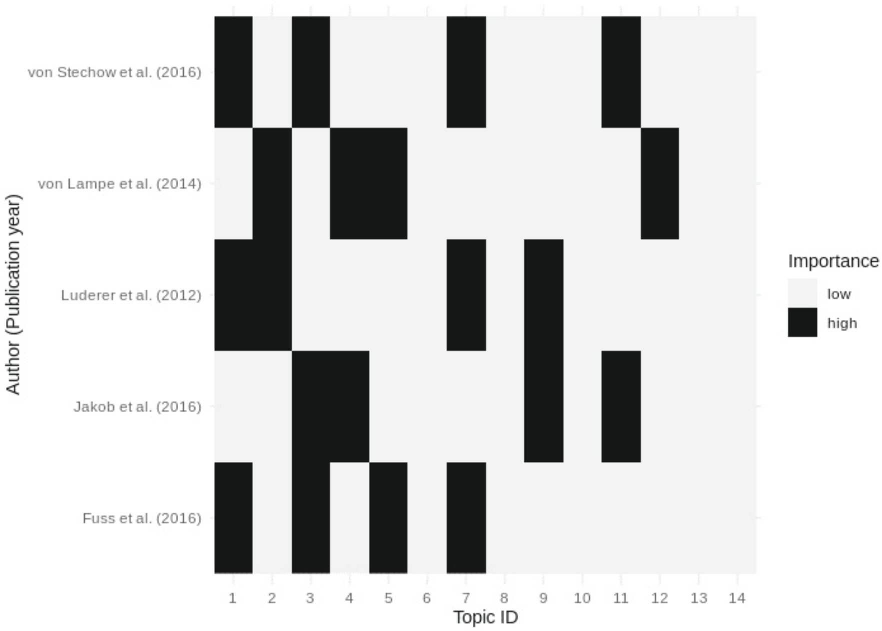


Figure S6.2.5: Documents featuring discussions involving 4 SDGs. We converted the topic scores into a scale with 2 values (Low and High). Topics with a score above 0.1 (High) are considered to have been discussed in a document.

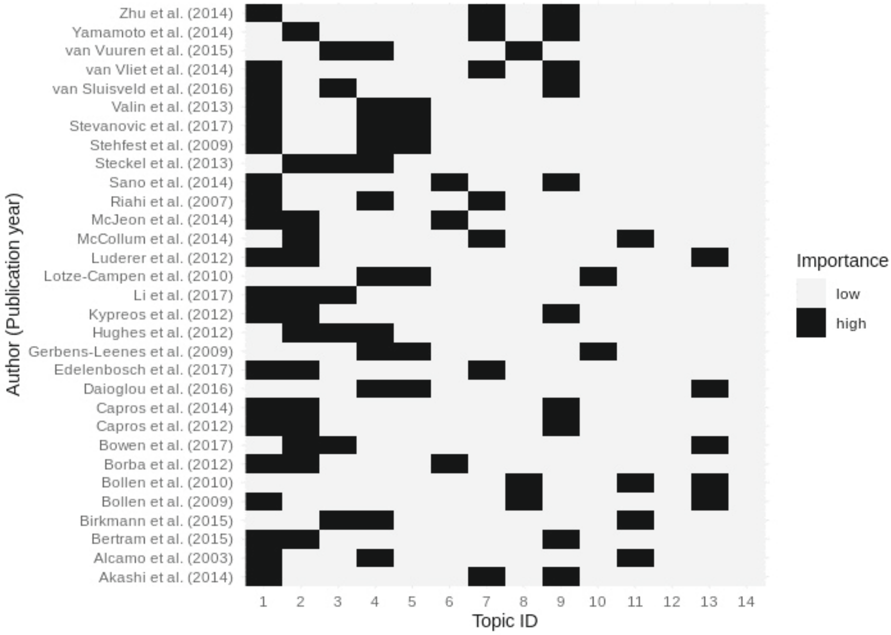


Figure S6.2.6: Documents featuring discussions involving three SDGs. We converted the topic scores into a scale with two values (Low and High). Topics with a score above 0.1 (High) are considered to have been discussed in a document.

S6.3 Supplementary Tables

Table S6.3.1: Respondents' comments on interactions

SDG (expertise of respondent)	Comment (different respondents indicated by letters)
1	for example, SDG 13 is applicable in the context that though the main goal is fighting poverty, the program needs to promote sustainable ways of adaptation and adopting mechanism that are environmental friendly and contribute further to the degradation
2	for the poor escape from hunger is only one objective of their life. Donor should support to actual hunger people.
3	a. SDGs 14 & 15: There may be trade-offs between making space for terrestrial and marine ecosystems and preserving them from further human encroachment and the need to feed a growing human population. Changes in diet and modes of cultivation can go a long way to resolve these tensions, but only if the enormous power of the meat/dairy/fishing industries are faced head on, which has not been the case to date (to put it mildly).

Table S6.3.1: *Continued.*

SDG (expertise of respondent)	Comment (different respondents indicated by letters)
	b. SDGs 5 & 10: I believe there is evidence that some hugely unequal (in terms of gender & economy) societies CAN in fact achieve good broad social outcomes in terms of health and well-being. This means equity goals have to be pursued in parallel, as their own agendas, rather than being expected to be outcomes of a well-being/health agenda. SDGs 14 & 15: I believe societies with good health & well-being outcomes will be more amenable to preserving marine & terrestrial ecosystem space for other species. SDGs 11 & 16: similar point to above. I believe that strong institutions and sustainable communities can only be built on a foundation of providing good outcomes for their populations. c. For SDG 13 my interpretation is that health is consistent with climate action, in that health is a beneficiary of climate action but SDG3 is not a pre-requisite for SDG 13. d. I am particularly concerned with root causes, social determinants of health and cross-cutting risk factors. Alcohol is one such root cause of poverty, ill-health, inequality and under-development. It is also a social determinant of health and a cross cutting risk factors adversely affecting 13 of 17 SDGs. Analysing the SDGs and working for their achievement from the distinct perspective of alcohol prevention and policy allows for seeing certain structural barriers to the implementation of the 2030 Agenda.
4	Education is the fundamental factor in solving all of the problems that human beings are faced all over the world.
5	
6	a. In particular for SDGs 2,7,8,9,13 : I have scored something, but it depends! b. Answer addresses 6.1-6.3 impact on SDGs. For water conservation, 2 on SDGs 1-5 [hard to achieve these unless we share the water], 3 on 6, 1 on SDGs 7-9[Water conservation assures enough to go around],2,2,3 [implied in SDG], 2 [adaptation requires sharing the water], 3 on SDGs 14 & 15 [otherwise there won't be anything for other life], 3, 2 [collective action encourages]. For IWRM, I am skeptical that IWRM does anything other than avoiding totally absurd policies, but it's pluralistic politics at best and at worst dominated by wealthy special interests. So, a big 0, with a potential for 3 if done well and -3 if done poorly]. For ecosystem protection, everything hinges on healthy ecosystems, so 3 for all goals. I include mitigation on 13.

Table S6.3.1: *Continued.*

SDG (expertise of respondent)	Comment (different respondents indicated by letters)
7	a. Focus is on Target 7.1 Energy access (both cooking and electrification). Most SDGs either create an enabling environment (poverty eradication, education and knowledge, purchasing power, global partnership) or have no direct effect (better nutrition, health, access to clean water). Climate mitigation action (SDG13) could be used to accelerate the transition, by using climate or international emissions trading to finance renewable energy development in developing countries. Technology development, for example the global renewable energy revolution in countries like Germany and China have pushed down prices, making them more competitive with fossil fuels in generating electricity in developing countries. Industrialisation (SDG9) requires electricity. Poor households could benefit from such developments. Peace, justice and strong institutions (SDG16) creates an interesting environment for investors b. Access to electricity is required to achieve almost every goal. Without electricity this is impossible. Access to clean cooking reduces the demand for biomass and thereby decreases related global GHG emissions (SDG13). - improved biomass stoves reduce biofuel demand - gaseous and liquid fuels are more efficient and therefore reduce CO2 emissions - electric cooking could lower emissions significant due to efficiency improvement and if generated with renewables CO2 neutral c.This kind of question is reducing the type of linkages there are: it is not one or the other way. In a global context there might be both synergies and trad-offs between one and the another SDG - especially looking at the targets level.
8	
9	
10	
11	11 to 2: more land available for agriculture if urban planning exists 11 to 14: via run-off pollution and via water treatment 11 to 16,17: institutions and partnerships are a must to achieve 11
12	
13	a. The health of the planet and planetary ecosystems is dependent on a stable climate. Without reducing the concentrations of GHGs in the atmosphere, the systems that currently support life on earth may be jeopardized by climatic instability. Addressing this challenge is essential to the implementation of Agenda 2030.

Table S6.3.1: *Continued.*

SDG (expertise of respondent)	Comment (different respondents indicated by letters)
	b. Climate change is already undermining societal aspirations to attain sustainable development. Poor harvests reduce household income, add to food insecurity, these factors impact human health, social inequality and institutional sustainability. Women and children are most vulnerable to these impacts. Ecologically, climate change is impacting on marine life and terrestrial biodiversity. c. For SDG 13 my interpretation is that if the earth gets too hot we won't be able to access water, grow crops or even breathe. Climate action is therefore indivisible from health. d. The Sustainable Development Goals are inextricably tied together as humanity tries to address 21st century challenges. The complexity of interactions and the scale of societal engagement is beyond anything we have attempted before. A fundamental question is: are existing institutions adequate to meet the challenge?
14	
15	a. SDG 1 - Wealth creation often results in the exploitation of natural resources, but also many vulnerable populations depend directly on forests for survival. This all depends on HOW the land sector is managed in contributing to economic growth. If sustainably managed, then this is reinforcing but if unsustainably managed then counteracting. - SDG 2- Currently agriculture (commercial and subsistence) is the main driver of deforestation (Target 15.1, 15.2, 15.5) and poor agricultural practices contribute to land degradation (15.3). Increased agricultural yield could both slow or incentivize deforestation depending on what policy constraints are put around it. - SDG 4 & 5 - There is a positive correlation between increased education and gender equality and better natural resource management - directly through improved management practices and indirectly through lower reproductive rates - SDG 6 - SDG 15 and 6.6 are in direct alignment. To the degree that environmental-flow is considered in the allocation of resources to achieve the other targets under SDG6 will determine the level to which there is mutually reinforcing benefits. - SDG 7 - The current assumptions that biofuels and bioenergy from forest biomass are carbon neutral and therefore put forward as clean energy solutions are and could continue to be disastrous for SDG15 for forests, grasslands and freshwater. The impacts on conversion from natural forest to plantation or agricultural field has significant negative consequences for biodiversity, soils, carbon, etc.

Table S6.3.1: *Continued.*

SDG (expertise of respondent)	Comment (different respondents indicated by letters)
	- SDG 8 - In the majority of cases, development without safeguards is disastrous for natural ecosystems. I would rescore this answer if sustainable management were guaranteed. - SDG 9 - Infrastructure development is the second major driver of deforestation and is compounded by enabling the Fish-bone extraction effect in forests. Increasingly infrastructure projects are being advanced to extract freshwater from some regions. If this development is done considered the natural environment in the design at the very first stages (15.9), then they can be mutually positive. When these considerations are not married - it results in negative impacts for forests, habitat, biodiversity and freshwater. - SDG 11 - Where cities can be designed to not sprawl and impact land use change, this is beneficial. Within Target 11.6 - it's not just the reduction of Smog and other air pollutants - but also making cities more efficient users of natural resources. The more distant humans get from actually interacting with nature to produce the goods they depend on - the more exploitation will happen per capita. Sustainable management must be maintained. - SDG 12 - Strong relationship between these two goals. Source reduction from addressing consumption will have a myriad of benefits for terrestrial ecosystems and freshwater. - SDG 13 - Slowing climate change impacts will benefit natural habitats by only marginally changing their climate regimes. However, if "renewables" from the land sector are not carefully considered in this energy transition - climate mitigation actions like BECCS could cause hugely negative impacts. - SDG 14 - To the degree that healthy fish/protein sources are produced in the oceans - that will limit the need for protein production on land as populations increase. - SDG 16 & 17 - good governance and adequate capacity and partnerships are the only way we will achieve any of the global goals. b. SDG 6 - Many of the headwaters of major rivers are held in forested ecosystems. SDG 7 - Success on SDG 15 will mean that alternative sources of energy like solar and wind were prioritized and limit impacts on land AND on human health. SDG 16 - it is easier to establish good governance systems when there are abundant resources. These processes break down in the face of scarcity.

Table S6.3.1: *Continued.*

SDG (expertise of respondent)	Comment (different respondents indicated by letters)
	c. Ref 'my' SDG 15 affected by: - SDG 1 - targets 1.1 to 1.3 can mean environmental degradation. Target 1.4 on 'rights' is individual whereas indigenous societies conserve communally - SDG 2 - targets 2.3 2.4 and 2.5 for their 'volume' 'area' 'labour' 'number' orientation all of which can increase pressures on ecosystems. - SDG 3 - targets 3.4 and 3.5 will be helped by populations (rural, hill and mountain, wetland and coastal, forest) being encouraged to work and maintain their biospheres. - SDG 4 - this should not be a 0 score, but I cannot see the descriptions of 'quality education' discussing environmental education. - SDG 5 - in many societies 'gendering' policy and practice is foreign because the unit to consider is household. Target 5.4 for example can be seen as upsetting the household balance of labour. Target 5.A however can be an enabling point. - SDG 6 - better degree of co-dependency here. Targets 6.2 6.3 6.4 6.6 6.A all contribute. - SDG 7 - the targets lack correlation with health and environment. Target 7.2 can encourage land loss in the name of 'renewable' (such as dams and reservoirs, solar 'farms' on cultivable land). - SDG 8 - target 8.4 helps, but its benefit is outweighed by the ill effects of 8.1 8.2 (both heavily GDP oriented) 8.9 (tourism burdens biosphere) 8.A (aid is unaccountable and trade's impacts on natural resources use are well known). - SDG 9 - most targets call for industrialisation with no reference to environment, health and wellbeing, resources use. GDP growth figures prominently, so does infrastructure. Any benefit from 9.4 would be outweighed by new manufacturing under 9.3. - SDG 10 - targets 10.1 10.2 focus on income and household expenditure which directly are connected to resources use. - SDG 11 - target 11.4 11.7 are aids. However, 11.1 11.2 are housing and transport infrastructure which affect terrestrial ecosystems. 'Inclusive and sustainable' urbanisation still means more towns and urban agglomerations. - SDG 12 - targets 12.2 12.3 12.4 12.5 12.6 12.8 are all complementary.

Table S6.3.1: *Continued.*

SDG (expertise of respondent)	Comment (different respondents indicated by letters)
	- SDG 13 - targets 13.2 13.3 are strong. However, the targets for SDG 13 are over-described in terms of country commitments and that makes their relation to SDG 15 unclear when it in fact is clear. - SDG 14 - for countries with small land areas (in particular SIDS) these must always be read together with SDG 15. Likewise, for coastal regions of countries. - SDG 16 - targets 16.6 16.7 16.10 will help (especially concerning land grabs and land use policies). They need much better definition with reference to SDG 15. - SDG 17 - target 17.7 the only potential benefit. The trade targets 17.10 17.11 17.12 are major burdens. d. Targets 15.1 15.2 15.3 15.4 15.5 all, when amplified properly by describing the holistic character of ecological and natural systems, contribute to the 1 2 and 3 scores I have given for other SDGs where they apply. On several SDGS (5 7 8 9 10 17) the 0 score reflects very inadequate correlations having been visualised and discussed from the start of the SDG process, and which continue to make them contradictory. e. This promises to be very useful work. The SDG process has been plagued by great inconsistencies and an opaqueness despite the wide simulation of participation. Why 17 and why these 17? If gender has an SDG why not culture? Your matrix survey should contribute much to looking at the SDGs critically. f. The scoring is not sensible at the SDG level. The interactions among individual targets are highly complex and can be positive, negative and neutral within a SDG by SDG interaction. For example: 15.1 interacting with 2.1 should probably be scored -2, assuming conventional agriculture approaches. Whereas the interaction between 15.1 and 2.5 is likely +2/+3. So how should the interaction between SDG 15 and SDG 2 be scored? Simply adding the scores of interactions among individual targets will not be appropriate as the scale and impact varies among target interactions. Overall your approach is too naive and you cannot draw any sensible conclusions from the scores as the coarse scoring of interactions among goals ignores subtleties and nuances in the interactions among targets. The interactions among targets within 2 goals can be contradictory with some scoring +3 and others -3.

Table S6.3.1: *Continued.*

SDG (expertise of respondent)	Comment (different respondents indicated by letters)
16	a. I see peace justice and strong institutions as impacted by all goals but particularly those that have an economic and political component. These would directly impact on institutions and justice. b. The conceptual direction and the legitimacy of development strategies should be examined in view of a comprehensive ecosystemic approach, not surrendering to specialization and fragmentation, but considering the ensemble of the multiple problems of difficult settlement or solution in the contemporary world. The ecosystemic approach counteracts public policies segmented programmes, market-place disguised interests, reduced academic formats and mass-media perfunctory treatment of problems; instead of an exploratory forecasting (projection into the future of the trends of today), a normative forecasting should be posited (previous definition of desirable goals and exploration of new ways to reach them). Beyond the anthropogenic views, that do not distinguish between the whole of the human beings and the destructive action on nature and culture of the political-economic establishment (governments and business corporations), we should consider the power asymmetries, that confer to a small and privileged part of the world population the decisions about the destiny of the entire mankind c. When we speak of human development and the reduction of poverty, we must not refer to the unleashed consumption of goods (from cars, computers, increasingly powerful cell phones down to an almost unlimited variety of any product), but to the fact that every human being should be able to satisfy his basic needs of food, health care, housing, education, for example, as well as having enough leisure time to enjoy culture and the arts, carry out enriching social relations, make our legitimate vocations come true in any field we chose, and also have enough time to rest. This is an idea of human richness, and therefore of poverty, which goes much further than the field of economy and its monetary or commercial evaluation. d. There should be greater appreciation of the need to matrix the SDGs, especially in conceptualising programme/project designs and solutions (inter-disciplinary approaches) among the development community e. My focus is on 16.4 (reduce illicit financial and arms flows, strengthen the recovery and return of stolen assets and combat all forms of organized crime), 16.5 (reduce corruption and bribery in all their forms) and 16.10 (citizen’s access to government information, increasing government transparency and thus, accountability).

Table S6.3.1: *Continued.*

SDG (expertise of respondent)	Comment (different respondents indicated by letters)
17	a. As I consider that SDG 17 has a peculiar nature, I'm not very sure that the matrix applies to this case. In general terms, partnership could be positives for all SDG, but the achievement of other SDG will not necessarily favour the emergence of partnerships. b. SDG 17 is rather difficult to assess with the ICSU scale, but I have assumed level 2 for most, where MoI are important to each SDG, and 3 for some, where MoI will be very key, notably where the SDG is more politically affected than others (e.g. 7, 10 and 13). The same is true for 17 being affected by others, with being a wealthy economy (SDG8), a democratic society (SDG10 in many ways) with good governance (SDG16) will have more impact on 17.

Table S6.3.2: SDG expert classification of the scale of the problem and solution dimensions of the SDG. Bold indicates the most occurring response, followed by italics. Underlined text indicates the most occurring response for the ‘means of implementation’ targets. MOI: Means of Implementation.

SDG	Problem	Solution	Comments
1	- ***Local,*** *MOI* <u>*global*</u> *- Mix global/local*	- ***Local*** *but 1 target transboundary, MOI* <u>*global*</u> *- Mostly local but 2 local, MOI b transboundary*	*- Very interesting initiative! Poverty (SDG 1) is in my opinion both a local and a global problem and requires both local and global action. Unfortunately, it was not possible to choose this option in answering the question.*
2	*SDG overall and targets 2, 4, 5* ***global****, targets 1 and 3 local, MOI* <u>*local*</u>	*SDG overall and targets 2, 4, 5* ***global****, targets 1 and 3 local, MOI* <u>*local / transboundary*</u>	*Local problem means problems of government. It should do land reform which provides land tenure to landless households to produce food they need.*
3	- ***Global*** *except target 3b: transboundary* *- Global except targets 1, 2, 3, MOI c:* <u>*transboundary*</u> *- Mostly global but 1, 2, 6 local, 9 transboundary, MOI global but d transboundary* *- Mostly local but 3, 4, 5 and SDG overall global, MOI mix local/transboundary*	- ***Global*** *- Global but targets 1, 2, 3, local* *- Mix local / global* *- Local but SDG overall global, MOI mix* <u>*local / transboundary*</u>	*- Putting global scale for all of these is perhaps going a bit far, but I do believe that these issues need to be addressed at the global scale. Downscaling responsibilities for single points (capacity building, health infrastructure ...) might seem convenient, but it too neatly omits the role of larger influences: for instance, anti-choice ideology guiding US aid to developing countries and constraining birth control options world-wide, multi-national tobacco and pharmaceutical industries and their roles in playing one country against another in the search for new profitable markets ... It is only by addressing these issues at a global level that a universal aspiration and standard towards health and well-being can be achieved.*

Table S6.3.2: *Continued.*

SDG	Problem	Solution	Comments
4	*- **Global** but MOI transboundary* *- Mix global / local (/ transboundary), MOI global but c local* *- Mostly global but 4 and MOI b local* *- Mix but MOI local, SDG overall global*	*- Mix local/transboundary, MOI transboundary* *- **Global** but 1 and MOI b, c transboundary*	
5			
6	*- Local* *- **Global** but 5 transboundary* *- Global*	*- Global* *- **Global** but 5 transboundary* *- Mix transboundary / local*	*- In a globalised economy, the problems are all global and part of the solutions must be Global as well. But water also is local and transboundary. So, I'm not certain whether the question will generate useful information. And even global solutions need local management and are often best handled by local authorities or indigenous local NGOs. Additionally, targets mix unlike problems together, further complicating a meaningful answer.*

Table S6.3.2: *Continued.*

SDG	Problem	Solution	Comments
7	*- **Global** except 1 respondent for target 7b: local* *- 1 transboundary / local, 2, 3, SDG overall global, MOI mix transboundary/global/ local* *- All global* *- Global but 1 local* *- All scales for all targets*	*- **Local** for SDG overall and targets 1, 2, 3, global for MOI a, b* *- Mix global / local / transboundary* *- All local but 2 global* *- Local* *- All scales for all targets*	*- The scale question is difficult to answer as energy solutions will need to be appropriate, which means they will differ according to the scale at which they are implemented/ targeted. Renewable energy solutions may vary from the solar home system, to a large offshore wind farm. Every situation will therefore be different.* *- The problems of not having clean energy or electricity manifests at the household level. Solutions are place-specific, depending on local resource availability, purchasing power, distance to existing grid. Target 7.a is about sharing technological advancement across countries and is thereby scored as being global. Renewable energy addresses a global problem (GHG emissions are). Solutions are local, especially when decentralised options are used, but transboundary when it relates to linking the grids of different countries to work together and benefits from other countries options (hydro, sun, wind, etc.) and global when it is about technology development and sharing. Energy efficiency addresses a global problem (GHG emissions are). Solutions depend on the sector, with some sectors having a much larger potential than others.*
8	*- Mostly **global**, but 1, 2, 3, 9, SDG overall local* *- Mostly global, but 7 and 9 local, 8 and MOI transboundary*	*- Mostly **local** but 1, 4, 7, 9, MOI global*	

Table S6.3.2: *Continued.*

SDG	Problem	Solution	Comments
9	*- SDG overall and targets 1, 4, 5* ***global****, target 2 transboundary, 3 local, MOI a and c transboundary, b local*	*- SDG overall and targets 1, 2, 5* ***local****, target 3 transboundary, 4 global, MOI a, b, c transboundary*	
10	*- Targets 1, 3, 4* ***local****, 5 global, MOI a, b, c, d global, e local*	*- Targets 1, 3, 4* ***local****, 5 global, MOI a, b, c, d global, e local*	*- Where I chose "Other" it was because this is a multi-layered problem, existing and requiring solutions at the local, national and global levels. It cannot be captured at just one level.*
11	*- All* ***global*** *- All global except target 2: local* *- Targets 1, 2, 6, 7 local, target 3 and MOI a transboundary, targets 4, 5 and MOI b, c global* *- Mostly global but 7 transboundary/local, MOI mix* *- Mostly transboundary but 3, 6 global, 7 local* *- All local but 5 transboundary, MOI c global*	*- SDG overall and targets 1, 2, 3, 7* ***local****, targets 4, 5 and MOI a, b, c global* *- Targets 1, 2, 6, 7, MOI a transboundary, targets 3, 4, 5 and MOI b, c global* *- Mix transboundary / local (/ global)* *- All local but 5 transboundary, MOI c global*	*- Local problems become global problems when they are not addressed* *- 11.6: between 30 and 70% of local pollution comes from transboundary sources, thus the solution is global and local*

Table S6.3.2: *Continued.*

SDG	Problem	Solution	Comments
12	*- Mix transboundary / global* *- Local, some global, MOI mix* *- SDG overall global, targets mix global/local and 12.3 transboundary, MOI transboundary/global*	*- Mix transboundary / global, some local* *- SDG overall transboundary, 5 targets transboundary and 1 global, 1 local, MOI mix local, transboundary, global*	
13	*- Mix transboundary / local but SDG overall* ***global****, MOI <u>transboundary/global</u>* *- Global but 2 local, MOI b transboundary* *- Global*	*-* ***Global*** *but 2 local, MOI b <u>transboundary</u>* *- SDG overall global but targets and MOI local/ transboundary*	*- This survey forces simplistic answers to a problem that demands action at all levels of society -- local, national, regional and global -- with all possible tools in combination. We must apply knowledge and existing technology to reduce GHG emissions in every sector, and we must provide incentives for research and development to find innovative ways of expanding the scale and impact of our remedial actions.*
14	*-* ***Global*** *but targets 6, 7 and MOI b <u>transboundary</u>*	*- SDG overall and target 3, MOI a and c* ***<u>global</u>****, targets 1, 2, 5 local, targets 4, 6, 7, MOI b transboundary*	*- This is VERY difficult to fill out because you cannot see the column headings as you answer farther Down in the list. Furthermore, the cross boundary and local gives no meaning when you have the EU. Almost all local laws regarding the ocean are EU law based as the ocean is, by definition, trans boundary!*

Table S6.3.2: *Continued.*

SDG	Problem	Solution	Comments
15	*- All* ***local*** *but 1 global and 7, 8, MOI c transboundary* *- Transboundary but 1, 2, 5, 9, MOI a global, 6 local* *- 5, 6, 7 local, 8 transboundary* *- Global but 5 and MOI c transboundary* *- Mostly local but some global* *- Mix global local, MOI global* *- Mix global / local / transboundary*	*- Most* ***global*** *but 3, 4, 5, 7 transboundary* *- 1, 2, 4, 5, a, b global, 3, 7, 8 transboundary, 6, 9, c local* *- Targets 1, 5, 8, MOI c local, 2, 6, 7, 9, a global, 3, 4, b transboundary* *- Mix transboundary / global / local* *- Mix global local, MOI global*	*- The spatial categories should not be mutually exclusive, there may be problems that have local and global solutions.* *- This has proved more difficult than it looks. Implementation of what the targets ask for can best be done locally and should be done locally so that for example livelihood opportunities are strengthened. But often it is only under international pressure and with international obligations specified and publicised that appropriate action is taken. Left to national level interpretation, these targets will not be applied in the ways they should be. For several targets I have said they are local problems with local solutions, even though the problems faced and solutions found are likely common in broad geographical areas. SDG 15 is overall local but whose enabling targets benefit greatly from international cooperation.* *- Action is needed at all levels in all cases; the problems manifest itself at local, national and global level* *- Given these are all global goals, all problems and solutions require involvement of local to global stakeholders.*

Table S6.3.2: *Continued.*

SDG	Problem	Solution	Comments
16	*- Mostly* ***global*** *but 6, 10, MOI b transboundary, 7 and 9 local* *- Mostly transboundary but 3, 4 global, 7 local* *- Mostly local but 3 global* *- SDG overall, target 2 and MOI a transboundary but rest local*	*- Mostly* ***global*** *but 7 and 9 local, 6 transboundary* *- Mix but MOI local* *- SDG overall local but targets mix local/transboundary*	*- According to the Reflection Group on the 2030 Agenda for Sustainable Development, the SDGs are being used not as a roadmap for social, economic and environmental transformation, but as a vehicle to entrench inequitable power relations; wealthy elites and rich multinational corporations translate their economic power into political access and influence government decisions that accommodate people to the market-oriented system, instead of changing it. In order to deal with environmental problems, quality of life and the state of the world, addressing the structural power asymmetries that divide common citizens and business corporations, public policies, research and teaching programmes should favour the development of healthy societies, that invest in each other rather than in mega-projects with intensive use of resources. Addressing structural exclusion through legal, social, or economic inclusion in the current system, such as civil rights, social norms, the expansion of the middle class and the market-oriented educational system do not change the present paradigms: once included, a new wave of egocentric producers and consumers reproduce the system responsible for their former exclusion, increasing the abuse of nature in the name of progress*
17	*- Transboundary but some local* *- All global* *- Mix* *- All local but 13 and 16 global*	*- Mostly* ***global****, some local* *- All global*	*- we need a combination of all of the above*

Table S6.3.3: Descriptions used for the normalisation of model scores for individual SDG representation. GEM-E3 and PRIMES scores were revised accordingly. While 0 remained 0 and 5 remained 5, original 1 scores were assigned 3 in most cases, but 2 where the indicator description mentioned exogenous calculations, and original 2, 3, and 4 scores were assigned 4.

	Assign 0, 1, 2, 3, 4, and 5 here					
	WITCH	IMAGE	AIM	DNE21+	GEM-E3 & PRIMES	China-TIMES
0 Not covered at all	0	0	Blank	0	0	0
1 Only exogenous assumptions for 1 target	1	1		1		1
2 Only exogenous assumptions for 2 or more, but not all targets	2	2				2
3 Only exogenous assumptions for all targets			2			3
4 Endogenous calculations for 1 target	3	3	3, 4	1, 2	1 (for targets indicated in column E)	4
5 Endogenous calculations for 2 or more, but not all targets	4	4	5	3, 4	2, 3, 4, and 5 (for targets indicated in column E) depending on the level of detail or sophistication in the endogenous model representation	5
6 Endogenous calculations for all targets	5	5		5	N/A	

Table S6.3.4: Top 20 terms characterizing each topic. Topic identifiers and manually chosen topic names are in the first two columns. The stemmed keywords and their associated scores are presented in the last column. Manually allocated SDGs are also provided. The scores are endogenously computed by the algorithm and quantify the importance of a term for a given topic.

ID	Name	SDG	Stemmed keywords (score)
1	Mitigation scenarios	13	emiss (0.99), scenario (0.42), reduct (0.36), mitig (0.35), target (0.28), cost (0.27), carbon (0.21), technolog (0.2), indc (0.19), baselin (0.16), abat (0.16), ppm (0.15), coe (0.15), temperatur (0.15), ghg (0.14), rate (0.12), achiev (0.11), countri (0.11), pathway (0.11), action (0.11)
2	Carbon pricing and mitigation costs	8	price (0.46), carbon (0.41), scenario (0.26), sector (0.26), product (0.24), countri (0.23), cost (0.22), tax (0.2), fuel (0.19), oil (0.17), gdp (0.16), leakag (0.16), imaclimr (0.16), effici (0.16), growth (0.15), transport (0.15), emiss (0.15), revenu (0.14), invest (0.14), subsidi (0.14)
3	Sustainable transitions and governance	NA	transit (0.24), govern (0.18), sustain (0.18), social (0.18), actor (0.17), human (0.17), sociotechn (0.13), approach (0.13), environment (0.13), materi (0.12), innov (0.11), access (0.11), life (0.1), process (0.1), health (0.1), need (0.1), societi (0.09), new (0.09), theori (0.09), iam (0.09)
4	Food security	2	food (0.58), crop (0.44), scenario (0.42), product (0.29), yield (0.29), hunger (0.25), agricultur (0.25), calori (0.19), incom (0.17), demand (0.17), price (0.16), popul (0.15), countri (0.15), cereal (0.14), risk (0.12), world (0.12), effect (0.11), consumpt (0.11), peopl (0.11), per (0.1)
5	Land-based mitigation	13	land (0.78), bioenergi (0.56), crop (0.4), forest (0.34), product (0.3), agricultur (0.27), carbon (0.25), cropland (0.25), biofuel (0.25), landus (0.22), area (0.2), deforest (0.16), yield (0.16), emiss (0.15), price (0.15), magpi (0.14), pastur (0.12), terrestri (0.12), biomass (0.11), irrig (0.11)
6	Low-carbon electricity	7	plant (0.46), power (0.41), brazilian (0.33), brazil (0.32), csp (0.24), electr (0.22), lca (0.2), solar (0.19), generat (0.18), cycl (0.17), coal (0.16), ccs (0.15), wind (0.14), gas (0.14), thermal (0.14), life (0.14), hydropow (0.13), capac (0.13), biomass (0.13), emiss (0.12)
7	CCS, bioenergy, and negative emissions	13	fulltech (0.54), ccs (0.46), scenario (0.4), bioenergi (0.36), technolog (0.27), emf (0.21), ppm (0.19), biomass (0.18), transport (0.16), effici (0.15), deploy (0.15), mitig (0.15), electrif (0.15), cost (0.14), becc (0.14), lowei (0.13), target (0.13), electr (0.13), sector (0.12), fuel (0.11)

Table S6.3.4: *Continued.*

ID	Name	SDG	Stemmed keywords (score)
8	Air pollution and health	3	pollut (0.66), air (0.57), emiss (0.42), aerosol (0.28), forc (0.25), control (0.23), ozon (0.22), scenario (0.18), health (0.15), nox (0.14), measur (0.14), reduct (0.12), qualiti (0.12), methan (0.12), concentr (0.11), gain (0.11), mortal (0.1), rcp (0.1), effect (0.1), fig (0.1)
9	Low-carbon electricity II	7	nuclear (0.73), technolog (0.51), electr (0.36), power (0.32), wind (0.29), ccs (0.25), solar (0.19), scenario (0.18), cost (0.17), renew (0.17), generat (0.14), phaseout (0.13), witch (0.13), reactor (0.11), capac (0.11), learn (0.1), decarbonis (0.1), ppme (0.09), deploy (0.09), japan (0.08)
10	Water availability and consumption	6	water (1.19), irrig (0.45), withdraw (0.41), cool (0.23), runoff (0.12), river (0.12), consumpt (0.12), scenario (0.11), demand (0.1), estim (0.1), crop (0.1), stress (0.09), resourc (0.09), waterstress (0.09), bioethanol (0.09), sector (0.09), biodiesel (0.08), basin (0.08), freshwat (0.08), nexus (0.08)
11	Energy security	NA	secur (0.66), oil (0.38), scenario (0.3), divers (0.25), indic (0.25), trade (0.21), fuel (0.16), tpes (0.15), vulner (0.14), jewel (0.14), gas (0.13), risk (0.12), vital (0.11), resourc (0.11), fossil (0.1), cherp (0.1), asian (0.1), resili (0.1), suppli (0.1), index (0.09)
12	SSP scenario framework	NA	ssp (1.45), ssps (0.31), scenario (0.18), rcp (0.13), narrat (0.1), socioeconom (0.09), mitig (0.08), challeng (0.08), marker (0.07), baselin (0.07), driver (0.07), gdp (0.06), fig (0.06), iam (0.06), assumpt (0.06), growth (0.06), demand (0.06), incom (0.06), storylin (0.06), popul (0.05)
13	CBA of climate policies	13	damag (0.62), cost (0.6), adapt (0.57), mitig (0.24), dice (0.21), residu (0.19), discount (0.18), cdc (0.15), regim (0.15), target (0.11), abat (0.1), action (0.1), alloc (0.1), benefit (0.09), optim (0.09), witch (0.08), estim (0.08), financ (0.08), fair (0.08), burdenshar (0.08)
14	Species abundance and biodiversity	15	speci (0.59), dispers (0.49), biodivers (0.33), msa (0.25), migrat (0.2), rang (0.15), predict (0.13), habitat (0.1), ecosystem (0.1), wetland (0.09), lake (0.08), area (0.08), cbd (0.08), disturb (0.07), driver (0.07), pixel (0.07), distribut (0.07), null (0.07), data (0.06), abund (0.06)

Table S6.3.5 shows that most topics relate to climate change mitigation. The top three topics are mitigation scenarios (70), carbon pricing and mitigation costs (55), and sustainable transition and governance (44). Air pollution and health (22), water availability (25), and energy security (16) need more research. Issues related to biodiversity remain poorly analysed.

Table S6.3.5: Number of documents by topic.

ID	Name	SDG	count
1	*Mitigation scenarios*	*13*	*70*
2	*Carbon pricing and mitigation costs*	*8*	*55*
3	*Sustainable transitions and governance*	*NA*	*44*
4	*Food security*	*2*	*41*
5	*Land-based mitigation*	*13*	*37*
6	*Low-carbon electricity*	*7*	*24*
7	*CCS, bioenergy, and negative emissions*	*13*	*30*
8	*Air pollution and health*	*3*	*22*
9	*Low-carbon electricity II*	*7*	*30*
10	*Water availability and consumption*	*6*	*25*
11	*Energy security*	*NA*	*16*
12	*SSP scenario framework*	*NA*	*20*
13	*CBA of climate policies*	*13*	*12*
14	*Species abundance and biodiversity*	*15*	*8*

As Table S6.3.6 shows, most IAM documents dealt with climate issues (149 out of 245). This is followed by the energy system and socio-economic aspects of sustainable development. Problems related to clean energy, economic growth, and hunger come with 54, 55, and 41 documents, respectively. Land biodiversity appears to lag behind seriously with only 8 documents. Issues related to health and water are also underrepresented, with only 22 and 25 documents, respectively.

Table S6.3.6: Number of documents by SDG.

SDG	count
13	*149*
15	*8*
2	*41*
3	*22*
6	*25*
7	*54*
8	*55*
NA	*80*

Table S6.3.7 shows that most IAM documents addressed either a single SDG or two SDGs. Despite the potential of current IAMs to deal with multiple interactions, only 37 documents dealt with more than two SDGs, most of which were related to SDG 13.

Table S6.3.7: Total number of documents in terms of total number of SDGs discussed.

Total number of SDGs discussed	Number of documents
1	*98*
2	*110*
3	*32*
4	*5*

Table S6.3.8 shows that among the documents discussing two SDGs simultaneously, most (71) featured interactions between climate change (SDG 13) and decent work and economic growth (SDG 8) as well as affordable and clean energy (SDG 7). This is followed by interactions between SDG 13 and SDGs 2 (Zero Hunger) and 3 (Good Health and Well-being), which are featured in 30 documents. The remaining interactions feature in fewer than 5 documents.

Table S6.3.8: Number of documents in which two SDGs are discussed simultaneously.

	SDG 2	SDG 3	SDG 6	SDG 7	SDG 8	SDG 13	SDG 15
SDG 2	*0*	*2*	*4*	*1*	*4*	*21*	*0*
SDG 3	*0*	*0*	*0*	*0*	*1*	*9*	*0*
SDG 6	*0*	*0*	*0*	*4*	*0*	*5*	*1*
SDG 7	*0*	*0*	*0*	*0*	*12*	*27*	*0*
SDG 8	*0*	*0*	*0*	*0*	*0*	*32*	*0*
SDG 13	*0*	*0*	*0*	*0*	*0*	*0*	*1*
SDG 15	*0*	*0*	*0*	*0*	*0*	*0*	*0*

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```
def thank_people(name):

        print(f"Thank you, {name}!")

for name in all_missed_names:

        thank_people(name)
```

Curriculum Vitae

Heleen van Soest was born on the 4th of December 1989 in Delft, the Netherlands. She spent most of her childhood in Pijnacker and went to secondary school (VWO) in Den Haag and Zutphen. In 2008, she started at Wageningen University with the B.Sc. degree in *Environmental Sciences* (major *Environmental quality and systems analysis*, minor *Climate change, a systems analysis approach*), completed Cum Laude in 2011, followed by an M.Sc. degree in *Climate Studies* (major *Earth system science*), completed in 2013. After university, she worked as a freelance researcher and consultant in the fields of philanthropy and climate science. Between 2014 and now, she has worked as a researcher on international climate policy at PBL Netherlands Environmental Assessment Agency, department of Climate, Air and Energy. In that position, she has been working on projects for the European Commission, supporting DG Climate Action, as well as the Horizon 2020 projects CD-LINKS and ENGAGE. She further worked on the MILES project and jointly managed the COMMIT project. She was a visiting researcher at IIASA (International Institute for Applied Systems Analysis) between October and December 2017. Her work involves providing DG Climate Action with scientific input for the climate negotiations, e.g. evaluating national climate and energy policies by quantifying their expected effect on greenhouse gas emissions until 2030 and comparing them to international emission reduction pledges (most notably NDCs). It further involves developing 2 °C-consistent scenarios starting from these policies and NDCs, using PBL's IMAGE model. In addition, she analyses country-level energy system and emission pathways from both global and national mitigation scenarios, including their implications for and links with other sustainable development goals.

List of publications

This thesis

Van Soest, H. L., de Boer, H. S., Roelfsema, M., den Elzen, M. G. J., Admiraal, A., van Vuuren, D. P., Hof, A. F., van den Berg, M., Harmsen, M. J. H. M., Gernaat, D. E. H. J., Forsell, N. (2017) Early action on Paris Agreement allows for more time to change energy systems. Climatic Change 144(2): 165-179. doi: 10.1007/s10584-017-2027-8

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