Environmental Science and Policy 135 (2022) 104–116

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Developing scenarios in the context of the Paris Agreement and application in the integrated assessment model IMAGE: A framework for bridging the policy-modelling divide☆

Mark Roelfsema [a,b,*], Heleen L. van Soest [a,b], Michel den Elzen [b,c], Heleen de Coninck [d,e], Takeshi Kuramochi [a,f], Mathijs Harmsen [a,b], Ioannis Dafnomilis [b], Niklas Höhne [f,g], Detlef P. van Vuuren [a,b]

[a] Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands
[b] PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands
[c] Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, the Netherlands
[d] Industrial Engineering & Innovation Sciences, Technical University Eindhoven, the Netherlands
[e] Environmental Science, Radboud University, Nijmegen, the Netherlands
[f] NewClimate Institute, Cologne, Germany
[g] Environmental Systems Analysis Group, Wageningen University, Wageningen, the Netherlands

ARTICLE INFO

Keywords:
Climate policy
Integrated assessment
Policy design
Policy cycle
Paris Agreement

ABSTRACT

The framework presented in this study aims to provide insights into how climate policy is represented in integrated assessment models, responding to the call to link model scenarios with concepts used in public policy literature and related fields. As such, it contributes to increased transparency leading to better understanding across disciplines and communication about the relevance of model outcomes with policymakers. The framework categorises climate policy into policy aims and policy implementation at different stages of the policy cycle, and can be used to demarcate different climate policy scenarios incorporating and linking the international and national level. This approach provides clarity on critical modelling assumptions concerning the workings of policy to scenario users (including policymakers), such as policy stringency and status. We discuss the framework in relation to scenarios exploring pathways meeting the long-term Paris goal to hold temperature well below 2 °C or 1.5 °C, Nationally Determined Contributions submitted to the Paris Agreement, and current implemented policies. Specifically, the application of the framework and model implementation of the scenarios is illustrated with implementation in the IMAGE model. To project the expected policy impact on greenhouse gas emissions, the policy goals and policy instrument targets are translated into model targets. This is implemented in the model by either changing parameters for available policy instruments, such as carbon price or subsidies, or adjusting model parameters such as efficiency and costs to meet targets.

1. Introduction

The strength of process-based integrated assessment models (IAMs) lies in their ability to picture the solution space of climate change mitigation options with varying policy and actions, including the feedback and trade-offs between energy system, environment, and economy (Keppo et al., 2021). The solution space is represented by scenarios characterising different policy stringency and socioeconomic trends, for

Abbreviations: IAM, Integrated Asssement Model; SSP, Shared Socioeconmic Pathway; GHG, Greenhouse Gas; UNFCCC, United Nations Framework Convention on Climate Change; NDC, Nationally Determined Contribution; LTS, Long-term Strategy; ITMO, Internationally Traded Mitigation Outcome; ETS, Emissions Trading System; AFOLU, Agriculture, Forestry, and Other Land Use; IPCC, Intergovernmental Panel on Climate Change; MNL, Multi-nomial Logit; MAC, Marginal Abatement Costcurve; F-gas, Fluorinated-gas.

☆ MR and DPvV. have received funding from the European Union's Horizon 2020 research and innovation programme (Grant agreement 837089, SENTINEL project).

* Corresponding author at: Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands.
E-mail address: m.r.roelfsema@uu.nl (M. Roelfsema).

https://doi.org/10.1016/j.envsci.2022.05.001
Received 14 December 2020; Received in revised form 19 April 2022; Accepted 1 May 2022
Available online 13 May 2022

example, visible in the Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017; van Vuuren et al., 2014). Over the last decades, IAMs informed policy makers and the general public on possible climate strategies (Schwanitz, 2013; van Beek et al., 2020). Key elements of the IAM research include timing of mitigation action, implications of different long-term climate targets, sectoral contributions, and the role of specific technologies (Clarke et al., 2014). IAMs have played a role in different policy stages, putting climate change on the policy agenda, showing the impact of different long-term goals, and assessing the greenhouse gas impact for large countries.

IAMs are models with a global coverage divided into regions, some representing individual large countries. Therefore, they can provide insights into the required greenhouse gas (GHG) reductions at the national level and evaluate their ambition vis-à-vis global goals and targets agreed at the international level. International climate policy involves agreements made in the global context of the United Nations Framework Convention on Climate Change (UNFCCC), for which the Paris Agreement secured the long-term goal to hold temperature increase to well below 2 °C and to pursue efforts to keep it below 1.5 °C (UNFCCC, 2015). However, implementation largely depends on ambition and the realisation of climate policies at the national level (Roelfsema et al., 2020; Rogelj et al., 2016). The two climate policy levels are linked through Nationally Determined Contributions (NDCs) and Long-term Strategies (LTS), in which (groups of) countries that have ratified the Paris agreement present their economy-wide efforts toward meeting the long-term temperature goals.

The origin of IAMs can be traced back to systems thinking introduced by Meadows et al. (1972) (van Beek et al., 2020). The what-if scenarios developed with these models initially showed stylised long-term pathways that represented a solution space of different long-term mitigation goals and socio-economic conditions. Mitigation is induced in these models by a global carbon price to identify cost-effective mitigation strategies (Clarke et al., 2014; Solomon et al., 2007). The carbon price in IAMs and the policy instrument of carbon pricing are sometimes assumed to be comparable, but the use in IAMs does not intend to say that this is the only or right instrument to induce innovation for deep emission reductions (Baranzini et al., 2017; Lilliestam et al., 2020). Instead, the carbon price must be seen as a shadow price for mitigation measures, i.e. a tool that IAMs use to induce mitigation action: it equals the marginal abatement costs in an idealised world. The carbon price in IAMs therefore does not represent the policy instrument of carbon pricing. To give insight into, for example, the distributional effects of carbon pricing, further specification of different actors, their behaviour, and the role of institutions would be needed.

Since the Paris Agreement, IAMs have been increasingly used beyond the analysis of global emissions pathways. They are now also used to analyse how to reach different long-term goals and are asked to assess sustainability transitions. However, IAMs focus mainly on physical, technical and economic factors and tend to neglect the dynamics introduced by institutions, actors, and power structures (De Cian et al., 2020). Nevertheless, what IAMs have done since Paris is including representations of actual policies instead of single carbon prices. For instance, they have analysed policies in the context of the 2020 reduction targets from pledges submitted as part of the Cancun Agreements (Riahi et al., 2015; Roelfsema et al., 2014) or analysed the effectiveness of specific mitigation options resulting from existing policy instruments (Deetman et al., 2015; Fekete et al., 2021; Kriegler et al., 2018; Roelfsema et al., 2018; van Soest et al., 2021). The improvement lies in more realistic projections of sectoral energy use and emissions, including interactions between activity levels, efficiency improvements, and CO_2 reduction measures. An increasing number of researchers have analysed the impact of current climate policies at the national level to meet the NDC targets by 2030 based on the assessment of national and global model studies (den Elzen et al., 2019; Kuramochi et al., 2021; Roelfsema et al., 2020; Vrontisi et al., 2018). In addition, integrated modelling of policy impacts is used in impacts assessments such as the Clean Planet for All (Capros et al., 2018; European Commission, 2018), the assessment of mitigation investment options for the UK International Climate Finance programme (VividEconomics et al., 2020), and the development of long-term strategies (Weitzel et al., 2019). The emerging literature has shown that the representation of policies in models is not unambiguous. Studies have implemented policies differently, e.g. focusing on the stated aims or representing the exact policy instrument and measures. Also, interpretation and coverage of current policies may differ between studies (den Elzen et al., 2019). Therefore, transparency is important, especially as these pathways are increasingly developed in cooperation with political, behavioural and other social science disciplines.

We conclude, that to further improve the realism of model-based policy scenarios, linkages with or embedding results in a variety of social sciences, in particular public policy and political science, is necessary (Victor, 2015). Different approaches exist to link social science to IAM scenarios. Most approaches discussed in literature so far, aim to link or integrate social science insights into IAM model implementation. A second approach discussed in this article, is to show how existing IAM scenario assumptions can be embedded in policy design literature. This embedding does not change the model results (much) but ensures speaking the same language between different scientists and policymakers and aims to increase model transparency.

For the first approach, different strands of social science are currently working together with IAMs and aim to increase the realism of model results. Arguably, the sustainability transitions and system innovation studies domain has most prominently sought collaboration with IAMs, resulting in insights into differences and commonalities, mutual learning and a research agenda (Geels et al., 2016; Köhler et al., 2019; Trutnevyte et al., 2019). For example, Geels et al. (2020) developed socio-technical scenarios based on technological substitution or broader system transformation in which included various interactions between models and multi-level perspectives. Another example is shown in Gambhir et al. (2021), who link technology innovation system analysis to technology costs projections. An extension of the systems thinking field is the introduction of transition dynamics in IAMs, to be able to identify intervention points (Meadows, 2008) that can set off self-reinforcing feedback loops and provide more insight into those factors that balance the system and include lock-in and path dependency that lead to inertia and stable regimes (Geels, 2002; Köhler et al., 2019). Social tipping points (Otto et al., 2020) and tipping cascades (Sharpe and Lenton, 2021) have been identified as potential accelerators of transformational change at a national and sectoral level. A recent development is the implementation of such insights in an integrated assessment model, which leads to faster transitions and different global dynamics (Mercure et al., 2018). Another strand of social science is earth system governance exploring political solutions and effective (global) governance mechanisms, where inequality or climate justice is becoming a central topic (Burch et al., 2019). Although justice issues are scarcely included in integrated assessment models thus far (Gupta and Lebel, 2020), other earth system governance topics such as climate clubs are starting to be investigated (Paroussos et al., 2019).

The second approach is the focus of this article, and aims to link concepts from public policy design to existing climate policy scenarios. One important step towards improving the realism of scenarios has already been taken by accounting for the impact of actual implemented policies instead of using a single carbon tax. What is missing in the step towards actual policy implementation is a theoretical framework for climate policy scenarios that could help modellers to better communicate the relevance of their results to policymakers by providing a familiar policy context and cross the bridge to political scientists by relating to their language and increasing transparency on assumptions of the policy scenario implementation.

One of various important issues in policy scenarios implementation is the interpretation of the term ‘climate policy’ across different disciplines, which is often interpreted and used differently (Rogge and

Table 1
Policy design framework from Howlett (2009, 2011).

Policy level / Policy component	Governance mode Favoured set of ideas and instruments[b]	Policy regime Preference for general policy tools and generic set of policy objectives	Programme Matching of the program means to specific policy targets	
Policy aim Basic aims and expectations of governments	Abstract policy objectives	Operationalizable goals[a]	Policy targets	Achieve policy targets
Policy means Tools used to attain the aims	General implementation preferences	Policy instruments choices	Policy instrument calibration	Organisational capacity, resource availability, rules of procedures)
Policy cycle stage	Agenda setting	Policy formulation	Decision-making	Implementation

[a] Note that the terms 'aims' and 'goals' used in this table are the 'goals' and 'objectives' as used in Howlett (2009), (2011). We changed it here to match the terms used in IPCC reports (and 'aim' is now used as the general term to cover 'objectives, goals and targets').
[b] Favoured set of ideas and instruments (legal, corporatist, market and network governance). See Howlett (2009) for detailed explanation.

Reichardt, 2016). Political scientists support effective policy implementation by studying the multi-level policy cycle and distinguish between policies implemented by governments and other actors, including their drivers and interests. 'Public policy' is defined as anything that governments do and do not do and as decisions taken by governments to select goals and means to achieve them (Howlett, 2009, 2011). Economists, in most cases, consider climate policy (implementation) instruments (e.g. Emission Trading System (ETS)) and assess the welfare-enhancing effects based on multiple objectives (Bouma et al., 2019) such as effectiveness, induced innovation and equity. Finally, integrated assessment modellers use the term climate policy to represent levers that decrease greenhouse gas emissions levels, often focussing on least costs.

Therefore, this article aims to give a conceptual foundation of climate policy scenarios implemented by IAMs based on concepts from the policy design literature combined with policy terms used in IPCC reports, and use this to increase transparency. We use the experience obtained during the CD-LINKS (CD-LINKS, 2017a) and Sentinel (2020) projects. The CD-LINKS project explored the interaction between climate policy and development, for which climate policy scenarios including explicit representation of current policies and comparing them to scenarios that represent long-term temperature goals was one of the main objectives (CD-LINKS, 2016). The SENTINEL project aims to build a suitable model for assessing the EU low carbon transition. Within these project policy design concepts where used, and the results and insights from both projects are brought together to develop a climate policy framework. This framework can be linked to policy scenarios, and especially gives an indication of the policy stringency and sufficiency, status of implemented policies, and uncertainty of implementation underlying the represented policies. This information can inform policymakers about the system-level impacts of their actions, help scholars operate the science-policy interface more effectively, and enable actors to hold politicians accountable. To illustrate the application of the framework and increase transparency, we use it to document the implementation of different policy scenarios in the IMAGE model (Stehfest et al., 2014).

This article adds to the literature by linking IAM scenario development to public policy design concepts used to increase the transparency of model implementation and contextualise policy stringency of model scenarios. Although elements of the public policy design were (implicitly) used in developing earlier climate policy scenarios (Roelfsema et al., 2020), this was never discussed in literature. We first developed a climate policy framework by comparing the definition of 'policy' between policy design literature and IPCC reports. Subsequently, this framework was used to define the contours of different climate policy scenarios, showing how this materialises for policies implemented in the international UNFCCC climate negotiations and the EU (and other economies in the Supplementary Information). Finally, we show how these scenarios are developed by translating policy assumptions to model inputs, illustrated with results from the IMAGE model.

2. Climate policy framework

The climate policy framework defined in this article is based on a comparison and combination of policy concepts from the Howlett policy design framework (Howlett, 2009, 2011) and climate policy terms consistent with the WGIII IPCC reports.

2.1. Policy design literature compared with IPCC reports on climate policy

One noteworthy observation from the comparison of policy terms from the selected policy design literature and IPCC reports is the agreement on terms, but also two clear differences: (1) Howlett (2009), (2011) uses the terms 'goals' and 'objectives' differently from the IPCC reports (see Table 1), and (2) policy instruments in IPCC reports are only considered at the decision-making stage, while Howlett (2009), (2011) dicusses instruments at all stages of the policy cycle. In this article, we comply with the language and practice of IPCC reports.

Policy design scholars aim to give insights to policymakers into the implementation of effective and efficient policies. Although several frameworks exist (e.g. Rogge and Reichardt, 2016), the policy design framework from Howlett (2009), (2011) is often referred to in climate policy literature, see for example, Harris (2014), Pahle et al. (2018) and Schaffrin et al. (2015). In this framework, policy is analysed at multiple levels that change from less tangible to more concrete policymaking: governance mode, policy regime and programme (Howlett, 2009, 2011), see Table 1. Governance modes are a favoured set of ideas and instruments; the policy regime defines the preference for general policy tools and a generic set of policy objectives; the programme matches means to specific policy targets (Howlett, 2011). Each level comprises complex entities consisting of policy aims achieved by policy means (see Table 1). Policy aims are basic aims and expectations of governments, while policy means are tools to attain these aims (Howlett, 2011). A policy aims to change from abstract policy objectives to operationalizable goals and concrete policy targets resulting from policy instrument calibration. Policy means are often viewed as (technical) implementation instruments in the decision-making stage. However, they are in this public policy design framework also regarded as less technical (e.g. procedural instruments) to occur in all stages of the policy cycle (Howlett, 2011). The policy levels in this framework correspond to the policy cycle, which is an idealised process of policymaking divided into several stages: agenda setting, policy formulation, decision-making, policy implementation and policy evaluation; problems come to the attention of governments, policy options are formulated, governments adopt a particular course of action, policies are put into effect and finally evaluated (Howlett, 2011; Lasswell, 1956). Note that the policy cycle is a simplifying representation of the policy process with the aim to reduce complexity and enable better examination (Howlett, 2009). In reality, the different stages could overlap. This especially holds for the decision-making and implementation stage that both involve policy targets, and the stages could be passed through interactively (Table 1). Nevertheless, they differ in aims and means because setting a specific target and calibrating the policy instrument parameters is done in the

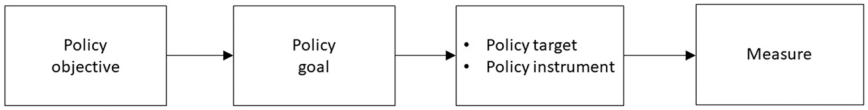

Fig. 1. Climate policy terms with decreasing abstraction level from IPCC WG III reports (IPCC, 1995, 1996, 2001, 2007, 2014b, 2018).

decision-making stage, while implementing measures to achieve the policy targets with available organisational capacity, resources and given rules of procedures is done at the implementation phase (Howlett, 2011, 2018).

IPCC reports summarise scientific information on climate change from different scientific disciplines, and specifically the IPCC Working Group III reports focus on climate mitigation policies and results of IAM studies. In these reports climate policy is not explicitly defined, but policy terms are used coherently (See Supplementary Information for references). The definition of the term 'policies' is broad, and covers all procedures developed and implemented by governments (IPCC, 1996), and are a course of action taken and/or mandated by a government (IPCC, 2014a). **Policy objectives** capture general notions, often qualitative, such as mitigating climate change and cost effectiveness, but also improving food security, energy security, energy access and air quality (IPCC, 2001, 2007), see Fig. 1. Furthermore, **policy goals** make the objectives more concrete, are defined as 'long-term and systemic', and are established in agreements to capture what needs to be achieved (IPCC, 2014b). They can be set at varying degrees of specificity (IPCC, 2007), either descriptive or using a quantitative target.

Technologies, policies and institutional settings are means to achieve climate policy goals (IPCC, 2014b). **Policy targets** follow from policy goals, are 'near term and specific', and can be classified according to whether they require absolute greenhouse gas reductions relative to a historical base year or baseline scenario, or reductions relative to economic output, population growth, or business-as-usual projections (intensity targets) (IPCC, 2014b). **Policy instruments** are not explicitly defined in the IPCC WG III reports, but are divided into economic, regulatory, voluntary and R&D (Gupta et al., 2007; IPCC, 2007). Up to now, these instruments are mainly discussed in the chapters not concerned with IAM results (but gain ground in IAM literature, see Introduction). They are identified as those being implemented by a group of countries (e.g. Internationally Transferred Mitigation Outcomes (ITMOs), see Edmonds et al., 2021), by individual countries unilaterally (i.e. feed-in-tariffs) or in a multilateral agreement (i.e. Bonn Challenge) (IPCC, 1995). In addition, the IPCC report considers measures and are defined as 'technologies, processes or practices that contribute to mitigation, for example renewable energy technologies, waste minimization processes, public transport commuting practices' (IPCC, 2014a). In accordance with the policy means from the policy design framework, a distinction is made between policy measures and technical measures, where a **policy measure** (e.g. ETS) is the same as a policy instrument or policy tool (Givoni et al., 2013), and **a technical measure** is the installation of technologies, for example solar PV. In this article, we will not use the term 'policy measure', but refer to it as policy instruments. In addition, measures signify 'technical measures'.

2.2. The framework

The combination of abstract policy concepts and terms from Howlett (2009), (2011) and the IPCC reports discussed in Section 2.1 constitute the building blocks of the climate policy framework that we develop in this paper and which includes climate policy components at different stages of the policy cycle (see Fig. 2). This framework defines key terms and concepts applicable to the assessment of climate mitigation policy in IAMs.

The foundation of the climate policy framework is the broad definition of the term 'climate policy' in all its forms, that is used in integrated assessments. We use the definition from Roelfsema et al. (2020) and adjust it to '*the result of agenda setting, formulation, decision-making and implementation by (groups of) governments considering actions to mitigate climate change at the international and economy-wide level that encompasses (aspirational) objectives and goals not necessarily secured by legislation, national targets secured by legislation, and policy instruments and targets designed and calibrated to implement these goals and objectives*'.

The climate policy framework is divided into two dimensions that both apply to international and economy-wide climate policy. The first dimension represents policy components and is divided into policy aims and policy means; the second dimension represents the different stages in the policy cycle. Applying this hierarchy to the identified climate policy terms from the previous section, one could see that climate policy is captured by objectives in the agenda setting stage and implemented through formalised goals defined in the policy formulation stage and targets in the decision-making stage in guise of policy instruments that are translated into (technical) measures to implement technologies and infrastructure. The changes in the physical system result in reductions in energy use, land use change and finally in reduction of greenhouse gas emissions. Note that opposite to Howlett (2011) the term 'instrument' is only used to refer to policy instruments which are calibrated in the decision-making stage, conform use in IPCC reports.

3. The climate policy framework used to define contemporary climate policy scenarios

Scenario analysis in IAMs is used to assess possible future patterns of greenhouse gas emissions, their drivers and their effect on the atmosphere (IPCC, 1995). In the CD-LINKS (2016) and Sentinel (2020) projects different policy scenarios (CD-LINKS, 2017b; Roelfsema et al., 2021) were developed that represented different policy stringency levels. Based on this experience, the climate policy framework from the previous section was developed, and is now used as starting point to document scenario assumptions representing contemporary policy-making in the context of the UNFCCC and its linkages to national and economy-wide levels. The framework is suitable for laying the

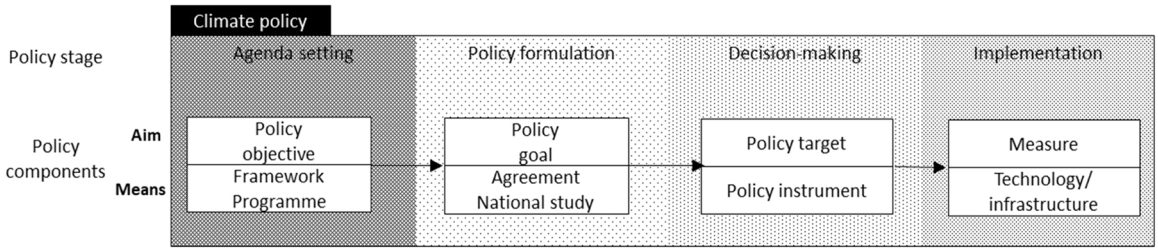

Fig. 2. Climate policy framework.

Table 2
Climate policy framework applied to the international (UNFCCC) and national (EU as example) context.

Climate policy	Components/ stages	Agenda setting	Policy formulation	Decision making	Implementation
International (UNFCCC)	Policy aims	**Policy objective** Article 2: Stabilise greenhouse gas concentrations in the atmosphere at a level that 'would prevent dangerous interference with the climate system'	**Policy goals** • Hold the increase in global average temperature to well below 2 °C above pre-industrial levels; and to pursue efforts to limit the increase to 1.5 °C • Reach global peaking of greenhouse gas emissions as soon as possible • To achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century	**Policy targets** Targets in NDCs (submitted to Paris Agreement): Emission reduction targets (e.g. EU: 55% reduction relative to 1990 by 2030) non-fossil targets (e.g. China: 20% non-fossil share by 2030) afforestation (e.g. India: additional carbon sink of 2.5–3 $GtCO_2eq$ by 2030) Targets in LTS (submitted to Paris Agreement): (e.g. EU: net-zero emissions by 2050)	
	Policy means	**Framework, Programme** UNFCCC	**Agreement, Protocol, Accord, Treaty** Paris Agreement	**Articles** of the Paris Agreement (instruments) Article 4.2: NDC Article 6: internationally Transferred Mitigation Outcomes (ITMOs)	
Economy-wide (EU)	Policy aims	**Policy objectives** EU: cut greenhouse gas emissions by taking the most environmentally and cost-effective policies and measures	**Policy goal** EU: Climate neutral through net zero greenhouse emissions by 2050	**Policy targets** EU: • (current) economy-wide emission reduction target: 40% reduction relative to 1990 • (current) ETS emission reduction target: 43% reduction relative to 2005 • (current) effort sharing reduction target: 30% reduction relative to 2005 • (planned) emissions target of 55% below 1990 levels by 2030	
	Policy means	**Programme** European Climate Change Programme	**Legislation** European Climate law **Climate strategies, roadmap** Green Deal	**Policy instrument (mix)** 2030 climate & energy framework with ETS and effort sharing as main policy instruments	**Measure** Installation of renewable energy (e.g. solar PV), insulation of residential buildings, reforestation

foundations of climate policy scenarios as it presents the different levels of policymaking and established aims and instruments in a structured manner. The resulting aims and means from each policy stage (see Fig. 2) represent the main substance of each scenario. As the framework represents all stages from the policy cycle, it can be used for any future policy environment. However, in this paper we focus on scenarios of contemporary climate policy implementation. For this purpose, we first describe the current policy environment and distil key goals, targets and instruments that define the climate policy scenarios.

3.1. Current climate policy environment

Current climate policy implementation is occurring at two levels that are interlinked. At the international level climate mitigation objectives and goals are negotiated within the UNFCCC. However, actual implementation takes place at the domestic or economy level (e.g. political union); for example, the EU has a long history of climate policy (Delbeke and Vis, 2015; European Commission, 2000; Nascimento et al., 2021). EU policies are analysed in the SENTINEL project (2020) to assess the transition to a low-carbon energy system, and it showed that current implementation covers all energy- and land use sectors, and is clearly documented (European Commission, 2022). For this reason, the EU is used as an example in this article. As the EU pledges a collective commitment to the UNFCCC, and is included as one economy in most IAMs, we do not consider the policies from different Member States, and refer to EU policies as being implemented economy-wide. We describe the EU policy context in this section, but policies from other large countries can be found in the Supplementary Information.

Climate policy was put on the global agenda by scientists in 1972 during the UN Conference on the Human Environment (UN, 1972), and continued at the first World Climate Conference in 1979 (WMO, 1979) where climate change was the only topic on the agenda. In 1992, the UNFCCC was established in 1992 and formulated the ultimate objective to 'stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system' (UNFCCC, 1992) (see Table 2). This objective is translated in the Paris Agreement into the long-term goal to hold global increase in temperature well below 2 °C above pre-industrial levels and to pursue efforts to limit the increase to 1.5 °C (UNFCCC, 2015). In order to achieve this goal, Parties to the agreement need to prepare, communicate and maintain NDCs that present national mitigation efforts to reach the climate goals of the Paris Agreement (UNFCCC, 2015, 2018), which represent the national or economy-wide ambition. NDCs are the link between international and national climate policy, as they include

national ambition towards meeting the Paris goals. They are instrumental (i.e. procedural instruments) to the Paris Agreement but need to be achieved at the domestic or economy level. In addition, instruments exist to transfer domestic mitigation outcomes between countries (Edmonds et al., 2021), such as Internationally Traded Mitigation Outcomes secured in the Paris Agreement's rulebook. In addition, Parties to the Paris Agreement are currently setting long-term targets in Long-term Strategies.

On the national level, climate policy is captured by legislation and climate strategies (Dubash et al., 2013; Iacobuta et al., 2018). Climate legislation is approved by parliament or equivalent processes containing objectives to reduce greenhouse gas emissions, whereas national climate strategies are non-binding, cover all sectors and promote climate change mitigation (Dubash et al., 2013). The climate strategies often include aspirational goals for greenhouse gas reductions, energy- and land-use. To achieve the national targets, policy instruments are implemented at the economy-wide level, with the climate strategies serving as the starting point for target level setting. The strategies result in implementation of several policy instruments, often as part of an instrument mix, which is a combination of instruments aimed at one or multiple policy objectives (Bouma et al., 2019; Rogge and Reichardt, 2016). Within the EU, climate policy formulation and decision-making is done at the overarching Union level, but implementation takes place at Member State level. The EU policy documents clearly define 'policies and measures' that are 'all instruments which aim to implement commitments [..], which may include those that do not have the limitation and reduction of greenhouse gas emissions as a primary objective' (EEA, 2019). Within this context, policy is a general term that sets an overarching frame that could include targets that do not aim for greenhouse gas (GHG) reduction (e.g. efficiency improvement, renewable share) and could include several (technical) measures that are concrete actions to implement a certain policy (e.g. insulation of buildings). The policy objective describes the expected effect of a policy, and targets specify how the general objectives are met (EEA, 2019).

The NDCs of three-quarter of all countries include emission targets (Climate Watch, 2021), but some countries also include other types of targets such as non-fossil shares and intensity targets (see Table 2 and Supplementary Information). As part of their NDC, the EU pledged a GHG reduction target of 40% below 1990 level by 2030, which has been updated to a reduction of net GHG emissions (including land use and land use change (LULUCF)) of at least 55% (European Commission, 2020). NDC targets for other countries can be found in the scenario protocol in the Supplementary Information. Although implementation takes place at Member State level, we consider the EU as one economy as since the Kyoto protocol, Parties are allowed to pledge and meet emission commitments collectively (UNFCCC, 2000). The EU has established the European Climate Change Programme in 2000 in response to the Kyoto Protocol, with the objective to address climate change to help identify the most environmentally and cost-effective policies (European Commission, 2020). Recently, the EU published the Green Deal roadmap with the goal to accomplish carbon neutrality defined as '*no net emissions of greenhouse gas emissions in 2050*'(European Commission, 2019). In 2014 the EU proposed a 40% reduction target of GHG emissions relative to 1990, which has now been secured by the Climate & Energy framework. This framework is a mix of different policy instruments, of which the Emission Trading System (ETS) and the effort sharing mechanism are the main policy instruments. The 2030 targets for these policy instruments are respectively 43% and 30% emission reduction relative to 2005. In response to the European Climate Law, both the EU Council and Parliament adopted the target to reduce GHG emissions by 55% relative to 1990 (European Commission, 2020). The policy plan Fit-for-55 that ensures implementation of this target is published (European Commission, 2021), but has not been accepted yet. Therefore, we label the 55% reduction as a planned policy target, and the 40% reduction as a current target. The full list of EU policies and those for other G20 countries is found in the model protocol in the Supplementary Information.

Table 3
Translation of climate policy framework to climate policy scenarios and examples of implementation in the IMAGE model. The agenda setting and implementation phase have been dropped as agenda setting for choosing the goals that would stabilise greenhouse gas concentrations has been completed and the instruments and targets established in the decision-making phase results in technical measures included in the current policies scenarios developed by integrated assessment models.

Climate policy	Policy formulation	Decision-making
Policy aims at international level (UNFCCC)	**2 °C/1.5 °C scenario** By 2100: translation to W/m^2, CO_2 budget, ppm	**NDC/LTS scenario** • Carbon price to implement (pledged/calculated) NDC targets • Carbon price to implement CO_2/GHG intensity target • Non-fossil target by adding minimum requirement to non-fossil technologies in investment decision
Policy means at economy level	(not modelled) Aspirational goals are checked afterwards and need to be achieved by implemented policy targets	**Current policies scenario** • Carbon price or energy tax (e.g. Canada carbon tax) • Change model input parameter to enforce target (e.g. Appliance standard) • Translate policy target to appropriate model input parameter (e.g. net-zero emissions buildings to 0 GJ/m^2) • Use aspirational goal from climate strategy (e.g. renewable auctions in Brazil) **Planned policies scenario** ● (not modelled)
No new climate policy		**No new policies scenario**

3.2. Climate policy scenarios

The goals, targets and policy instruments from the applied climate policy framework (Table 2) are the basis for the climate policy scenarios. As the UNFCCC policy objective from the agenda-setting phase has already been translated to the temperature goals in the Paris Agreement, the focus in the CD-LINKS project was on these global goals and policy implementation for large G20 countries, from which we only address global and EU policy in this section. However, the scenarios from the Special Report on Emission Scenarios (SRES) could be seen to represent the assessment of the UNFCCC objective to stabilise greenhouse gas concentrations (Riahi et al., 2007) from the agenda-setting phase. Nevertheless, we only consider the policy formulation stage at the international level where agreements on collective goals are made, and the decision-making stage at the international and economy-wide level where policy targets, policy instruments and measures are implemented. The international policy aims from the climate policy framework are the basis for the 2 °C, 1.5 °C and NDC scenarios, while the policy targets connected to the policy means from the economy-wide level are input to the current policies scenario (see Table 3). The policy targets and policy instruments that are implemented in the model result in implementation of specific measures (e.g. renewable energy technologies such as solar PV, see Section 4).

The temperature goals underlying the 2 °C and 1.5 °C scenarios were established during the policy formulation stage and hold for the global level. These two scenarios together give a range for the implementation of the Paris climate goals. It is assumed the temperature targets hold for the end of this century, which implies that overshoot is allowed. However, the temperature goals can only be met with a certain probability

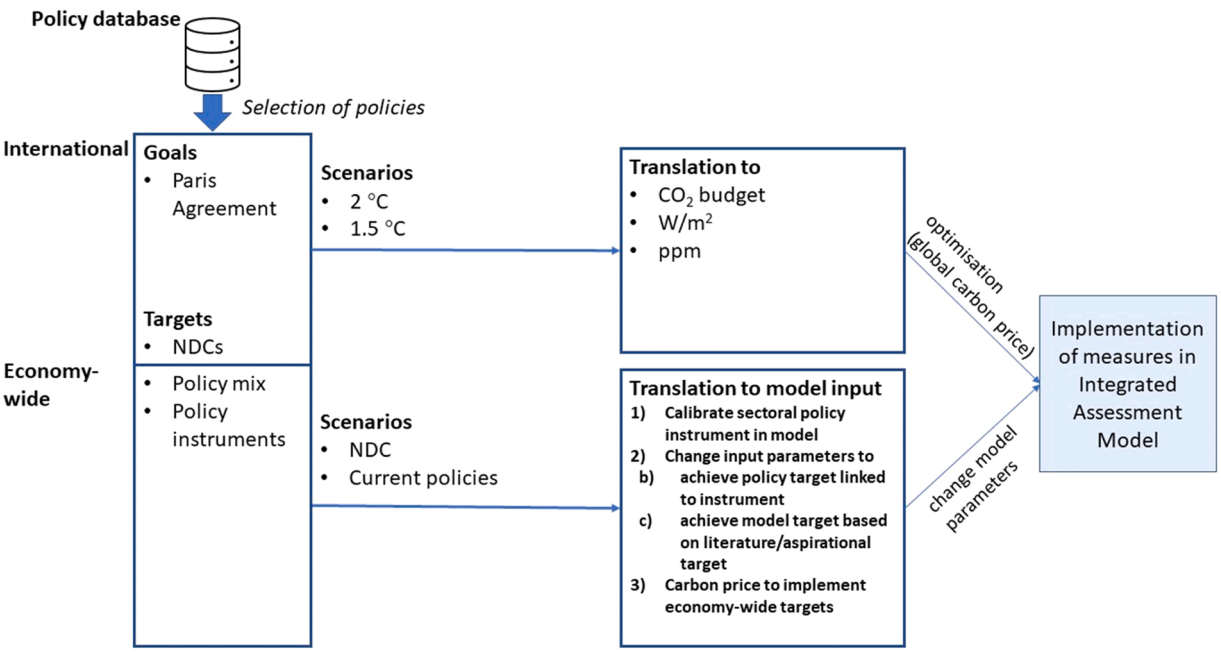

Fig. 3. Implementation of climate policy scenarios in integrated assessment models: a selection of policies (in terms of goals or targets) are translated into model input for models and result in the implementation of measures.

due to climate system uncertainty. Common practice is to use > 66% probability ('likely' according to IPCC parlance (Mastrandrea et al., 2010)). The NDCs are the results of the decision-making stage, and the NDC scenario assumes full implementation of the conditional pledged targets that are submitted on the international level, but need to be achieved at the economy level. These pledges are in some cases conditional on finance or international cooperation (den Elzen et al., 2016). Note that most countries have (also) pledged unconditional targets. NDC targets can be divided into (1) economy-wide absolute emission reduction targets from historical base-year emissions, (2) emission reductions relative to a business-as-usual projection, (3) emission intensity reduction targets, (4) submitted actions absent of GHG-emission targets (King and van den Bergh, 2019; UNEP, 2015), (5) fixed level targets and trajectory targets (Climate Watch, 2021), and a few include additional non-fossil and forestry targets (CD-LINKS, 2017b; Roelfsema et al., 2020). The current policies scenario is also categorised under the decision-making stage, but at the economy-wide level. The end state of the decision-making process is the introduction of the policy instrument and the connected (quantitative) policy target. The current policies scenario assumes all domestic or economy-wide (sectoral) policies to be implemented if they are secured in legislative decisions, executive orders or equivalent, and no additional measures are taken (Averchenkova et al., 2017; UNEP, 2019). Planned policies that are in the pipeline to be adopted, are not included including targets set in economy-wide or national climate strategies (e.g. EU 2030 Climate Plan). Many studies also include a reference or baseline scenario in which no or few steps are taken to limit GHG emissions (IPCC, 1995). Since almost all countries have implemented climate policies by now this has become less significant and is only used as a starting point for the policy scenario model implementation, and is a hypothetical reference to determine the impact and costs of climate policy. Generally, the no new policies scenario relies on general narratives of alternative futures for societal development, such as the SSPs (Riahi et al., 2017; van Vuuren and Carter, 2014).

4. IMAGE implementation

After having developed and applied the climate policy framework to the present-day climate policy environment, we show how this was implemented in the IMAGE model (see Table 3). This clearly illustrates that more stringent and less abstract scenarios involve more details on assumptions and increased modelling efforts.

The IMAGE model is an integrated assessment model analysing global change by identifying future challenges and constructing different scenarios (Stehfest et al., 2014). The model is built up from different sub-models and includes 26 geographical regions covering all energy, industry, agriculture, and land use sectors. The IMAGE land use model includes agricultural production, land cover and land use. The TIMER model includes the energy supply and demand sectors and are relatively detailed in terms of activities and technologies. Investment decisions are represented by the multinomial logit (MNL) function that assigns market shares based on (time dependent) production costs including also non-economic costs, for instance to represent behaviour, and assigns the highest share to the cheapest option (van Vuuren, 2007). The model describes dynamic relationships in the energy system, such as inertia and learning-by-doing in capital stocks, depletion of the resource base and regional trade. Innovation in TIMER is modelled through 'learning-by-doing' to represent technological development (van Vuuren, 2007). The FAIR model analyses mitigation costs, benefits, emission reductions after emissions trading and climate goals (Hof et al., 2017). More detailed information on the IMAGE model is found at PBL (2020b), (2020a). For assessments such as defining optimal policy packages based on different economic and social criteria or assessments of smaller countries, other types of (national) models and tools need to be used.

The starting point for the current policies scenario is the no new policies scenario, which excludes the impact of climate policies after a certain recent historical date (e.g. 2020). The SSP2 scenario (Fricko et al., 2017) is a middle-of-the-road scenario and the IMAGE implementation is used and calibrated to historical data to include the historical impact of climate policies. In the CD-LINKS, (2017a), (2017b) different climate policy scenarios were implemented (McCollum et al., 2018; Roelfsema et al., 2020), which were updated for this article based on updated SSP scenarios (Vuuren et al., 2021) and COVID impact assessments (Dafnomilis et al., 2021). The policies included in this scenario were retrieved from the Climate Policy Database (Iacobuta et al., 2018; NewClimate Institute, 2015), which is an open, collaborative platform and collects information on currently implemented policies from countries worldwide (see Fig. 3). From this database, a selection of quantifiable high-impact policies was made based on literature, expert

Table 4
Description of policy implementation per policy type in the IMAGE model (PBL, 2020b, 2020a).

Policy type	Example policy instruments	Implementation in IMAGE
AFOLU	Forest code	Mitigation is introduced via increased protection levels for carbon-intensive ecosystems and reforestation of degraded or abandoned land
Appliances	energy labels, energy conservation standards	The autonomous efficiency improvement for specific appliances is increased to meet the set target
Biofuels road transport	biofuel/renewable fuel standard	The biofuels target applies to the full fleet, while the electricity target to new vehicles. The results of the multinomial logit (MNL) model (investment shares) is adjusted to the level that meets the target; the share of (non-bio) fossil fuelled cars is decreased, keeping the original oil, gas ratios constant.
Electric vehicle adoption targets	subsidy, reward as part of vehicle standard	
Building Code	building code	The policy target is achieved by increasing the insulation level. If this does not reach the building code target, additional heat pumps are installed to cover heating demand efficiently. Finally, rooftop PVs are installed to reach the target level.
Carbon price	carbon tax, cap and trade (emission trading system, certificates/permits)	Carbon price is endogenous to the TIMER model, resulting in higher fossil technology prices affecting the MNL, resulting in changed allocation
Efficiency vehicles (cars, trucks)	CO_2 performance standards, fuel economy standard	The MNL without constraints is adjusted by minimising the difference between new and original new fleet composition, and adding the constraint to meet the average fleet efficiency set by the target
F-gases	ban/penalty	Tax is levied on F-gas emissions and is implemented with a MAC curve. The tax is set to the level that would meet reduction target
Power Plants	CO_2 or efficiency standard for new and existing plant	Restrictions are imposed on the MNL to prevent installing power plants with CO_2/kWh or efficiency above/below set target Existing power plants that do not meet the target are early depreciated (with lag of 3 years)
Renewable Electricity	renewable auction, feed-in-tariff, renewable portfolio standard	Capacity targets- The MNL without constraints is adjusted to meet the set targets, and the fossil-capacities are decreased making sure the original mutual ratio is preserved Renewable generation share - First the MNL is calculated without constraints resulting in different weights per technology. The weights are adjusted for those technologies in the generation share. The remaining weights are adjusted making sure the original ratios apply

judgement, and the criterion that no evidence exists of implementation barriers (Roelfsema et al., 2020).

Current policies are implemented in the model with a focus on replicating the expected impact of climate policies on GHG emissions, energy-, and land use. There are three possibilities to implement a specific policy instrument into the model, and a fourth to implement an economy-wide target (see box 'Translation to model input' in Fig. 3). First, in some cases, the policy instrument is included in the IMAGE model, and the existing carbon price, energy tax or subsidy can be directly implemented (see Fig. 3). This price results in technology investments with lower GHG intensity or higher energy efficiency. An example is the carbon tax in Canada. Second, the policy target can be implemented by changing model parameters. For this purpose, two variants exist: (a) the policy target linked to the policy instrument can be directly implemented by changing an input parameter to the model, for example the target for EU appliance standards (after the target year, the TIMER model gradually reverts to the standard (SSP2) parameters); (b), if no explicit policy targets exist (e.g. renewable auctions in Brazil), either a literature estimate is used or the underlying aspirational target from the national climate strategy (e.g. renewable electricity target from the energy plan PNE 2030 (Brazilian Ministry of Mines and Energy, 2007)) is assumed to be implemented until the target year. This target year is possibly beyond the current phase of the instrument for which policy settings are fixed (e.g. Renewable auction period) (Roelfsema et al., 2020). Third, economy-wide targets from legislation or connected to policy mixes (e.g. 40% reduction target in the EU) are implemented for NDCs through an economy-wide carbon price, but are not explicitly implemented in the model for current policies as the aggregated impact of the underlying policy targets (connected to policy instruments) should result in achieving this target. However, attainment of these targets is checked afterwards by comparing the overall targets with model results. Table 4 describes how each identified policy type is implemented in IMAGE. The list of policies and linked policy targets for different countries can be found in the Supplementary Information.

If the target belongs to a country that is part of a larger model region, the regional target is a weighted average assuming that the other countries would follow no new policies scenario trends (CD-LINKS, 2017b), see Supplementary Information. Targets for Australia, Argentina and Republic of Korea are first aggregated from country to model region. EU climate policies are implemented in both the Western- and Central European region of IMAGE, although those contain non-EU countries as well, accounting for approximately 5% of the total regional GHG emissions (in 2015).

Fig. 4 shows the emission pathways from the current policies scenario, and illustrates the impact of adding one policy type at the time starting from the no new policies scenario into the IMAGE model for the World and EU (in order of the TIMER sectors supply, industry, transport, buildings, second from the IMAGE AFOLU sectors). GHG emissions are expressed using the 100-year global warming potentials (GWPs) from the IPCC Fourth Assessment Report. The policies were categorised into ten policy types (see Table 4). Note that the impact depends on the order policy types were added to the decomposition, but discussion on this falls outside the scope of this article. It shows that both on a global and EU level, carbon pricing (Canada carbon tax, EU and South Korea ETS, India's PAT scheme) has the largest impact. The global reduction due to the renewable energy policies is much lower than presented in Roelfsema et al. (2020) due to update of the SSP2 scenario, which takes into account the fast decrease in costs and high penetration of these technologies in the last few years.

For the NDC scenario, a list of NDC targets for major emitting countries was developed in the ADVANCE project (Luderer et al., 2018; Vrontisi et al., 2018), and was adjusted for G20 countries in the CD-LINKS project (McCollum et al., 2018; Roelfsema et al., 2020). The targets were updated with the NDCs for the EU, Brazil and China (announcement) as submitted in December 2020. NDC targets are implemented through a country or regional carbon price on top of the current policies scenario that additionally includes non-fossil and intensity targets included in a few NDCs (e.g. China, India). The LTS scenario is work in progress, and therefore out of the scope of this paper.

The 2 °C and 1.5 °C scenarios represent the implementation of the long-term climate goals of the Paris Agreement. Given the choice of target year and probability, these targets are translated into a concentration goal (ppm), carbon budget ($GtCO_2eq$) or radiative forcing (W/m^2) to be implemented in IAMs. In the CD-LINKS project, the 2 °C and 1.5 °C temperature limits were translated to carbon budgets for the period 2011–2100 of 1000 $GtCO_2$ and 400 $GtCO_2$ in accordance with keeping temperature increase below the temperature goal with a 66% probability, as often used in assessments included in IPCC reports (IPCC, 2014b; Roelfsema et al., 2020). In the updated scenarios we aimed to achieve a radiative forcing of 2.6 and 1.9 W/m^2 respectively. The 2 °C or 1.5 °C scenarios were implemented in the IMAGE model by implementing a global carbon price starting in a specific year and assuming

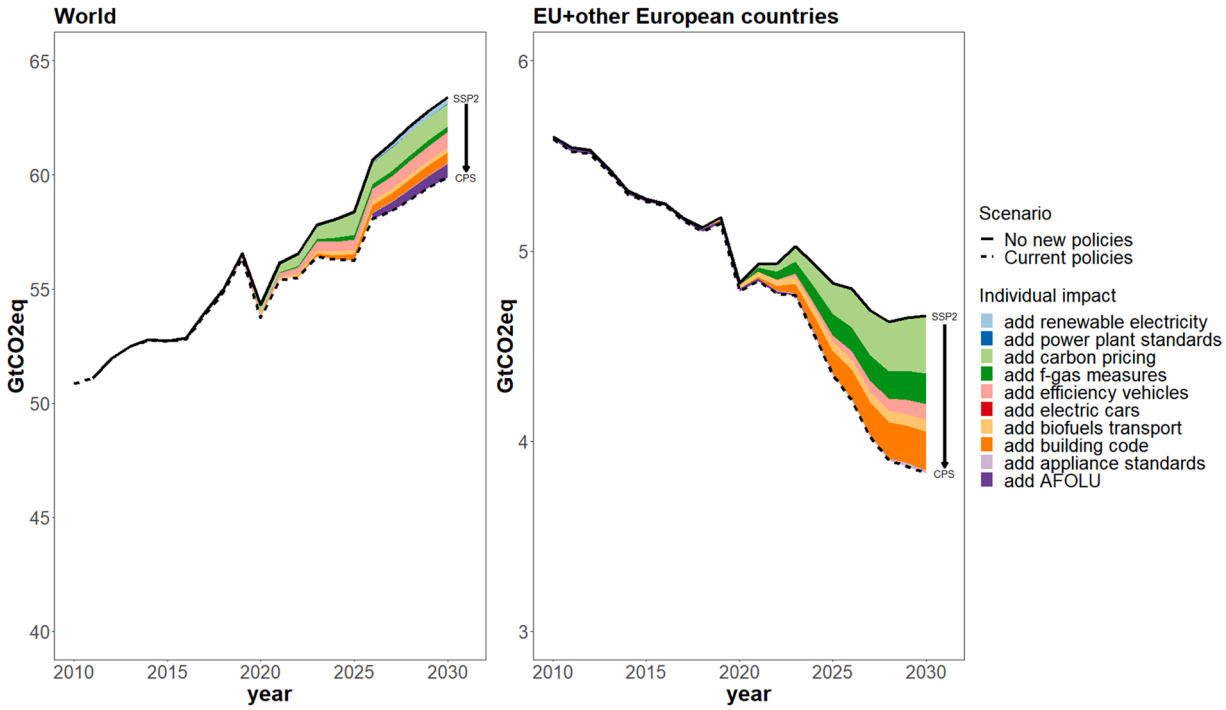

Fig. 4. Contribution of the impact of individual policies in the aggregate emission reduction between the no new policies scenario (SSP2) and the current policies scenario (CPS). The impact of each policy (implemented into the model in the order shown in the legend) is shown by each coloured area are and model implementation is described in Table 4.

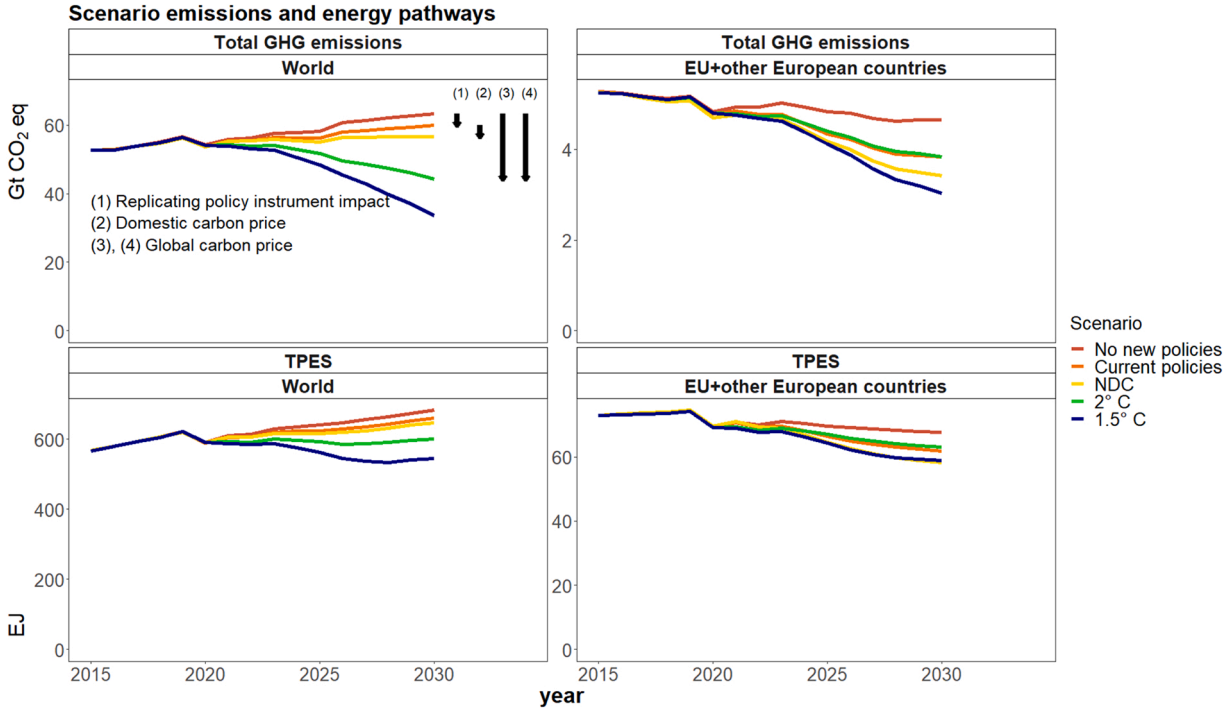

Fig. 5. Impact of climate policy on global and economy-wide greenhouse gas emissions and total primary energy supply (TPES) for the World and EU.

climate policies are implemented where this has lowest costs. We chose the starting year of cost-effective implementation immediate (e.g. 2020). Optimisation is done in the FAIR model which is soft-linked to the TIMER and IMAGE land use models that supply MAC curves as input.

Fig. 5 shows the resulting emissions and primary energy pathways for the World and EU from the IMAGE model implementation between 2015 and 2030. The results confirm the insights that the world is not on track to achieve the Paris temperature goals, both with current policies and NDCs (Roelfsema et al., 2020; UNEP, 2020). Note that the results illustrate the results for one model, while for example the Emissions Gap report (UNEP, 2020) gives a multi-model range (10th-90th percentile) showing by 2030 39–46 $GtCO_2eq$ global emissions for the 2 °C scenario, and 31–41 $GtCO_2eq$ global emissions for the 1.5 °C scenario. The updated EU NDC target (55% reduction relative to 1990) now lies

between the 2 °C and 1.5 °C emission levels by 2030.

5. Discussion and conclusion

The climate policy framework that we introduced categorises climate policy terms from the IPCC WGIII reports and maps them to policy scenarios with increasing ambition levels secured by policy objectives, goals and targets. This framework attempts to respond to call to integrate social sciences insights, in particular public policy design (Victor, 2015), and to the criticism that IAMs lack transparency on input assumptions and have an inadequate representation of real-world policies (Gambhir et al., 2019).

Climate policy questions at both the international and national level have changed since the Paris Agreement from 'where do we go' to 'how do we get there', two of the key questions from the Talanoa Dialogue (Winkler and Depledge, 2018). This resulted in a shift of focus to domestic and economy-wide actions. Therefore, IAMs have started to include explicit representation of domestic and economy-wide climate policies, enabling them to compare the aggregated impact of these policies to pathways adhering to the global temperature targets established in the Paris Agreement. It shows that IAMs have changed from cost-effective implementation to real policy impact on the short-term until 2030.

However, it is clear that not all elements concerning climate policy can be analysed with IAMs. Cost-effective implementation of long-term climate policies assumes an economy with frictionless markets that produces a social optimum achieved by a fully informed social planner (Staub-Kaminski et al., 2014) and tends to emphasize technological rather than social constraints (Anderson and Jewell, 2019). This implies that most models have only a limited ability 'to reflect the specific social and economic dynamics of the developing and transition economies' such as market imperfections, institutional barriers or dynamics of the informal sector (IPCC, 1995). Also, political credibility and feasibility is not well represented. Credibility means that countries will fully implement their international commitments (Averchenkova et al., 2017). Political feasibility encompasses the ability to intervene in the economy and to create a path for actors to realize set policy aims (Jewell and Cherp, 2020). For this, it is necessary to be able to meet the costs of action and the availability of capacity and skills, finance for successful implementation (Averchenkova et al., 2017). Currently, linkages and integration of feasibility and social acceptance concepts are being developed (Geels et al., 2020; Jewell and Cherp, 2020).

We identify two next steps for the climate policy framework. First, this framework could for example be used by IAM modellers and public policy design scholars to work together and learn from historical climate policy implementation by linking past IAM scenarios to introduction or changes of climate polices within the policy cycles. This could improve current policy scenario implementation, and give insights into the effectiveness of individual or mix of policies or identify the effects of political economy insights (Peng et al., 2021). Second, it can be used to expand the suite of climate policy scenarios, by including policies not having climate as primary objective (but with impact on GHG emissions), planned policies, propose enhanced policies (as done in van Soest et al. 2021)) or 2 °C or 1.5 °C scenarios that achieve long-term goals with a specific mix of policy instruments (see for example (Pollitt et al., 2019)). This would enable including more local circumstances in the scenario design. Future work might expand the coverage of the current policies scenario to also include subnational governments (e.g. cities, regions, states and provinces) and bilateral or multi-lateral agreements such as the International Maritime Organisation (IMO). However, including subnational policies in IAMs is not straightforward due to the difficulty of matching actor baselines and the overlap with national policies (Hsu et al., 2019; Kuramochi, Roelfsema et al., 2020). Another extension is to include submitted net-zero emissions goal for the second half of this century (UNFCCC, 2015) and country contributions secured in the Long-Term Strategies submitted to the UNFCCC. Finally, future research could develop a 2 °C and 1.5 °C scenario based on a selection of policy targets and instruments instead of a global carbon tax.

We conclude that clarifying the conceptual climate policy framework by linking public policy and political science to IAM scenarios improves both the understanding of policy stringency and transparency and avoids misunderstanding of use climate policy scenarios. However, complementary analysis to integrated assessments is required (Gambhir et al., 2019; Staub-Kaminski et al., 2014), but this does not mean that improvements cannot be taken to increase real-world representation of IAMs even further, and linking and integrating these model with social science insights.

CRediT authorship contribution statement

Mark Roelfsema: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, project coordination. **Heleen van Soest**: Methodology, Software, Validation, Formal analysis, Investigation, Writing – review & editing. **Michel den Elzen**: Methodology, Writing – review & editing, Supervision. **Heleen de Coninck:** Methodology, Conceptualization, Supervision, Writing – review & editing. **Takeshi Kuramochi**: Methodology, Investigation, Writing – review & editing. **Mathijs Harmsen**: Software, Validation, Formal analysis. **Ioannis Dafnomilis:** Software, Validation, Formal analysis. **Niklas Höhne**: Methodology, Conceptualization, Supervision, Funding acquisition. **Detlef P. van Vuuren**: Methodology, Conceptualization, Writing – original draft, Supervision, project coordination, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

These projects have received funding from the European Union's Horizon 2020 Societal Challenges Programme under grant agreement No. 837089 (SENTINEL) and the European Union's Horizon 2020 research and innovation programme under grant agreement No. 821471 (ENGAGE).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.05.001.

References

Anderson, K., Jewell, J., 2019. Debating the bedrock of climate-change mitigation scenarios. Nature 573, 348–349.

Averchenkova, A., Fankhauser, S., Nachmany, M., 2017. Trends in Climate Change Legislation. Edward Elgar Publishing Limited,. ⟨http://ebookcentral.proquest.com/lib/uunl/detail.action?docID=5199689⟩.

Baranzini, A., van den Bergh, J.C.J.M., Carattini, S., Howarth, R.B., Padilla, E., Roca, J., 2017. Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. WIREs Clim. Change 8 (4), e462. https://doi.org/10.1002/wcc.462.

Bouma, J.A., Verbraak, M., Dietz, F., Brouwer, R., 2019. Policy mix: mess or merit? J. Environ. Econ. Policy 8 (1), 32–47. https://doi.org/10.1080/21606544.2018.1494636.

Brazilian Ministry of Mines and Energy. (2007). Plano nacional de energia 2030. Ministério das Minas e Energia. http://www.mme.gov.br/mme/galerias/arquivos/publicacoes/pne_2030/PlanoNacionalDeEnergia2030.pdf.

Burch, S., Gupta, A., Inoue, C.Y.A., Kalfagianni, A., Persson, Å., Gerlak, A.K., Ishii, A., Patterson, J., Pickering, J., Scobie, M., Van der Heijden, J., Vervoort, J., Adler, C., Bloomfield, M., Djalante, R., Dryzek, J., Galaz, V., Gordon, C., Harmon, R., Zondervan, R., 2019. New directions in earth system governance research. Earth Syst. Gov. 1, 100006 https://doi.org/10.1016/j.esg.2019.100006.

Capros, P., Kannavou, M., Evangelopoulou, S., Petropoulos, A., Siskos, P., Tasios, N., Zazias, G., DeVita, A., 2018. Outlook of the EU energy system up to 2050: The case of

scenarios prepared for European Commission's "clean energy for all Europeans" package using the PRIMES model. Energy Strategy Rev. 22, 255–263. https://doi.org/10.1016/j.esr.2018.06.009.
CD-LINKS. (2017b). Protocol for WP3.2 Global low-carbon development pathways, http://www.cd-links.org/wp-content/uploads/2016/06/CD-LINKS-global-exercise-protocol_secondround_for-website.pdf.
CD-LINKS. (2017a). High impact policies, http://www.cd-links.org/wp-content/uploads/2016/06/Input-IAM-protocol_CD_LINKS_update_July-2018.xlsx.
CD-LINKS. (2016). CD-LINKS website. https://www.cd-links.org/.
Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P. R., Tavoni, M., Van der Zwaan, B.C. C., & Van Vuuren, D.P. (2014). Assessing transformation pathways. In Chapter 6 in: Working Group III contribution to the IPCC 5th Assessment Report "Climate Change 2014: Mitigation of Climate Change." IPCC. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter6.pdf.
Climate Watch. (2021). Explore Nationally Determined Contributions. https://www.climatewatchdata.org/.
Dafnomilis, I., Chen, H.-H., den Elzen, M., Fragkos, P., Chewpreecha, U., Soest, H. van, Fragkiadakis, K., Karkatsoulis, P., Paroussos, L., Boer, H.S. de, Daioglou, V., Edelenbosch, O., Kiss-Dobronyi, B., & van Vuuren, D. P.. (2021). Targeted green recovery measures in a post-COVID-19 world enable the energy transition (Nature Portfolio). https://doi.org/10.21203/rs.3.rs-667715/v1.
De Cian, E., Dasgupta, S., Hof, A.F., van Sluisveld, M.A.E., Köhler, J., Pfluger, B., van Vuuren, D.P., 2020. Actors, decision-making, and institutions in quantitative system modelling. Technol. Forecast. Soc. Change 151, 119480. https://doi.org/10.1016/j.techfore.2018.10.004.
Deetman, S., Hof, A.F., van Vuuren, D.P., 2015. Deep CO_2 emission reductions in a global bottom-up model approach. Clim. Policy 15 (2), 253–271. https://doi.org/10.1080/14693062.2014.912980.
Delbeke, J., Vis, P., 2015. EU Climate Policy Explained. Routledge. https://doi.org/10.4324/9789279482601.
Dubash, N.K., Hagemann, M., Höhne, N., Upadhyaya, P., 2013. Developments in national climate change mitigation legislation and strategy. Clim. Policy 13 (6), 649–664. https://doi.org/10.1080/14693062.2013.845409.
Edmonds, J., Yu, S.H.A., McJeon, H., Forrister, D., Aldy, J., Hultmand, N., Cuii, R., Waldhoff, S., Clarke, L., Clara, S.D.E., Munnings, C., 2021. How much could Article 6 enhance nationally determined contribution ambition towads Paris Agreement goals thourgh economic efficiency? Clim. Change Econ. 12 (02), 2150007. https://doi.org/10.1142/S201000782150007X.
EEA. (2019). Guidelines for reporting on policies andmeasures by Member Statesunder Regulation (EU) No 525/2013(EU Monitoring Mechanism Regulation). https://cdr.eionet.europa.eu/help/mmr/MMR Article 13 Reporting Manual PaMs (2018).pdf.
den Elzen, M.G.J., Admiraal, A., Roelfsema, M., van Soest, H., Hof, A.F., Forsell, N., 2016. Contribution of the G20 economies to the global impact of the Paris agreement climate proposals. Clim. Change 137 (3–4). https://doi.org/10.1007/s10584-016-1700-7.
den Elzen, M.G.J., Kuramochi, T., Höhne, N., Cantzler, J., Esmeijer, K., Fekete, H., Fransen, T., Keramidas, K., Roelfsema, M., Sha, F., van Soest, H., Vandyck, T., 2019. Are the G20 economies making enough progress to meet their NDC targets? Energy Policy 126 (October 2018), 238–250.
European Commission. (2000). European Climate Change Programme. https://ec.europa.eu/clima/policies/eccp_en#tab-0–0.
European Commission. (2018). In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (Issue November). European Commission (EC). https://ec.europa.eu/clima/system/files/2018–11/com_2018_733_analysis_in_support_en.pdf.
European Commission. (2019). The European Green Deal. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. https://ec.europa.eu/info/sites/default/files/european-green-deal-communication_en.pdf.
European Commission. (2020). Submission by Germany and the European Commission on behalf of the European Union and its Member States. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/European Union First/EU_NDC_Submission_December 2020.pdf.
European Commission. (2021). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. "Fit for 55": delivering the EU's 2030 Climate Target on the way to climate neutrality. COM/2021/550 fi. In European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0550.
European Commission. (2022). Climate action. https://ec.europa.eu/clima/index_en.
Fekete, H., Kuramochi, T., Roelfsema, M., Elzen, M.G.J, den, Forsell, N., Höhne, N., Luna, L., Hans, F., Sterl, S., Olivier, J., van Soest, H., Frank, S., Gusti, M., 2021. A review of successful climate change mitigation policies in major emitting economies and the potential of global replication. Renew. Sustain. Energy Rev. 137, 110602 https://doi.org/10.1016/j.rser.2020.110602.
Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D.L., Obersteiner, M., Pachauri, S., Riahi, K., 2017. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Glob. Environ. Change 42 (Supplement C), 251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004.
Gambhir, A., Butnar, I., Li, P.-H., Smith, P., Strachan, N., 2019. A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. Energies 12 (9), 1747. https://doi.org/10.3390/en12091747.
Gambhir, A., Green, R., Grubb, M., Heptonstall, P., Wilson, C., Gross, R., 2021. How are future energy technology costs estimated? can we do better? Int. Rev. Environ. Resour. Econ. 15 (4), 271–318. https://doi.org/10.1561/101.00000128.
Geels, F.W., McMeekin, A., Pfluger, B., 2020. Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: bridging computer models and the multi-level perspective in UK electricity generation (2010–2050). Technol. Forecast. Soc. Change 151, 119258. https://doi.org/10.1016/j.techfore.2018.04.001.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31 (8), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.
Geels, F.W., Berkhout, F., van Vuuren, D.P., 2016. Bridging analytical approaches for low-carbon transitions. Nat. Clim. Change 6 (6), 576–583. https://doi.org/10.1038/nclimate2980.
Givoni, M., Macmillen, J., Banister, D., Feitelson, E., 2013. From policy measures to policy packages. Transp. Rev. 33 (1), 1–20. https://doi.org/10.1080/01441647.2012.744779.
Gupta, J., Lebel, L., 2020. Access and allocation in earth system governance: lessons learnt in the context of the Sustainable Development Goals. Int. Environ. Agreem.: Polit., Law Econ. 20 (2), 393–410. https://doi.org/10.1007/s10784-020-09486-4.
Gupta, S., Tirpak, D.A., Burger, N., Gupta, J., Höhne, N., Boncheva, A.I., Kanoan, G.M., Kolstad, C., Kruger, J.A., Michaelowa, A., Murase, S., Pershing, J., Saijo, T., Sari, A., 2007. Policies, instruments and cooperative arrangements. Clim. Change 2007: Mitig. Clim. Change 747–807.
Harris, P.G., 2014. Risk-averse governments. Nat. Clim. Change 4 (4), 245–246. https://doi.org/10.1038/nclimate2176.
Hof, A., den Elzen, M.G.J., Admiraal, A., Roelfsema, M., Gernaat, D., & van Vuuren, D. (2017). Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2°C and 1.5°C (in press). Environmental Science and Policy.
Howlett, M., 2009. Governance modes, policy regimes and operational plans: a multi-level nested model of policy instrument choice and policy design. Policy Sci. 42 (1), 73–89. https://doi.org/10.1007/s11077-009-9079-1.
Howlett, M., 2011. Designing Public Policies: Principles and Instruments. Routledge.
Howlett, M., 2018. Moving policy implementation theory forward: a multiple streams/critical juncture approach. Public Policy Adm. 34 (4), 405–430. https://doi.org/10.1177/0952076718775791.
Hsu, A., Höhne, N., Kuramochi, T., Roelfsema, M., Weinfurter, A., Xie, Y., Lütkehermöller, K., Chan, S., Corfee-Morlot, J., Drost, P., Faria, P., Gardiner, A., Gordon, D.J., Hale, T., Hultman, N.E., Moorhead, J., Reuvers, S., Setzer, J., Singh, N., Widerberg, O., 2019. A research roadmap for quantifying non-state and subnational climate mitigation action. Nat. Clim. Change 9 (1), 11–17. https://doi.org/10.1038/s41558-018-0338-z.
Iacobuta, G., Dubash, N.K., Upadhyaya, P., Deribe, M., Höhne, N., 2018. National climate change mitigation legislation, strategy and targets: a global update. Clim. Policy 18 (9), 1114–1132. https://doi.org/10.1080/14693062.2018.1489772.
IPCC. (2014b). Working Group III Contribution to the IPCC 5th Assessment Report "Climate Change 2014: Mitigation of Climate Change." Cambridge University Press PP - Cambridge.
IPCC. (2014a). Annexes. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seybo (O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx (eds.)). Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-i.pdf.
IPCC. (1995). Climate change 1995: Economic and social dimensions of climate change. Contribution of Working Group III to the second assessment report of the intergovernmental panel on climate change. Press Syndicate of the University of Cambridge.
IPCC. (1996). Technologies, Policies and Measures for Mitigating Climate Change. https://www.ipcc.ch/publication/technologies-policies-and-measures-for-mitigating-climate-change/.
IPCC. (2001). Climate Change 2001: Mitigation. Contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Cimate Change. Cambridge University Press.
IPCC. (2007). Climate change 2007: Mitigation of climate change. Working group III contribution to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
IPCC. (2018). IPCC special report on the impacts of global warming of 1.5°C - Summary for policy makers. Intergovernmental Panel on Climate Change (IPCC).
Jewell, J., Cherp, A., 2020. On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5°C? WIREs Clim. Change 11 (1), e621. https://doi.org/10.1002/wcc.621.
Keppo, I., Butnar, I., Bauer, N., Caspani, M., Edelenbosch, O., Emmerling, J., Fragkos, P., Guivarch, C., Harmsen, M., Lefèvre, J., Le Gallic, T., Leimbach, M., McDowall, W., Mercure, J.-F., Schaeffer, R., Trutnevyte, E., Wagner, F., 2021. Exploring the possibility space: taking stock of the diverse capabilities and gaps in integrated assessment models. Environ. Res. Lett. 16 (5), 53006. https://doi.org/10.1088/1748-9326/abe5d8.

King, L.C., van den Bergh, J.C.J.M., 2019. Normalisation of Paris agreement NDCs to enhance transparency and ambition. Environ. Res. Lett. 14 (8), 84008. https://doi.org/10.1088/1748-9326/ab1146.

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Wells, P., 2019. An agenda for sustainability transitions research: State of the art and future directions. Environ. Innov. Soc. Transit. 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.

Kriegler, E., Bertram, C., Kuramochi, T., Jakob, M., Pehl, M., Stevanović, M., Höhne, N., Luderer, G., Minx, J.C., Fekete, H., Hilaire, J., Luna, L., Popp, A., Steckel, J.C., Sterl, S., Yalew, A.W., Dietrich, J.P., Edenhofer, O., 2018. Short term policies to keep the door open for Paris climate goals. Environ. Res. Lett. 13 (7), 74022. https://doi.org/10.1088/1748-9326/aac4f1.

Kuramochi, T., Roelfsema, M., Hsu, A., Lui, S., Weinfurter, A., Chan, S., Hale, T., Clapper, A., Chang, A., Höhne, N., 2020. Beyond national climate action: the impact of region, city, and business commitments on global greenhouse gas emissions. Clim. Policy 20 (3), 275–291. https://doi.org/10.1080/14693062.2020.1740150.

Kuramochi, T., Nascimento, L., Moisio, M., den Elzen, M.G.J., Forsell, N., van Soest, H., Tanguy, P., Gonzales, S., Hans, F., Jeffery, M.L., Fekete, H., Schiefer, T., de Villafranca Casas, M.J., De Vivero-Serrano, G., Dafnomilis, I., Roelfsema, M., Höhne, N., 2021. Greenhouse gas emission scenarios in nine key non-G20 countries: An assessment of progress toward 2030 climate targets. Environ. Sci. Policy 123, 67–81. https://doi.org/10.1016/j.envsci.2021.04.015.

Lasswell, H.D. (1956). The Decision Process: Seven Categories of Functional Analysis. Bureau of Governmental Research, College of Business and Public Administration, University of Maryland. https://books.google.nl/books?id=RKgdAAAAMAAJ.

Lilliestam, J., Patt, A., Bersalli, G., 2020. The effect of carbon pricing on technological change for full energy decarbonization: A review of empirical ex-post evidence. WIREs Clim. Change n/a (n/a), e681. https://doi.org/10.1002/wcc.681.

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O.Y., Pietzcker, R.C., Rogelj, J., De Boer, H.S., Drouet, L., Emmerling, J., Fricko, O., Fujimori, S., Havlík, P., Iyer, G., Keramidas, K., Kitous, A., Pehl, M., Krey, V., Riahi, K., Saveyn, B., Kriegler, E., 2018. Residual fossil CO_2 emissions in 1.5–2 °C pathways. Nat. Clim. Change 8 (7), 626–633. https://doi.org/10.1038/s41558-018-0198-6.

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W., & Zwiers, F. W. (2010). Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf.

McCollum, D.L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., Després, J., Drouet, L., Emmerling, J., Fay, M., Fricko, O., Fujimori, S., Gidden, M., Harmsen, M., Huppmann, D., Iyer, G., Krey, V., Kriegler, E., Nicolas, C., Riahi, K., 2018. Energy investment needs for fulfilling the Paris Agreement and achieving the sustainable development goals. Nat. Energy 3 (7), 589–599. https://doi.org/10.1038/s41560-018-0179-z.

Meadows, D.H., Meadows, D.L., Randers, J., & Behrens, W. w. (1972). The limits to growth. https://ia802508.us.archive.org/27/items/TheLimitsToGrowth/TheLimitsToGrowth.pdf.

Meadows, H., 2008. Systems Thinking. Chelsea Green Publishing Co.

Mercure, J.-F., Pollitt, H., Viñuales, J.E., Edwards, N.R., Holden, P.B., Chewpreecha, U., Salas, P., Sognnaes, I., Lam, A., Knobloch, F., 2018. Macroeconomic impact of stranded fossil fuel assets. Nat. Clim. Change 8 (7), 588–593. https://doi.org/10.1038/s41558-018-0182-1.

Nascimento, L., Kuramochi, T., Iacobuta, G., den Elzen, M.G.J., Fekete, H., Weishaupt, M., van Soest, H.L., Roelfsema, M., Vivero-Serrano, G., De, Lui, S., Hans, F., Jose de Villafranca Casas, M., Höhne, N., 2021. Twenty years of climate policy: G20 coverage and gaps. Clim. Policy 1–17. https://doi.org/10.1080/14693062.2021.1993776.

NewClimate Institute. (2015). Climate Policy Database. http://climatepolicydatabase.org.

Otto, I.M., Donges, J.F., Cremades, R., Bhowmik, A., Hewitt, R.J., Lucht, W., Rockström, J., Allerberger, F., McCaffrey, M., Doe, S.S.P., Lenferna, A., Morán, N., van Vuuren, D.P., Schellnhuber, H.J., 2020. Social tipping dynamics for stabilizing Earth's climate by 2050. Proc. Natl. Acad. Sci. 117 (5), 2354–2365. https://doi.org/10.1073/pnas.1900577117.

Pahle, M., Burtraw, D., Flachsland, C., Kelsey, N., Biber, E., Meckling, J., Edenhofer, O., Zysman, J., 2018. Sequencing to ratchet up climate policy stringency. Nat. Clim. Change 8 (10), 861–867. https://doi.org/10.1038/s41558-018-0287-6.

Paroussos, L., Mandel, A., Fragkiadakis, K., Fragkos, P., Hinkel, J., Vrontisi, Z., 2019. Climate clubs and the macro-economic benefits of international cooperation on climate policy. Nat. Clim. Change 9 (7), 542–546. https://doi.org/10.1038/s41558-019-0501-1.

PBL. (2020b). Model Documentation - IMAGE. https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_IMAGE.

PBL. (2020a). IMAGE 3.0 Documentation. https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation.

Peng, W., Iyer, G., Bosetti, V., Edmonds, J., Fawcett, A.A., Hallegate, S., Victor, D., Vuuren, D.P., W, J., 2021. Climate policy models need to get real about people — here's how. Nature 594, 174–176. ⟨https://www.nature.com/articles/d41586-021-01500-2⟩.

Pollitt, H., Chewpreecha, U., Lee, S., Lee, T., Mercure, J.F., 2019. Policy mixes to meet CO_2 emission reduction targets in all sectors of the economy in East Asia. Energy Environ. Econ. Sustain. East Asia 99.

Riahi, K., Grübler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol. Forecast. Soc. Change 74 (7), 887–935. https://doi.org/10.1016/j.techfore.2006.05.026.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M.G.J., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D. L., Mima, S., Turton, H., van Vuuren, D.P., Wada, K., Bosetti, V., Edenhofer, O., 2015. Locked into copenhagen pledges - implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technol. Forecast. Soc. Change 90, 8–23. https://doi.org/10.1016/j.techfore.2013.09.016.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Tavoni, M., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Change 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Roelfsema, M., Elzen, M.G.J, Höhne, N., Hof, A.F., Braun, N., Fekete, H., Böttcher, H., Brandsma, R., Larkin, J., 2014. Are major economies on track to achieve their pledges for 2020? an assessment of domestic climate and energy policies. Energy Policy 67. https://doi.org/10.1016/j.enpol.2013.11.055.

Roelfsema, M., Fekete, H., Höhne, N., den Elzen, M.G.J., Forsell, N., Kuramochi, T., de Coninck, H., van Vuuren, D.P.D.P., 2018. Reducing global GHG emissions by replicating successful sector examples: the 'good practice policies' scenario. Clim. Policy 18 (9), 1103–1113. https://doi.org/10.1080/14693062.2018.1481356.

Roelfsema, M., van Soest, H.L., Harmsen, M., van Vuuren, D.P., Bertram, C., den Elzen, M.G.J., Höhne, N., Iacobuta, G., Krey, V., Kriegler, E., Luderer, G., Riahi, K., Ueckerdt, F., Després, J., Drouet, L., Emmerling, J., Frank, S., Fricko, O., Gidden, M., Vishwanathan, S.S., 2020. Taking stock of national climate policies to evaluate implementation of the Paris Agreement. Nat. Commun. 11 (1), 2096. https://doi.org/10.1038/s41467-020-15414-6.

Roelfsema, M., Oreggioni, G., Mikropoulos, S., Staffel, I.., & Van Vuuren, D. P. (2021). SENTINEL intercomparison protocol. Utrech University. https://sentinel.energy/outputs/deliverables/.

Rogelj, J., den Elzen, M.G.J., Hohne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 degrees C. Nature 534 (7609), 631–639. https://doi.org/10.1038/nature18307.

Rogge, K.S., Reichardt, K., 2016. Policy mixes for sustainability transitions: an extended concept and framework for analysis. Res. Policy 45 (8), 1620–1635. https://doi.org/10.1016/j.respol.2016.04.004.

Schaffrin, A., Sewerin, S., Seubert, S., 2015. Toward a comparative measure of climate policy output. Policy Stud. J. 43 (2), 257–282. https://doi.org/10.1111/psj.12095.

Schwanitz, V.J., 2013. Evaluating integrated assessment models of global climate change. Environ. Model. Softw. 50, 120–131. https://doi.org/10.1016/j.envsoft.2013.09.005.

Sentinel. (2020). SENTINEL website. https://sentinel.energy/.

Sharpe, S., Lenton, T.M., 2021. Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope. Clim. Policy 21 (4), 421–433. https://doi.org/10.1080/14693062.2020.1870097.

Solomon, S., Qin, D., Manning, M., chen, Z., Marquis, M., Averyt, K.B., Miller, H.L., & Press, C.U. (2007). Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Chagne. Intergovernmental Panel on Climate Change (IPCC).

Staub-Kaminski, I., Zimmer, A., Jakob, M., Marschinksi, R., 2014. Climate policy in practice: a typology of obstacles and implications for integrated assessment modelling. Clim. Change Econ. 5 (1), 1–30. ⟨http://www.jstor.org/stable/climchaneon.5.1.04⟩.

Stehfest, E., Van Vuuren, D.P., Bouwman, L., Kram, T., Alkemade, R., Bakkenens, M., Biemans, H., Bouwman, A., den Elzen, M.G. J., Janse, J., Lucas, P, Van Minnen, J., Müller, C., & Prins, A. (2014). Integrated Assessment of Global Environmental Change with Model description and policy applications IMAGE 3.0. PBL Netherlands Environmental Assessment Agency.

Trutnevyte, E., Hirt, L.F., Bauer, N., Cherp, A., Hawkes, A., Edelenbosch, O.Y., Pedde, S., van Vuuren, D.P., 2019. Societal transformations in models for energy and climate policy: the ambitious next step. One Earth 1 (4), 423–433. https://doi.org/10.1016/j.oneear.2019.12.002.

UN. (1972). Report on the United Nations Conference on the human environment. United Nations. https://undocs.org/en/A/CONF.48/14/Rev.1.

UNEP. (2015). The Emissions Gap Report 2015: A UNEP Synthesis Report. United Nations Environment Programme (UNEP).

UNEP. (2019). Emissions Gap Report 2019. https://www.unenvironment.org/resources/emissions-gap-report-2019.

UNEP. (2020). Emissions Gap Report 2020. United Nations Environment Programme. https://doi.org/978–92-807–3812-4.

UNFCCC. (2015). Paris Agreement. https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

UNFCCC. (1992). United Nations Framework Convention on Climate Change, FCCC/INFORMAL/84: Vol. FCCC/INFOR. UNFCCC.

UNFCCC. (2000). Tracing the origins of the Kyoto Protocol: an article-by-article textual history. https://unfccc.int/resource/docs/tp/tp0200.pdf.

UNFCCC. (2018). Decision 18/CMA-1. https://unfccc.int/sites/default/files/resource/cma2018_3_add2_new_advance.pdf.

van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D., Cassen, C., 2020. Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970. Glob. Environ. Change 65, 102191. https://doi.org/10.1016/j.gloenvcha.2020.102191.

van Soest, H.L., Aleluia Reis, L., Baptista, L.B., Bertram, C., Després, J., Drouet, L., den Elzen, M., Fragkos, P., Fricko, O., Fujimori, S., Grant, N., Harmsen, M., Iyer, G., Keramidas, K., Köberle, A.C., Kriegler, E., Malik, A., Mittal, S., Oshiro, K., van Vuuren, D.P., 2021. Global roll-out of comprehensive policy measures may aid in bridging emissions gap. Nat. Commun. 12 (1), 6419. https://doi.org/10.1038/s41467-021-26595-z.

van Vuuren, D.P., 2007. Energy systems and climate policy: long-term scenarios for an uncertain future. Utrech Univ. Vol. PHD.

van Vuuren, D.P., Carter, T.R., 2014. Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. Clim. Change 122 (3), 415–429. https://doi.org/10.1007/s10584-013-0974-2.

van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., Winkler, H., 2014. A new scenario framework for Climate Change Research: scenario matrix architecture. Clim. Change 122 (3), 373–386. https://doi.org/10.1007/s10584-013-0906-1.

Victor, D., 2015. Climate change: Embed the social sciences in climate policy. Nature 520, 27–29. https://doi.org/10.1038/520027a.

VividEconomics, Adam Smith International, Factor, & PBL. (2020). BEIS ICF Mitigation Investment Options: Synthesis Report. https://acc-www.pbl.nl/sites/default/files/downloads/pbl-2020-beis-icf-mitigation-investment-options-synthesis-report_4521.pdf.

Vrontisi, Z., Luderer, G., Saveyn, B., Keramidas, K., Lara, A.R., Baumstark, L., Bertram, C., de Boer, H.S., Drouet, L., Fragkiadakis, K., Fricko, O., Fujimori, S., Guivarch, C., Kitous, A., Krey, V., Kriegler, E., Broin, E.Ó., Paroussos, L., van Vuuren, D., 2018. Enhancing global climate policy ambition towards a 1.5 °C stabilization: a short-term multi-model assessment. Environ. Res. Lett. 13 (4), 44039. https://doi.org/10.1088/1748-9326/aab53e.

Vuuren, D.P., Stehfest, E., Gernaat, D., Boer, H.S., D., Daioglou, V., Doelman, J., Edelenbosch, O., Harmsen, M., Zeist, W., van den Berg, M., Dafnomilis, I., Sluisveld, M., Tabeau, A., Vos, L., Waal, L., D., van den Berg, N. J., Beusen, A. H. W., Bos, A., Biemans, H., … Zapata, V. (2021). The 2021 SSP scenarios of the IMAGE 3.2 model. https://doi.org/10.31223/x5cg92.

Weitzel, M., Vandyck, T., Keramidas, K., Amann, M., Capros, P., den Elzen, M., Frank, S., Tchung-Ming, S., Díaz Vázquez, A., Saveyn, B., 2019. Model-based assessments for long-term climate strategies. Nat. Clim. Change 9 (5), 345–347. https://doi.org/10.1038/s41558-019-0453-5.

Winkler, H., Depledge, J., 2018. Fiji-in-Bonn: will the 'Talanoa spirit' prevail? Clim. Policy 18 (2), 141–145. https://doi.org/10.1080/14693062.2018.1417001.

WMO. (1979). Proceedings of the World Climate Conference - a conference of experts on climate and Mankind. https://library.wmo.int/index.php?lvl=notice_display&id=6319.