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Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970

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ABSTRACT

Integrated Assessment Models (IAMs) have gained a prominent role in the climate science-policy interface. The article reconstructs the evolution of IAMs and their changing role in this interface, investigating how and why IAMs have become so prominent. Based on literature analysis, quantitative document analysis and semi-structured interviews, we describe the historic evolution of the interactions between IAMs and policy-making between 1970 and 2015. We identify five historic phases in which IAMs played distinct mediating roles between science and policy, succeeding to adjust their scenario efforts to the continuously changing demands for knowledge from the policy community. In explaining the prominent role of IAMs, we differentiate between background conditions (material and sociological) and more contextual factors, most notably the flexible, hybrid and broad nature of IAMs as well as the pro-active character of the IAM community to enhance their policy relevance. We draw on the notion of institutional work to explain this success. In light of the urgency of responding to the climate crisis, we suggest that the IAM community may expand their scope of anticipated futures and consider engaging a wider range of publics and societal stakeholders beyond the science-policy interface.

1. Introduction

Human-induced climate change presents a major challenge for future human development. As of 2020, the impacts are becoming more and more visible and the need for rapid low-carbon transformations of our current social, economic and technological systems seems increasingly evident. In 2015 this urgency was recognized in the political realm as countries under the United Nations Framework Convention on Climate Change (UNFCCC) agreed to keep global temperature to well below 2 °C and pursue efforts to limit warming to 1.5 °C in the Paris Agreement (UNFCCC, 2015). Accordingly, policy-makers face the challenge of developing mitigation strategies. The Paris Agreement has stressed the

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Abbreviations: AR, Assessment Report; ASF, Atmospheric Stabilization Framework; BAU, business-as-usual; BECCS, Bioenergy with carbon capture and storage; CBA, Cost-benefit analysis; COP, Conference of the Parties; DICE, Dynamic Integrated Climate-Economy Model; EIA, Energy Information Administration; EMEP, Cooperative Program for Monitoring and Evaluation of the LRTAP in Europe; EMF, Energy Modelling Forum; EPA, Environmental Protection Agency; FAR, First Assessment Report; GCM, General Circulation Model; IAM, Integrated Assessment Model; IAMC, Integrated Assessment Modeling Consortium; IIASA, International Institute for Applied Systems Analysis; IMAGE, Integrated Model to Assess the Global Environment; IPCC, Intergovernmental Panel on Climate Change; LRTAP, Long-Range Transboundary Air Pollution; MIP, Modelling Intercomparison Project; NAS, National Academy of Science; NDC, Nationally Determined Contributions; NET, Negative Emissions Technology; PIK, Potsdam Institute for Climate Impact and Research; RAINS, Regional Acidification Information and Simulation; RCP, Representative Concentration Pathway; RIVM, National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezonheid en Milieu); SAR, Second Assessment Report; SEDs, Structured Expert Dialogues; SPM, Summary for Policy-makers; SRES, Special Report on Emissions Scenarios; TAR, Third Assessment Report; TGNES, Task Group on New Emissions Scenarios; UN-ECE, United Nations Economic Commission for Europe; UNEP, United Nations Environment Programme; UNFCCC, United Nations Framework Convention on Climate Change; WG, Working Group; WMC, Model of Warming Commitment; WMO, World Meteorological Organization.

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need for tools and approaches to anticipate possible futures in global climate governance (Vervoort and Gupta, 2018). The multitude of possible climate strategies and the uncertainties regarding their challenges, effectiveness and interlinkages, inevitably involves an exploration of possible socio-economic transformation pathways that are consistent with the temperature goals. This culminated in 2015 when the UN Intergovernmental Panel on Climate Change (IPCC) announced its new direction from the attribution of causes towards response strategies (Goldenberg, 2015). This implied a prominent role for Integrated Assessment Models (IAMs) which form the basis of the defined response strategies of the IPCC since the Fifth Assessment Report (AR5; IPCC, 2014 cf. Cointe et al., 2019).

IAMs are in essence computer simulations that represent complex interactions and feedbacks on a long time scale between the socioeconomic system (including climate policies) and the natural system, which are explicitly designed to inform climate policy-making (Parson and Fisher-Vanden, 1997; Van Vuuren et al., 2011). The models vary largely in their structure, detail and type of policy questions they are designed to address (Kelly and Kolstad, 1998; Weyant et al., 1995). An important distinction is made between (1) detailed process-based IAMs, which form the basis of IPCC's assessments of transformation pathways towards temperature targets, and (2) highly aggregated cost-benefit IAMs that estimate optimal mitigation levels relative to economic costs of climate impacts, which play a less prominent role in the IPCC, but are particularly influential in US climate policy (Weyant, 2017; Wilson et al., 2017). One of the first contributions of process-based IAM scenarios was to show how existing socio-economic trends resulted in high emission levels and as the political ambition grew, IAMs were increasingly used to construct mitigation pathways (Weyant, 2017). An analytical strength of IAMs is their ability to integrate information from various scientific disciplines into a single framework, enabling the coherent analysis of social, technological and physical processes relevant to low-carbon transformations (Geels et al., 2016). However, the use of IAMs for developing mitigation strategies is also criticized. The epistemic, political and ethical implications of the various dimensions of uncertainty and how modelers deal with those are often brought up for discussion (see Beck and Krueger, 2016; Van der Sluijs, 1996; Van Asselt and Rotmans, 2002 for overviews). With regard to their use to inform climate mitigation policy specifically, IAM scenarios are often criticized for favoring large-scale supply-side solutions like negative emissions technologies (NETs) (Fuss et al., 2014; Anderson and Peters, 2016; Vaughan and Gough, 2016) and more generally their limited ability to conceive of radical transformation pathways beyond economic and technological measures (Anderson and Jewell, 2019; Gambhir et al., 2019; Van Vuuren et al., 2018).

IAMs are the backbone of scenario analysis of Working Group III (WGIII) of the IPCC – which focuses on response strategies – since the IPCC AR5. Consequently, the IAM community plays a leading role in climate policy research and assessment (Cointe et al., 2019). Fig. 1 illustrates this trend, showing a growing prominence of IAM analyses in subsequent IPCC reports, as well as an increasing number of IAM publications on climate change, signaling the growing modelling community around this topic. Another observable trend in Fig. 1 is the sharp increases in IAM publications towards each IPCC report, which indicates a strong ambition to provide policy-relevant information. The relative high share in IPCC reports compared to academic climate research further underline this aspiration. The underlying science-policy dynamics that explain these trends however, remain unclear. The first studies on the application of climate models in the science policy interface focused on General Circulation Models (GCMs), the first generation of climate modelling that constitute the backbone of IPCC WG I (e.g. Edwards, 1996; 1999; 2010; 1996; 2001;; Hulme and Dessai, 2008; Mahony and Hulme, 2016; Miller, 2004; Shackley and Wynne, 1995, 1996). At the time of writing, only a handful of studies on organization and application of IAM research in climate policy exist (i.e. Beck and Krueger, 2016; Beck, 2018; Beck and Mahony, 2017; 2018;; Cointe et al.,

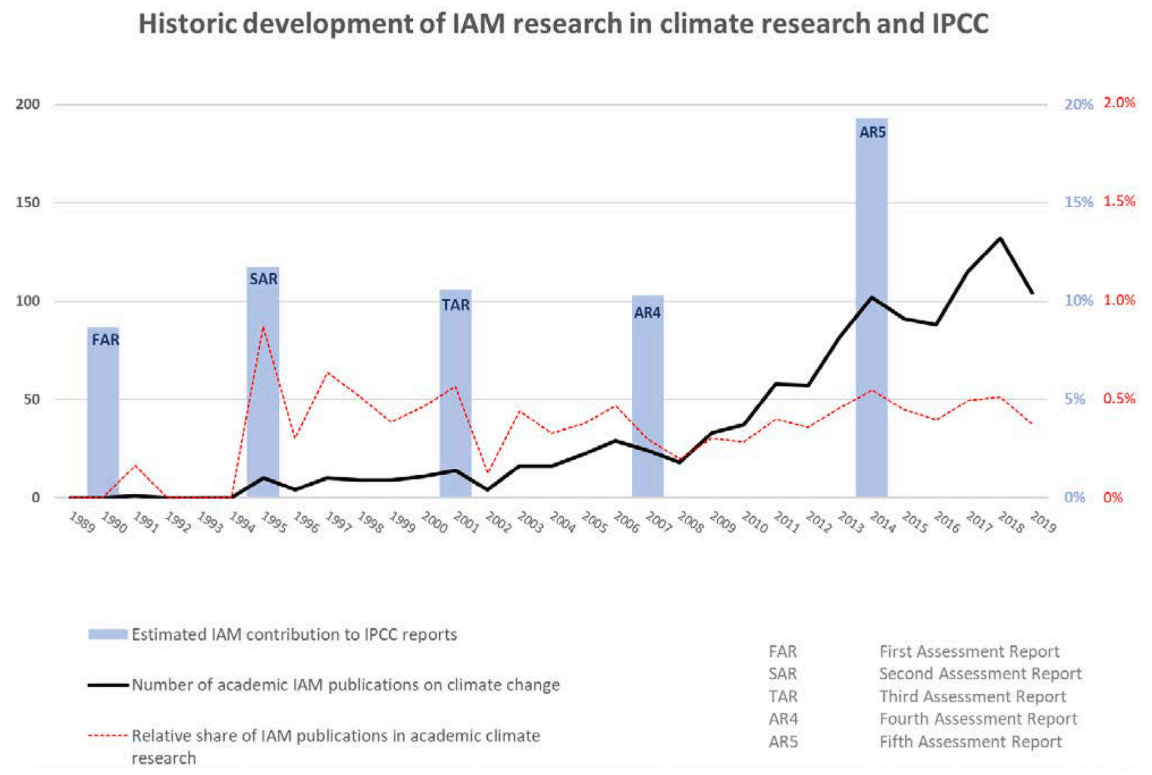

Fig. 1. Number of publications involving IAM in academic literature between 1989 and 2019 (black line),estimated percentage of IAM results in IPCC Synthesis Reports (blue bars) and relative share of academic IAM publications within the total body of academic climate research (red dotted line).(see Supplementary Material B for methodology). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2019; Corbera et al., 2016; Edwards, 1996; Hughes and Paterson, 2017; Lövbrand, 2011; Low and Schäfer, 2020; McLaren and Markusson, 2020). These studies repeatedly find that although IAMs aim to function as 'heuristic guides' to explore strategies (Edwards, 1996), they are in fact *performative:* they shape the possibility space in which future options for climate action are discussed and thus the content of policy deliberation in international climate politics (Beck and Mahony, 2017; 2018;; Lövbrand, 2011; McLaren and Markussen, 2020). As Beck and Mahony (2018, p.1) put it: IAMs exercise a "[…] 'world-making' power by providing new, politically powerful visions of actionable futures". While the prominence and performative effect of IAMs in the climate science-policy interface is evident, we still lack an understanding of how and why IAMs gained this position. This is only more relevant given the fact that any modelling effort will necessarily render certain possible futures more actionable and legible at the expense of other possible futures, thus guiding the transformation towards a post-fossil society. To improve our understanding of the emergence of IAMs, this paper is driven by the following research question: *how and why have IAMs become prominent in the climate science-policy interface?*

In order to answer this question, we applied an analytical strategy with a historical focus for which we used different sources: academic work on the history of IAM (e.g. Parson and Fisher-Vanden, 1997; Weyant, et al., 1995) and the history of international climate politics (e.g. Bodansky, 2001; Gupta, 2010; 2014), 18 semi-structured interviews and document analysis (see Supplementary Material for an elaboration on the methodology). We describe historic developments in modelling and policy and identify the changing 'role' of IAMs over time (referring to how the alignment of science and policy was negotiated, such as agenda-setting, target formulation or evaluation of response strategies). The focus of this role was on both the characteristics of IAMs as well as on the emerging community of experts around IAMs: both the *model* and the *modeler* are relevant to understand the role of IAM in the science-policy interface. With regard to the model, since model results are typically represented in the form of scenarios, we attend to the type of *future representation* (referring to how possible futures were represented using scenarios, with varying numbers of alternatives, distinct framing and action orientations). With regard to the modeler, we analyze the *strategies to obtain policy relevance* (referring to efforts of the modelling community in pursuing policy-relevance).

The paper is structured as follows. In section two, we introduce five distinct phases and discuss their dynamics. In section three we interpret these historical developments and discuss the key factors that explain the prominent role of IAMs in the climate science-policy interface and provide a set of reflections on their future role.

2. The historic evolution of the role of IAMs in the climate science-policy interface

Most climate IAMs appeared in the early 1990s and their development largely co-evolved with the UN climate negotiations. Yet, their origins can be traced back to the early 1970s, to the first global models such as used for the Limits to Growth study (Meadows et al., 1972), the energy-economic modelling that appeared after the 1973–74 oil crisis and early efforts in climate-economics (Weyant et al., 1995; Edwards, 1996; Parson and Fisher-vanden, 1997). We identify five historic phases from 1970s up until 2015 that are each characterized by a shift in IAM-policy interactions (see Fig. 2).

2.1. PHASE 1: The emergence of global modelling (1970–1985)

2.1.1. The first global models urging concern of finite resources

In the vein of early warning of environmental degradation starting in the '60s, the publication of the Limits to Growth (Meadows et al., 1972), initiated by the Club of Rome, truly marked a shift from local pollution to awareness of the global environment. Forrester and his MIT research team convinced the Club of the capability of their system dynamic modelling technique, developed in the late 1950s for analysis of industries and cities (e.g. Forrester, 1970), to offer an understanding of the complexity of the "world problématique" (Elichirigoity, 1999). The final model, 'World 3', included population, agricultural production, natural resource depletion, industrial output and pollution (which included CO_2). Aurelio Peccei (chair of the Club of Rome) deliberately used the World 3 model runs "[…] to move men on the planet out of their ingrained habits" (Ashley, 1983, p. 497). The report was first sent to selected policy-makers and later published in more popular language, becoming an international bestseller. Its powerful neo-Malthusian message – of an exponentially growing population and economy ending in societal collapse - was quickly adopted by the public and the global policy community (Edwards, 1996). The World 3 model runs were thus powerful in shifting the environmental discourse from local pollution to appreciating processes of global environmental change (Fig. 3). It marked the advent of using computer models capable of forecasting long-term futures into the imagination of governments and scientists worldwide (Ashley, 1983). Although the World 3 model was criticized for its simplicity and lack of data and although the Limits to Growth was regarded with suspicion because of the elite character of the Club of Rome (Edwards, 1996), the World 3 model was a true paradigm change (interview 4,6,7,10,13,17): *"It wasn't called an IAM but in effect it pioneered this notion of computational science to look at the deep future of the planet by simulating different dimensions of human development and*

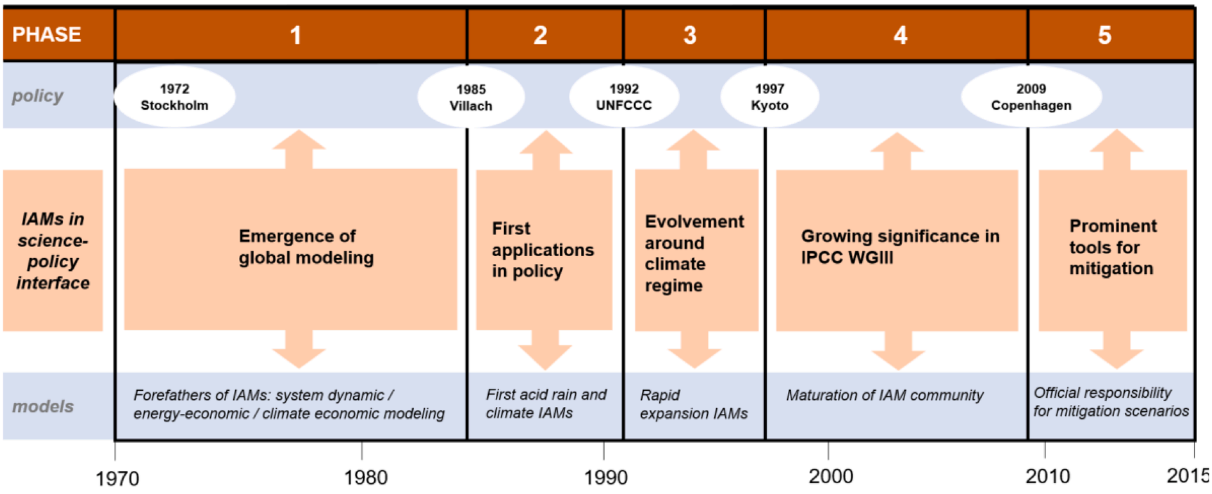

Fig. 2. Overview of phases representing shifts in the position of IAMs in the climate science-policy interface (1970 – 2015).

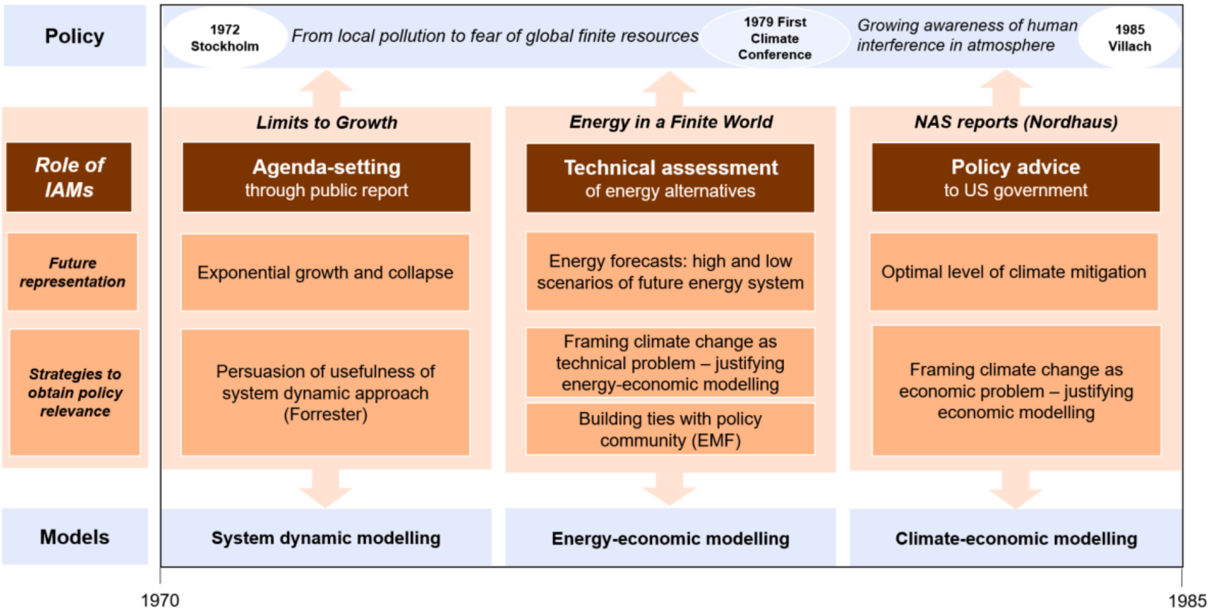

Fig. 3. Overview of the IAM-policy interface in phase 1 (1970–1985).

environmental impact” (interview 10). Supported by advances in computer technology and data availability, six other global models rapidly appeared across the USA, Latin America, Europe and Japan (e.g. Mesarovic and Pestel, 1974; Herrera et al., 1976). The modelling groups often strongly criticized the political-economic assumptions of the World 3 model, such as assuming continuation of North-South inequalities (Blanchard, 2010). Despite the critiques and methodological differences however, the global modelling teams generally agreed that population growth and capital could not grow indefinitely (Meadows et al., 1982). The launch of Limits to Growth coincided with the first UN Conference on the Human Environment in Stockholm in 1972. Moreover, the International Institute for Applied Systems Analysis (IIASA) was established in Austria in the same year, which marked an exceptional scientific cooperation between East and West (Schrickel, 2017). It was by no means self-evident that global modelling should play an important role at IIASA. While strongly advocated by Peccei, opponents feared that the controversy around Limits to Growth would harm its reputation (Rindzevičiūtė, 2016). As a compromise, rather than building a global model, IIASA played a key role in coordinating global modelling efforts by organizing symposia where modelers shared insights, enabling them to evolve into a community of scholars (Meadows et al., 1982). IIASA has continued to operate as a central node in the IAM field ever since (Hughes and Paterson, 2017; Schrickel, 2017).

2.1.2. Emergence of energy-economic modelling in the aftermath of the oil crisis

The 1973–74 oil crisis brought worldwide fear of finite fossil energy supplies. This mobilized a vast amount of energy forecasting projects and institutes around the world, such as the US Energy Information Administration (EIA). The usefulness of computer models to do projections as well as the dependency of economic development on energy was soon realized, which gave birth to a new discipline: energy-economic modelling, such as the famous MARKAL energy model (Taylor et al., 2014). Although this field was rapidly expanding, the actual use of models in policy had “[…] fallen short of expectations” (Greenberger, 1976, p. 26). In the US, the Energy Modeling Forum (EMF) was established in 1976, which was a deliberate attempt to bring together energy modelers and policy-makers in order for the models to gain policy relevance (Fig. 3). The EMF functioned as crucial platform for energy-economic modelers and later IAM modelers to come together, compare modelling practices and enabled the first steps towards a scientific practice: *“The EMF […] was really powerful because it brought together the community every year. It was really important in building the social capital, the community of practice of IAMs”* (interview 1). One of the most elaborate global energy assessments following the oil crisis was IIASA’s Energy Project, which lasted for 9 years and involved more than 250 scientists (Thompson, 1997). Three models were used to construct a low and high scenario of future global energy demand, which formed the most visible elements of the publication Energy in a Finite World (Häfele et al., 1981). The authors explicitly aimed at a “hard science” approach, following the rationale that modelling would lead to more credible and analyzable scenarios (Wynne, 1984). Thereby, their “hard” technocentric and top-down energy path, based on fossil fuels and nuclear power to meet energy demand, was made more conceivable at the expense of micro-level ‘soft’ energy paths (Thompson, 1984). Despite significant critiques, particularly regarding that the models would play only a minor role in scenario construction (Keepin, 1984), the report’s conclusions were influential in shaping policy discussions on future energy (Fig. 3). Namely, the scenarios were adopted by the European Commission as well as national governments to formulate energy policy (Wynne, 1984). Moreover, the authors framed the energy problem deliberately as a ‘technical’ problem, which justified the use of energy-economic modelling.

2.1.3. Climate-economic modelling

One of the economists involved in the Energy Project was Nordhaus, professor of Economics at Yale University. In several IIASA papers, he laid out the principles of a linear programming model of energy supply constrained by peak concentrations of CO_2 (Nordhaus, 1975; 1977). These early papers introduced a new heuristic in thinking about climate policy as part of an economic assessment of costs and benefits of reducing emissions (Randalls, 2011; Schrickel, 2017). Nordhaus’ conceptualization justified the use of economic analysis to the climate problem and was in sharp contrast with the Limits to Growth, which he and other economists critiqued for lacking data and underestimating the role of technology (Nordhaus, 1973). His early efforts grew out into the most widely used CBA-type IAM: the Dynamic Integrated Climate and Economy (DICE) model (Nordhaus, 1993). Nordhaus is recognized as a key figure in the history of IAMs. He pioneered the climate-economics field – for which he received a Nobel prize in 2018 - and many followed on his tradition (interview 1, 4, 5, 7, 8, 17). During the early 1980s, Nordhaus served in several committees of the National Academy of Science (NAS) such as the Carbon Dioxide Assessment Committee (Randalls, 2011) (Fig. 3). As the use of CBA has a long-standing tradition in US policy (Porter, 1996), Nordhaus' analyses rapidly moved from general claims about climate action to direct policy advice (Randalls, 2011; interview 9). For instance, one of the NAS Committee reports concluded that considering the costs of mitigation and unclear benefits, advising adaptation and further research. The DICE work has also been important for the political stance of the US in the climate debate, i.e. too radical early policies can be costly (Bodansky, 1993). Co-evolving with US climate science-policy interface, the work with DICE still remains important in 2020 in the international climate debate.

2.2. PHASE 2: First applications in policy (1985–1992)

The 1970s and 1980s saw an increased awareness of human impacts on the global atmosphere: first acid rain and ozone depletion dominated the debate and later climate change (Kowalok, 1993). The Vienna Convention (1985) and the Montreal Protocol (1987) on Ozone raised optimism that other atmospheric issues could be addressed by international conventions as well (Agrawala, 1998). The first World Climate Conference was convened by the World Meteorological Organization in 1979 in Geneva and was followed by several international workshops in the 1980s in Villach to better understand the climate problem (Agrawala, 1998). The last 'Villach workshop' in 1985 marks the "arrival" of climate change on the global political agenda, as scientists reached consensus that global temperature would exceed all historical records (Hajer and Versteeg, 2011). In 1988, the IPCC was established at the World Conference on the Changing Atmosphere in Toronto. The Second Climate Conference in Geneva (1990) attracted numerous ministers and government leaders and the IPCC's First Assessment Report (FAR) in 1990 clearly concluded that trends in human activities were causing substantial increases in GHG emissions in the atmosphere. Together with a context of optimism for political cooperation on global environmental issues triggered by the fall of the Berlin Wall, this led to the adoption of the UNFCCC in 1992.

2.2.1. IAMs to support acid rain negotiations

One of the first applications of IAMs were to model acid rain. Acid rain was first raised as a problem by the Swedish government at the Stockholm conference in 1972, as research demonstrated relationships between sulphur emissions in Europe and acidification of Scandinavian lakes (Tuinstra et al., 2006). An international research program followed and this led to the Long-Range Transboundary Air Pollution (LRTAP) treaty signed by 30 countries in 1979 under the auspices of the UN Economic Commission for Europe (UN-ECE) (Hordijk, 1991; Levy, 1995). The first protocol was the Cooperative Program for Monitoring and Evaluation of the LRTAP in Europe (EMEP). It was soon discovered that acid rain threatened not just Scandinavian lakes, but terrestrial ecosystems over the entire continent and this forged the need for strong science-based emission reductions targets (Tuinstra et al., 1999; Hordijk, 1991). Meanwhile, IIASA initiated a project to integrate ecology, meteorology and technology with an ambition to aid the negotiations and started building the Regional Acidification Information and Simulation (RAINS) model (interview 5). Although the RAINS modelers were not officially allowed at the negotiations and their added value compared to EMEP was not self-evident, they managed to present their model runs during coffee breaks and convinced some UN-ECE members of the usefulness of their method (Tuinstra et al., 2006; interview 5). A few years later, the RAINS modelers organized a number of review meetings with negotiators and scientific experts to simultaneously maintain policy relevance and scientific credibility (Hordijk, 1991; interview 5). The emission reduction targets that later followed were largely based on model runs from RAINS and the model became officially adopted in the subsequent protocols (Hordijk, 1995). It was a major success story: *"Very few models can show a direct impact on policy. RAINS was actually used to formulate policy."* (interview 1). There are various reasons for this success (Hordijk, 1991 for overview): the fact that RAINS was developed at IIASA, which was considered a politically neutral institute and therefore trusted by negotiators, the expert review meetings that safeguarded credibility and relevance, the use of data from the already established EMEP and its broad coverage of acid rain aspects as well as geographical dispersion. This flexibility and breadth enabled RAINS to adjust to new scientific insights as well as emerging knowledge demands and thus functioned as communicative bridge between scientific experts, modelers and negotiators from different nationalities (Sundqvist et al., 2002). This way, RAINS served various roles: agenda-setting, target-setting and evaluation of abatement strategies (Fig. 4). Regarding target-setting, the concept of "critical loads" used in RAINS - a maximum allowable range of deposition that ecosystems could endure – was particularly successful in helping to break the deadlock of the negotiations, as it served as science-based policy objective (interview 5). The success of RAINS was a true inspiration for the pioneering climate IAMs.

2.2.2. The first climate IAMs during the emerging climate regime

As climate change was emerging on the global political agenda, several scholars started working on building IAMs in Europe and the US in the mid-80s, with an ambition to support climate policy-making. As outlined by Weyant et al. (1995), significant efforts were (1) the Model of Warming Commitment (MWC) (Mintzer, 1987), (2) the Atmospheric Stabilization Framework (ASF) (Lashof and Tirpak, 1989) and 3) the Integrated Model to Assess the Global Environment (IMAGE) (Rotmans, 1990). Two of these models, ASF and IMAGE were used to construct the first set of emissions scenarios for the IPCC: *"When the IPCC was established, it appeared they needed scenarios […] and it quickly became apparent only two models existed that could produce scenarios with all greenhouse gas emissions"* (interview 3). In the early days of the IPCC the emphasis was still on WGI, with a strong quantitative focus: *"The core of the IPCC was WGI. Everything else that happened had the primary goal to support WGI. And they wanted numbers."* (interview 3). IAMs could provide scenarios with a similar scenario lay-out as WGI, which could arguably explain their use in this report despite their relative infancy (Fig. 4). The IMAGE model, initiated by Rotmans in the Netherlands as an intern at the National Institute for Public Health and the Environment (RIVM), was a pioneer in climate IAMs (Dowlatabadi and Morgan, 1993; Weyant et al., 1995; interview 2,3,4,7,10): *"It was to my knowledge the first of what we now call an Integrated Assessment Model of climate change"* (interview 10). IMAGE and ASF were both also influential in respectively Dutch and US policy discourses. The IMAGE model runs became adopted in 'Zorgen voor Morgen' ('Concern for Tomorrow'; RIVM, 1988; interview 3,17), a highly influential report in Dutch political discourse that dramatically pictured an environmental crisis, ranging from local pollution to global threats (Hajer, 1995, p.175 ff.). The ASF model was developed at the consultancy company ICF and used by the US Environmental Protection Agency (EPA) to develop a report to the US Congress on policy options to climate change (Lashof and Tirpak, 1989). The EPA involved influential actors in the climate debate and was highly involved in the establishment of the IPCC. Due to its close connections with the EPA, the ASF model instead of Mintzer's model was chosen to construct the WGIII scenarios (interview 3,4,8,17). Despite large differences between modelling frameworks and sometimes contrasting results, the US and Dutch modelers succeeded in developing a coherent set of emissions scenarios for the FAR (IPCC, 1990). The so-called SA90 scenarios represented possible futures similar to those in the EPA report: a business-as-usual scenario resulting in high levels of emissions with several policy scenarios associated with lower emission levels (Lashof and Tirpak, 1989; IPCC, 1990). The SA90 scenarios were strongly criticized by the political community, arguing policy scenarios would not be allowed because it would assume international conventions that were not yet existent (interview 3). As a result, a second set of emissions scenarios was developed, the IS92 (IPCC, 1992), which only presented reference scenarios in the absence of policy (Girod et al., 2009; interview 3,8).

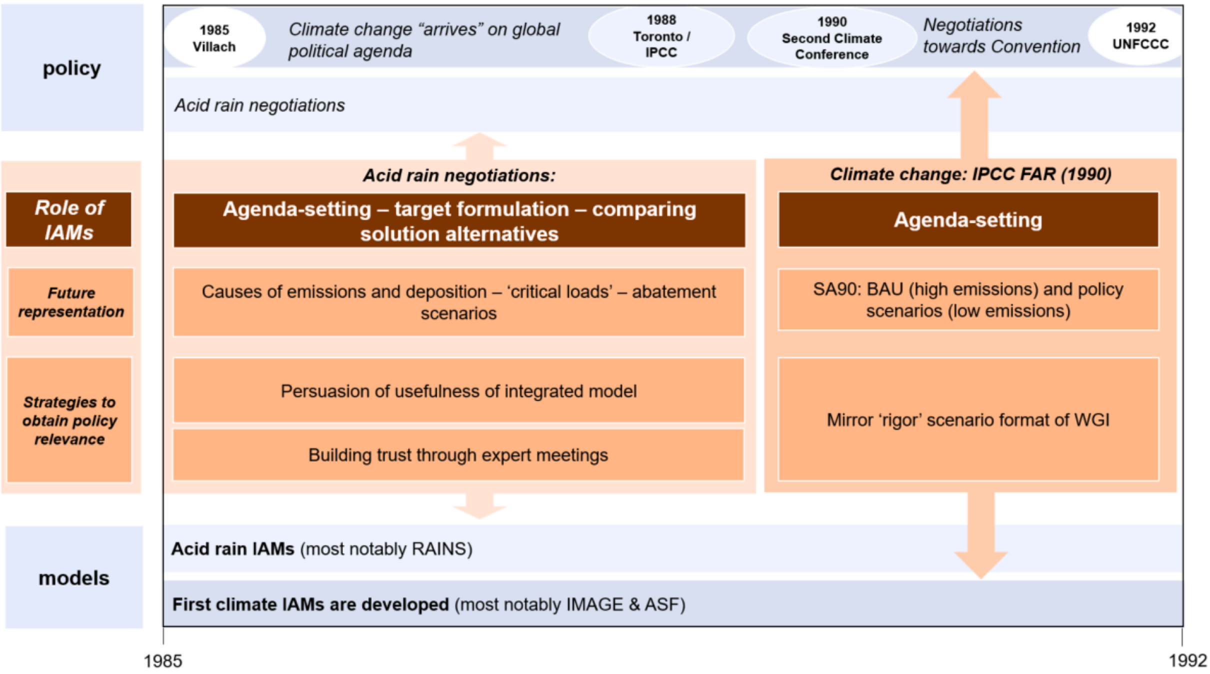

Fig. 4. Overview of the IAM-policy interface in phase 2 (1985–1992).

Nevertheless, the scenarios were crucial in agenda-setting as they drew an upsetting picture of where the world was headed without policy intervention (interview 8) (Fig. 4).

2.3. PHASE 3: From agendas to targets in emerging climate regime (1992–1997)

The Brundtland Report (WCED, 1987) as well as the establishment of the UNFCCC at Rio (1992) caused a 'new wave' in global scenario development, especially global modelling efforts (Swart et al., 2004). The UNFCCC was the first cornerstone of the international climate regime (the international climate negotiations under the convention), followed by the adoption of the Kyoto Protocol in 1997. While countries at Rio agreed to keep warming below dangerous interference, however with ambiguous formulations of stabilization levels (Bodansky, 2001), the Kyoto Protocol imposed legally binding commitments to Annex I countries (mainly OECD countries). In the meantime, the conclusions of the Second Assessment Report (SAR; IPCC, 1995) confirmed that human-caused greenhouse gas emissions contributed, which set the stage for the Kyoto Protocol. IAMs became more formally adopted in the IPCC and were used to inform emission targets setting under Kyoto.

2.3.1. How the newly born discipline became quickly adopted in IPCC WGIII

The emergence of the climate regime forged a rapid expansion of climate IAMs; from three models in 1990 to 40 in 1997 (van der Sluijs et al., 1998). Despite the fact that the IAM field was relatively underdeveloped, it was nonetheless quickly adopted in IPCC WGIII, for several reasons. First, the establishment of the UNFCCC raised new policy questions, from understanding the problem, to impacts, strategies and costs. It appeared that the complex GCMs of WGI were unable to provide answers (interview 10): *"That provided the entry point for IAMs and other forms of simple calculative devices because it could bring together questions around economics, impacts, and policy" (interview 10).* Secondly, the IPCC recognized the need to assess social and economic aspects with a similar scientific rigor compared to WGI that is rooted in physical science (interview 3,8). Several IPCC workshops organized at IIASA evaluating existing scenario approaches, concluded that assessments of impacts and costs should be integrated in a single modelling framework. The IPCC thus adopted the IAM approach to the core of its WGIII assessments (Kaya et al., 1992; Nakicenovic et al., 1994). The SAR (IPCC, 1995) devoted an entire chapter to IAM, where the authors emphasized the benefits of IAM compared to other IA approaches (see Weyant et al., 1995)[1]. A third important reason was that IAM were calibrated on the much more compressive GCMs, which are rooted in the "*non-negotiable laws of physics",* thereby holding an "*epistemic power to make prognostications"* (interview 10). IAMs could thus perform similar - albeit much more simplified - analyses much faster and for a fraction of the costs while leaning on the epistemic power of GCMs. This not only resulted in an increasing prominence of IAM in IPCC's assessments, the IPCC also proved crucial for the advancement of the IAM field; […] *the IPCC Lead Author Meetings were very powerful and intense processes which were multiple times a year for each assessment report. That provided an environment in which they could grow and be applied"* (interview 1).

2.3.2. Facilitating quantitative target-setting towards Kyoto

As the international convention was being negotiated and the need for scenarios emerged, several modelling projects were funded in the US, Europe and Japan (Weyant et al., 1995). These and earlier climate IAMs provided crucial inputs to the negotiations towards Kyoto (Fig. 5). One of the key applications of IAMs were the 'tolerable windows' or 'safe landing' concepts, which represented lower and higher bounds of emissions that would prevent dangerous climate change. The concepts were inspired by the success of 'critical loads' in the acid rain negotiations (interview 2,4,5,7,10). The tolerable windows approach was used in an integrated assessment project at the Potsdam Institute for Climate Impact and Research (PIK) and the safe landing concept resulted from a number of workshops in the Netherlands (the 'Delft workshops') using the IMAGE model involving modelers and policy-makers (Bruckner et al., 1999; Alcamo and Kreileman, 1996). The latter was directly inspired by the expert review meetings of RAINS, a success they hoped to

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[1] At the time of SAR (IPCC, 1995), IAM analysis are however only part of the landscape of the reviewed evaluations. Chapter 8 and 9 in the SAR are dedicated to the costs of climate policies, primarily concerning the divide between bottom-up (sectoral modelling) and top-down (macro-economic modelling) including national, regional and global (IAM) analysis

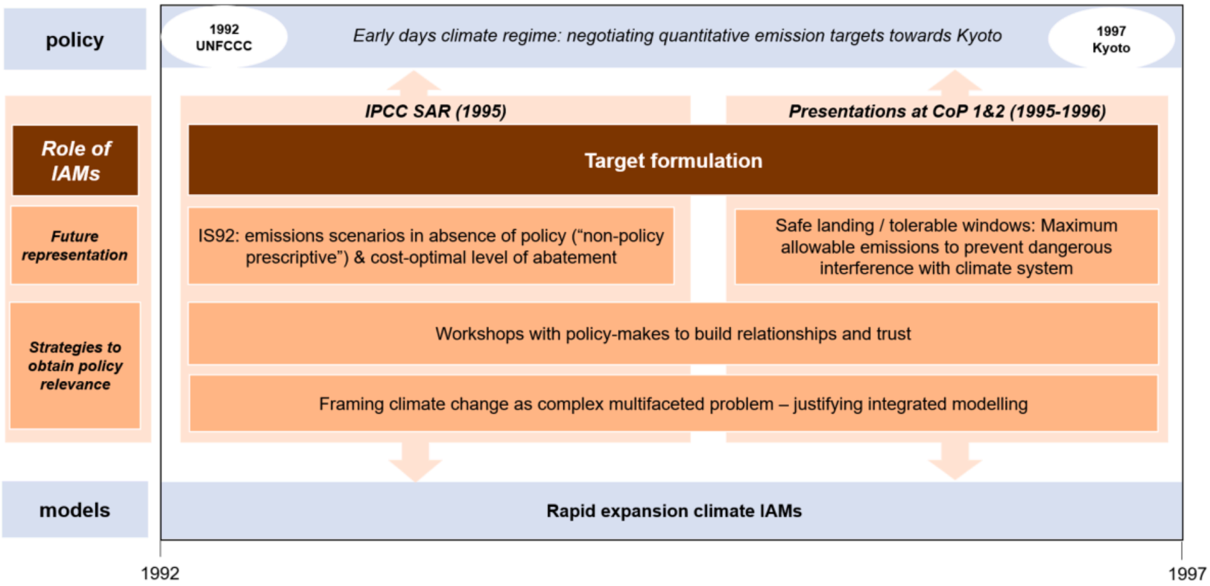

Fig. 5. Overview of the IAM-policy interface in phase 3 (1992–1997).

repeat with IMAGE (Alcamo and Kreileman, 1996; interview 4). The concepts presented at the first two Conferences of the Parties (COPs) in 1995 and 1996 helped to formulate the quantified emission targets under the Kyoto Protocol (Van der Sluijs, 2002). Various approaches were also proposed to determine the allocation of emission reduction ('burden sharing') between UNFCCC parties. The 'triptych' approach that allocated emissions based on three categories of emissions developed by Phylipsen et al. (1998) was particularly influential in formulating an EU-wide abatement target during the years preceding Kyoto (Groenenberg et al., 2001). The tolerable windows / safe landing concepts and the IS92 emissions scenarios played a considerable role in the emergence of the 2 °C target. The history of the target can actually be traced to Nordhaus (1975); (1977;), albeit merely as heuristic, and began to emerge as a concrete target due to a confluence of political events during 1980s to early 1990s (Randalls, 2010; Morseletto et al., 2017). It was first officially raised as a political target at the first COP in 1995 by the German Advisory Council on Global Change (WBGU, 1995), basing their argument largely on the tolerable windows principle (Morseletto et al., 2017). Moreover, the rationale of the adoption by the European Union of the 2 °C target in 1996 was partly based on the IS92 emissions scenarios constructed with IAMs (Randalls, 2010). The 2 °C goal was certainly not *only* the result of IAM analyses, but the model outputs arguably played a significant role in target formulation (Fig. 5).

2.4. PHASE 4: Growing significance in IPCC WGIII (1997 – 2009)

The decade that followed the Kyoto protocol were the "mature years of the IPCC and the UNFCCC" (Hajer and Versteeg 2011, p. 83). The ratification of the protocol by at least 55 countries appeared quite challenging, especially after the failed negotiations at COP6 and the US withdrawal. With the EU taking the lead, political attention was on ratification of Kyoto which finally entered into force in 2005 (Gupta, 2014). The 'alarmist repertoire' (Hulme 2009) triggered by the period following 9/11 was further augmented by mounting evidence of anthropogenic climate change in the Third Assessment Report (TAR) (IPCC, 2001) and emerging metaphors of 'tipping points' and 'abrupt climate change' (Gardiner, 2009). The Fourth Assessment Report in (AR4; IPCC, 2007) further highlighted the need for action, accompanied by Al Gore's *An Inconvenient Truth* in 2006 that largely raised public awareness. Slowly but surely, the political ambition for mitigation began to stabilize throughout this phase. Climate change was predominantly framed as an economic challenge to be solved by market-based mechanisms, as exemplified by the EU Emissions Trading System launched in 2005. This phase also saw a 'frame diversification' of climate change, which was reflected in the IPCC, such as climate change as ethical and development issue (Hulme et al., 2018).

2.4.1. The emergence of alternative perspectives on the climate problem

As the IPCC matured, it began to be criticized from various angles, most notably on the limited social science perspectives and the lack of representation of developing countries in their assessment (Hulme and Mahony, 2010). This debate in fact remained unresolved even after AR5t (Victor, 2015). Together with the underestimation of sources of socio-economic uncertainty in IS92, this critique led to the development of a new set of emissions scenarios (interview 3), which were published in a WGIII Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000). In contrast to previous scenario sets, the SRES started with qualitative storylines, which were then used as input for six (process-based) IAMs to derive quantified emissions pathways (Fig. 6). Responding to the critiques, the SRES authors organized an 'open process', allowing for involvement of a wide range of disciplines and ensuring a considerable proportion of representatives from developing countries in the author team (Nakicenovic et al., 2000; Girod et al., 2009; interview 3). The use of (process-based) IAMs seemed inevitable: *"The SRES covered everything from driving forces of the future development all the way to consequences. For that you needed integrated models, there was no other way of doing it"* (interview 7). The ability of process-based IAMs to produce such socio-economic scenarios that involve a wide range of perspectives is arguably one of the reasons for the emerging predominance of process-based as opposed to CBA-IAMs in IPCC assessments. A second reason was presumably the controversy raised by developing countries around the valuation of human life in the damage calculation in CBA-IAMs in the preparation of the Summary for Policymakers (SPM) of the SAR (O'Riordan, 1997). A third development considering the role of CBA-IAMs and the legitimacy of the CBA approach more generally was the Stern Review of Economics of Climate Change (Stern, 2006), which proposed a social discount rate of almost zero based on ethical considerations, concluding that climate action now would be more cost-effective than later (Fig. 6). It was the literal opposite of what Nordhaus had been reiterating for decades and economically legitimized early climate action (Nordhaus, 2007; Ackerman et al., 2009). The political effect of the Stern Review remains debated: on the one hand it forged improvements of CBA-IAMs and preserved its use in decision-making, yet its legitimacy was no longer given (Randalls, 2011).

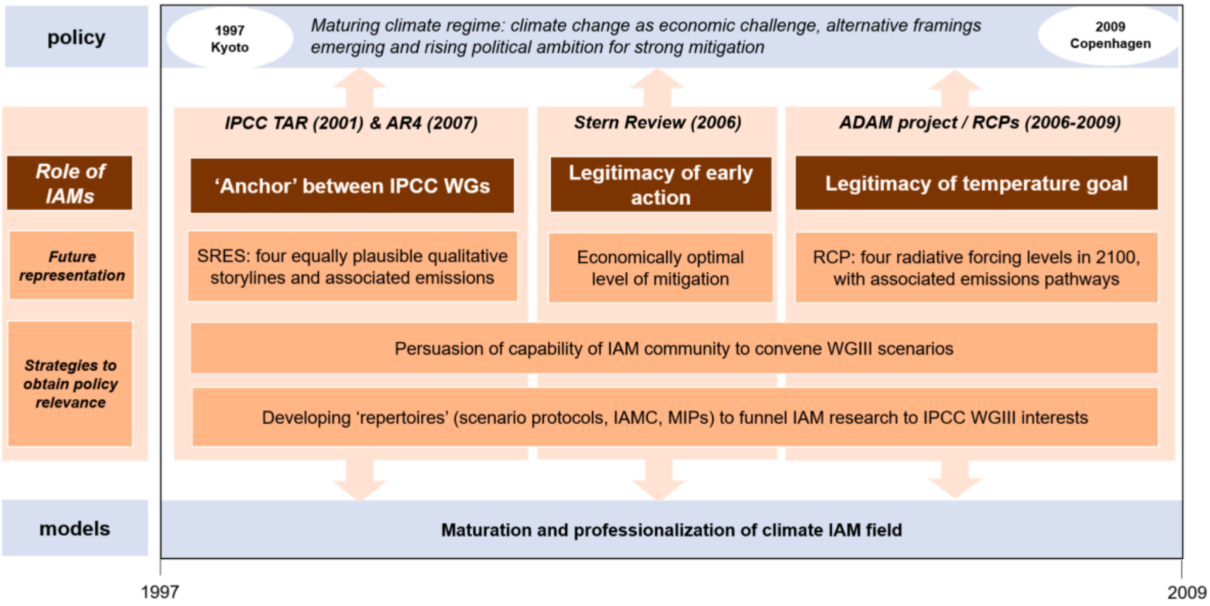

Fig. 6. Overview of the IAM-policy interface in phase 4 (1997–2009).

2.4.2. *IAMs as an anchor to connect the Working Groups*

Starting with the preparation of the SRES (Nakicenovic et al., 2000), IAMs began to serve an important 'anchoring' function within the IPCC (Fig. 6). The SRES became one of the most often cited IPCC WGIII reports ever produced and was used as input for the TAR (IPCC, 2001) and AR4 (IPCC, 2007). The SRES was used by all three WGs and particularly forged more formal collaboration between the GCM and IAM communities (interview 1,2,8,16). This proved vital for the IPCC to bring the complex and dispersed information into a coherent report (interview 1,2,7). As several limitations of the SRES became apparent, the IPCC created a Task Group on New Emissions Scenarios (TGNES) in 2005 in which IAM teams were heavily involved (Cointe et al., 2019). The TGNES proposed the Representative Concentration Pathways (RCPs): four pathways spanning a range of radiative forcing values in the year 2100 from low to high (2.6–8.5 W/m2). As a solution to the 'tedious' sequential scenario process, the RCPs could be used in parallel by the IAM and GCM communities (Moss et al., 2010). IAMs were used to construct the RCPs as well as the socio-economic emissions scenarios and thus played a more important role in the IPCC scenario practice. Moreover, the mandate of the IPCC in scenario making began to be disputed: an assessment bureau should evaluate rather than produce scenarios (Cointe et al., 2019, interview 3,14). IAM teams convinced the bureau that they were capable of organizing the scenario process (Cointe et al., 2019, interview 11). The modellers established the IAM Consortium in 2007 (IAMC), which indeed became responsible for the coordination of IPCC's emissions scenarios (Fig. 6).

2.4.3. *The role of IAMs in the feasibility of the 2 °C goal*

While no 'additional climate policy initiatives' were requested in the terms of references of the SRES (IPCC, 1996), the adoption of the Kyoto Protocol and discussions around a future global agreement by 2005 increased the political interest for mitigation scenarios in this historic phase, as reflected in the titles of the WGIII reports where 'mitigation' began to emerge[2]. The IPCC expert meeting in Noordwijkerhout in the Netherlands in 2007 – where the RCP framework was discussed – marked a critical moment in the evolution of the role of IAMs in the evaluation of mitigation scenarios. UNFCCC negotiators at the meeting showed explicit interest in mitigation targets and policy responses, discussing the feasibility of RCP2.6 – a low mitigation scenario (Lövbrand, 2011; Moss et al., 2010). That scenario had been developed some years before by the IMAGE research team in response to an emerging increase in the 2 °C target, for the first time identifying what would be needed to reach such a target using an IAM model (Van Vuuren et al., 2006). The IAM work and the selection of RCP2.6 induced a range of subsequent research activities into the feasibility of the 2 °C target (Fig. 6). This includes, for instance, the Adaptation and Mitigation Strategies (ADAM) project (Lövbrand, 2011) and other Modelling Intercomparison Projects (MIPs) including EU-funded projects and EMF sessions (Cointe et al., 2019). These MIPs and the RCP process introduced a far more regular contact among modelling teams as well as scenario protocols, standardized reporting and documentation and common databases gathering model results. These 'repertoires' appeared crucial to hold the heterogenous IAM field together and organize their research towards providing policy-relevant knowledge (Cointe et al., 2019). The IAM research into the feasibility of RCP2.6 was also used strategically by the EU to explore different pathways towards 2 °C, that could be used internally (to legitimize its 2008 Climate and Energy Package) and to legitimize the temperature goal in the UN climate negotiations (Lövbrand, 2011) (Fig. 6).

2.5. *PHASE 5: Prominent tools for mitigation analysis (2009–2015)*

Despite the disappointment following the Copenhagen conference, this phase represents a breakthrough in international climate negotiations, characterized by political ambition for strong mitigation targets, with the official inclusion of the 2 °C target at Bali. First emission targets ('the carbon budget') and later temperature goals were debated in this phase (McLaren and Markusson, 2020). It also marks a shift from a top-down and legally binding (Kyoto and Copenhagen attempt) to a more fragmented and decentralized governance architecture (Bodansky, 2010; Bäckstrand and Lövbrand, 2019). The Paris Agreement in 2015 went a step further in this paradigm shift as countries agreed to keep global temperature increase "well below 2°" and "pursue efforts" to limit warming even further to 1.5 °C (UNFCCC, 2015), which was hailed by many as a major political breakthrough. IAMs gained an increasingly important position in the climate science-policy interface by becoming the backbone of IPCC's Fifth Assessment Report (AR5; IPCC, 2014),

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[2] Titles of subsequent IPCC reports: FAR (1990) "Response Strategies", SAR (1995): "Social and Economic Analysis of Climate Change", TAR (2001) "Mitigation", AR4 (2007) & AR5 (2014) "Mitigation of Climate Change

where they adopted an important function regarding the legitimacy of the temperature targets as well as monitoring progress of the UNFCCC in their political ambition (Fig. 7). The realization that climate change is closely connected with other environmental and social issues forged the rise of co-benefit analysis (e.g. Ürge-Vorsatz et al., 2014) and a broader agenda of 'sustainability', ultimately culminating in the Rio + 20 conference held in 2012.

2.5.1. *IAMs to explore the feasibility of stringent temperature targets*

As shown in Fig. 1, the number of IAM publications in scientific journals exploded in the period 2008–2014 and the prominence of IAM analyses in AR5 was substantial compared to previous reports. Likewise, Cointe et al. (2019) observed that with the AR5, for the first time IAMs truly functioned as backbone of the assessment where it was described as "invaluable" to guide policy decisions (IPCC, 2014, p. 51). As emissions continued to rise, resolving for the cumulative carbon budget would require later withdrawals and this forged the idea of negative emissions in IAM scenarios (McLaren and Markusson, 2020). The use of NETs became prominent in the AR5 pathways – most notably Bioenergy with Carbon Capture and Storage (BECCS) - as it would make the 2 °C more attainable (Guillemot, 2017). The RCP scenario framework functioning as 'red thread' throughout the report and the explicit inclusion of mitigation pathways towards the 2 °C target in turn forged the development of simulation consistent with 2 °C in a wider range of scientific communities (Guivarch and Hallegatte, 2013). The IAM scenarios in the AR5 were thus crucial in showing economic and technological feasibility of achieving the 2 °C and were arguably pivotal in the run up to the Paris Agreement in 2015 (Fig. 7). IAM modelers were also involved in the Structured Expert Dialogues (SEDs) held between 2013 and 2015, which can be viewed as a 'live' version of the AR5 in which UNFCCC delegates and authors across all three WGs as well as experts outside the IPCC engaged in a face-to-face interaction. The difference between 1.5 °C versus 2 °C was a central topic in these discussions and the adoption of the 1.5 °C target in the Paris Agreement can to a considerable extent be attributed to these dialogues (Guillemot, 2017; Livingston and Rummukainen, 2020; Tschakert, 2015; interview 6). The 1.5 °C target was clearly a politically negotiated rather than a science-based target, yet the so-called IAM-based 'deep carbonization pathways', were widely used by protagonists of the 1.5 °C (Guillemot, 2017, p. 47).

2.5.2. *UNEP gap reports: monitoring the level of ambition*

Although arguably less authoritative compared to the IPCC SPMs, which are negotiated and approved line-by-line by government representatives, the Emissions Gap Reports published by UNEP have also provided significant input into the negotiations. Rather than an elaborate assessment of available science, the UNEP 'gap reports' answer the simple question: are the pledges made by UNFCCC countries sufficient meet the 1.5 °C and 2 °C targets? These calculations of the 'gap' between expected emissions resulting from pledges and those compatible with the temperature goals are primarily performed based on IAM scenarios, thereby IAMs function as monitoring progress on policy targets. The first gap report was published in 2010 as a response to the pledges made by 85 countries under the Copenhagen Accord in 2009 (UNEP, 2010). Since then, the reports have been published annually and since the Paris Agreement evaluate the Nationally Determined Contributions (NDCs). With several IAM authors, the UNEP gap reports thus ensured a policy-relevant outlet of IAM work along the decentralization of the international climate regime (Fig. 7).

3. Discussion

The historic IAM-policy interactions between 1970 and 2015 reveal the increased prominence of IAMs in the climate science-policy interface. Their policy-relevance came out in the capability to represent a range of possible futures and meet emerging knowledge demands on behalf of the policy community. Over the years IAMs adopted various roles between science and policy from agenda-setting in early phases to target-setting and monitoring political ambition for mitigation in later phases. To explain the 'career' of IAMs we refer to several material and sociological background conditions as well as to particular features of both the models and the IAM community.

3.1. *Material conditions enabling model building*

Two obvious conditions that have enabled model building are advances in computer technology and data availability. An essential driving force behind global environmental modelling in general is the exponential growth in computing power (Heymann et al., 2017). As computer technology was becoming increasingly available, computer scientists became interested in applying models to policy-making across a wide range of issues already since the 1970s (Greenberger et al., 1976). This diversity in models later allowed IAM modelers to combine multiple models into coherent frameworks. The development of internet technology and software development further facilitated the sharing of

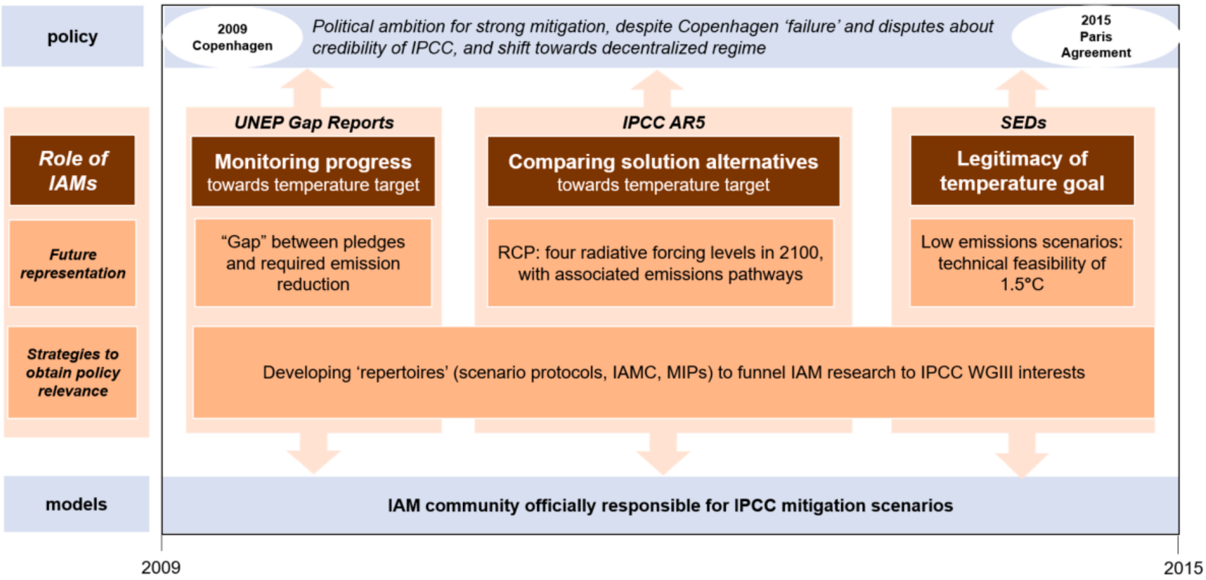

Fig. 7. Overview of the IAM-policy interface in phase 5 (2009–2015).

practices, computer code and online data sets, enabling to look into a couple thousand scenarios from a large set of models, thus facilitating the connections among individual modelling groups. A second and related material condition underlying the development of IAMs is the growing data availability since the first models. Especially the availability of socio-economic data was an important condition enabling the rapid growth of climate IAMs in the early 1990s (Weyant et al., 1995).

3.2. Sociological trends in the authority of global and quantitative forms of knowing climate change

The prominence of IAMs cannot be fully understood without appreciating how the practice of 'modelling' could tap into the established position of statistics and quantified indicators in modern policy making. First of all, the general 'trust in numbers'. Theodore Porter has shown how trust in quantified knowledge is deeply embedded in Western cultures. Indeed, it proved vital for decision-makers to construct policy legitimation from the nineteenth century onwards (Porter, 1996). As the trust in traditional elites declined, quantitative forms of knowledge became increasingly important according to the logic that "A decision made by the numbers […] has at least the appearance of being fair and impersonal." (Porter, 1996, p. 8). This trust in numbers is persistent: statistics still tend to take the center stage in the environmental science-policy interfaces (Wesselink et al., 2013). Clearly, this sociological fact, that legitimate decision making depends on a solid quantitative basis, helps understand how IAMs could gain such a prominent role in climate policy making.

Secondly, IAMs should be understood against the background of the emergence of predictive practices that gained significant scientific and political authority from the second half of the 20th century onwards (Heymann et al., 2017). The first climate models that were built soon after WWII that are rooted in meteorology became the single possible way of conceiving of global climate change (Edwards, 2010). GCMs have grown out into an authoritative scientific discipline with a vast infrastructure of data collection and distribution and set the stage for the 'cultures of prediction' to become to increasingly dominant in our understanding of global environmental change (Heymann et al., 2017). The system dynamic and energy-economic modelling efforts in the 1970s and 1980s, which are the roots of IAMs, helped to further establish and reinforce these cultures of prediction (Ibid.). It is against this background that IAMs added the possibility of 'what-if' queries: their analytical strengths lie in comprehensive insights in human-nature interlinkages and the exploration of climate policy alternatives under various conditions (Geels et al., 2016). Paradoxically, the desire for numbers and predictions of policy communities certainly helps explain the influence of IAMs, yet is incongruent with the goals and conclusions of IAM analyses, which are explicitly non-predictive.

A third and intricately related factor is that climate models have consistently represented climate change as a global phenomenon, rather than a local or national issue, and thus a problem to be governed on a global scale (Miller, 2004). From a macro-level perspective, this tight coupling between knowledge-making and social order essentially amounts to a form of 'co-production' (Jasanoff, 2004). Since GCMs were the primary epistemic entry point to understand future climate change, it became the backbone of IPCC WGI right at its establishment, which implied a global governance approach (the UNFCCC). This global governance architecture in turn legitimizes the use of global models, such as GCMs and IAMs. This co-production has several implications for policy deliberation on climate strategies. In particular, the top-down technocentric approach to climate action has legitimized the use of international carbon markets and technologies such as BECCS (Lövbrand, 2011; Hourcade et al., 2015).

3.3. Adopting various roles in the evolving science-policy interface

Where the material conditions explain the capacity of building models in the first place, and the sociological trends of trust in quantification and legitimacy of global models helps to explain the authority of modelling in general, our historical reconstruction also suggests additional, more contextual, explanatory factors relating to both the particular features of the IAMs as models as well as to the role of the communities that shaped up around the IAMs. Overall, we observed that the role of IAMs in the science-policy interface shifted from agenda-setting (Forrester, phase 1) towards monitoring progress of climate mitigation policy (UNEP gap reports, phase 5). Moreover, IAMs have applied to various environmental issues that emerged over the past 50 years: from population growth and energy (phase 1) to acid rain (phase 2) and finally to climate change (phase 3–5). IAMs seem to have succeeded to anticipate and respond to emerging developments in the science-policy interface through adjusting their analysis to emerging knowledge demands from the policy community. Rather than being responsive to policy developments however, IAMs were active in helping to shape policy change as well. For instance, the World 3 model runs in the Limits to Growth were a key paradigm change that raised environmental awareness globally. In later stages, the low-emissions scenario played a key role in the legitimacy of the global temperature goals. IAMs were thus able to co-evolve with the continuously changing climate science-policy interface and adopt different roles. Informed by the descriptions of the *future representation* and *strategies to obtain policy relevance,* we believe this capacity to adopt different roles results from specific model characteristics of IAMs as well as the pro-active role of the modelling community.

3.3.1. Flexibility, breadth and hybridity of IAMs

The ability of IAMs to play various distinct roles between science and policy in various environmental policy domains (energy, acid rain, climate) throughout the historic phases can partly be explained from the structure of the modelling frameworks. A first key characteristic of IAMs is their *flexibility*, allowing for multiple sub-models to be coupled or decoupled. This flexibility is conducive to their wide application (Weyant, 2017). Secondly, IAMs are typically broad in scope, enabling the integration of information from a wide range of disciplines and covering environmental problems from causes to response strategies. Their breadth and flexibility allow IAMs to remain up-to-date, incorporating new scientific insights as well as providing knowledge inputs relating to newly emerging societal interests and political concerns. Third, the "hybrid" nature of IAMs, bringing together scientific and policy elements, provide the modelers to move backwards and forwards between experts, modelers and policy makers. For instance, the RAINS modelers started out with showing emission maps (the problem) and, responding to knowledge needs from acid rain negotiators, then started developing abatement scenarios. This hybridity is also apparent in their *representation of futures*, such as the critical loads, safe landing and 2 °C target, which cater both for expertise as well as to the evolving policy-makers' needs. With regard to the IPCC specifically, the capacity of IAMs to connect the scientific communities underlying the three different WGs appeared crucial to achieve coherence of its assessment reports. This capacity explains why the IPCC and IAM community became progressively mutually interdependent in the last three phases and their growing prominence in assessment reports (see Fig. 1). Considering the dense network of a relatively small group of authors and institutions underlying WGIII, this prominent position may be problematic as it risks "narrowing" the construction of climate mitigation within the IPCC (Hughes and Paterson, 2017).

3.3.2. The pro-active modelling community in anticipation of policy-relevance

A final element of our explanation for the evolution of IAMs in the science-policy interface is the pro-active nature of the modelling community in their search for policy-relevance. Our analysis indicates that modelers were not only reactive to the developments in science and policy; at crucial moments they were able to *anticipate* (and sometimes even helped to generate) policy makers' future demands. We think this agency of modelers, listening to policy conversations and assessing possible responses, can be understood as part of their 'institutional work', which is defined as "the purposive action of individuals and organizations aimed at creating, maintaining and disrupting institutions" (Lawrence and Suddaby 2006, p. 215). In our historical analysis, we recognized multiple forms of institutional work as distinguished by Lawrence and Suddaby (2006, p. 221).

One form of institutional work that we observed is 'advocacy': the mobilization of support through deliberate social persuasion (Lawrence and Suddaby, 2006). For instance, Jay Forrester deliberately persuaded the Club of Rome of the applicability of his system dynamic modelling approach to the 'world problématique' (phase 1). In a similar vein, the RAINS modelers convinced acid rain negotiators of the usefulness of their model (phase 2) and more recently the IAM community assured the IPCC bureau of their ability to convene the WGIII scenario process (phase 4). A second form of institutional work distinguished by Lawrence and Suddaby (2006) is 'theorizing': developing abstract categories or understandings of cause-effect relationships. This more indirect and discursive form of institutional work occurred through primarily through the particular *representation of possible futures* that legitimized the use of models for policy purposes. In phase 1 for instance, the energy-economic and climate-economic modelers framed the energy problem as technical and economic problem, legitimizing energy and climate economic models. Later on, the RAINS modelers formulated cause-impact-strategy relationships, legitimizing an IAM approach to acid rain (phase 2). Similarly, when climate change emerged on the political agenda in phase 3, modelers framed climate change as a complex multifaceted problem in need for integrative modelling approaches (e.g. Weyant et al., 1996). A third form of institutional work is 'mimicry': associating new practices with former practices or technologies in order to facilitate their adoption (Lawrence and Suddaby, 2006). A key example is the replication of the success of the RAINS model to the issue of climate change: not only was this success an inspiration, but specific lessons such as the set-up of expert workshops were explicitly repeated. Another form of mimicry was observable in phase 3, when the IAM community mimicked the scientifically rigorous, trusted and well-established GCM practice, by adopting the visual language of comprehensive graphs with quantitative long-term scenarios. The fourth form of institutional work that we recognized is 'defining': the development of rule systems that define boundaries of a field, such as the creation of standards (Lawrence and Suddaby, 2006). This primarily occurred in the last two historic phases when the IAM community established a number of 'repertoires' that organizes their research (Cointe et al., 2019). For instance, the IAM community formulated a number of criteria that scenario developers need to meet in order to be included in the scenario database that was used for the IPCC AR5 (Ibid.). These criteria, such as a minimum set of variables and a full energy system representation, thus strongly defined the scenario practice within the IPCC WGIII and excluded scenario approaches such as sectoral modelling.

The institutional work concept is commonly used organizational studies and less so in understanding science-policy interactions (Arpin et al., 2016 for a notable exception). However, the concept begins to emerge in environmental governance literature to better understand the diverse forms of agency in transformations of governance systems (Beunen and Patterson, 2019). Institutional work as a conceptual lens helps to grasp the micro-dynamics through which actors support, maintain or disrupt institutions (Ibid.). We believe that the concept may hold strong analytical strength explaining the role of models in policy-making on top of the more commonly used concept of 'epistemic communities' (Haas, 1992). Whereas the concept of epistemic communities has been valuable to explain the capacity of the IAM field to organize itself and reach consensus among peers - such as through a dense network of IPCC WGIII authors and institutions (Corbera et al., 2016; Hughes and Paterson, 2017) - it ignores the pro-active 'work' of a scientific community to show the relevance of its findings for policy making. We believe the notion of institutional work is a helpful addition to existing conceptual understandings of science-policy interactions, illuminating the actual micro-practices through which actors (either deliberately or not[3]) support, maintain and disrupt institutions.

3.4. Implications for the future role of IAMs

Our research indicates that between 1970 and 2015, IAMs became more prominent and adopted various roles in the evolving science-policy interface. Their strong embeddedness in IPCC's scenario practice implies that IAMs will most likely continue to play an important role. However, since IAMs have historically adopted various mediating functions between science and policy, this role is not at all fixed. The need for radical and rapid low-carbon transformations implies that their role should be continuously reevaluated, especially since IAMs are powerful in making certain pathways more legible and actionable at the expense of other strategies that may be crucial in responding to the climate crisis (Beck and Mahony, 2017; 2018). Modelers themselves are active in this debate by expanding their typical scenario set to alternative pathways (e.g. Van Vuuren et al., 2018) and propose ways to complement IAM with alternative analytical approaches to explore low-carbon futures (Geels et al., 2016). Yet, the fundamental technological, economic and socio-cultural transformations necessary to evolve to a decarbonized society points raises a debate on the ability of IAMs to conceive of more radical societal reorganization. These fundamental socio-cultural transformations points to the need for IAM community to seek new engagement with a broader range of disciplines that are rooted in social sciences and humanities. An example of such an engagement is a broader conception of human agency beyond rational choice, which implies an integration of heterogeneous agent profiles within IAMs (Otto et al., 2020). Future research could further explore if, how and under what conditions such links could be fruitful. Moreover, the climate debate is transpiring far beyond the realm of the climate negotiations. Climate action that is happening on the ground ('seeds') could be insightful for IAM modelers to identify new processes, patterns or social relations relevant to their scenario practice (Raudsepp-Hearne et al., 2020). Another implication of the widening debate is that the IAM community may need to expand their role to engage a wider range of publics and societal stakeholders in order to involve a wider range of perspectives on possible and desirable futures.

4. Conclusion

In this article we investigated how and why have IAMs became prominent in the climate science-policy interface. We identified five phases between 1970 and 2015 in which IAMs adopted various roles towards science and policy, from agenda-setting in early phases to target formulation and monitoring political ambition for mitigation in later phases. While IAMs found ways to provide policy makers with relevant knowledge in each phase, we found that the interaction between IAMs and the policy world had distinct characteristics in each of the five phases. The fact that IAMs adopted multiple distinct mediating roles between science and policy helps explain how they maintained and indeed could enhance their relevance. We found that the number of articles in academic journals drawing on IAMs per year rose from incidental in 1990 to over 140 in 2015, indicating the growing relevance of and recognition for IAM findings. We suggest there are several factors that help explain the growing prominence of IAMs in the climate-science policy interface. We differentiate between material and sociological background conditions and particular features of the IAM as model as

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[3] Apart from intentional strategies, recent studies in institutional work suggests unintentional strategies might be at play as well (for a discussion on intentionality, see Beunen and Patterson, 2019, p. 5). The unintentional strategies of the IAM community are beyond the scope of this paper.

well as the role of the communities that shaped up around the IAMs.

In terms of the background conditions we first signal the advances in computer technology and data availability that provided the material conditions for model-building in the first place. Secondly, the IAM-policy interactions played out against more persistent trends in growing authority of global and quantitative forms of knowledge. Yet we cannot fully explain the rise to prominence of IAMs without taking the specifics of the interaction around IAMs into account. On the one hand, the particular features of IAMs, their breadth, flexibility and hybrid nature explains their diversity in their applications and their 'anchoring' function between IPCC's Working Groups. On the other hand, our research reveals that the IAM field acted as pro-active scientific community deploying several purposive strategies to gain policy-relevance over time.

We conclude that the current prominence of IAM to explore low-carbon futures is a result of complex historic science-policy dynamics. The urgency of the societal response to the climate crisis and the broadening of the issue to the wider public debate points to the need to continuously and actively reevaluate the role of IAMs and reflect on their use in combination with alternative approaches to explore possible futures.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2020.102191.

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