Modeling climate change impacts at the science-policy boundary

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

A version of the first manuscript included in this dissertation has been published. I, Marisa Beck, was the main contributor and lead author of the work that has been published and the manuscript in preparation for publication.

The first manuscript included in this dissertation is a version of a published journal article entitled "The epistemic, ethical, and political dimensions of uncertainty in integrated assessment modeling." This article was co-authored by Dr. Tobias Krueger. Following the guidelines set forth by the University of Waterloo, this work is predominantly comprised of my intellectual contribution. The contribution of each author was: conceptualization (MB 80%; TK 20%); research (MB 90%; TK 10%); analysis (MB 90%; TK 10%); writing (MB 80%; TK 20%).

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Abstract

Climate change is a daunting policy challenge, where decision-makers must respond to a high-uncertainty and high-risk problem in an environment with a diverse multitude of stakeholders and unresolved ethical questions. For the past 25 years, integrated assessment models (IAMs) of global climate change have become standard tools for informing climate policy. IAMs are computer models that combine representations of biophysical systems and socioeconomic systems; they are used to simulate the causes, dynamics, and impacts of climate change. While IAMs are typically developed by scientists, their explicit purpose is to generate policy-relevant information. In this paper-based dissertation, I use a pragmatic model of science-policy relations as a theoretical and normative framework to examine the production and application of IAMs. My research contributes conceptually and empirically to the existing scholarship on the role of scientific models in policymaking. Together, the three articles included in this dissertation advance our understanding of the various inputs and outputs of policy-relevant scientific models, using climate change IAMs as a case study.

In Article #1, my co-author and I investigate the sources and consequences of the numerous difficult modeling choices that IAM developers are required to make as a result of the pervasive uncertainty—both scientific and ethical—surrounding this topic. We argue that these choices are made in particular epistemic, ethical, and social contexts. Correspondingly, we illuminate the epistemic, ethical, and political consequences of these choices. Finally, adopting a co-productionist approach, we suggest that past modeling choices may constrain future model development by setting epistemic benchmarks, establishing ethical norms, and creating biases in academic publishing and policy application. We review and build on findings from various literatures to unpack the complex intersection of science, ethics, and politics that IAMs occupy. This leads us to suggest avenues for future empirical and theoretical research that may enable an integrated epistemic-ethical-political understanding of IAMs. Such transparency is necessary to judge the usefulness of IAMs in supporting climate change policymaking that is scientifically sound, ethically fair, and politically acceptable.

Articles #2 and #3 extrapolate practical consequences from the conceptual groundwork established in Article #1. In Article #2, I apply a narrative research approach to examine how values and beliefs embedded in modeling choices may influence policy. I draw on research on the role of storytelling in scientific modeling, as well as a growing literature in policy studies investigating the

influence of stories on policy outcomes. These two streams of research have yet to be connected in an investigation of how scientific models, in addition to delivering numerical results, also influence policy through the stories that are told with them. In this paper, I present a framework for analyzing the composition and content of policy-relevant stories produced with scientific models. I argue that an appreciation of these modeled stories is essential for a full understanding how models are used in policymaking—whether they are models of climate change, public health, or the economy. For illustration, I apply the framework to the analysis of stories produced with the DICE model, arguably the most prominent IAM of global climate change.

In Article #3, I provide a normative, empirically grounded analysis of two of the major critiques of IAMs: that they are a) arbitrary and b) value-laden, and therefore unfit for policy use. Interviews and participant observations with IAM developers reveal that, indeed, many factors other than scientific theory and empirical observations influence modeling choices. The modelers also recognize that some of their choices in the modeling process do have a partially normative character. So, do these findings validate the above critiques and disqualify IAMs from policy use? Not necessarily. Current work in philosophy of science demonstrates the need for a more nuanced approach to this question, revealing that the ideal of objectively true and value-free models is unattainable—indeed, in some aspects, perhaps even undesirable. Instead, models should be evaluated with respect to their 'fit for purpose.' Uncertain and value-laden assumptions should be addressed with transparency and conditionality. Adopting such a pragmatist perspective on IAMs, this paper concludes that IAMs are a useful, albeit imperfect, tool for assessing climate policy. Practical recommendations for how to enhance the usefulness of IAMs for policy are provided.

Acknowledgments

As my PhD research draws to a close, I would like to take this opportunity to thank the many people and organizations who made this project possible and enjoyable for me. First of all, I am indebted to my study participants who kindly agreed to be interviewed and to spend time with me, sharing their insights on integrated assessment modeling.

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Chapter 1

Introduction: Modeling climate change impacts at the science-policy boundary

Climate change is the arguably most complex, controversial, and urgent policy issue of our time. Policymakers face great challenges when deciding whether, when, and how to respond. Scientific uncertainty about the dynamics and consequences of climate change prevents decision-makers from being able to fully grasp the practical impacts of alternative options for mitigation and adaptation (Morgan, 2011).[1] Unresolved ethical questions, including matters of distributional justice and valuation (Gardiner, 2004), imply that—even if scientific consensus existed—climate policy would still be controversial. Finally, the many diverse stakeholders engaged with the problem of climate change disagree about the values that should guide policy; even its basic framing as a policy problem is politically contested (Hulme, 2009). In addition, the risk that tipping points in the climate system may be crossed, triggering irreversible and possibly catastrophic consequences, raises the urgency of making decisions—and raises the cost of being wrong (Lenton and Ciscar, 2013).

Given these challenges, what information do policymakers use to prepare and justify their decisions? Since the early 1990s, when climate change appeared on the political agenda, integrated assessment models (IAMs) of global climate change have become standard tools for supporting climate policy. IAMs are computer models that combine representations of biophysical systems and socioeconomic systems; they are used to simulate the causes, dynamics, and impacts of climate change. While IAMs are typically developed by scientists, their explicit purpose is to generate policy-relevant information. But in the face of uncertainty and value disputes, building IAMs requires modelers to make substantive assumptions and choices. This is true not only in climate change, but in a wide variety of complex high-uncertainty and high-risk policy problems where mathematical models are used to inform decisions, such as public health and economic stability.

How do modelers make these choices? What factors drive their decisions? What values and beliefs about climate change and climate change policy become embodied in these choices—and

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[1] Climate change mitigation refers to efforts to abate and prevent emissions of greenhouse gases (GHGs) and other pollutants to limit climate change (IPCC, 2014a, p. 125). Climate change adaptation refers to the adjustment of human or natural systems to already existing or expected climate change in order to prevent or reduce harm (IPCC, 2014a, p. 118).

how? And what are the implications for the value of IAMs as policy aids?

These are some of the questions that I set out to examine in this paper-based dissertation. Combined, the three articles included in this dissertation advance our understanding of the various inputs and outputs of policy-relevant scientific models, examining climate change IAMs as a case study. Using a pragmatic model of science-policy relations as a theoretical and normative framework, I examine the production and application of IAMs of global climate change. I connect literature in philosophy, science and technology studies (STS), and policy studies in innovative ways, and I also draw on in-depth interviews and observations with IAM developers to provide a comprehensive and nuanced examination of the factors influencing IAM development. My dissertation contributes conceptually and empirically to the scholarship on the role of scientific models in policymaking.

This dissertation contains an introduction, three articles, and a conclusion. In the remainder of the introduction, I establish the historical and analytical context for the three articles:

- Section 1.1 outlines the history of IAMs, the current model landscape, and important debates in the IAM literature.
- Section 1.2 discusses theoretical insights from the existing literature on the role of scientific models in policy that have shaped my thinking about IAMs.
- Section 1.3 reviews three normative models of science-policy relations, and I explain why I use a pragmatic model as the theoretical and normative framework for this research.
- Section 1.4 highlights the novelty of my research and summarizes the contributions of this dissertation to the literature.
- Section 1.5 explains my methodology.
- Section 1.6 provides a brief overview of the structure of this dissertation.

1.1 Integrated assessment models of global climate change

This brief overview of the history of IAMs, the current model landscape, and ongoing discussions about the models' faults and merits illustrates that IAMs are scientific[2] models with an explicit purpose to inform policy. While IAMs are developed by scientists and IAM studies are commonly published in academic journals, these models also have a long history of being employed in a policy context. Critiques of IAMs often suggest that the key issues with using IAMs for policy assessments relate to the high degree of uncertainty about climate change and its impacts on people and the natural environment. The uncertainty requires modelers to make choices in the construction of IAMs, which, critiques argue, are subjective, ethically indefensible, and politically biased. Combined with a lack of transparency about these assumptions, IAMs—in the eyes of some

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[2] Throughout this dissertation, I use the terms ‘science’, ‘scientific’, and ‘scientist’ in a broad sense, referring not only to the natural sciences but also to the social sciences and the humanities.

skeptics—may cause more damage than good to climate policy.

Definition

Numerous definitions of IAMs of global climate change exist in the literature but the selection of definitions compiled in Table 2.4 illustrates that there are two universal defining characteristics.[3] First, IAMs integrate mathematical representations of natural systems and socioeconomic systems. Second, the explicit purpose of IAMs is to inform decision-makers in public policy and industry.

A complete IAM models the causal relationships between human activity, greenhouse gas (GHG) emission levels, and climate change, as well as the impacts of climate change on human and non-human life. IAMs can be used to analyze the environmental and economic consequences of alternative socio-economic scenarios or policy programs, to translate mitigation targets into possible emissions trajectories, or to optimize key policy variables such as emissions abatement or a carbon tax rate (van der Sluijs, 2002, p. 137). Currently, one of the key applications of IAMs is the calculation of the social cost of carbon (SCC). The SCC is the monetized impact caused by one additional ton of carbon emitted into the atmosphere. The higher the SCC, the higher are the expected damages from climate change. In the terminology of economic theory, the SCC equals the "marginal monetized externality value" (Metcalf and Stock, 2015, p. 1) and corresponds to the optimal carbon tax rate in a welfare-maximizing policy scenario. In practice, SCC estimates function as a crucial guide for policymakers in regulatory impact analysis. The higher the SCC, the higher the return on investment from regulations and projects that contribute to reducing carbon emissions.

Quantitative models such as IAMs represent one of the available methods for performing integrated assessment of complex policy problems. The impacts on humans and the natural environment of many issues related to global environmental change are so diverse that their comprehensive study requires the cooperation of researchers from multiple disciplines. Integrated assessment (IA) is the process through which knowledge from all of the relevant scientific domains is combined, interpreted, and communicated (Parson, 1995). The objective of IA is to create "added value compared to assessment based on a single discipline" in order to "provide useful information to decision makers" (Rotmans and van Asselt, 1996, p. 121). Parson (1995) argues that formal computer models are popular as a tool for IA of climate change, because a "model is an identifiable product" (p. 469) for scientists to deliver to policymakers. Other IA methods such as qualitative models and informal tools such as policy exercises and expert panels (Parson, 1995, 1997; Weyant et al., 1996) may result in less tangible deliverables. Moreover, the model building process imposes quite specific, well-defined, and technical challenges on the researchers—attractive features (Parson, 1995, p. 469). Substantively, a perceived strength of IAMs is their ability to "transparently and effectively impose [...] discipline of consistency and mutual intelligibility across subdomains of the problem"

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[3] This overview of definitions is an update of the previous work by van der Sluijs (1997), pp. 6-7. He identifies the same defining features of IAMs.

Table 1.1: Defining IAMs of climate change

Schneider (1997)	“One of the principal tools used in integrated assessment (IA) of environmental science, technology and policy problems is integrated assessment models (IAMs). These models are often comprised of many sub-models adopted from a wide range of disciplines. [...] Rather, my purpose here is to examine the analytic tools that analysts often turn to in search for rational enlightenment in the bewilderingly complex global climate change policy debate: integrated assessment models (IAMs)” (p. 229).
Parson and Fisher-Vanden (1997)	“Integrated assessment models seek to combine knowledge from multiple disciplines in formal integrated representations; inform policy-making, structure knowledge, and prioritize key uncertainties; and advance knowledge of broad system linkages and feedbacks, particularly between socioeconomic and biophysical processes. They may combine simplified representations of the socioeconomic determinants of greenhouse gas emissions, the atmosphere and oceans, impacts on human activities and ecosystems, and potential policies and responses” (p. 589).
Kelly and Kolstad (1999)	“We define an integrated assessment model broadly as any model which combines scientific and socio-economic aspects of climate change primarily of the purpose of assessing policy options for climate change control” (p. 3).
Böhringer et al. (2007)	“Integrated assessment models (IAMs) link mathematical representations of the natural system and the socio-economic system to capture cause-effect chains including feedback” (p. 1).
Nordhaus (2011b)	“Integrated assessment models (IAMs) can be defined as approaches that integrate knowledge from two or more domains into a single framework. These are sometimes theoretical but are increasingly computerized dynamic models of varying levels of complexity” (p. 2).
Weyant (2014)	“Since the relationships within and between the various bio-geochemical and socioeconomic components of the earth system can be quite complex, a number of quantitative models have been developed to study earth-system-wide climate changes and the effect of various types of public policies on projections of future climate change. These models have become known as ‘integrated assessment of climate change’ or ‘integrated assessment’ models (IAMs). The objective of these models is to project alternative future climates with and without various types of climate change policies in place, in order to give policy makers at all levels of government and industry an idea of the stakes involved in deciding whether or not to implement them” (p. 380).

(Parson, 1995, p. 468), with mathematics as a unifying language between these subdomains.

Policy application

As was shown in the previous section, the explicit intention behind developing and running IAMs is to inform public policymaking regarding GHG emissions.[4] I review three recent examples, where IAMs have been employed within a policy context:

- At the international level, the *IPCC Fifth Assessment Report*[5] (AR5)—like all of the previous IPCC assessment reports—relied on outputs from IAMs. AR5 draws on a database of results generated from 30 large-scale, detailed IAMs for producing long-term mitigation scenarios (Clarke et al., 2014). The results from the model simulations feature prominently in the Summary for Policy Makers in the contribution of the Working Group III and may thus inform both the international negotiations on climate change as well as national policy (IPCC, 2014b).
- In 2007, the *Stern Review of the Economics of Climate Change* was published, a report produced by economist Nicholas Stern on a commission by the UK government (Stern, 2007). The Review features a cost-benefit analysis of global climate change that was produced with a modified version of the PAGE model, a global IAM. The modeling results were an important piece of evidence in support of the Review's argument for strong and urgent action on climate change. While it was only one of multiple types of evidence used in the Review to address the many facets of climate change, the analysis produced with PAGE arguably received the most attention in the academic literature (see Hansen (2011) and references therein). The Review had significant influence on climate policy, particularly in Europe (Jordan and Lorenzoni, 2007).
- In 2010 and 2013, the U.S. EPA employed three IAMs (the DICE, FUND, and PAGE models) to calculate the official estimates of the SCC that the government uses to perform regulatory impact assessments (Greenstone et al., 2013). The first set of estimates from 2010 was updated in 2013, drawing on the new versions of the same three models (Interagency Working Group on Social Cost of Carbon, 2010, 2013). The Canadian government has adopted the U.S. SCC estimates with some minor adjustments (Environment and Climate Change Canada, 2016).

History of IAMs and the current model landscape

IA has been used to support policy decisions on complex environmental issues since the 1970s (Weyant et al., 1996, p. 376). The first integrated assessment *model* that incorporated the entire

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[4] Only a small number of studies uses IAMs to analyze adaptation policies. For examples, see Ward et al. (2013) and Hinkel et al. (2014); for an overview, see Füssel (2010). Generally, the economic analysis of adaptation policies is less advanced than for mitigation (Li et al., 2014).

[5] IPCC stands for Intergovernmental Panel on Climate Change, which is the international body for compiling and reviewing science related to climate change. The central mandate of the IPCC is to provide policymakers with up-to-date scientific information about climate change and policy options.

causal chain of an environmental problem—from the sources of emissions to the impacts—did not address the climate change, but acid rain. The Regional Acidification and Information Simulation (RAINS) model was developed by the International Institute for Applied Systems Analysis in Vienna in the early 1980s (Alcamo et al., 1985, 1987). It was used to evaluate regulation of sulfur dioxide emission, and it played an important role in international negotiations under the United Nations Convention on Long-Range Transboundary Air Pollution (van der Sluijs, 2002). In contrast to RAINS, early climate IAMs were more limited in scope. For example, the MINK project (Rosenberg and Crosson, 1991) focused on regional influences and impacts, while Nordhaus (1979), Nordhaus and Yohe (1983), and Edmonds and Reily (1985) only modeled climate change entailed by emissions from fossil fuel energy sources. The energy-economic models used in these latter studies can be considered "the most prominent heritage" of many current IAMs (Parson and Fisher-Vanden, 1997, p. 591).

In the late 1980s, efforts were made to extend the capacities of climate IAMs. In particular, the National Institute of Public Health and Environmental Protection (RIVM) in the Netherlands developed IMAGE, the Integrated Model to Assess the Greenhouse Effect (Rotmans, 1990). Early modeling initiatives in the United States included the U.S. EPA's Atmospheric Stabilization Framework (ASF) (Lashof and Tirpak, 1990) and the Model of Warming Commitment developed by a researcher at the World Resources Institute (Mintzer, 1987).

The number of models and projects increased rapidly in the early 1990s, making IAMs the dominant tool for producing IAs of global climate change (Weyant et al., 1996, p. 377). Multiple parallel developments contributed to this surge of modeling activity. Importantly, in 1992, for the first time, virtually all countries agreed on common targets for slowing global emissions with the objective to reach "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations Framework Convention on Climate Change (UNFCCC), Article 2). The establishment of the UNFCCC increased the policy demand for information on the cost and benefits of mitigating GHG emissions, and IAMs gained increasing acceptance as an effective tool for producing that information (Weyant et al., 1996, p. 376). The First IPCC Assessment Report from 1990 featured both IMAGE and ASF; the Second Assessment Report from 1996 already included a review of 22 IAMs (Bruce et al., 1996). This report also made another important case for increased investment in IAMs development, by stating that climate change is indeed associated with human activities (Schneider and Lane, 2005, p. 49). In addition to the increasing academic and political interest in IAMs, advances in computing technology, enhanced data availability, access to funding, and progress in climate science and in the underlying research fields all contributed to the launch of numerous new modeling projects (Parson and Fisher-Vanden, 1997, p. 592). Many of these new initiatives were described and discussed in two special issues of *Energy Policy* on IAMs, published 1993 and 1995 (Energy Policy, 1993, 1995). A pioneering study from that time, titled "To slow or not to slow," was written by economist William Nordhaus in 1991. Nordhaus used a simple, static integrated modeling framework to determine the optimal global emissions targets (Nordhaus, 1991). In his analysis, Nordhaus supposed an upper bound for the damages from unmitigated climate change at 1–2% of global output. These damage estimates have become important benchmarks against which the results of many subsequent climate economic analyses were compared (Risbey et al., 1996; Dietz and Stern, 2015). Shortly after the publication of his 1991 paper, Nordhaus enhanced his static modeling framework to become the Dynamic Integrated Climate Economy (DICE) model (Nordhaus, 1992), which has since become one of the most well-known and widely-used IAMs. In 1996, the IPCC's Second Assessment Report stated that "the current level of integrated assessment activity on global climate change is unprecedented" (Weyant et al., 1996, p. 374). Over the past 25 years, some of the initial modeling efforts from the early 1990s became obsolete (e.g. the CETA model (Peck and Teisberg, 1992)), while others have been updated regularly and are still in use (e.g. the IMAGE model and the DICE model). In addition, new models were launched such as the WITCH model, which was first developed in 2006 (Emmerling et al., 2016).

Today, over 30 IAMs of global climate change exist. Their institutional homes are universities or other semi- or non-governmental research institutes. The IAM landscape features a variety of models that differ significantly in terms of their structure and key parameter assumptions. Numerous typologies of IAMs exist (see, for example, Dowlatabadi (1995); Weyant et al. (1996); Stanton et al. (2009); Sarofim and Reilly (2011)). For the purpose of this analysis, the broad distinction put forward by Weyant (2014) between two types of IAMs is most relevant: disaggregated, non-economic IAMs and aggregated, economic cost-benefit models. These two types differ with respect to the way they model climate change impacts.

The first type of IAM is generally more detailed and disaggregated, seeking to estimate climate impacts on specific regions and/or sectors. Sarofim and Reilly (2011) call IAMs of this type 'science-based models.' Sometimes this type of IAM provides an economic evaluation of these impacts, but often, impact estimates are merely expressed in physical units of measurement (Weyant, 2014). The modeling teams building this type of IAM are often large, including researchers from the various disciplines that are represented in the model. Examples of this type of IAM include the IMAGE model that was mentioned earlier, the REMIND model (Luderer et al., 2015) and the GCAM model (Joint Global Change Research Institute, 2016).

The second type of IAM is significantly more aggregated. The aim here is to compile the regional and sectoral impacts of climate change and express them in a single economic metric. That is why Sarofim and Reilly (2011) refer to IAMs of this type as 'economics-focused models.' IAMs of this type can be used to perform economic cost-benefit analyses of alternative policy proposals, but a common application is to determine the optimal policy strategy that maximizes societal welfare.[6] An alternative, and increasingly popular application of cost-benefit IAMs is the calculation of the

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[6] These two types of IAM are not independent: often, aggregate cost-benefit IAMs draw on results of more disaggregated models for calibration (Weyant, 2014).

SCC (Rose, 2012; Metcalf and Stock, 2015). This type of IAM is typically developed by smaller teams, and the researchers working with these models often (but not always) have a background in economics. The most prominent examples of this type of IAM are the DICE model (Nordhaus and Sztorc, 2013), the FUND model (Anthoff and Tol, 2014), the PAGE model (Hope, 2011). It is the latter type of IAM that this research primarily focuses on.

Current debates and criticism

Despite their 25-year history, there is still significant disagreement among climate economists, policymakers, and observers about how IAMs can best fulfill their key mandate—to represent the complexities of climate change in a mathematical model that delivers results that are useful for policy. I briefly introduce three ongoing debates in the IAM literature that are relevant to the articles in this dissertation: the discounting of future climate damages in IAMs, the modeling of risks related to catastrophic climate change, and the incorporation of climate change impacts on economic growth.

IAMs apply discount rates to determine the present value of climate damages occurring in the future. The higher the value of the discount rate, the smaller the weight given to future damages in today's climate policy decisions. Two basic positions on how to set the discount rate can be distinguished (Schelling, 1999; Dasgupta, 2008; Baum, 2009). First, the descriptive position argues that observed market interest rates should determine choices about the discount rate in IAMs, because in market interest rates, people express their preferences for inter-temporal trade-offs. The prescriptive position supposes that the choice of discount rate is primarily an ethical choice and should thus be driven by moral considerations concerning distributive justice between present and future generations. The publication of the *Stern Review* considerably fueled the debate about discounting. In the *Review* a very low discount rate is used, based on an explicitly ethical argument (Stern, 2007). Consequently, the *Review* contained recommendations for ambitious and urgent policy intervention—unlike many previous cost-benefit studies (Nordhaus, 2007). A vivid discussion in the literature ensued in the following few years, engaging climate economists, modelers, and ethicists (Nordhaus, 2007; Weitzman, 2007; Schneider, 2008; Tol and Yohe, 2009; Broome, 2012; Nordhaus, 2012).

In 2011, the seminal 'dismal theorem' proposed by economist Martin Weitzman raised the issue of 'fat tailed' climate damage functions and the risk of extreme climate change with possibly catastrophic impacts (Weitzman, 2009, 2011, 2012a,b). Weitzman argues that the probability distributions of important model variables may be significantly skewed, to the effect that the likelihood of extreme values is relatively high, which then may result in unbounded (or at least extremely large) values of the SCC. Again, Weitzman's claim triggered a debate among economists and modelers. Some modelers criticized Weitzman's argument (Nordhaus, 2011a), while others adopted its implications in their model studies (Anthoff and Tol, 2013; Pycroft et al., 2011; Dietz and Stern, 2015). A related issue—often discussed in the same context because it has similar implications—is the possibility of abrupt, irreversible, and catastrophic impacts from climate change occurring when stochastic 'tipping points' in the climate system are crossed (Lenton and Ciscar, 2013; Fisher and Le, 2014).

A currently burgeoning debate concerns the long-term effects of climate change on economic growth (Burke et al., 2016). To date, many IAMs only account for climate damages to current economic output, ignoring the potential for more permanent impacts on future growth trajectories. In recent years, multiple empirical studies have investigated the relationship between climate and growth (Dell et al., 2012; Burke et al., 2015), and a few IAM studies have implemented this relationship as a new feedback loop, typically arguing that its exclusion results in unjustified lenient recommendations for emission cuts (Krakauer, 2014; Estrada et al., 2015; Moore and Diaz, 2015; Dietz and Stern, 2015).

In addition to these substantive academic debates about particular issues in integrated assessment modeling, there is a considerable body of work reviewing and critiquing IAMs as tools for policy support more generally, produced by scholars from both within and outside the climate economics community. A review of these critiques reveals that commonly identified shortcomings of IAMs are linked to the high degree of uncertainty under which the models are built; uncertainty surrounds almost every aspect of IAM building, because the scientific theories and empirical data feeding into IAMs are incomplete and often contested. Consequently, modelers are required to make numerous choices in model development. According to some IAM critiques, these choices are ripe with subjective and value-laden judgments and assumptions. Moreover, critiques often consider the explicit treatment of uncertainty in the model to be inadequate, and falsely leading to the impression that model results are more precise and certain than they actually are. A related criticism focuses on transparency around the modeling process and communication of model results. Interestingly, the core points of IAM critiques seem to be as relevant today as they were a generation ago, as the following chronological summary reveals.

In 1993, Grubb (1993) explains that IAMs "can greatly improve our understanding of the nature of the climate change problem in all its complexity" (p. 208), but that "[a]t the present stage of modeling, expert judgment is a better guide to policy than any particular model result" (p. 203). The crucial challenge that Grubb sees is the incomplete "understanding of the climate system, its stabilities and instabilities, the likely impact of radiative changes on local climates, and of how to evaluate the welfare impacts of these changes" (ibid., p. 204). He argues that models which incorporate the probability of high-cost surprises, the dynamics of technology development, inertia technical and social systems—all within a "framework of uncertainty" (ibid., p. 208)—are still missing. In a similar vein, Risbey et al. (1996) suggest that given the large uncertainties and long time scales of the climate problem, "it could well be the case that IA [integrated assessment] efforts will not provide any concrete policy advice" (p. 370) since "there is no guarantee that even the most rigorous IA studies will produce knowledge that drives policy" (p. 370).

In 1997, Schneider (1997) argues that IAMs have the potential to offer policymakers a coherent decision-making framework, but only in the context of transparency and the explicit communication of value-laden modeling assumptions. Conversely, if value-laden assumptions (both in the natural scientific and social scientific elements of IAMs) are not explicitly addressed and clearly communicated, the models will likely lead to misunderstandings and misconceptions among lay audiences. Schneider moreover emphasizes the participation of diverse policy actors in a modeling process as a means of preventing political bias (whether intentional or inadvertent) and, again, enhancing transparency. Overall, he concludes that "[i]t would be foolish to not to take the hedged qualitative insights from a family of IAMs seriously as it would be to take their individual quantitative results literally" (ibid., p. 246).

A few years later, van der Sluijs (2002) finds that IAMs are in a "credibility crisis," a target of academic and public outrage about the models' lack of reliability, transparency, and accuracy. He agrees that "[a] major problem with climate IAMs is that our present-day knowledge and understanding of the modeled system of cause-effect chains and the feedbacks in between is incomplete and is characterized by large uncertainties, knowledge gaps, unresolved scientific puzzles and limits to predictability" (ibid., p. 138). Modeling under uncertainty requires choices and assumptions that are often subjective and value-laden, which make IAMs vulnerable to political manipulation and compromise their trustworthiness. To regain credibility, van der Sluijs (2002) calls for participatory modeling processes and identifies "a need for more open, dynamic (interactive) forms to accommodate value diversity and to cope with plurality" (p. 144) among stakeholders.

In 2009, Stanton et al. (2009) find that, despite the widespread use of IAMs in policymaking, the models still look "like a 'black box' to all but a handful of researchers" (p. 179). In addition to calling for greater transparency about the assumptions and judgments that inevitably come to shape model development, the authors also express critique regarding the ethical stance taking in IAMs; in particular, they worry that "[s]ome models seem to ignore (and implicitly endorse the continuation of) gross regional imbalances of both emissions and income" (p. 166).

In July 2013, economist Robert Pindyck (2013) offers the perhaps harshest critique of cost-benefit IAMs, arguing that the models have not been worth the effort and investment that has gone into their development over the past 25 years, because they have not helped to reduce the disagreement about the value of the SCC. Provocatively, Pindyck asks "What have these IAMs (and related models) told us?" and promptly gives his own answer—"very little" (ibid., p. 3). He goes on to explain that "the models are so deeply flawed as to be close to useless as tools for policy analysis. Worse yet, precision that is simply illusory, and can be highly misleading" (ibid., pp. 2-3). In particular, he criticizes the inadequate treatment of uncertainty in IAMs, the arbitrariness of modeling assumptions, and models' inability to incorporate the risk of catastrophic climate change. Pindyck uses less strong language in a follow-up analysis (Pindyck, 2015), but his conclusion remains the same: that inferences from IAMs are not trustworthy, but that the "use of

IAMs [...] creates a veneer of scientific legitimacy that is misleading" (ibid., p. 3). As a better alternative, he suggests that policymakers should "rely on 'expert' opinion, perhaps combined with relatively simple, transparent, and easy to understand models" (ibid., p. 3).

Economist Nicholas Stern (author of the *Stern Review*) argues in a recent paper that the risks related to and the ethical questions arising from the policy problem of climate change make it too complex to be represented in conventional cost-benefit frameworks:

> "Attempting to shoe-horn a problem involving the management of risk on this scale into an economic framework with modest perturbations in a narrow, often one-good growth model, together with taking a blinkered and overconfident view of the information that markets can provide on related ethical values and possible outcomes, carry profound risks of suggesting ill-founded, misleading and dangerous policies" (Stern, 2013, p. 2).

In other words, Stern concludes that IAMs (in their current form) are inherently unable to meet the ethical standards that an adequate assessment method should meet. More recently, Stern (2016) argues that "[c]urrent economic models tend to underestimate seriously both the potential impacts of dangerous climate change and the wider benefits of a transition to low-carbon growth. There is an urgent need for a new generation of models that give a more accurate picture" (pp. 407-408).

1.2 Policy-relevant scientific models

Setting the context for this dissertation requires a discussion of science-based models that are used to inform policy, and thus become the "identifiable product[s]" (Parson, 1995, p. 469) of the science-policy relationship. Scientific models have been used in international negotiations and national policymaking in various policy areas, including economics (den Butter and Morgan, 2000; MacKenzie, 2006), public health (McKenzie and Samba, 2004; Mansnerus, 2013, 2014), and the environment (Hordijk, 1991; van Daalen et al., 2002; van Egmond and Zeiss, 2010; Edwards, 2010). I begin with a brief definition of scientific models, before elaborating on how they are used as policy aids.

Scientific models

The philosophical literature on scientific models is large and growing, as the importance of computer models in scientific research practice expands commensurately. It is beyond the scope of this dissertation to fully review this literature and the many meanings of the term 'model' it incorporates (see Frigg and Harmann (2012) and Portides (2013) for brief overviews). In the context of this dissertation, it is important that a model is a representation of a "selected part of the world (the 'target system')" (Frigg and Harmann, 2012). Moreover, a model's representation of the world is inherently partial in that it is typically abstracted, approximated, or idealized (Portides, 2013, p. 429). In fact, it is the explicit purpose of models in science to render the complexity of the world more workable by these means (Knuuttila, 2009).

Many disciplines in the natural and the social sciences develop and apply different types of models as instruments for inquiry. While numerous types of scientific models exist—including physical models, simulation models, imaginary models, and theoretical models—the most commonly used are arguably mathematical models, i.e. models that employ mathematical language to represent the target systems. This dissertation is primarily concerned with simulation models of complex systems that are based on mathematical models and that are run on digital computers. Simulation models use "step-by-step methods to explore the approximate behavior of a mathematical model" (Winsberg, 2015), imitating the evolution of a complex, real-world system over time (Winsberg, 2003, 2015). For example, IAMs are computer programs that simulate the interactions between two complex systems—the Earth's climate and the human economy. IAMs are equation-based computer simulation models, which means the underlying mathematical model is based on differential equations that describe system behavior (Winsberg, 2015). The other type of computer simulation model is agent-based models, which simulate the behavior of a large number of individual agents whose behavior is not dictated by a set of global equations but rather by each agent's own set of local rules.

Models are, at the same time, products and means of scientific research. Theories, hypotheses, and data about the world, collected from measurements and observations, provide key building blocks for the construction of scientific models—although model construction certainly involves many other 'ingredients' as well, such as hypotheses, creativity, metaphors, and mathematical techniques (Boumans, 1999). In other words, models are not determined by theories and data about the target system; there is no automatic algorithm for translating these building blocks into a set of mathematical equations. In fact, it is exactly their partial independence from both theory and the world that Morrison and Morgan (1999) argue is key to why models are able to function as tools or instruments to learn more about either: "By its nature, an instrument or tool is independent of the thing it operates on, but it connects with it in some way" (p. 11). In line with this view on models as partially autonomous instruments, Frigg and Harmann (2012) call models "vehicles for learning about the world" (Frigg and Harmann, 2012) and Knuuttila (2009) speaks of models as "epistemic artifacts."

Many philosophers have examined the ways in which scientists use models as investigative devices and how scientists learn from using them (Knuuttila, 2009; Winsberg, 2010; Morgan, 2012). Many of these accounts emphasize that learning from models occurs in the process of building them, manipulating them, asking them questions, and interpreting their answers. That is why Winsberg (2003) understands 'simulation' in a broad sense as to include the processes of building, running, and making inferences from computational models as well as studying and sanctioning these inferences.

Many questions regarding the epistemology of scientific models and computer simulations are still controversial among philosophers. A vivid discussion exists about model verification and validation: how can we trust the conclusions we draw from computer simulations to teach us anything about the world? Furthermore, is the goal of such computer simulations to generate numerical predictions of data points that we cannot retrieve through other means such as measurement and observation? Or is the goal to improve our understanding of the modeled systems? Or should researchers regard simulations as heuristics that are useful for exploring the implications of "alternative representational structures" (Winsberg, 2015)? As pointed out earlier, because of the partial autonomy of models from theory and data, the credibility and validity of these more traditional elements of scientific enquiry do not inherently extend to the inferences made from models. While the literature on the topic of validation and verification is too large to provide a comprehensive review here, it should be noted that views on this topic diverge significantly. For instance, in a widely cited paper, Oreskes et al. (1994) question that simulations of complex systems can ever deliver 'objective' knowledge because the process of building and using models inevitably involves a number of heroic assumptions that, ultimately, cannot be validated. In contrast, Norton and Suppe (2001) contend that simulation models absolutely can deliver 'good science' and illuminate 'real effects' and that it is the task of the modeler to identify and communicate these real effects.

Models as boundary objects

Scholars in science and technology studies and policy studies are key contributors to the empirical and theoretical literature on the role of scientific computer models in policy-making (Shackley et al., 1999; den Butter and Morgan, 2000; van Daalen et al., 2002; van Egmond and Zeiss, 2010; Edwards, 2010; Mansnerus, 2013, 2014). Policy-relevant scientific models are models that are built by scientists and used for scientific inquiry, but that are also applied to provide information to policymakers; they are of a "hybrid nature" (van Egmond and Zeiss, 2010). These models are the result of scientific practice, but they are also an explicit part of the political world. They are subject to academic peer review and publishing norms, but also subject to the scrutiny of political actors and (possibly) of the public at large. For example, Cash et al. (2003) argue that all environmental assessments (including those produced with models) should not only be scientifically robust, but also responsive to the specific demands of decision-makers and produced in a fair and inclusive manner. Therefore, hybrid science-policy models are subject to power relations within both academia and the policy process.

It should be noted that scientific models can be used for policy in various ways. In some cases, models are used "at a distance, when primarily research-oriented models generate evidence that eventually informs policy" (Mansnerus, 2014, p. 45). For instance, the results of climate science models may reach policymakers only through the IPCC reports, which compile published academic research. Alternatively, models may be used in the context of a government-commissioned research report. An example here is the application of the PAGE model in the Stern Review (Stern, 2007).

However, in other cases, the model-building process may be closely integrated with the policy process that the model is supposed to inform. For example, the three IAMs that were used to calculate the official U.S. SCC estimates were run (but not developed) by bureaucrats within the U.S. Environmental Protection Agency (Greenstone et al., 2013). In either of these cases, computer modeling becomes not only a scientific but also a political process.

The concept of 'boundary objects' is employed in multiple studies to describe the role of scientific models in policy.[7] These models (or specific aspects of modeled representations) are considered boundary objects between science and policy because of their coordinating function between these two social worlds (Shackley and Wynne, 1996; Cash et al., 2003; White et al., 2010; van Egmond and Zeiss, 2010). Star and Griesmer (1989) first introduced the concept, based on the observation that scientific research involves numerous different actors from various social worlds, holding divergent viewpoints on the research objects. Therefore, while "[c]ommon myths characterize scientific cooperation as driving from a consensus imposed by nature" (ibid., p. 388), the authors argue that intentional activities are necessary for translating between the divergent viewpoints for the sake of generalizable findings. One such activity is the creation of 'boundary objects' that are able to function as translators between the different social worlds in which they exist, because they are flexible enough to "satisfy the informational requirements of each of them" (ibid., p. 393). Therefore, effective boundary objects need to be "both adaptable to different viewpoints and robust enough to maintain identity across them" (ibid., p. 387). For example, Hordijk (1991) describes the guidelines for building the RAINS model, a scientific model with the purpose of informing international negotiations on acid rain governance. Some of these guidelines speak directly to that plasticity and appear to deliberately establish the RAINS model as an effective boundary object between science and policy. The stated objective of these model guidelines is to design and use RAINS in ways that satisfy the expectations of both negotiators and scientists at the same time. Thus, on the one hand, user-friendliness is considered "a very important issue" (ibid., p. 601) and negotiators' preferences were explicitly considered in model development. On the other hand, the scientific community and the scientific advisors to the negotiators in particular also "had to be convinced that RAINS was a credible product" (ibid., p. 600). One mechanism for ensuring scientific credibility of the RAINS model was the peer review process, and therefore academic papers about RAINS were submitted for publication in reputable academic journals.

1.3 The science-policy interface

The notion of scientific models such as IAMs as boundary objects between science and policy requires a more detailed discussion of science-policy relations, providing another important piece of context for my dissertation. Here, I outline three prominent models—the technocratic model,

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[7] The most prominent application of this idea in the context of environmental governance, however, is with regards to boundary *institutions*. See the special issue of *Science, Technology, & Human Values* from 2001.

the decisionist model, and the pragmatic model—and I explain why I choose the last of these as the appropriate framework for my research.

Before continuing, it is important to clarify some terminology. For the purpose of this dissertation, I define ‘science’ as “the systematic pursuit of knowledge” (Pielke, 2007, p. 31) and ‘policy’ as the “commitment to a particular course of action” (ibid.), where defining a course of action includes setting goals and determining the means to achieve them. Finally, I understand ‘politics’ to mean the “arrangements of power and authority in human associations as well as the activities that take place within those arrangements” (Winner, 1980, p. 123). One of these activities is of course, the deliberation of policies. The mechanisms through which lawmakers and interest groups resolve conflicts about policy—bargaining, negotiations, and compromise—are inherently political, because these mechanisms reflect struggles for power and authority.

When I speak of the science-policy relationship, I am well aware that power relations shape this relationship, because policymaking is a political activity. When scientific knowledge informs the decisions on policy, that scientific knowledge becomes political. However, whether the production of scientific knowledge itself is shaped by power relations and thus political, is a more controversial question—as discussed in the following. In fact, this issue defines one of the key points of disagreement between the three above models of science-policy relations.

1.3.1 Technocracy, Decisionism, and Pragmatism

The sociologist Jürgen Habermas described three ideal models of the relationship between science, policy, and politics (Habermas, 1971). The technocratic, decisionist, and pragmatic models suggest varying levels of interaction between the two social subsystems of science and policy; importantly, they also imply varying distributions of authority and responsibility between them. Habermas’ trio is still of great relevance in the current scholarly discourse about the science-policy interface, since more contemporary accounts of the topic largely fit into one of Habermas’ categories (Edenhofer and Kowarsch, 2015)[8].

According to the *technocratic model*, policy decisions should be exclusively based on scientific expert knowledge. The role of the government is reduced to formalizing the recommendations made by scientists. The intention is to de-politicize policymaking. Only when policy is guided by rationality rather than power relations, can society achieve the economically efficient allocation of resources (McQuaid, 2002, p. 253). Disagreements are settled with the help of cost-benefit analyses and other quantitative assessment tools rather than political mechanisms. Underpinning the technocratic model of science-policy relations is the assumption that conflicts between policy actors merely result from a lack of information and that all rational actors will agree on the

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[8] See also the Appendix of Edenhofer and Kowarsch (2015) for a comprehensive discussion.

optimal course of action, once sufficient information is available. Another fundamental assumption is that scientific knowledge, and the tools to obtain it, are objective, universal, and value-neutral (Sörensen, 2012, p. 195). Technocrats understand science as an autonomous social institution that is governed by its own set of norms, which, as famously proposed by Merton (1973), are universalism, communism, disinterestedness, and organized skepticism. The mechanism for enforcing these norms is scientific peer review. This perceived independence of science is seen to legitimize the cognitive authority it is given in the policy process.

Compared to technocracy, the *decisionist model* of science-policy relations suggests a different allocation of authority between government and scientists. Policymakers—not experts—determine policy objectives by way of governmental processes. Once the decisions on objectives are made, scientists are asked to deliver impartial advice and information about how to achieve the set objectives in the most efficient way. Pedersen (2014) proposes that "there should be a division of cognitive and deliberative labour, generally corresponding to the division between facts and values" (p. 547). Like technocracy, the decisionist model assumes that science is (or at least can be) objective and independent from politics, and that in science, empirical and normative questions can be neatly separated. Because of the perceived ability of science to deliver universal causal explanations, the decisionist model considers expert advice a powerful corrective measure against political arbitrariness (Pedersen, 2014).

The *pragmatic model* of science-policy relations is sometimes called the democratic model, because it is more inclusive than either technocracy or decisionism. The pragmatic model implies a more even distribution of authority between scientists, the government, and society as a whole, calling for participation of all stakeholders in the deliberative policy process. Legitimization of the pragmatic model requires a different philosophy of knowledge. While technocracy and decisionism are based on the ideal of logical positivism, the democratic model of the science-policy interface engages ideas of social constructivism that challenge the perceived independence of science from politics, which is the traditional justification for its authority. Scientific knowledge is seen as incomplete, uncertain, often contested and in need of interpretation (Maasen and Weingart, 2005b). Sheila Jasanoff argues that "[w]e regard a particular factual claim as true not because it accurately reflects what is out there in nature, but because it has been certified as true by those who are considered competent to pass upon the truth and falsity of that kind of claim" (Jasanoff, 1990, pp.12-13). Taking this argument to the extreme, some proponents of the democratic model do not inherently consider scientific knowledge to be more reliable, objective, or 'true' than other types of knowledge, such as local or indigenous knowledge, and they see no inherent justification for giving it any greater weight in policymaking (see Maasen and Weingart (2005b) for a brief discussion of this issue).

Many pragmatic accounts of science-policy relations criticize the technocractic and decisionist models on empirical grounds. As many policy scholars have argued, in practice, the exchange of information between science and policy is hardly as linear and one-directional as the technocratic model implies (see Cairney (2015) and the numerous references therein). Only rarely does scientific evidence compel immediate policy action, and often, political or economic factors determine what pieces of scientific information policymakers pick up in the first place. Moreover, scientific information is not considered and used in isolation, but framed and communicated by policymakers in the context of existing policy narratives (Stone, 2012). Similarly, numerous empirical studies by STS scholars illustrate that the production of scientific knowledge is neither objective nor value neutral, arguing that scientific practice itself can be considered a contingent and political activity (Hackett et al., 2008).

The pragmatic model assumes a more complex science-policy relationship. In particular, giving up the idea that the defining feature of science is its independence from policy and politics means that the distinction between science and non-science becomes flexible (Gieryn, 1983; Jasanoff, 1987). This flexibility may motivate scientists to engage in what Gieryn (1983) calls "boundary work": strategic, ideological efforts "*by scientists* to distinguish their work and its products from non-scientific intellectual activities" (Gieryn, 1983, p. 782, italics in the original). Picking up on that idea, Jasanoff (1987) investigates how scientists use language to demarcate the boundary between science and policy. This boundary, Jasanoff argues, is constantly negotiated by scientists, policymakers, and interest groups—all of them seeking to strengthen their authority over the interpretation of knowledge in line with their interests. The ways in which actors define the key concepts in the controversy have implications on whether certain questions are classified as a matter of science or as a matter of policy, which then determines who is responsible, which in turn may influence how the issue is ultimately decided.

Finally, Weinberg (1972) and Funtowicz and Ravetz (1993) argue that different science-policy models are appropriate for different types of questions: while the technocratic or decisionist approach may work for issues that are relatively technical and well understood, a pragmatic approach should be taken when the problem involves high levels of uncertainty and responses inherently involve value judgment. Weinberg (1972) calls such questions 'trans-scientific.' He argues that many of the issues on which policymakers consult scientists involve trans-scientific questions that appear to be "questions of fact" but that "cannot be answered by science; they transcend science" (ibid., p. 209). A question is trans-scientific when it requires not only cognitive knowledge, but also moral, political, or practical judgments. Put differently, these questions "deal not with what is true but rather with what is valuable" (ibid., p. 212). Trans-scientific questions commonly concern high-stakes issues about which scientific uncertainty exists. Typical examples of trans-scientific problems include many of the policy-relevant questions about climate change and nuclear safety. In fact, the normative authority of technocracy was seriously challenged for the first time in the 1970s, when debates about nuclear risks diminished the public's confidence that science alone was adequately equipped to inform decision-making (McQuaid, 2002, p. 252). While the decisionist model of science-policy interactions is appropriate for dealing with conventional scientific questions that are relevant for policymaking, trans-scientific questions are either resolved through political processes or in court. Hence, according to Weinberg (1972), the cognitive authority of scientists (and thus the technocratic model) is only challenged when it comes to trans-scientific issues, where scientists can be replaced by politicians, judges, or lay citizens. In all other cases, their authority remains intact. This is where the position of Weinberg differs significantly from that of the social constructivists, who argue that scientific authority on *all* issues is contested. Hence, in Weinberg's model, the boundary between science and policy is assumed to be clear and fixed, but it is the boundary between science and trans-science that is conditional and negotiated: it is here that scientists and policymakers compete for influence (Jasanoff, 1987). Scientists are typically reluctant to admit the limits of their expertise and of the scientific method (Weinberg, 1972).

Engaging in an argument similar to that by Weinberg (1972), Funtowicz and Ravetz (1993) conclude that a new type of research, a 'post-normal science,' is needed to assess policy dilemmas that combine radical, partly irreducible uncertainty with high 'decision stakes.' Here, decision stakes refer to the costs, benefits, and value commitments of the various stakeholders. Traditional science, the authors argue, is incapable of providing helpful guidance to policymakers on such issues, because that would require commitments to 'soft values' as much as to the production of 'hard facts.' In post-normal science, "the traditional fact/value distinction has not merely been inverted; in post-normal science the two categories cannot be realistically separated" (Funtowicz and Ravetz, 1993, 751). Because of this inextricable link, the resolution of policy issues in post-normal science requires the establishment of 'extended peer communities' that involve diverse stakeholders into the knowledge generation process. Like Weinberg, Funtowicz and Ravetz (1993) emphasize the general legitimacy of traditional science; "what can be questioned is the quality of that work in these new contexts" (ibid., pp. 753-754).

Adopting the pragmatic model

At first glance, the choice of a pragmatic model may appear counterintuitive—the use of IAMs to inform climate policy may appear to be a prime example of the decisionist model in practice. After all, IAMs seem to embody rationality: they are quantitative, positivist, computer-based decision tools that are often explicitly based on a cost-benefit framework. In particular, it is considered one of the strengths of IAMs that they can be used to calculate 'optimal' emissions reduction targets or the 'most efficient' policy trajectories.

And yet, one quickly finds that two fundamental assumptions underpinning decisionism and technocracy are not met in the context of IAMs of global climate change. The first assumption in the technocratic model is that any existing disagreement among policy actors is caused by a lack of full information about the issue. While a high degree of scientific uncertainty about climate change still exists, and that uncertainty may make some policymakers hesitant to take action, there is also general acceptance of the notion that disagreement about climate change policy is *not* exclusively a matter of missing information. The latest IPCC report presents a strong scientific consensus on the key causalities of climate change: that global warming is man-made, that it may lead to catastrophic impacts, and that these impacts are distributed unevenly across the world's regions. For some decision-makers, this knowledge is sufficient to take action, while others claim that more certainty is needed. In other words, people disagree about climate change *because* they have different interpretations of the available information. These interpretations may be shaped by political, cultural, or moral values. Even those who agree on adopting ambitious climate protection targets may differ in their motives: some may act to reinstate intergenerational justice, others to preserve biodiversity, yet others to appease a political constituency. In short, why we agree or disagree about climate change pertains to our value-laden interpretation of information rather than simply the availability of information (Hulme, 2009). The second assumption underpinning both the technocratic and the decisionist model is that science is independent, objective, and normatively neutral. In the case of IAMs as scientific devices, these conditions cannot be assumed to apply a priori. In fact, as previously indicated, some critics of IAMs question exactly these qualities of the models. They argue that assumptions underlying the models are arbitrary, value-laden, and politically biased.

A parsimonious argument for arriving at the same conclusion is that the questions posed to IAMs are trans-scientific or post-normal; they cannot be answered without making value judgments. Hence, to be policy-relevant, IAMs fundamentally cannot be value-neutral, because scientific information alone is not what policy-makers use to settle conflicts.

Given the above, I start my exploration from the understanding that the technocratic and the decisionist models are not useful frameworks for investigating the dual function of IAMs as both scientific devices and policy analysis tools. In fact, the questions that I am most interested in arise exactly *because* IAMs do not comply with the assumptions underpinning the technocratic model. I am interested in the aspects of IAMs that are not 'pure science' but incorporate beliefs, judgment, and value commitments. Moreover, I am interested in the ways in which IAMs influence policy beyond the delivery of numerical model results, by creating meaning and shaping narratives about climate change and climate policy. Hence, the pragmatic model of science-policy relations with its underlying post-positivist epistemology and its acknowledgment of complexity in the relationship between science and policy is the appropriate framework for examining these questions.

In turn, my research contributes to enhancing transparency, which is necessary for the pragmatic model to work; Weinberg (1972), Funtowicz and Ravetz (1993), and Pielke (2007) all require transparency about the (sometimes hidden) value commitments in scientific research and the practical consequences of these commitments as a necessary step toward improving the usefulness of science for policy. The second pillar of the pragmatist model, which is a call for greater public and stakeholder participation in the production of policy-relevant science, I only address tangentially in this dissertation. When science is no longer believed to hold the monopoly on wisdom, the democratization of expertise becomes possible—and, many argue, desirable (see contributions in Maasen and

Weingart (2005a)). In favor of the democratization project, Wynne (1992) contends that “the social judgments of a relatively private research community [...] need to be reopened (deconstructed) and renegotiated in a wider social circle, possibly one involving different epistemological commitments and expectations” (pp. 126-127). While I acknowledge the practical importance of participation and the intellectually challenging questions it entails, a thorough discussion of either is beyond the scope of this project; I briefly address participatory IAM modeling in the final conclusion.[9]

1.3.2 Pragmatic analytical frameworks

Recent contributions to the literature on the pragmatic model of science-policy relations include the concept of co-production of science and politics developed in the field of STS (Jasanoff, 2004b,c), the notion of scientists as ‘honest brokers’ proposed by Pielke (2007), and the ‘pragmatic enlightened model’ suggested by Edenhofer and Kowarsch (2015).

Co-production

The concept of co-production is based on the observation that scientific knowledge and social order are so closely and systematically linked that they should be understood as co-producing each other. Both scientific research (the ordering of human knowledge about nature) and the establishment of power structures (the ordering of society) are the results of human actions—and these actions are inherently interdependent. While many STS scholars had previously used co-productionist ideas in their research, Jasanoff (2004a,b) was the first to pull these various strands together in order to provide a coherent outline of the concept’s theoretical and methodological underpinnings. Jasanoff describes the concept of co-production as follows:

> “Briefly stated, co-production is shorthand for the proposition that the ways in which we know and represent the world [...] are inseparable from the ways in which we choose to live in it. Knowledge and its material embodiments are at once products of social work and constitutive of forms of social life; society cannot function without knowledge any more than knowledge can exist without appropriate social supports. Scientific knowledge, in particular, is not a transcendent mirror of reality. It both embeds and is embedded in social practices, identities, norms, conventions, discourses, instruments and institutions—in short, in all the building blocks of what we term the *social*” (Jasanoff, 2004a, pp. 2-3, italics in original).

This quote highlights multiple features of the co-productionist approach to understanding and explaining science-policy relations. First, the concept of co-production assumes neither that scientific

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[9] The contributions in Maasen and Weingart (2005a) provide a wider overview of the opportunities and challenges related to the democratization of scientific expertise.

research leads to value-neutral, 'true' representations of nature, nor the opposite, that scientific representations are fully determined by socio-political structures and processes. Co-production seeks to avoid falling entirely into the positivist or the constructivist camp, but it has the "self-conscious desire to avoid both social and technoscientific determinisn in [...] accounts of the world" (Jasanoff, 2004b, p. 20). Hence, while science and social order are understood to shape each other, they do not fully determine each other; scientific knowledge is neither 'a mirror of reality', nor simply a mirror of society. Second, society needs science, because knowledge plays a crucial role in legitimizing political decision-making on policy; at the same time, scientific practice and knowledge production requires supportive social structures that ensure the availability of funds as well as the freedom to research and publish. Third, the co-productionist approach recognizes that scientific knowledge can manifest in 'material embodiments' such as scientific artifacts, organizations, and modifications of the human body (Jasanoff, 2004a, p. 3), as well as social practices, identities, norms, discourses, and institutions. All of these embodiments are seen as sites of co-production of science, policy, and politics and can be studied as such.

The Honest Broker

In his analysis of the interactions between science, policy, and politics, Pielke (2007) observes the increased reliance of policymakers on expert knowledge to inform and legitimate their decisions—a trend which he terms the 'scientification of politics.' At the same time, he warns of a 'politicization of science' where policymakers' demand for specific evidence in support of their political interests comes to influence how scientific research is carried out. Political influence on science may be explicit (e.g. through funding decisions) or occur in more subtle ways. Ignoring the politics of science and blindly holding on to the technocratic ideal may easily result in a situation where 'objective' scientific knowledge is used to reframe policy-relevant questions of value as scientific questions of facts in order to legitimize policy decisions (Jasanoff, 1990; Litfin, 1995). Against this backdrop, Pielke (2007) distinguishes four basic roles of scientists acting as policy advisors: the pure scientist, the science arbiter, the honest broker, and the issue advocate. Which of these roles is appropriate is determined by the degree of value consensus and scientific uncertainty existing around the policy issue at hand. The lower the degree of value consensus and the higher the degree of scientific uncertainty, the more important it is for advising scientists to focus on available options, rather than presenting narrow solutions. In situations with high uncertainty and significant value disputes, it would be counter-productive for scientists to hide behind the impossible ideal of value-neutrality. Rather, scientists should act as honest brokers, embracing their involvement in politics in a responsible and transparent manner. Such 'honest brokering' is a balancing act, where scientists must be careful not to jeopardize their credibility (and that of the scientific enterprise in general): "If the public or policy-makers begin to believe that scientific findings are simply an extension of a scientist's political beliefs, then scientific information will play an increasingly diminishing role in policy-making, and a correspondingly larger role in the marketing of particular political agendas" (ibid., p. 95).

The pragmatic-enlightened model

The 'pragmatic-enlightened model' of environmental policy assessments developed by Edenhofer and Kowarsch (2015) explains how scientific assessments of policy problems can be policy-relevant without being policy-prescriptive. Because scientific knowledge about high-uncertainty, high-stakes policy problems inherently involves moral and political commitments (Funtowicz and Ravetz, 1993; Weinberg, 1972), these commitments may, of course, constrain and bias policymakers' choices. At the same time, completely ignoring the moral and political implications of these problems (possibly with the technocratic ideal in mind) diminishes the policy relevance of assessments and may, as explained earlier, lead to science being misused for symbolic legitimization of particular, pre-defined policy positions (Edenhofer and Kowarsch, 2015, p. 57). The pragmatic-enlightened model (PEM) provides guidance on how to achieve policy assessments that are both scientifically sound and relevant for decision-makers at the same time. The model assumes that policy objectives and policy means are inextricably entangled and must be considered in parallel. In line with the pragmatic tradition, both policy objectives and the means to achieve these objectives should be evaluated in terms of their practical consequences (including both direct effects and unwanted side-effects) and in an iterative manner. It is the "systematic idea of a feedback loop" between policy objectives and means that distinguishes the PEM from previous science-policy models (Edenhofer and Kowarsch, 2015, p. 61). The PEM moreover requires that this exploration and evaluation of alternative policy pathways (i.e. combinations of means and objectives) involve an extensive dialogue between scientists, policymakers, and the public. The result of this process is a 'cartography' of "alternative viable policy pathways, with transparency of important assumptions, value judgments, and uncertainties" (ibid., p. 61). Such a cartography, the authors argue, can support policymakers' deliberations in search of political consensus.

Models as sites of co-production

While I refer to both the ideas put forward by Pielke (2007) and the PEM (Edenhofer and Kowarsch, 2015) at multiple points in the three articles included in this dissertation, I most strongly draw on the concept of co-production as an analytical framework. This is because the co-productionist approach allows me to focus on IAMs (or by extension, policy-relevant scientific models) as the unit of analysis—rather than the scientists (Pielke, 2007) or the scientific advisory process (Edenhofer and Kowarsch, 2015). In the following, I discuss the implications of using the co-productionist framework as an analytical resource for studying models on the science-policy boundary.

Jasanoff (2004b) shies away from calling the concept of co-production a fully-fledged theory. She argues that its aim is neither to generate deterministic causal explanations of science-society linkages nor to establish a rigid set of methodological rules as guidance for future studies in co-production (ibid., p. 38). Rather, the goal is to compile resources from the STS literature and make them available to allow for the systematic exploration, description, and explanation of the intricate ways in which science and technology shape society, and vice versa (ibid.). This goal requires bringing awareness to “the constant interplay of the cognitive, the material, the social and the normative” (ibid.) in contemporary social life—of which science is such an influential part.

Adopting a co-productionist approach in this dissertation recognizes that policy-relevant models, in their function as boundary objects between science and policy, become sites of co-production. Jasanoff suggests that one can study co-productionist dynamics at various sites where they take place; well-studied examples of sites include the making of institutions, identities, discourses, and scientific representations (Jasanoff, 2004b, pp. 39-41). Indeed, it was shown earlier in this introduction that scientific models are representations of certain aspects of the world, and that the purpose of building a model is to learn about the world it represents. Hence, scientific models are epistemic artifacts, and if they are run on a computer, they are technical artifacts as well. How then do these modeled representations become sites of co-production? First of all, as argued previously, it seems common wisdom among philosophers of science that the construction of scientific models is never entirely dictated by theory and empirical data, but that this process inherently requires additional assumptions, techniques, and creative elements. In line with a pragmatic model of science-policy relations, we cannot inherently assume that these ‘extra-scientific’ elements are ahistorical, value neutral and free of political commitments. At the same time, if what is learnt from modeled representations informs political decisions about policy (i.e. when models become boundary objects), the modeling process suddenly has political implications. Using the terminology of co-production, one can therefore say that these modeled representations not only order our knowledge about nature but they also order society—for example, by legitimizing particular solutions to the modeled problem, or by allocating authority to act to particular actors.

The three articles included in this dissertation investigate in greater detail how IAMs mediate the co-production of climate change science, policy, and politics. I ask: how do politics enter the model equations, and how do the models’ calculations shape climate change policy and politics? The co-productionist framework allows me to examine these questions in a nuanced fashion, drawing my attention to the power relations, value commitments, and technical constraints that may influence the inputs and outputs of policy-relevant scientific models.

1.4 Research contributions

My dissertation contributes conceptually and empirically to the existing scholarship on the role of scientific models in policymaking by examining the production and application of climate change IAMs.

As outlined earlier in this introduction, the existing research on IAMs is predominantly technical in nature. It is largely produced by scholars within the modeling community, and it often concerns methodological challenges related to individual models. In contrast, the research on IAMs produced by scholars in the humanities and the social sciences is considerably smaller. This dissertation aims to address this gap by providing a systematic analysis of how IAMs are developed and used at the science-policy interface as well as of their usefulness for policymaking.

Contemporary contributions to the literature on policy-relevant science widely agree that the relationship between science and policy is not as linear and direct as the technocratic model implies. Instead, policy-relevant scientific research is understood to be inherently value-laden and easily politicized (Jasanoff, 1990; Pielke, 2007; Edenhofer and Kowarsch, 2015)—at least when it concerns issues such as climate change where both uncertainty and the stakes involved are high (Weinberg, 1972; Funtowicz and Ravetz, 1993). Against this backdrop, the three articles included in this dissertation advance our understanding of the various inputs and outputs of policy-relevant scientific models, using climate change IAMs as a case study.

Article #1 establishes a conceptual groundwork for studying the production and use of IAMs in a systematic way. It delivers a deeper understanding of the pervasive uncertainty surrounding climate change and the consequences of this uncertainty on IAM modeling. It delivers a careful analysis of the complex intersection of science, ethics, and politics that IAMs occupy: modeling choices are influenced by the particular epistemic, normative, and political contexts they are made in, and at the same time have the potential to shape these contexts. This comprehensive description of the context in which scientific modeling for policy is carried out represents a key contribution of this paper.

Article #2, as a novel contribution to the literature combines philosophical research on the role of storytelling in scientific modeling with policy research on the importance of stories in policy processes, developing an analytical framework for studying the policy-relevant stories told with scientific models. This approach generates new insights into the values and beliefs embedded in models and their potential influence on policy. In this article, I apply the framework to the analysis of stories produced with the DICE model, arguably the most prominent IAM of global climate change, but my approach is transferable to other models in other policy areas as well.

Article #3 provides, to my knowledge, the first empirical examination of the factors that drive the modeling choices of climate change IAM developers in practice. Based on this new data and current work in philosophy of science on modeling and computer simulations, this article also delivers a normative analysis of the adequacy of using IAMs for policymaking—a direct response to some of the models' most prominent critiques. The article closes with a list of practical recommendations for enhancing the usefulness of IAMs for policy.

Although my dissertation almost exclusively focuses on IAMs of climate change, I expect my findings to be relevant for the study of other policy-relevant computer simulation models used to inform policy on other complex issues, with scientific uncertainty and value disputes such as global health (Mansnerus, 2014). The characteristics of the specific policy problems and modeling approaches will differ in important aspects, but key outputs from this dissertation may be instrumental to further research on other models at the science-policy interface as well. In particular, the conceptual groundwork established in article #1, the analytical tool for studying model narratives developed in article #2, and the pragmatic discussion of model usefulness in article #3 are outputs I consider transferable. In the conclusion to this dissertation I outline in greater detail avenues for future research emerging from this project.

In addition to the concrete findings outlined above, I moreover argue that a key contribution of this dissertation to the advancement of knowledge on policy-relevant scientific models lies in its interdisciplinarity. Stock and Burton (2011) define interdisciplinary studies as those that force the researcher "to cross [disciplinary] boundaries to create new knowledge" (p. 1096) about a complex system problem. Here, the authors distinguish between 'big' and 'small' interdisciplinarity. The former involves crossing boundaries between the social and the natural sciences, while the latter implies the exchange of tools and knowledge "between isolated [...] sub-disciplines" (Stock and Burton, 2011, p. 1097) within either category. This dissertation can be considered 'small' interdisciplinary project. My research questions about IAMs inherently require the integration of knowledge from various disciplines. Using the science-policy interface as the conceptual framework to examine IAMs forces me to cross disciplinary boundaries (in the 'small' sense), because these two subsystems of society and their relationship with each other are studied by scholars in various social-scientific sub-disciplines and in the humanities. To answer my research questions, I primarily integrate insights from philosophy of science and moral philosophy with science and technology studies (STS) and policy theory. IAMs themselves, of course, are 'big' interdisciplinary projects, integrating knowledge about both biophysical and socio-economic systems produced in the natural and social sciences. To develop an understanding of how IAMs work, it was indispensable to my research to understand the models and thus to also engage with the various literatures studying these systems. This dissertation is not a true example of 'big' interdisciplinarity because my research design and methodology for studying these systems do not involve elements of both natural and social sciences. Nevertheless, I do integrate knowledge from the social sciences and philosophy, thus enabling a comprehensive examination of modeling at the science-policy boundary.

Multiple scholars have recently expressed demand for such efforts in policy-relevant research (Tuana, 2010; Briggle and Frodeman, 2016). The accounts by Haimes (2002) and Hedgecoe (2004) have particularly inspired and encouraged my research. Both argue in favor of a greater engagement of the social sciences with questions in ethics. They believe that more cooperation between philosophers and social scientists on current topics such as technological progress, environmental change, and public health may advance knowledge in either discipline while also informing better policy outcomes. In particular, social scientific methodology is capable of describing and analyzing ethical decision-making on the ground as well as the practices through which "issues become constituted as ethical concerns" (Haimes, 2002, p. 91). My research contributes to this interdisciplinary research program broadly outlined in Haimes (2002) and Hedgecoe (2004). Specifically, in article

#1, I illustrate that integrated assessment modeling has inherent ethical implications, because the policies that IAMs are used to inform are inevitably ethical. In line with Hedgecoe (2004), IAM modelers can therefore be seen to practice applied ethics. In article #3, I examine this idea from the perspective of the modelers, learning how and why they recognize some aspects of IAMs, but not others, as explicitly ethical in nature.

1.5 Methodology

Case study selection
I use IAMs as a case study to examine the intersection of science, policy, and politics typically occupied by policy-relevant scientific models. Two key factors motivated my case study choice.

First of all, climate change is an urgent policy problem and the analysis of models used to provide information to decision-makers is thus timely and relevant. Climate change IAMs are subject to a vivid discussion in the scholarly literature (as demonstrated in Section 2.4 of this introduction) and among policymakers. They even received some coverage in the popular media (Leonhardt, 2007; Childers, 2013). Consequently, research to advance our understanding of how climate change IAMs are developed and used may have practical relevance beyond the borders of academia.

My second motivation for studying IAMs concerns my personal capability to successfully carry out this research. I am convinced that providing a meaningful examination of scientific models for policymaking—even when conducted from a social scientific or humanistic perspective—requires an intimate understanding of how these models function. In fact, over the course of my research for this dissertation, I worked through hundreds of pages of model code, received model demonstrations from developers, and conducted multiple observation sessions with a modeler to learn about their coding practice. All of these activities would have been significantly more difficult and less effective without my extensive background knowledge in economics, climate change, and climate policy, which I was able to accumulate in my previous academic studies and my work experience. In particular, I hold graduate degrees in both business studies (with a focus on economics) and environmental policy and regulation. Both my previous master's theses focused on issues in climate change economics. Before starting my PhD, I worked for two years as a global carbon analyst, covering the global carbon markets established under the Kyoto protocol for a leading market research and data provider for clean energy and carbon markets. Finally, during my graduate studies at the University of Waterloo, I was also a research assistant in a multiple-year project undertaking an economic analysis of Canadian climate policy, using computable general equilibrium (CGE) modeling. While the CGE model framework considerably differs from IAMs—the model we worked with did not have a full representation of the climate system—I learnt a lot about computer modeling techniques.

Methods for data collection and data analysis

I employed a purely qualitative, mixed-methods approach. I gathered data from multiple sources, primarily written documents, but also including semi-structured interviews and participant observations.

For article #1, my data collection consisted of a thorough review and critical analysis of the literature on uncertainty in integrated assessment modeling and the numerous modeling choices that uncertainty requires modelers to make in the model-building process. This literature is dispersed over multiple fields of study, including climate science, economics, philosophy, science and technology studies.

For article #2, I combined insights from the philosophy of economics with findings from policy studies to develop a analytical framework for studying the manifestation of worldviews in IAMs. For illustration, I apply this new framework to four recent IAM-based studies.

For article #3, I collected data from semi-structured, in-depth interviews with the developers of three IAMs, over the time period from May 2015 to April 2016. Many previous studies researching the development and use of policy-relevant models in science have used interviews and participant observations for data collection, including Evans (2000), Lahsen (2005), and van Egmond and Zeiss (2010). Since I am using IAMs as a case study for discussing questions about the development of computer simulations at the science-policy boundary, I chose as interview partners five modelers, including the key architects of three policy-influential cost-benefit IAMs. These three modelers have been involved in integrated assessment modeling since the early/mid 1990s. As such, these modelers are deeply knowledgable of the entire modeling process, the numerous choices involved in this process, model maintenance over time, and the relationship between the models and policy. The two other interviewees are modelers at earlier stages of their modeling career, who presently work with one of these three IAMs or have worked with them in the past. I analyzed and coded my empirical data using the qualitative data analysis software NVivo. I describe my interview methodology and my coding strategy in greater detail in the materials and methods section of article #3.

I also attended relevant meetings and conferences in the context of my dissertation research to further establish my expertise on IAMs, and to learn about the current debates in the community. In particular, I attended two meetings of the Integrated Assessment Modeling Consortium (IAMC), in November 2014 and November 2015. Furthermore, I was involved in two meetings of an international working group on Climate Ethics and Economics, in November 2014 at the University of Helsinki and in March 2016 at Duke University. At the meeting in Helsinki, I presented an early version of article #1.

1.6 Outline of the dissertation

Following this introduction is the main body of this dissertation comprising of the three article manuscripts.

Article #1, titled “The epistemic, ethical, and political dimensions of uncertainty in integrated assessment modeling”, develops the conceptual groundwork for this dissertation, locating IAMs at the intersection of science, ethics, and politics. The pervasive uncertainty in IAM building requires modelers to make numerous choices, which have representational, ethical, and social consequences.

Articles #2 and #3 extrapolate practical consequences from the conceptual groundwork established in Article #1. Article #2, titled “Telling stories with models and making policy with stories: an exploration”, develops an analytical framework for studying the policy stories produced with scientific models. I argue that an appreciation of these modeled stories is essential for a full understanding of how models are used in policymaking.

Article #3, titled “Are IAMs too arbitrary and value-laden to be useful for policy?”, provides a normative, empirically grounded analysis of two of the major critiques of IAMs: that they are a) arbitrary and b) value-laden, and therefore unfit for policy use. Adopting a pragmatist perspective, this article concludes that IAMs are a useful, albeit imperfect, tool for assessing climate policy. Practical recommendations for how to enhance the usefulness of IAMs for policy are provided.

Each article is briefly introduced. These introductions provide me the opportunity to explain how the article fits into my larger dissertation project and how it contributes to existing scholarship. Here, I also provide information about previous publication of the article (if applicable), or my plans for publication in the future.

This dissertation ends with a brief conclusion, where I summarize my key findings and elaborate on avenues for future research that I see emerging from this project.

Chapter 2

The epistemic, ethical, and political dimensions of integrated assessment modeling under uncertainty

2.1 Preface

This article concerns the numerous modeling choices that IAM developers are required to make as a result of the pervasive uncertainty—both scientific and ethical—surrounding global climate change and its impacts on human systems. To better understand the role of IAMs as boundary objects between science and policy, we have to examine the drivers and implications of these choices. My co-author and I argue that modeling choices are made in particular epistemic, ethical, and political contexts and, in turn, have epistemic, ethical, and political consequences. These contexts determine different criteria for what defines 'good' modeling choices: the epistemic context determines that modeling choices should enhance the trustworthiness of the model and its usefulness as a scientific device; the ethical context implies that modeling choices should lead to just allocation and valuation of climate change costs between regions and generations; the political context determines that modeling choices should make model studies more publishable and more policy-relevant. We also suggest that, over time, positive feedback loops between the consequences and contexts of modeling choices may incentivize modelers to make modeling choices in line with the established perceptions of trustworthy, fair, publishable, and policy-relevant models. This dynamic may lead to a 'lock-in' of possibly sub-optimal modeling choices and slow innovation. Improved understanding of the factors driving modeling choices is necessary to ultimately evaluate the usefulness of IAMs in supporting climate change policy that is scientifically sound, ethically fair, and politically acceptable.

This article contributes to the existing body of research in multiple ways. It provides an in-depth discussion of the scientific and ethical uncertainty that IAM developers face in the modeling process. This discussion draws on various literatures including the technical modeling literature, STS literature, and climate ethics literature. The focus is on ethical uncertainty, because this type of uncertainty appears to be given less attention in the existing body of research on uncertainty in IAMs. This article also synthesizes insights from existing knowledge about IAMs dispersed across multiple literatures to develop a theoretical outline of the relationships between uncertainty, epistemic-ethical-political choices, and the implications of these choices in IAM development. This outline includes a new explanation of stability in model development over time. While this article exclusively focuses on IAMs, I expect its key findings to be useful for studying the construction of other policy-relevant scientific models—or at least provide an interesting starting point for a similar analysis.

In the context of this dissertation, this article elaborates on some of the central themes outlined in the introduction, including the dual function of IAMs as instruments for scientific inquiry and tools for policy analysis, as well as the co-productionist relationship between science and policy. IAMs stand in the centre of this relationship, functioning as a boundary object. This article also lays the conceptual foundation for the two following articles, which extrapolate practical consequences from this groundwork. In article #2, I investigate how modeling choices may affect political consequences by shaping a specific policy narrative about climate change and climate change policy. In article 3, I address some of the empirical and normative questions raised in the conclusion to this manuscript.

An earlier version of this article that I co-authored with Dr. Tobias Krüger was published in the journal *Wiley's Interdisciplinary Reviews Climate Change* in June 2016 (see Statements of Contributions, p. iii). Since publication, my thinking on the issues discussed here has further advanced, which led me to make some changes to the manuscript. Hence, the manuscript included in this dissertation differs from the published article. In particular, I clarified terminology and elaborated on the explanation of the suggested feedback loops and 'lock-in' of modeling choices discussed in Section 7. I also added the diagram to summarize and illustrate my argument. However, the overall scope of the article as well as its key conclusions remain the same.

Much of the research for this article was conducted during my time as a visiting researcher at the Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys) at the Humboldt-Universität zu Berlin in Germany, the home institution of my co-author Dr. Krüger. This article benefited from many discussions with members of IRI THESys, in particular Dr. Jörg Niewöhner and Dr. Gabriel Wollner. I presented an early version of this argument to the participants of a workshop on the ethical underpinnings of climate change economics at the University of Helsinki in November 2014 and received helpful feedback.

2.2 Overview

Integrated Assessment Models of global climate change (IAMs) that combine representations of the economy and of the climate system have become important tools to support policymakers in their responses to climate change. Yet IAMs are built in the face of pervasive uncertainty, both scientific

and ethical, which requires modelers to make numerous difficult choices in model development. In this paper we argue that these modeling choices are made in particular epistemic, ethical, and political contexts that shape how they are made. Correspondingly, we illuminate the epistemic, ethical, and political consequences of these choices. First, modeling choices determine how well our current knowledge (or lack thereof) about the elements and processes of the modeled system is represented. Second, modeling choices have ethical implications regarding issues related to valuation and distributional justice. In the case, for example, of a social discount rate, these implications have been well-documented, but for other modeling choices, the ethical assumptions and implications are more subtle. Third, numerical model results may influence policy outcomes, and the models may shape the political discourse around climate change. Finally, adopting a co-productionist approach, we suggest that past modeling choices may constrain future model development by setting epistemic benchmarks, establishing ethical norms, and creating biases in academic publishing and policy application. We review and build on findings from various literatures to unpack the complex intersection of science, ethics, and politics that IAMs occupy. This leads us to suggest avenues for future empirical and theoretical research that may enable an integrated epistemic-ethical-political understanding of IAMs. Such transparency is necessary to judge the usefulness of IAMs in supporting climate change policymaking that is scientifically sound, ethically fair, and politically acceptable.

2.3 Introduction

Uncertainty is omnipresent in policy decisions regarding whether, when, and how to respond to climate change. Scholars commonly make a distinction between scientific uncertainty and ethical uncertainty. Scientific uncertainty exists when knowledge about the causes, processes, and consequences of climate change is incomplete. Ethical uncertainty exists when it is not clear what frameworks we should apply to address the ethical questions raised by climate change, including questions of historical responsibility, valuation of climate change impacts, distribution of adaptation and mitigation costs, and of future emission allowances. Scientists broadly agree that there is a divergence between (1) the distribution of the historical responsibility for greenhouse gas (GHG) emissions and (2) the anticipated exposure and vulnerability to its effects. While responsibility for emissions mainly lies with past and present generations in industrialized countries in the Global North, the damages from climate change are expected to be most severe for future generations in developing countries with low income in the Global South.

Integrated Assessment Models of global climate change (IAMs) that combine representations of the economy and of the climate system have become important tools for policy-makers in their responses to climate change. Yet the existence of scientific and ethical uncertainty requires modelers to make numerous difficult choices in model development: choices about model scope, equations, parameter values and output presentation. In this paper we argue that these modeling choices are made in particular epistemic, ethical, and political contexts that shape how these choices are made. Correspondingly, we illuminate the epistemic, ethical, and political consequences of these choices. First, modeling choices determine how well our current knowledge (or lack thereof) about the elements and processes of the modeled system is represented. Second, modeling choices have ethical implications regarding issues related to valuation and distributional justice; in the case, for example, of a social discount rate, these implications have been well-documented, but for other modeling choices such as the models' regional disaggregation the ethical assumptions and implications are more subtle. Third, numerical model results may influence policy outcomes, and the models may shape the public discourse around climate change—with political implications.

Against this backdrop, some critics perceive the current generation of IAMs as 'black boxes' unfit for use in policy-making (Stanton et al., 2009; Pindyck, 2013; Stern, 2016). They claim that in these models, scientific uncertainty about the socioeconomic causes, dynamics, and impacts of climate change is addressed through arbitrary assumptions, and ethical uncertainty through normatively indefensible judgments, causing model results to be inherently biased and motivated by political interests (Ackerman et al., 2009; Pindyck, 2013; Saltelli et al., 2016). Integrated assessment modelers themselves recognize uncertainty as one of the key challenges they face in their work and have produced numerous studies on the assessment and representation of uncertainty in IAMs. While the focus of most of these studies is on scientific uncertainty (for example, Kelly and Kolstad (1999); Peterson (2006); Golub et al. (2011); Gillingham et al. (2015)), some explicitly discuss ethical uncertainty (for example, the cultural theory applications of van Asselt and Rotmans (2002)).

This overview article is concerned with the complex intersection of science, ethics, and politics in which IAMs are developed and used to inform decision-makers. The epistemic, ethical, and political contexts and consequences of choices in integrated assessment modeling under uncertainty have so far been explored and discussed in a fragmented way and within different intellectual traditions: the natural sciences, economics, moral philosophy, and the social sciences. With this article we wish to synthesize this fragmented knowledge from model studies and model documentations, studies in climate change economics and science and ethics, and research in the philosophy of science and science and technology studies (STS). We believe that an improved understanding of the interrelation of the epistemic, ethical, and political contexts and consequences of choices in integrated assessment modeling is necessary for evaluating and improving the usefulness of IAMs in supporting climate policy-making. How integrated assessment modelers make modeling choices under scientific and ethical uncertainty has important implications for the usefulness of IAMs in informing scientifically sound, ethically defensible, and politically acceptable climate policies.

Before continuing, it is important to clarify our terminology and, in particular, to explain what we mean by the terms 'modeler' and 'decision-maker.' Because IAMs are used for both scientific research and policy advice, the roles that different actors play in the modeling process can be complex. In this paper, we call a modeler someone who makes modeling choices in the context of a policy analysis exercise. The modeler may or may not be the original developer of the IAM used. By contrast, those we call decision-makers have formal authority to formulate climate-change policies. They may use IAM results to inform their decisions about these policies. The distinction between modelers and decision-makers is not without problems; the line between modeler and decision-maker can be blurry in practice (Pielke, 2007). Decision-makers may give extensive instructions regarding the model specifications for a specific policy appraisal, effectively taking on part of the role of the modeler. The opposite may be true as well; through their modeling choices, modelers may come not only to advise but in fact to prescribe policy choices. This article specifically focuses on the perspective of the modeler, while the interpretation and use of model results by decision-makers is not explicitly considered.

The paper is structured as follows:

- Section 2.4 defines IAMs and provides a brief overview of the current landscape of IAMs and their common applications.
- Section 2.5 reviews the literature about scientific and ethical uncertainty in the context of quantitative climate policy analysis, and IAMs in particular.
- Section 2.6 discusses the epistemic, ethical, and political contexts and consequences of choice in integrated assessment modeling under uncertainty.
- Section 2.7 provides examples of coupled epistemic-ethical modeling choices in integrated assessment modeling.
- Section 2.8 discusses the political context and consequences of policy-relevant climate change research.
- Section 2.9 synthesizes findings, and Section 2.10 concludes.

2.4 IAMs of global climate change

IAMs constitute a family of computer models that integrate mathematical representations of climate change knowledge from multiple disciplines in the natural and social sciences for the purpose of generating policy-relevant information (Weyant et al., 1996; Parson and Fisher-Vanden, 1997; Schneider, 1997; Kelly and Kolstad, 1999). IAMs may include, for example, representations of the socioeconomic determinants of GHG emissions, the atmosphere and oceans, the biosphere, the impacts of climate change on human and non-human life, and policy responses such as abatement, adaptation, and geoengineering (Parson and Fisher-Vanden, 1997).

Today, there are more than 20 IAMs worldwide (Weyant, 2014). A historical account of economic IAMs and a review of relevant model studies are beyond the scope of this paper but are provided elsewhere.[1] For this study, we focus on IAMs that combine an economics module with a relatively simplified version of complex climate models. The economics module serves as the

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[1] See the introduction to this dissertation and Parson and Fisher-Vanden (1997), Schneider and Lane (2005), Sarofim and Reilly (2011), and Nordhaus (2011b).

decision-making framework (Nordhaus, 2011b; Clarke et al., 2014). Typically, *economic IAMs* are used to compare the monetary costs of efforts to slow down GHG emissions with the damages of unmitigated climate change.

A consistent classification of different economic IAMs is difficult (Parson and Fisher-Vanden, 1997; Clarke et al., 2014) but we review some differentiating features: (1) *Cost-effectiveness models* only calculate the costs of various mitigation policies, while full *cost-benefit models* also consider the avoided damages from climate change (Dowlatabadi, 1995). (2) *Policy optimization models* seek to determine optimal policies according to a specified objective function (typically the maximization of social welfare), while *policy evaluation models* simulate the climatic and social impacts of predefined policy options (Weyant et al., 1996; Kelly and Kolstad, 1999). (3) Highly *disaggregated IAMs* include detailed representations of regional and sectoral impacts of climate change, while more *aggregate models* compile impacts across sectors and regions, sometimes into a single economic metric (Weyant, 2014). (4) *Deterministic IAMs* include 'best guess' values for uncertain inputs, while *probabilistic models* perform stochastic simulations by sampling values from probability distributions (Parson and Fisher-Vanden, 1997). Other structural differences between economic IAMs include the assumed level of foresight of the modeled actors and the assumed level of economic flexibility, the representation of trade and technological change, and the degree of technological and GHG detail (Clarke et al., 2014).

Weyant (2014) identifies two common applications of economic IAMs in climate policy analysis. First, optimization models have been used to calculate optimal global emission trajectories and the corresponding optimal global carbon prices. Second, economic IAMs have been used to estimate the social cost of carbon (SCC), defined as the net present value of all future damages caused by releasing one additional ton of carbon dioxide (CO_2) into the atmosphere (Pizer et al., 2014; van den Bergh and Botzen, 2015). National governments use the SCC measure to inform their cost-benefit analyses of climate policies and to perform regulatory impact analyses of other policies that influence carbon emissions (Greenstone et al., 2013; Interagency Working Group on Social Cost of Carbon, 2013). Nordhaus (2014) finds that three aggregate global cost-benefit models dominate the published estimates of optimal global carbon prices and SCC estimates: the Dynamic Integrated Climate-Economy (DICE) model (and its regionalized version RICE), the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model, and the Policy Analysis of the Greenhouse Effect (PAGE) model.

2.5 Uncertainty in IAMs

2.5.1 Definition and types of uncertainty

The literature on uncertainty is vast and encompasses numerous disciplines from mathematics to sociology (Bammer and Smithson, 2008). For this article, we focus particularly on the sources and consequences of uncertainty in model-based policy analysis regarding climate change or other environmental issues. In this context, Walker et al. define uncertainty as "any departure from the unachievable ideal of complete deterministic knowledge of the relevant system" (Walker et al., 2003, p. 6). While this definition is not unchallenged (Norton et al., 2006), it has in common with other definitions the central focus on absent, incomplete, or imprecise knowledge or information (Rowe, 1994; van Asselt, 2000). Scholars widely agree that uncertainty may have ontological or epistemic sources (Kelly and Kolstad, 1999; van Asselt and Rotmans, 2002; Walker et al., 2003; Peterson, 2006; Sarofim and Reilly, 2011). Ontological uncertainty is inherent to the relevant systems or processes; it is therefore sometimes referred to as variability (van Asselt and Rotmans, 2002) or stochasticity (Peterson, 2006). Because variability is an inherent feature of the studied systems or processes, this type of uncertainty is irreducible. Examples pertaining to IAMs include the unpredictability of human behavior (Wynne, 1992), future economic growth rates, sunspots and volcano eruptions (Kelly and Kolstad, 1999, p. 8). In contrast, epistemic uncertainty is caused by human shortcomings in the acquisition and processing of information about the systems or processes of interest. Investment in scientific research may reduce these shortcomings over time. Examples pertaining to IAMs include inexact measurements of the lifetimes of GHGs and the lack of data on temperature feedbacks (van Asselt and Rotmans, 2002, p. 80).

Numerous different overviews, heuristics, and taxonomies exist of uncertainty in climate policy analysis, and terminology is often inconsistent between studies (Wynne, 1992; van Asselt, 2000; van Asselt and Rotmans, 2002; Walker et al., 2003; Smith and Stern, 2011). Some of the alternative taxonomies of uncertainty operate on a gradual scale defining different types of uncertainty on a spectrum that has the ideal of determinism at the one end and total ignorance at the other (for example, van Asselt (2000) and Kandlikar et al. (2005)). A common distinction is made between risk-type uncertainty, uncertainty 'proper', and ignorance.

Risks are uncertainties that are known and perceived as quantifiable. Modelers deal with risk when they feel confident that they can define a statistical relationship between the 'true value' of a variable or parameter in the modeled system and its representation in the model (Walker et al., 2003), for example, in the form of a unique probability distribution. These probabilities express (in line with the Bayesian paradigm) subjective degrees of belief in the adequacy (or truth) of the chosen values. Other terms used in the literature to describe risk-type uncertainty include Knightian risk (Knight, 1921), imprecision (Smith and Stern, 2011), measurable uncertainty (van

Asselt, 2000), and statistical uncertainty (Walker et al., 2003).

Uncertainty proper describes a situation where modelers feel unable to describe the known uncertainty in statistical terms, i.e. they feel unable to define probabilistic beliefs about alternative modeling choices (Millner et al., 2013). Economists refer to uncertainty proper as ambiguity (Millner et al., 2013) (note the different use of the term ambiguity by Stirling (2007) below).

Recognized ignorance describes a situation where modelers consider their understanding of the causal processes in the modeled system as too poor to develop plausible alternative modeling choices and thus consciously ignore these (Walker et al., 2003).

Total ignorance implies that modelers are not aware of what they do not know. Modelers may leave out potentially vital aspects in their models, just because of the inherent limitations of current knowledge. It is impossible for them to know precisely how incomplete and limited their models are (Wynne, 1992). This state of total ignorance is what Knight (1921) calls 'uncertainty.' Often misinterpreted (Langlois and Cosgel, 1993), Knightian uncertainty in the modeling context refers to a situation where modelers do not realize that they do not know whether the range of alternative modeling choices under consideration is adequate. In other words, they are ignorant of the incompleteness of the considered range; there are unknown potential alternatives that are not considered (Knight, 1921).

Beyond these different levels of uncertainty, two other types of uncertainty that are qualitatively different from risk, uncertainty proper, and ignorance, are relevant for this analysis: the concept of indeterminacy as understood by Wynne (1992) and the the concept of ambiguity as understood by Stirling (2007). With these categories Wynne (1992) and Stirling (2007) address a weakness of the conventional treatment of uncertainty in policy analysis: the primary focus on quantifying uncertainty at the expense of addressing indeterminacy and ambiguity, as well as ignorance.

Wynne (1992) defines *indeterminacy* as irreducible ignorance that is of an ontological nature. Wynne further distinguishes between 'social indeterminacy' and 'indeterminacy due to openness', both of which he considers to be inevitable in modeling of human-environment systems. Social indeterminacy exists due to stochastic factors, secondary to the variability and unpredictability of human behavior. Indeterminacy due to openness is different—this type of indeterminacy has no stochastic origins. Rather, indeterminacy due to openness exists because nature and society are open, dynamic networks of processes. Consequently, even the definition of a system and its borders necessary for modeling implies that modelers impose artificial closure on these open entities, with indeterminate consequences on the validity of model results. Wynne argues that both kinds of indeterminacy exist in addition to all other uncertainties in the modeling process, because what is perceived as uncertain will always be contingent on the often implicit assumptions about future human behavior and on how the system borders were drawn in the first place. He argues that conventional treatments of uncertainty in policy analysis fail to recognize this inherent contingency and thereby convey overconfidence.

Stirling (2007) defines *ambiguity* as uncertainty that is due to multiple legitimate interpretations or evaluations of the present or possible future states of the world. Ambiguity is not quantifiable. Examples of ambiguities in the climate change context include the various meanings that different stakeholders assign to the concepts of 'adaptation' (de Franca Doria et al., 2009) and 'dangerous climate change' (Dessai et al., 2004) and the implicit and explicit evaluations attached to these concepts. Therefore, ambiguity according to Stirling explicitly recognizes the inherent role of values in the assessment of uncertainty. This value sensitivity stands in contrast to the wider, quantitative literature on uncertainty in IAMs. While many studies mention the importance of values and value disputes, they are considered somewhat separately from the ultimate focus, which often remains on quantifiable scientific uncertainty (Walker et al., 2003; Smith and Stern, 2011; Heal and Millner, 2014b).

2.5.2 Scientific and ethical uncertainty in climate policy analysis

Scientific uncertainty

The basic causes, processes, and consequences of climate change are considered well understood (Morgan, 2011); nevertheless, natural and social scientists have extensively documented the persisting gaps in empirical data and theoretical understanding that impede predictions for climate impacts. As a result, projections of future climate change, its socioeconomic drivers, and its impacts on human and non-human life are uncertain (Heal and Kriström, 2002; Hope, 2006; Schneider and Mastrandrea, 2009; Morgan, 2011; Anthoff and Tol, 2013; Berliner, 2003; Heal and Millner, 2013, 2014b).

Ethical uncertainty

In addition to scientific uncertainty, there is ethical uncertainty about climate change because it is not clear which framework should be applied to resolve the associated complex ethical issues (Lockhart, 2000; Schienke et al., 2010). Moral philosophers study the complex ethical questions that anthropogenic climate change generates (Gardiner et al., 2010; Broome, 2012).

Most ethical analyses start with an assumption that the science is sufficiently settled to detect the phenomenon's central ethical implications, namely the uneven distribution of both historical responsibility for anthropogenic climate change as well as its adverse impacts on human welfare, economic wealth, and power (Sagar and Banuri, 1999). Past and current generations in the Global North achieved industrialization and economic growth based on their access to inexpensive energy from fossil fuels, a major source of GHG emissions. In contrast, adverse impacts from climate change are expected to disproportionally harm (1) poor people in the Global South, who are also particularly vulnerable to a changing climate (Sokona and Denton, 2001), and (2) future generations, who have no voice in today's decision-making. Climate change, of course, also damages the non-human environment (Nolt, 2011).

Issues in climate ethics are multifaceted and interlinked. They can be broadly grouped into issues related to justice (or fairness or rights) and questions related to valuation (although there is some overlap). *Distributive justice* concerns relate to the allocation of costs and benefits of emissions, abatement, and adaptation (Beckerman and Pasek, 1995; Ridgley, 1996; Shue, 1999; Singer, 2006; Gardiner, 2010). *Corrective justice* concerns relate to the obligations arising from past contributions to the problem (Neumayer, 2000; Posner and Sunstein, 2008), while *procedural justice* concerns relate to the ways in which decisions on climate policy should be made (Heyward, 2008). Jamieson (2010) understands the ethics of climate change to be intimately linked with society‘s broader value system that dictates "how we ought to live and how humans should relate to each other and to the rest of nature" (p. 82). For example, setting an emissions reduction target implies a particular value assigned to the prevention of climate change and its consequences on human life and the natural environment.

Three important theoretical approaches inform ethical analysis of climate change action: First, *consequential approaches* include, for example, utilitarianism (Sunstein, 2007), the pursuit of outcome equity (Grasso, 2007), and the minimization of vulnerability (Moellendorf, 2015). Second, *deontological approaches* include, for example, the polluter pays principle (Caney, 2005) and the precautionary principle (Gardiner, 2006). Third, *virtue ethics* establish "green virtues" as guidance (Jamieson, 2007). There is disagreement among philosophers about which approach, or combination of approaches, should be applied in designing climate policy (Driver, 2005; Jamieson, 2007; Posner and Weisbach, 2010; Grasso, 2013). There are also theoretical controversies within these schools of thought, for example, about the adequate benchmarks for justice (Grasso, 2007) and the pricing of costs and benefits (Dasgupta, 2014).

Heterogenous stakeholders of climate change hold diverging views about what ethical values are appropriately applied to address these ethical issues in climate policymaking. Different stakeholder groups, e.g. from the Global North and the Global South, tend to prioritize and adopt opposing moral positions in support of their policy positions (Ikeme, 2003). There is no agreement about how to solve the ethical disputes, not even among moral philosophers. In fact, ethical uncertainty is typically characterized as ontological in nature (Rowe, 1994; van Asselt and Rotmans, 2002) and thus not simply reducible through scientific research. Importantly, despite the existence of such ethical uncertainty, any action on climate change will always, explicitly or not, be entangled in the ethical issues related to climate change.

Interactions of scientific and ethical uncertainty

Scientific and ethical uncertainty about climate change are distinct from each other, but they do interact. The existence of scientific uncertainty complicates deliberations about values and raises new ethical questions about how to make climate policy decisions in the face of incomplete knowledge and predictability. At the same time, the presence of ethical uncertainty complicates scientific climate research for policy because it introduces questions into the research process that are not resolvable by scientific means alone. For example, even if we were able to project with certainty the physical impacts of climate change on future generations, that factual knowledge can support but not replace deliberations about how the current generation should value such impacts. The intricate link between scientific and ethical uncertainty in policy-relevant science is well-established in the literature. Weinberg (1972) calls policy-motivated research that is subject to both scientific and ethical uncertainty trans-scientific because it transcends empirical and theoretical efforts and requires ethical value judgment. Funtowicz and Ravetz (1993) question whether policy-relevant issues can be addressed using conventional scientific techniques “when facts are uncertain, values in dispute, stakes high, and decisions urgent” (p. 744). In this situation, they claim a post-normal science that explicitly acknowledges that the interweaving of knowledge and ethics is required. Rockström et al. (2009) emphasize the central role of normative judgments in interpreting scientific findings about global environmental change and planetary boundaries.

Modeling scientific and ethical uncertainty

There are numerous approaches and techniques to incorporate scientific uncertainty into quantitative integrated assessment; see Morgan and Henrion (1990), Morgan et al. (2009), and Golub et al. (2011) for overviews. By contrast, approaches that attempt to incorporate pluralistic values and ethical uncertainty are fewer in number. Exceptions include Lave and Dowlatabadi (1993), Tol (2001), and van Asselt and Rotmans (2002), who apply “multiple perspective-based model routes” (p. 83) to explicitly incorporate the influence of an assumed perspective or worldview on decisions about model structure, inputs, and parameters. The authors draw on cultural theory to define a set of alternative perspectives to illustrate how models change as a result. van der Sluijs (2002) applies the post-normal science framework to scientific and ethical uncertainty in integrated assessment modeling, claiming that the best approach would be to actively engage stakeholders in the modeling process. To this end, the NUSAP (Numeral Unit Spread Assessment Pedigree) framework, enabling a multidimensional assessment of uncertainty in model assumptions, has been extended to account for ambiguity in problem framings and valuation (van der Sluijs et al., 2005). However, none of these approaches that explicitly recognize ambiguity due to heterogenous meanings and values have been adopted into mainstream assessments of uncertainty in IAMs—although recently, Drouet et al. (2015) produced an innovative study of uncertainty in IAMs, accounting for both scientific uncertainty and alternative preferences at the same time.

2.6 Modeling under uncertainty

2.6.1 The epistemic context and consequences

The epistemic context and consequences of modeling in science generally concerns the relationship between the "world in the model" (Morgan, 2012) and the real world as experienced by other means, including measured data (Frigg and Harmann, 2012). Model validation describes the process of comparing the model to that other evidence; a valid model is a model that faithfully replicates data on real world processes. However, in the presence of scientific and ethical uncertainty, the real world becomes a moving target as factual knowledge is contested. For instance, as mentioned earlier, the definition of adequate model boundaries is indeterminate if the modeled systems are open and dynamic (Wynne, 1992); our ignorance prevents us from ensuring model completeness and hence validating the model in terms of what is actually happening in the world (Oreskes et al., 1994). The appropriate model scope then depends on the model's specific purpose, and model validation becomes an assessment of the model's trustworthiness in a particular context (Winsberg, 2010): does the model represent the relevant system components well enough to deliver results that can be trusted to help solve the identified problem? Several evaluation studies of IAMs and other types of models for climate policy analysis exist, and in these studies model quality is explicitly linked to its usefulness for a specific purpose rather than its universal truth (Risbey et al., 1996; Schneider, 1997; Risbey et al., 2005; Schwanitz, 2013). Hence, IAM building under uncertainty inherently requires modelers to make choices based on judgment, starting with choices regarding the definition of the problem and specification of the model's purpose (Kloprogge et al., 2011; Krüger et al., 2012). Modelers may make these judgments informally, based upon their own views, or they can formally elicit the opinions of experts or stakeholders, for example, through surveys (Nordhaus, 1994; Weitzman, 2001) or participatory modeling exercises (Voinov and Bousquet, 2010; Krüger et al., 2012; Voinov et al., 2016). Naturally, the elicited opinions can diverge significantly as experts and stakeholders interpret scientific and ethical uncertainties differently (see for example Roughgarden and Schneider (1999)).

Importantly, even in the (hypothetical) absence of scientific uncertainty about how the underlying theory conforms with reality, model formulation is never a one-to-one translation of theory about how the world works into the language of mathematics. By definition, models are meant to be approximate representations of reality to help render a complex situation workable (Portides, 2013). Hence, modeling always requires a number of non-theory driven ingredients including simplifying abstractions and idealizations in addition to the modeled theory. These additional ingredients make models partly independent from theory (Morrison and Morgan, 1999). Boumans (1999) thus compares the process of economic modeling in particular to "baking a cake without a recipe" (p. 67), where numerous diverse ingredients are mixed together to form a model, in a process of trial-and-error. The language of mathematics coherently links the ingredients but also introduces new constraints into the modeling process, namely analytical tractability and numerical solvability (Knuuttila, 2009). Bouman's analogy implies that model building in economics is not a deterministic process that follows its own, fixed logic. Rather, it is contingent and negotiated: "Model building is an art and not a mechanical procedure" (Frigg and Harmann, 2012, p. 25). The correct baking recipe, i.e. the list of model ingredients and proportions, can vary over time and place, or with the arrival of new scientific research.

Various values may inform expert judgment in modeling decisions (Kloprogge et al., 2011). Traditionally, a distinction has been made between epistemic values (e.g. "predictive accuracy, explanatory power, scope, simplicity" (Douglas, 2009, p. 89)); and non-epistemic values (e.g. ethical and social values). Recent literature in the philosophy of science, however, calls this distinction into question (Rudner, 1953; Douglas, 2009, 2014). Douglas (2009, 2014) argues that even our selection and understanding of epistemic values is necessarily shaped by social and ethical commitments. We elaborate on this coupling of epistemic and ethical values in policy-relevant research in Section 2.6.2.

Modeling choices have representational consequences. IAMs are scientific models; they are instruments for scientific inquiry. One purpose of building IAMs is to advance our understanding of climate-economic interactions. Modeling choices determine how well our current knowledge (or lack thereof) about the elements and processes of the systems modeled in IAMs is represented. Epistemically 'good' modeling choices increase the trustworthiness of model results and usefulness of the models with regards to the specific scientific questions that the models are used to answer. Conversely, the epistemic consequence of a modeling decision that turns out to be wrong is that an incorrect piece of information is incorporated into the body of scientific knowledge.

2.6.2 The ethical context and consequences

The ethical context and consequences of modeling choices concerns the ethically relevant judgments that modelers apply explicitly or implicitly in their choices under scientific and ethical uncertainty. Tuana (2010) distinguishes three types of ethical concerns in policy-relevant scientific research: procedural ethics, intrinsic ethics, and extrinsic ethics. *Procedural ethics* are what is commonly understood as research ethics, i.e. the widely accepted norms of good scientific conduct. These general norms concern issues such as plagiarism, care for subjects (human and non-human), and conflicts of interest (Tuana, 2010, pp. 479-480). In the context of integrated assessment modeling, procedural ethical values are relevant simply because IAMs are tools of scientific research. More specific norms pertaining to IAM development in particular have been suggested (Schwanitz, 2013), but these do not seem to be widely accepted and practiced yet. By contrast, *intrinsic ethics* refer to ethical values and assumptions that become embedded and hardwired into analytical methods and results, whether explicitly and deliberately or implicitly (Tuana, 2010; Schienke et al., 2010). For some modeling choices, their intrinsically ethical character (and the ethical uncertainty surrounding them) is widely recognized and often explicitly addressed. These choices include selection of parameters that represent a human value choice or preference (sometimes called 'ethical parameters' (Dietz et al., 2007; Nordhaus, 2011b)) and selection of normative objective functions by which to evaluate alternative policies (Morgan and Henrion, 1990; Morgan et al., 2009). A much debated example pertaining to IAMs is the choice of a social discount rate that is applied to future effects of climate change. Some modelers advocate the use of observed market interest rates, while others suggest a discussion about intergenerational justice as an appropriate starting point (see section 2.7.3).

More often than not, the ethical value judgments manifested in modeling choices remain implicit; they are subtly implied by judgments that are often perceived by modelers to be of a purely epistemic nature, i.e. concerned with only the factual content of the model representation (Tuana, 2010). In IAMs, ethical judgments may be implicitly encoded in choices about model structure and parameter values, but also in the ways in which modelers manage uncertainty and error (Schienke et al., 2010). We discuss a number of concrete examples of such implicit 'intrinsic coupled epistemic-ethical issues' (Tuana, 2010) in Section 2.7.

When model results inform policy-making, intrinsic ethical issues in the model may have important ethical consequences for the wider society. Such *extrinsic ethics* in scientific research refer to the societal effects of research outputs. Returning to the example of the social discount rate, since the rate has great influence on SCC estimates (see, for example, Hope (2006) and Nordhaus (2007)), this modeling choice may ultimately influence policies and thus the allocation of climate change costs between generations and nations. Douglas (2000, 2009, 2014) argues that extrinsic ethics (and other non-epistemic consequences of scientific choices) create a specific responsibility for researchers who work on policy-relevant issues with an uncertain evidence base. Like all researchers, they must decide whether the existing evidence is sufficiently certain to support the knowledge claim that they wish to make, but because the contested knowledge claim may influence policies, Douglas sees another moral obligation for researchers to take into account both the epistemic and the non-epistemic consequences of making an incorrect decision. The extrinsic ethical consequence of the decision may be the implementation of suboptimal policies with possibly significant societal consequences (Douglas, 2014). Extrinsic ethics are also concerned with the appropriate influence of political pressure on scientific decision-making. Such pressure can be exercised, for example, through funding arrangements (Pielke, 2007). We discuss the political dimension of uncertainty in IAMs in greater detail in the following section.

2.6.3 The political context and consequences

The political context and consequnces of the modeling choices under scientific and ethical uncertainty in IAMs relates to the position of IAMs at the science-policy interface, implying that modeling decisions may be subject to political influence and, in turn, may influence politics. We understand the terms 'politics' and 'political' broadly as concerning any "arrangements of power and authority in human associations as well as the activities that take place within those arrangements" (Winner, 1980, p. 123). Despite being a central concept in the social sciences, power is surprisingly ill-defined, and as with the concept of uncertainty, discussions about power are dispersed across numerous disciplines (Allen, 2014). One way of dissecting the large philosophical literature on power is to distinguish action-theoretical conceptions of power from broader systemic conceptions (Allen, 2014). The former conceptions consider power relations to be manifested in the instrumental actions or dispositional abilities of particular actors. By contrast, systemic conceptions suggest that power plays out via wider historical, political, economic, and cultural forces that systematically structure actors' possibilities to exercise agency (Allen, 2014). In line with the systemic conception, Haugaard defines power as "the ways in which given social systems confer differentials of dispositional power on agents, thus structuring their possibilities for action" (Haugaard, 2010, p. 425). Saar (2010) stresses that action-theoretical and systemic conceptions of power are not alternative ways of thinking about power; instead, individuals exercise power instrumentally within the confines of the external system of power relations and at the same time shape these relations through their actions.

In the context of IAMs, the action-theoretical perspective on power emphasizes the agency of modelers in their modeling choices. Modelers' agency presupposes "an idea of counterfactuals" (Guzzini, 2005, p. 511), where counterfactual possibilities pertain to the alternative modeling choices that the agent might make. In other words, modelers' agency requires latitude for such agency and political deliberation around modeling choices (Stirling, 2008). Indeed, this study so far shows that integrated assessment modeling choices are not determined entirely and unconditionally by the world as it presents itself to us, nor by undisputed ethical perspectives about the world as it should be. Such agency creates space for values other than epistemic and ethical ones to enter scientific decision-making, including political and economic interests (Edwards, 1999). Modelers may have an interest in securing research funds, furthering their academic careers, gaining public credibility, or producing model results that encourage specific policy actions on climate change. For example, the analysis by Boehmer-Christiansen of the IPCC (Intergovernmental Panel on Climate Change) suggests that scientists contributing to the IPCC assessment reports have been partly motivated by such interests (Boehmer-Christiansen, 1994a,b).

The systemic perspective on power highlights the influence of wider social forces on the modeling process. In this study, due to limited space, we focus on two (interlinked) systems of power relations that IAMs are embedded in: the systemic power relations within the scientific community and the systemic power relations that exist between the two social spheres of science and politics. Scholars in STS have developed theoretical frameworks that explain the role of politics and social relations both within and outside the scientific community in shaping the standards of good science and subsequent practice. For example, within the scientific community, scientific paradigms (Kuhn, 1962), the academic reward system (Mulkay, 1976), and peer review processes (Jasanoff, 1987; Berkenkotter, 1995) are all found to exert structuring power over scientific decision-making. Regarding the relationship between science and politics, a common view in the contemporary STS literature is that the generation of scientific knowledge, policy-making, and social order all exist in a co-productive relationship with each other (Jasanoff, 2004b). The institutions and processes involved in the production of scientific knowledge are seen to reflect and validate systems of power and authority in wider society (Jasanoff, 2004c; Thorpe, 2008).

The political implications of integrated assessment modeling choices relate to the models' potential influence back on systemic power relations. This influence may be relatively explicit when model-based recommendations for action feed directly into the policy process, although it would be naive to assume a linear translation from science into policy (Pröpper, 1993; Pielke, 2007; Cairney, 2015). The influence is more implicit when climate change research contributes to framing the climate change issue in the political sphere (Demeritt, 2001). In the context of climate models, Shackley et al. (1998) suggest that modeling can effectively depoliticize issues by removing them from the political sphere and turning them into a matter of (supposedly) politically neutral science. These issues then become subject to the implicit and socially contingent judgments of experts rather than a wider political discussion among the numerous and heterogenous stakeholders of climate change. Ultimately, modeling decisions may prematurely narrow the content of policy deliberations (Stirling, 2008). IAMs necessarily only represent a subset of stakeholder views, which, through being incorporated in the models, will be privileged in the policy process to the extent that model results influence policy. As a result, the stakeholder positions excluded from influence on the modeling choices may be systematically disempowered in decision-making. For instance, Nelson (2008) points out how the decision to apply a cost-benefit framework to climate change systematically disadvantages the global South because cost-benefit analysis commonly assumes the existing distribution of global wealth as given. This exclusion raises questions regarding the democratic legitimacy of expert assessments in policy-making (Turner, 2001) and thus procedural justice. In section 2.8 we will review examples of the political dimension of climate change research and modeling in particular.

2.7 Epistemic-ethical modeling choices

In this section we discuss examples of coupled epistemic-ethical issues from the IAM literature. Krüger et al. (2012) identify multiple points in the modeling process at which expert judgment may enter informally, including the construction of the underlying perceptual model, the specification of a formal model structure, the setting of parameter values, and the presentation and evaluation of model output. Although presented in sequential order, in practice, the choices made at each point are understood to be interdependent and iterative.

2.7.1 Construction of the perceptual model

The perceptual model underlying IAMs is the structured and qualitative understanding of the climate change problem, including its causes, processes, and consequences (adapted from Beven (2009)). This understanding includes a particular framing of the problem that the model is intended to address. Problem framing inherently involves an ethically relevant evaluation of what is important about the problem and its relevant trade-offs; it also often involves indications of how the problem can be solved. Many economists understand climate change as a 'market failure' that exists because the negative external effects associated with GHG emissions are not accounted for in market prices (Stern, 2007). This perceptual model of the climate change problem legitimizes introducing GHG emissions as externalities into a standard economic growth model for policy analysis. The market failure framing also makes it plausible to ask very focused research questions about the optimal carbon price to fix the market distortion. This price is set by the intersection of marginal climate damages with the marginal cost of abatement.

From an ethical perspective, the market failure framing not only assumes high substitutability between human goods, such as technology and capital, and non-human goods, including biodiversity, ecosystems, and landscapes (Klinsky and Dowlatabadi, 2009). It also turns the atmosphere into a commodity (Liverman, 2009; Randalls, 2011). Commodification of the atmosphere assumes the application of property rights to the atmosphere, which is commonly considered a public good. In fact, Singer (2006) suggests that the "best way to understand how global warming is an ethical problem is to think of it as a question about how best to divide a scarce resource that no one owns" (p. 418). Commodification also implies specific conceptions of climate change justice. First, pricing carbon emissions directly attributes causal responsibility to the emitter (Klinsky and Dowlatabadi, 2009). Second, the market failure framing inherently assumes all emissions to be equal because their market distorting effects are the same, independent of where and why they are released into the atmosphere. Hence the logic of this approach does not easily accommodate a distinction between subsistence emissions caused by the poor to achieve a certain standard of living, and luxury emissions caused by the rich, as suggested by some climate ethicists (Agarwal and Narain, 1991; Shue, 1993; Vanderheiden, 2008).

2.7.2 Specification of model structure

At this stage in the modeling process the perceptual model is translated into a formal model structure, i.e. a set of mathematical equations that formalize the relationships between the elements and processes of the modeled system. Specifying a model structure for IAMs involves choices about which elements and processes of the climate and socioeconomic systems should be included. These choices may require modelers to make trade-offs between different epistemic values. In particular, modelers may need to weigh model completeness against model reliability when deciding whether to include poorly understood aspects of climate change that are nevertheless expected to have significant impacts on model results. For example, it is generally considered likely that climate change will cause or worsen violent conflicts, although the empirical basis for quantifying the causal mechanism between climate change and conflicts is still small (Hsiang et al., 2013). The modeler's decision to include or exclude this aspect not only affects the epistemic quality of the model (in terms of completeness vs. reliability) but has intrinsic and extrinsic ethical ramifications as well. Excluding climate change effects on violent conflicts from the model prevents any future victims of such conflicts (who will likely not have contributed to causing climate change) from being recognized in the policy process and, *ceteris paribus*, likely results in an undervaluation of climate change damages and possibly misleading policy recommendations.

Schienke et al. (2010), comparing two different IAMs, identify various ethical as well as epistemic implications of the choice of model structure. One of these IAMs is the model used by Nordhaus (1992) in an influential study from 1992; the other is used in a more recent study by McInerney and Keller (2008). Both are optimizing models, meaning that they maximize social welfare over time. While the Nordhaus model runs without additional constraints, McInerney and Keller introduce an additional constraint on optimization: their model requires that the probability of a certain event, namely the irreversible collapse of the North Atlantic meridional overturning circulation, must never exceed a predetermined limit. Schienke et al. discuss the ethical nature of these model formulations. Both models adopt a utilitarian objective function, which generally ignores disparities in welfare distribution between the rich and the poor. The threshold constraint that is introduced in McInerney and Keller‘s model implies ethical judgments about (1) a specific outcome that should be avoided (partly independent of economic costs) and (2) an acceptable probability of this outcome occurring anyway. These decisions would be ethically controversial even if the science of irreversible system thresholds were settled (Schienke et al., 2010).

Specifying a model structure also involves decisions about the level of regional disaggregation, i.e. the number of geographical regions in the model, which Morgan and Henrion (1990) call a 'domain parameter.' Other domain parameters include model time horizon and time increment. While domain parameters are often neglected in model uncertainty analysis, their impacts on model results may be large (Morgan and Henrion, 1990). In IAMs, the criteria by which model regions are defined (e.g. economic, geographic, or geopolitical homogeneity) and the number of regions in the model have ethical implications: the greater the regional disaggregation, the more value is placed on detailing the differential impacts of climate change across regions. In particular, some IAMs incorporate equity weights to make the cost of climate change more comparable across poor and rich regions (Fankhauser et al., 1997; Hope, 2008; Anthoff and Tol, 2010). These equity weights are typically determined based on average regional income. Therefore, the degree of regional disaggregation in the model and the methodology that is used to define model regions affect the fairness of the resulting weighting scheme. Dennig et al. (2015) moreover show that many IAMs ignore income distributions *within* regions and thereby fail to address important implications for distributional justice both within and between generations.

2.7.3 Setting of parameter values

The estimation of parameter values involves choices, too. In the IAM literature to date, the most explicit discussion of coupled epistemic-ethical choices concerns one specific model parameter: the social discount rate used to calculate the present value of future consumption losses due to climate change. Economists treat climate change mitigation efforts as investments in future consumption (Stern, 2007; Nordhaus, 2007), and the act of discounting acknowledges that consumption may be valued differently depending on when it occurs. In the context of climate change, discounting has ethical importance; it reflects the weight that the current generation assigns to the welfare of future generations in relation to its own, considering that current economic activity is causing future climate impacts. A common technique for determining the social discount rate in IAMs is the Ramsey optimal growth model, which defines it as a function of the pure rate of time preference, the consumption elasticity of marginal utility, and the projected growth rate of consumption. The pure rate of time preference is essentially a measure of impatience; it measures the loss of utility that is experienced simply because consumption occurs in the future rather than today. The consumption elasticity describes how quickly the marginal utility of consumption declines with increasing consumption. It essentially measures the value of a dollar's worth of consumption to the poor vs. the rich.

Economists commonly pursue either a descriptive or a prescriptive approach to define the social discount rate. The former, as promoted for example by Arrow et al. (1996) and Nordhaus (2007, 2012) takes as its foundation individuals' inter-temporal decision-making, observed either in the market or in experiments. The intention is to treat the rate of time preference as an uncertain empirical quantity rather than the subject of value diversity. In contrast, the prescriptive approach addresses value disputes directly by starting from an ethical argument about inter- and intragenerational justice, deriving values accordingly for the pure rate of time preference and the consumption elasticity of marginal utility (Dasgupta, 2008). This approach was taken in the Stern Report (Stern, 2007), resulting in a considerably lower discount rate compared to the one used by Nordhaus and a consequently higher SCC estimate. There is no consensus in the economics literature on which approach is preferable (Heal and Millner, 2014a).

However, several philosophers argue that, independent of the method chosen, the choice is never ethically neutral. Broome (2010) emphasizes that choosing the descriptive approach implies a normative judgment: governments should consider individuals' everyday decision-making to determine what consideration future generations receive in climate policy-making. Baum (2009) illustrates the inevitable ethical judgments involved in observing, measuring, and aggregating society's discounting behavior. Fischhoff (2015) argues that any use of market prices in policy assessments always implies the ethically relevant assumption that the observed market is functioning properly, i.e. that all relevant externalities are priced in.

2.7.4 Presentation and evaluation of model outputs

IAMs can theoretically deliver various types of model output, but as mentioned earlier, the most commonly presented results are optimal global abatement targets, carbon tax rates, and SCC estimates. In the face of scientific and ethical uncertainty, these output choices have both epistemic and ethical importance because of the information they conceal. For example, the SCC is a single monetary impact metric that is aggregated from already highly aggregated estimates of climate damages across time and regions. Aggregation obscures the boundaries between groups and complicates the determination of who exactly is bearing the costs of climate change (Watkiss, 2011). The use of a single indicator that contains no information about underlying ethical judgments regarding, for example, discount rates and equity weights, implies that distributive justice is not a relevant decision criterion. This kind of practice also complicates the direct comparison of outputs from different studies because the variances in internal model processes and assumptions remain invisible (Krüger et al., 2012). Morgan (2011) raises related questions about the epistemic and ethical judgments that are intrinsic to the framing of IAM-generated abatement targets and carbon tax rates as being 'optimal.' Morgan argues that the idea of a universally optimal solution is misleading, given the scientific uncertainty surrounding IAMs and the heterogenous values among climate change stakeholders.

Having identified examples of concrete coupled epistemic-ethical choices in the development of IAMs, we now turn to identifying concrete examples of the political dimension of modeling choices as reported in the literature.

2.8 The politics of IAMs

From an integrated assessment modeler's perspective, Tol (2008) explains why the number of IAMs and IAM-based studies has been small: "The reasons are lack of funding (this work is too applied for academic sources, while applied agencies do not like the typical results and pre-empt this by not funding it), lack of daring (this research requires making many assumptions, and taking on well-entrenched incumbents), and lack of reward (the economics profession frowns on the required interdisciplinarity)" (p. 440).[2] Tol addresses some of the political and economic aspects of climate change research, including funding arrangements, controversy and competition within the climate research community, as well as the academic reward system. These factors have also been identified by scholars in STS as possible points for politics to enter the scientific process. However, the scholarly discussion of the politicization of IAMs and of the numerous choices involved in IAM development, is small, and the evidence mostly anecdotal. In the following, we review some empirical studies from the somewhat more systematic research on the politics surrounding the development of climate models. While we are not suggesting that the two types of models are equivalent, these studies may provide entry points for future research on the political context and consequences of choice under uncertainty in IAMs.

Krueck and Borchers (1999) perform an institutional comparison between two climate modeling centers in Europe to investigate how the modelers deal with the challenge to generate policy relevant knowledge about a politically charged issue in the face of scientific uncertainty and value diversity. The authors find that the centers' socio-political environments, including their funding arrangements, have influenced research agendas and affected scientific practice. The interviewed modelers describe their work as a balancing act between maintaining scientific autonomy and independence and delivering funders "some attractive results" (Krueck and Borchers, 1999, p. 109). Losing balance in either direction can compromise what Krueck and Borchers consider the most critical resource for modelers in their interaction with decision-makers, namely credibility, both with their "political customers" (Krueck and Borchers, 1999, p. 118) and with their academic peers. The quote by Tol cited above indicates that integrated assessment modelers may face a similar trade-off; the options are either to give up on policy relevance to attract academic funders, or to possibly compromise scientific independence to satisfy non-academic funding agencies.

Shackley et al. (1998) use a co-productionist framework to explain how climate models of a specific type, General Circulation Models (GCMs), have become a powerful tool for informing policy formation. The authors argue that the mutually reinforcing dynamics between modelers, decision-makers, and users of model outputs from related disciplines have led to a general consensus within this network of actors that GCMs represent the best available tool for projecting future climate change when regional detail is needed. Decision-makers in particular consider such consensus helpful for facilitating political agreement on the appropriate policy response. Shackley and colleagues argue that these social rather than scientific factors have led to the exclusion of other model types—for instance, simpler models and stochastic models—from the toolbox available for policy advice. Again, Tol's quote cited above indicates that similar dynamics may be at work in the IAM community. However, the conclusions that Shackley et al. have drawn from their study were met

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[2] Tol is the developer of one of the most prominent economic IAMs, the FUND model.

with criticism from the climate modeling community. Henderson-Sellers and McGuffie (1999), for example, argue that the view presented by Shackley et al. underestimates the capacity of modelers for self-reflection and the efforts of modelers to entertain a variety of models that stand in no particular hierarchical order. The dominance of GCMs certainly seems to be a question of scale of application. As one of the reviewers of this article pointed out, much of the policy work in the IPCC, where no regional detail was required, has been based on simpler climate models, not GCMs.

In another empirical study, Shackley et al. (1999) investigate how climate modelers manage disagreement within the climate modeling community and the communication of such disagreement to outside audiences. The authors look at one technical modeling issue, the use of flux adjustments in coupled Atmosphere-Ocean GCMs, and its politicization in policy debates. Flux adjustments are a possible way for modelers to compensate for drifts in model outputs that often occur when atmosphere and ocean models are linked. The drift indicates underlying errors in the model but these errors are not definitively fixed by the flux adjustment; the adjustment simply corrects for drifts after the fact (Shackley et al., 1999). Scientifically, there is no correct answer as to whether or not flux adjustments should be used in climate models, and the study shows that the modelers' scientific cultures, i.e. their tacit assumptions and practices, influence their judgments on this issue.

The emergence of different scientific cultures among modelers is, among other factors, related to the modelers' individual career trajectories as well as institutional factors such as funding arrangements and leadership. Shackely and colleagues distinguish between a pragmatic and a purist culture. Pragmatists are more willing to accept that models have errors but are sufficiently good to inform policy-making and generally recognize "the need for a model which can provide answers about anthropogenic climate change" (Shackley et al., 1999, p. 19). In contrast, purists tend to be more concerned with improving the models and reducing errors to advance academic research. Importantly, the authors also find that climate modelers consider in their choices the implicit ideas they hold about the expectations and knowledge needs of decision-makers. The authors find that the modelers are aware that their judgments on flux adjustments happen "in an institutional-political context which stresses the importance of presenting a clear storyline about the likelihood and broad-brush pattern of future climate change to the outside world" (Shackley et al., 1999, p. 32). Hence, the modeling community prefers to discuss controversial modeling issues such as flux adjustments among themselves and to "reserve criticism for internal dealings within their own peer community" (Shackley et al., 1999, p. 30), because acknowledging uncertainty is seen to make the credibility of climate science in the policy process vulnerable to the attacks of climate skeptics.

It is worth highlighting that there are multiple examples of academic exchanges where climate scientists and modelers have disagreed with the conclusions that social scientists have drawn from studying their work; for example, the clashes of views about the extent to which climate models are social constructions of climate science (see Schneider (2001) in response to Demeritt (2001)) and to which climate science is influenced by politics (see Moss (1995) in response to Boehmer-

Christiansen (1994a,b) and Henderson-Sellers and McGuffie (1999) in response to Shackley et al. (1998)). Again, we are not aware of equally comprehensive empirical research on the politics of IAMs, but we hypothesize that integrated assessment modelers deal with trade-offs and pressures that are similar to those facing climate modelers. In the following, we take a more detailed look at co-production of knowledge and politics in modeling for policy-making to explain how modeling choices under uncertainty can become 'locked-in' over time.

2.9 Epistemic-ethical-political modeling choices

To summarize the findings of this analysis so far, uncertainty, both scientific and ethical, requires modelers to make numerous choices at multiple points in the modeling process: the construction of the underlying perceptual model, the specification of a formal model structure, the setting of parameter values, and the presentation and evaluation of model output. Epistemic, ethical, and political contexts shape how these modeling choices are made because they determine criteria by which such choices are evaluated.

The epistemic context exists because IAMs are scientific models. They are (partly) based on scientific theories and empirical data, and one of their objectives is to help advance our understanding of climate-economic interactions. The epistemic consequences of modeling choices include the quality of representation of knowledge (or lack thereof) and the contribution of IAMs to the advancement of our understanding of the relationship between climate change and society. Hence, the evaluation criteria for modeling choices in the epistemic context relate to the trustworthiness of the model's representation and its usefulness in terms of the specific research questions they are applied to answer.

The ethical context of modeling choices relates to AMs' other function, informing policy decisions that may have real consequences for the distribution of the cost of climate change across regions and generations. Because of this dual nature of IAMs (scientific device and policy analysis tool), the implications of modeling choices pertain not only to procedural and intrinsic ethics, but also to extrinsic ethics. While a set of norms for procedural ethics in scientific research has been widely established, a similar set of norms of good conduct with regards to intrinsic and extrinsic ethics in policy-relevant research has yet to be developed (Tuana, 2010). In fact, while some modeling choices are explicitly acknowledged and discussed as ethical issues, the ethical consequences of other modeling choices are subtle and implicit, and these choices are often not recognized as matters of 'ethics' in the first place. In particular, coupled epistemic-ethical modeling choices may be perceived as purely epistemic decisions, while in fact they also have ethical consequences. Section 2.7 provides numerous examples. Appropriate ethical norms of integrated assessment modeling would encourage policy outcomes perceived as just and as a manifestation of appropriate valuations of the costs and benefits of climate change.[3] But even more fundamentally, such norms would need to be able to unveil the hitherto invisible ethical judgments in modeling choices that then trickle down, unexamined, into policy outcomes.

Finally, the political context of modeling choices relates to the fact that IAMs are embedded in two social systems—science and policy—and the power relations within these systems. These power relations define the evaluation criteria for modeling choices. Politically 'good' modeling choices enable academic publication of model-based studies, attract research grants, and enhance the policy influence of model results. At the same time, modeling choices may have multiple consequences for policy and politics. First, numerical model results—such as SCC estimates—may relatively directly feed into policy design. Second, the models may influence the framing of policy problem of climate change in the public discourse and the dominant narratives about climate change. The use of IAMs for informing policy may also influence the distribution of political power among various stakeholder groups (which, of course, has ethical implications with regards to procedural justice in decision-making on climate policy).

Positive feedback loops and 'lock-in'

Looking at model development over time, it becomes clear that modeling choices are not made in a vacuum—history matters. Modeling choices, once made, influence what is perceived as a 'trustworthy' choice in future models; they set epistemic benchmarks. They also contribute to establishing the norms of ethical conduct in IAM development that determine what modeling choices are perceived as ethically appropriate in the future. And past modeling choices also shape the expectations of journal editors, funding agencies, and policy-makers with regards to what they perceive as policy-relevant, publishable, or worth of funding. In other words, there exist positive feedback loops wherein the epistemic, ethical, and political consequences of modeling choices reinforce the contexts they are made in. Past modeling choices influence the evaluation criteria by which future modeling choices are judged. Future models will be rewarded for their alignment with the epistemic benchmarks and ethical norms established through past models because they are more likely to be published, funded, and used by policy-makers. The epistemic, ethical, and political aspects of these feedback loops are, of course, not independent from each other. In particular, publishing and funding criteria are likely guided by the established epistemic benchmarks and ethical norms. Policy demand and publishing bias may be considered tangible embodiments of the structuring power that epistemic benchmarks and ethical norms exert over decisions in model development.

The concept of co-production of science and social order provides a theoretical framework for this argument about positive feedback loops and path dependence in modeling choices. Jasanoff

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[3] It is not inherently clear, who should develop such ethical norms: the modeling community, moral philosophers, elected decision-makers, selected experts, or the public at large? I address this issue in the conclusion to this dissertation.

(2004b) provides a comprehensive outline of the concept. Co-production suggests that science (understood as the process of ordering our knowledge about nature), and politics (the process of creating social order), are so closely and systematically linked that they should be understood as mutually interdependent. Science informs politics, and politics shapes how scientific knowledge is produced. Because of their dual function, one can consider IAMs as sites of co-production of natural and social order. First, IAMs function as epistemic devices; the models are an embodiment of scientific knowledge. Modeling choices order and advance our understanding of climate change and climate change policy in particular ways. Second, IAMs also influence social order—through their direct influence on policies and the policy discourse, as well as through their influence on perceptions of trustworthiness, ethical appropriateness, and policy-relevance. The epistemic benchmarks, ethical norms, and biases in publishing, funding, and policy application that are thus established in turn constraint future modeling choices (Figure 2.1).

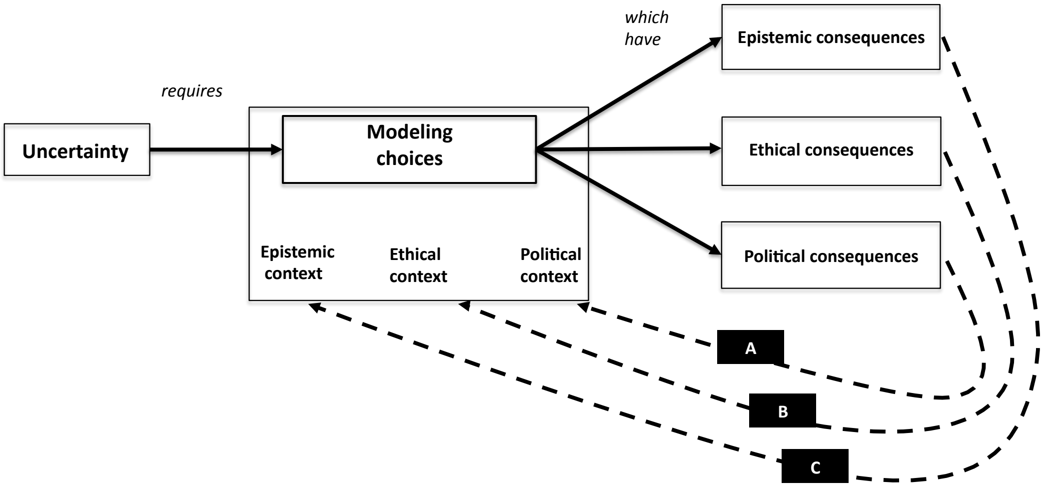

Figure 2.1: Positive feedback loops in model development: A—publishing bias, policy relevance, B—ethical norms, C—epistemic benchmarks.

It is easy to see how such dynamics of co-production may create and maintain stability in the choices modelers make despite the high level of scientific and ethical uncertainty in the field that otherwise might be expected to produce wide variability in modeling approaches . An example is described by Risbey et al. (1996), who note how choices made in early IAM studies can settle modelers' choices in subsequent studies by producing an epistemic benchmark for what scholars and decision-makers accept as credible. In particular, the authors observe that many IAMs "share a number of core approaches, assumptions, or component models" that "are usually based on earlier models or pioneering work" (ibid., p. 377). Risbey et al. call these shared core elements 'archetypes.' For example, one of the first estimates of global climate change damages was generated from a static predecessor of the DICE model in 1991, stating that climate change will cost 1–2 percent of global GDP (Nordhaus, 1991). This estimate has become an archetype—a yardstick for gauging the epistemic plausibility of subsequent IAM studies. Risbey et al. (1996) state that these "loss figures have become enshrined in the policy analysis/IA community as being somehow 'reasonable'" (p. 377). Conversely, modelers challenging the enshrined wisdom of this representational benchmark may implicitly work against the power relations that have been established in conformity with these conventions because only 'reasonable' studies gain access to funding and only 'reasonable' modelers are considered experts and can expect institutional support.

Other theoretical accounts exist of how positive feedback loops may govern model development. Boumans (1999) argues that the process of building a model ('context of discovery') is not independent from the process of evaluating the resulting model ('context of justification'). Boumans' comparison between modeling and baking a cake without a recipe was referenced earlier already, in Section 2.6.1. He argues that, essentially, modeling is the process of integrating a number of different ingredients—theory and empirical data, but also metaphors, policy views, and so forth—with the help of the unifying language of mathematics. The appropriate list of ingredients to be integrated depends on the particular purpose of the model. Models that are to be useful for policy will need to incorporate certain elements in order to be considered adequate according to predetermined quality criteria. In short, Boumans argues that the context of model discovery (the process of integration) is closely connected to the context of its justification; modelers will engage in a trial and error process until their model meets these predefined criteria. Coming back to Boumans' cake analogy, the modeler may not have a recipe of the cake she is baking, but she has a clear idea of what the final result should look and taste like. We argue here that the modeler has such a clear idea because she had previously seen and tasted other cakes, and because she knows what others expect from the cake she is baking.

Winsberg (2003, 2010) claims that the credibility of computer simulations is importantly derived from their reliance on simulation techniques that are considered credible. By techniques, Winsberg refers to the activities, practices, assumptions, and 'rules of thumb' involved in the modeling process (Winsberg, 2010, p. 45). These techniques gain in credibility each time that they are applied successfully, where success means producing results "that fit well into the web of our previously accepted data, our observations, the results of our paper-and-pencil analysis, and our [...] intuitions" (ibid., p. 122). Building on their successful track record, these techniques become ‘self-vindicating’, which means they begin to “carry their own credentials” (Winsberg, 2003, p. 121).[4] That is why, Winsberg argues, it is fair to say that these simulation practices “have their own life: they evolve and mature over the course of a long period of use, and they are ‘retooled’ as new applications demand more and more reliable and precise techniques and algorithms” (Winsberg, 2010, p. 45). Weitzman’s dismal theorem in 2009 triggered such a ‘retooling’ of existing techniques for the simulation of uncertainty; the theorem created new demands for IAMs to more appropriately address the risks related to extreme climate events (Weitzman, 2009). More recently, empirical studies of the effects of climate change on economic growth trajectories (rather than economic output in a given period) may represent a new impetus for evolution and ’retooling’ (Dell et al., 2012; Burke et al., 2015; Sterner, 2015).

Regarding the political feedback loop, Shackley et al. (1999) in a study referenced previously, examine policy pressure on climate modelers and their modeling decisions. The authors do not find direct empirical evidence of policymakers’ concerns and expectations influence on concrete modeling choices. They indicate that if such influence existed, it was likely indirect and implicit; pressure may be exerted through funding agencies and through scientific institutions such as the IPCC. But ultimately, the authors conclude that “the scientifically do-able problem and the needs of policy may have been constructed together” (ibid., p. 23), and that therefore the validation of particular modeling techniques cannot considered fully independent from policy requirements. Instead, certain modeling choices may manifest ideas about the knowledge demands of policy. Conversely, policy may imply normative ideas about what is credible, desirable and policy-relevant science in the modeling domain (ibid., pp. 23-24).

While Winsberg’s approach in particular emphasizes change and evolution over time, we argue that as a result of these positive feedback loops, co-production can lead to a “lock-in” to possibly suboptimal models and modeling techniques (Stirling, 2010). Theoretically, such lock-in seems likely with regards to both the evolution of individual models over time and the convergence of the entire fleet of IAMs. However, only empirical research into the history of IAMs from a coproductionist perspective could reveal whether lock-in has prevented significant model innovations and caused IAMs to become increasingly homogenous. To our knowledge, such empirical research is currently lacking.

2.10 Conclusion

In this paper, we have drawn on disparate literatures to review and discuss the epistemic, ethical, and political contexts and consequences of IAM modeling choices under uncertainty. In this section,

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[4] Here, Winsberg draws on earlier work by Hacking (1988, 1992) on stability in the relationship between theory and laboratory experiments.

we draw two key conclusions from our analysis and then suggest directions for future research. First, although we have reviewed the epistemic, ethical, and political dimensions of modeling choices sequentially in this paper, their intricate entanglement in integrated assessment modeling can hardly go unnoticed. To return to an example we have discussed, the economists' framing of climate change as a market failure justifies choosing an economic growth model with climate externalities as the basic model structure. This modeling choice has intrinsic ethical importance; for instance, it tends to go together with the assumption of substitutability of natural and other forms of capital and with a commodification of the atmosphere. The outputs generated from the resultant IAMs are specifically relevant for policy approaches that assign a monetary price to carbon, while alternative responses are sidelined. The implementation of market-based responses, in turn, legitimizes and reinforces the initial framing of the problem and secures continuing demand for further model studies to determine optimal carbon prices or emission caps. With this and other examples we have illustrated the co-production of climate-change research and politics. Building on Tuana (2010), who identifies the coupling of epistemic-ethical issues in policy-relevant scientific research, our analysis calls for an extension of this notion to include the political context in which the epistemic-ethical issues are addressed.

The second key conclusion from our analysis is that the primary focus of the discussion about uncertainty and about the modeling choices that uncertainty requires within the IAM community is often still limited to the epistemic dimension. This is despite the fact that in 1996, Risbey et al. (1996) advised the IAM community to accept that building IAMs to support policy-making involves "an additional responsibility" (p. 369), namely to openly acknowledge pervasive uncertainty and irreducible ignorance despite the "political (and motivational) pressure to provide policy guidelines" (ibid.). Twenty years later, some suggest that IAM modelers by and large have not internalized this additional responsibility (Revesz et al., 2014; Stern, 2016). The ethical context and consequences of choice under uncertainty in IAMs is diffused in disparate literatures, and the political embeddedness of the integrated assessment modeling process has received especially little attention.

IAMs are under-researched both theoretically and empirically. While social scientists and philosophers have highlighted some of the ethical and political implications of integrated assessment modeling choices, empirical studies in particular have focused on climate models rather than IAMs. What is missing are theory-led empirical investigations on how modeling choices are made in practice, what influences these choices, and what types of political relations they are embedded in. A starting point is to focus on the modelers first, as suggested by Kovacic and Giampietro (2015), in order to examine their implicit or explicit roles as scientists, moral agents, and political actors. Much can be learned from empirical studies of this type on environmental models (Landström and Whatmore, 2011) and climate models (Shackley et al., 1998; Krueck and Borchers, 1999), as outlined in this article. Part of this approach will involve examining the communication of model results and uncertainties and, more broadly, the use of IAM-based evidence in the policy process.

What theories may usefully guide this empirical work? The theoretical lens that most extensively informed this study is that of co-production, originating in the field of STS. As outlined in the previous Section, the central idea is that IAMs by functioning as boundary objects between scientific research and policymaking, are a site of co-production of social order and knowledge. The co-productionist approach allows for explaining both stability and change in IAM development over time. Further empirical research may inter alia improve our theoretical understanding of the mechanisms of co-production, the identified feedback loops, and, in particular, the links between their epistemic, ethical, and political aspects. To conclude, we briefly identify three alternative theoretical lenses (with no claim of completeness) through which the epistemic-ethical-political nature of IAMs may be analyzed in a more holistic way. Each lens brings into view different aspects of the interlinked dimensions of modeling under uncertainty. All of these lenses may be applicable to studying the development of IAMs (the focus of this article), as well as to the communication of model results and the use of model-based evidence in the policy process.

Within the heterogenous field of STS, Actor-Network Theory (ANT) analyses how the involvement of both human and non-human actors in network clusters create and stabilize meaning (Latour, 2005). Non-human actors can include material practices and technological artifacts. Adopting this theoretical lens implies that IAMs do not merely function as mediators between science and politics but *are* themselves mediators, i.e. actors in their own right. They hold a powerful position in the actor network as they produce authoritative representations of dominant perceptions of the world. Consequently, this lens emphasizes that modeling choices do not only encode epistemic-ethical judgments and power relations but also *actively* contribute to their (re)production and, some scholars argue, can even take on moral agency in their own right (Adam, 2008). ANT emphasizes an aspect of IAMs that has received little attention in this study, but should be addressed in future studies, namely the fact that IAMs are also strings of computer code, written in a particular programing language, and run on machines with limited computational capacity. Modelers need to accommodate in their choices that model functions must be solvable (Winsberg, 2010). In particular, uncertainty analysis is computationally expensive so that modelers may perceive a trade-off between complexity of model structure and explicitness of uncertainty treatment. In these cases, technical restrictions guide modeling choices—with coupled epistemic-ethical-political implications.

The sociological and anthropological STS are increasingly being complemented by a political ecology perspective. Political ecology describes an interdisciplinary body of research focusing on the political, economic, and cultural causes and implications of environmental change. While definitions of political ecology vary, a common focus is on the effects of unequal distributions of power and the costs and benefits of environmental change (Bryant and Bailey, 1997; Robbins, 2012). Another common focus is on the local social and environmental implications of global environmental regimes. This theoretical lens brings the political dimension of model development into sharp focus so that modeling choices and the assimilation of model-based evidence into policy are seen as largely driven by existing power arrangements. Coupled epistemic-ethical judgments are themselves considered determined by political circumstances and the distribution of power resources. There may be much to gain from combining this political charge with STS (Forsyth, 2003; Jasanoff, 2004c; Goldman et al., 2008). For example, a political ecology lens may help explore the role of IAMs in promoting the political project of 'climate capitalism'—the collective transformation to a low-carbon society while maintaing a commitment to economic growth (Newell and Paterson, 2010). From a more critical perspective, this lens allows for investigating the role of IAMs in upholding existing power relations between developed and developing countries. The argument is that the policy path dependencies introduced by current IAMs ignore historical responsibilities, benefit industrialized countries over developing countries, and thus reproduce global socio-economic inequities and power relations (Newell and Bumpus, 2012; Böhm et al., 2012; Marino and Ribot, 2012). Some activist scholars refer to this phenomenon as 'carbon colonialism' (Bachram, 2004; Bumpus and Liverman, 2010).

Another political science lens is epistemic community theory, which explains the influence of networks of experts in global governance (Haas, 1989, 1992). Originally, the concept of epistemic communities was developed in sociology, defined as "knowledge-oriented work communities in which cultural standards and social arrangements interpenetrate around a primary commitment to epistemic criteria in knowledge production and application" (Holzner and Marx, 1979, p. 108). Haas (1989, 1992) expanded the concept to make it suitable for explaining international cooperation. An epistemic community is here defined as a network of professionals with recognized competence in a particular domain and an authoritative claim to policy-relevant knowledge within that domain or issue-area (Haas, 1992). The bureaucrats and researchers from different disciplines that are thus united share values, moral and causal beliefs about the processes leading to the problem, beliefs in the validity of certain approaches to knowledge generation and validation, and a common policy enterprise, i.e. the framing of the issue and possible solutions. Coming back to the concept's sociological roots, Knorr-Cetina (1999) speaks of epistemic communities sharing a specific "epistemic culture" that shapes their processes of knowledge production. Applying this theoretical lens to integrated assessment modeling would suggest that the models represent the focal point of, or the binding link between, an established epistemic community of modelers, researchers, and decision-makers who share a common epistemic culture. It is this entrenched and unchallenged culture then that constrains modeling decisions and resultant policies in ways that remain mostly unnoticed.

Only when we acknowledge and unpack the epistemic, ethical, and political contexts and consequences of the choices under uncertainty in integrated assessment modeling, the communication of results, and the policy uptake will we be able to judge the usefulness of IAMs in supporting climate change policymaking that is scientifically sound, ethically fair, and politically acceptable.

Chapter 3

Telling stories with models and making policy with stories: an exploration

3.1 Preface

This article is an exercise in connecting theoretical ideas from two different disciplines: the idea that scientific models are composed of both mathematical structures and verbal narratives developed in philosophy and history of science, and the idea developed by political scientists that stories and storytelling have significant influence on policy outcomes. The result of my exploration is an analytical framework for studying the policy stories produced with scientific models. I argue that, in addition to numerical results, these models also deliver narratives[1] into the policy process. Since these narratives express certain values and beliefs about the modeled policy problem, it is necessary to study their composition and content in order to fully understand the role of scientific models as policy aids. In this paper, I demonstrate this analytical framework, employing it to examine the stories produced with four different versions of the DICE model, an influential integrated assessment model of global climate change.

In the context of this dissertation, this article elaborates on the notion of policy-relevant scientific models as sites of co-production by illuminating the effects of the models' calculations on climate change policy and politics. The analytical framework presented here provides one methodological entry point for studying *how* models mediate the mutually formative relations between science, policy, and politics—through narrative.

Regarding the existing scholarship on models as policy aids, this article contributes to both of the research streams it seeks to reconcile. First, it is one of the first empirical applications of the theoretical concept of 'modeled stories' to contemporary models since the concept was comprehensively introduced by Morgan (2001, 2012). Second, narrative policy analysis is still a young branch within political science, and the discussion of modeled stories as a specific type of policy narratives introduces a new aspect to this emerging scholarship.

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[1] I use the terms 'story' and 'narrative' interchangeably in this paper.

More specifically, regarding the existing scholarship on IAMs and climate change governance, this article and its post-positivist methodology also responds to a call expressed by Jasanoff (2010) to pay more attention to issues of 'meaning' in the scientific assessment of climate change.[2] Jasanoff argues that often in scientific research on climate change, knowledge becomes detached from matters of meaning, although scientific facts are not free of implicit values and beliefs. While this article does not contribute to exploring the local, subjective, and specific meanings of climate change to those affected by it (Jasanoff's primary objective), it enables a discussion of the 'meaning-making' function of scientific representations of climate change. By recognizing that ostensibly abstract, universal, and impersonal scientific models are also story-telling devices, and by identifying the values and beliefs that become expressed in the modeled stories, this article contributes to "turning matters of fact into matters of conversation" (Jasanoff, 2010, p. 245). This understanding is of course compatible with the notion that policy outcomes also are not dictated by scientific facts alone, but crucially shaped by policy actors' interpretations of facts and how these facts relate to their pre-existing values and beliefs. Jasanoff also notes that, unlike art or literature, science does not allow for infinitely varied interpretations but that "interpretations fall into a few broadly defined camps" (p. 245). In this article, we therefore draw on a typology of four such broadly defined camps when analyzing the values and beliefs expressed in modeled stories about the policy problem of climate change: the classification of environmental worldviews by Clapp and Dauvergne (2011).

I am planning to submit this article for publication in a policy research journal. Since IAMs are only used as an illustrative example here, I do not envision an audience that is specialized on climate change policy. In fact, I believe that the analytical framework developed in this article may be useful for researchers working with policy-relevant models in a variety of policy areas beyond climate change. The *Policy Studies Journal* has published multiple important papers advancing narrative policy analysis over the past decade, and therefore I believe that this journal would be a fitting choice for this manuscript as well. The article would reach the relevant expert community to apply my framework, criticize it, and continue the exploration.

3.2 Overview

Narrative research is in vogue, both among philosophers and policy researchers. A current debate in philosophy of economics concerns the role of storytelling in economic modeling, and a growing research program in policy studies investigates the influence of stories on policy outcomes. These two streams of research have yet to be connected in an investigation of how scientific models, in addition to delivering numerical results, also influence policy through the stories that are told with them. In this paper, I present a framework for analyzing the composition and content of policy-

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[2] This call was echoed by Hulme (2011): "[T]he importance of story-making and story-telling around climate change needs elevating alongside that of fact-finding" (p. 178).

relevant stories produced with scientific models. I argue that an appreciation of these modeled stories is essential for a full understanding how models are used in policymaking—whether they are models of climate change economics, public health, or the economy. For illustration, I apply the framework to the analysis of stories produced with the DICE model, arguably the most prominent integrated assessment model of global climate change.

3.3 Introduction

Philosophers of economics and public policy researchers have recently shown an increasing interest in the role of storytelling in their respective areas of study. Mary S. Morgan (2001; 2012) claims (as others have before, see Gibbard and Varian (1978) and McCloskey (1990)) that storytelling is an integral part of how economists use mathematical models to learn something about the world. Morgan argues that economic modeling encompasses both manipulating a mathematical structure to obtain a new set of numerical model results and producing a narrative[3] that interprets, explains, and evaluates the model changes and the new results.

A new research program in policy studies examines the role of stories in policy processes (McBeth et al., 2005; Jones and McBeth, 2010; Shanahan et al., 2011; Stone, 2012; Jones and Radaelli, 2015). The fundamental assumption is that political actors, through storytelling, construct policy problems and their solutions in ways that align with their values and beliefs about the world. The Narrative Policy Framework (NPF) is an analytical tool for studying policy narratives, their composition[4], and their content, in order to detect these underlying systems of values and beliefs (Jones et al., 2014).

Although mathematical models have become standard tools for informing policy decisions in important areas such as public health (Mansnerus, 2014), economic policy (den Butter and Morgan, 2000), and climate change (Edwards, 2010; Weyant, 2014), these two streams of research have not yet been connected to investigate how mathematical models, in addition to delivering numerical outputs, also influence policy through the stories that are told with them.

This paper addresses that gap. I develop a framework for analyzing the narratives produced with policy relevant mathematical models. I operationalize insights from Morgan's work to adapt the NPF into a useful tool for studying this particular type of policy stories: modeled stories. For illustration, I apply this framework to study four narratives told with the Dynamic Integrated Climate Economy (DICE) model, arguably the most widely used Integrated Assessment Model (IAM) of global climate change. IAMs model the interactions between the climate system and economic growth and they can generate estimates of the costs and benefits of policies for the

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[3] I use the terms 'story' and 'narrative' interchangeably in this paper.

[4] The NPF literature typically uses the term 'structure' to refer to a narrative's composition, but I use the latter to avoid confusion with the mathematical structure of models.

abatement of greenhouse gas (GHG) emissions. Common outputs of IAMs include estimates of optimal emissions targets, the economically efficient carbon tax rate, and the social cost of carbon[5] (SCC). Integrated assessment modeling informed the reports of the IPCC, the Stern Review (Stern, 2007), and the official U.S. government's estimate of the SCC (Interagency Working Group on Social Cost of Carbon, 2010, 2013).

This paper argues that the production of policy-relevant knowledge occurs not only in the act of performing mathematical simulations and producing numerical outputs, but also in the act of narrating. The common perception is that mathematical models deliver policy-relevant information in form of numerical outputs, but the stories that embed mathematical modeling and make their numerical findings understandable have so far not been studied. The framework for the analysis of policy-relevant model narratives presented in this paper guides a structured examination of the composition and content of policy-relevant modeled stories.

This paper is structured as follows:

- Section 3.4 clarifies the roles of stories in modeling and policy-making.
- Section 3.5 develops the analytical framework for studying policy-relevant model narratives.
- Section 3.6 then demonstrates the framework, applying it to the study of four stories told with different variations of the DICE model.
- Section 3.7 concludes by discussing the implications on future research.

3.4 Stories in modeling and policymaking

3.4.1 Model stories

Economic historian Mary Morgan argues that mathematical models in economics consist of two elements: a mathematical structure and the stories one can tell using this structure (Morgan, 2001, 2012). A model's mathematical structure encompasses the equations, variables, and parameters that, together, deliver the model's numerical results. Its narrative begins with the question about the world that the model helps answer. In economics, a common question asked from models is: "What happens if . . . ?" The question motivates manipulation of the model structure and sets into motion the model's internal workings to create new results (Morgan, 2001). In the model narrative the modeler explains, interprets, and evaluates these numerical results. This narrative forms an integral part of the model, because only in in the act of telling a story with the mathematical model structure is new knowledge produced (ibid., p. 367).[6]

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[5] The SCC are defined as the net present value of all future damages caused by releasing one additional ton of carbon dioxide (CO_2) into the atmosphere (Pizer et al., 2014).

[6] That is why, as another economic philosopher observes, "[i]n seminars on mathematical economics a question nearly as common as 'Haven't you left off the second subscript?' is 'What's your story?'" (McCloskey, 1990, p. 15).

The role of narration in modeling has been recognized for models in other disciplines as well. Describing the relationship between model structures and stories in physics, Hartmann (1999, p. 344) suggests that a story is "an integral part of a model; it complements the formalism." And mathematics more generally, Doxiadis and Mazur (2012, pp. vii-viii) argue, is "incomprehensible" when one fails to recognize the "narrative aspects intrinsic to it" since mathematics is a human enterprise and people "live, grow think, and create stories."

Model structure and model story mutually constrain each other, but do not fully determine each other. A model's mathematical structure is largely determined by the relevant scientific theories and mathematics. The structure limits the range of stories that can be told with it because "we can only ask questions and tell stories about terms and relations that are represented in the structure, and only within the range allowed by the mathematics or materials of the structure" (Morgan, 2001, pp. 369-370). But still, the story is "neither a deductive consequence of the model nor of the underlying theory" (Hartmann, 1999, p. 344), although it may draw on the terminology introduced by the theory. In other words, there is some flexibility as to the range of questions that can be asked from—and stories that can be told with—a particular model structure, and therefore "the user has to make sensible choices in order to tell meaningful stories" (Morgan, 2001, p. 378).

Model stories are not merely rhetorical devices, but they have an epistemic function: only with the help of narratives can we make inquiries of a model's mathematical structure and draw inferences from the model results about the world that the model represents. A set of numerical model results by itself can hardly provide a satisfying answer to the question that was asked; what is needed is a story that, by integrating the model results with the question, makes the numbers accessible, understandable, and communicable (Winsberg, 2010). As such, model stories are more than an interpretation of the quantitative model results. They function as cognitive tools "by which we explain something or come to understand something about the world" (Morgan, 2001, 376). More concretely, the story connects the model's internal dynamics to the world that the model represents, and it allows users to infer conclusions from what is happening in the model to what is happening in the world.

Storytelling constitutes one of the two links between models and the world (Morgan, 2001). The other link is established in the process of model building, where modelers express something about the world in mathematic equations drawing on scientific theories and hypotheses about how the world functions. In the process of using the models to answer specific questions, modelers establish the second link, connecting the model results back to the world by telling a story with it. Following a narrative logic (as opposed to the model structure's deductive logic of science and mathematics) they employ the results to explain something about the world and to make a specific argument.

Model narratives also become "informal tests of the validity of mathematical models" (Morgan, 2012, p. 246), complementing formal, empirical tests. A good model story is consistent and meaningful with respect to the theories and hypotheses that the model is based on, and it provides a coherent and plausible account of the world/events that the model represents (Morgan, 2012, p. 251). Importantly, truthfulness is not a necessary, or even common, criterion in the evaluation of model stories (Morgan, 2012, p. 248). And yet, a good story may correct weaknesses in the models' empirical adequacy—to what extent depends on the aim of the modeling exercise (Hartmann, 1999, p. 344).[7]

Morgan's argument implies that using mathematical models to learn about public policy issues and to support decision-making inevitably involves storytelling. A model is policy-relevant if the typical questions asked from it are policy-driven. The questions may concern the optimal policy choice, the performance of alternative policy options, or the policies required to achieve a particular objective. Through narration, modelers explain and interpret the numerical model results and infer conclusions from them that answer the initial questions about the policy problem. In other words, the modeled narrative links the workings inside the mathematical model to a specific public policy situation. Modeled narratives are constrained by the the logic of mathematics and by our theoretical knowledge about the policy issue, but they are not dependent on them. They also involve interpretations and evaluations that are not determined by theory and mathematics alone and yet are relevant to answering the posed policy question. I therefore argue that the production of policy-relevant knowledge using scientific models occurs as much in the act of narrating as in the act of performing mathematical simulations and producing numerical outputs. Therefore, to understand how mathematical models are used to produce policy-relevant knowledge, we need to study the stories that are told with them.

3.4.2 Policy Stories

Narrative Policy Analysis (NPA) is concerned with the explanatory power of stories in the formation of public policy. The underlying assumption is that narratives can serve as vehicles through which policy actors express their beliefs and values and feed them into the policy process. In particular, policy actors use language and stories to construct the policy problem in a particular way that implies solutions which are in line with their beliefs and values (Stone, 2012). Policy actors' stories explain the problem's origin, assign blame and responsibility, and approve certain actors as 'fixers' of the issue (ibid., p. 227).

Policy actors craft these stories to appeal to the public, stakeholders, and decision-makers, with a view to gaining authority over competing narratives and thus influencing the policy outcome. Studying the policy narratives invoked by different actors can therefore help uncover the "socially constructed elements of public policy" (Shanahan et al., 2011, p. 536)—the conflicting values, beliefs, and ascriptions of meaning that inform actors' policy positions (Stone, 2012). Ultimately,

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[7] While the qualitative evaluation of modeled stories is beyond the scope of this paper, unpacking the relationship between the quality of model stories, criteria for their truthfulness, and the empirical validity of models opens interesting avenues for future research.

NPA can also help explain why certain policy narratives translate into policy outcomes and others fail to gather support (Roe, 1994).

Empirical studies in NPA have *inter alia* investigated the influence of stories on global health policy (Ney, 2012), conservation policy (McBeth et al., 2005), climate policy (Liverman, 2009; Curran, 2011), and energy policy (Miller et al., 2015).

Little research exists about the role of model stories as a particular type of narrative in policy-making. More generally, it is a common understanding in the NPA literature that actors use science and scientific findings strategically in the construction of their policy stories (e.g. see McBeth et al. (2005)). Also, Stone (2012) observes how numbers, when used in political arguments, tell "hidden stories" about the boundaries of the problem, the gravity of the problem, and the authority of those who produced the numbers. But to my knowledge, Mansnerus (2013) is the only empirical study of how *model stories* function as evidence in policy making. Mansnerus studies the use of mathematical modeling in the governance of pandemics; she argues that these models generate narratives as policy-relevant evidence, and that these narratives gain quantitative authority in the policy discourse due to their origination in mathematical models. These narratives are perceived as accurate and valid, despite substantial uncertainties, and Mansnerus shows how they come to influence the governance of pandemics. Therefore, she argues that "modeling no longer appears as an innocent instrument but as a practice that embodies power relations" (Mansnerus, 2013, p. 287). But Mansnerus does not unpack this general observation further to the level of the individual modeled stories, the values, beliefs, and power relations that they embody, and how exactly they do so.

In this paper, I suggest mathematical models as a specific origin for policy narratives. To examine the structure and content of policy-relevant model narratives, I employ an analytical tool developed by NPA scholars for the study of policy stories—the Narrative Policy Framework (NPF) (McBeth and Shanahan, 2004; McBeth et al., 2005; Jones and McBeth, 2010; Shanahan et al., 2011). The NPF helps accurately capture and describe policy narratives by identifying key compositional elements and providing guidance for their content analysis. The NPF can also be used to generate concrete, testable hypotheses about the influence of policy narratives on public opinion, policy change, and policy outcomes, but investigating the influence of model narratives on policy in general is the topic of a future study. In the present paper, I focus on laying the conceptual groundwork for applying an adapted version of the NPF to study policy-relevant model stories.

3.5 Framework for the analysis of policy-relevant model narratives

3.5.1 A brief word about theory

The philosophical paradigm underpinning the epistemological study of narratives as objects of inquiry in the social sciences is a post-positivist one (Kaplan, 1993; Dryzek, 1993; Shanahan et al., 2011; Jones and Radaelli, 2015), because such research is concerned with how people use language to express meaning and to make an argument in a specific historical context; it is not concerned with statements of objective, universal truths (Kaplan, 1993). The study of narratives in policy assumes that public policy problems have socially constructed elements. While the physical phenomenon climate change in itself is not a social construct, the *policy problem* climate change certainly is. Different definitions of the climate change policy problem—its causes, consequences, and remedies—are expressed through language, and they compete for influence on policy outcomes (Stone, 2012). Recognizing that policy problems are socially constructed also implies a deviation from the idea of rational instrumentalism, which says that good policy decisions are based on a value-free analysis that identifies the best means to a given end, because the end cannot be objectively determined—it depends on the definition of the problem (Dryzek, 1993, p. 214). Mathematical models are commonly considered tools for policy analysis that are of great appeal to the ideal of rational instrumentalism, because they are seen as ‘objective’, quantitative tools (Dryzek, 1993, p. 221). Yet if the narrative element intrinsic to IAMs performs at least part of the policy analysis, and if the story is at least partly independent from the model’s underlying scientific theory and mathematics, then the narrative analysis is yet another argument against the adequacy of rational instrumentalism—“objective” numerical results alone do not drive policy.

Narratives can be both an object and a method of analysis. The framework presented in this paper takes stories as its objects of analysis. It is concerned with “how stories are produced through social action and [how they] function in mediating action and constituting identities” (Ewick and Silbey, 1995, pp. 201–202). Its application assumes that people construct, organize, and communicate their understanding and sense-making of the world through stories (Polkinghorne, 1988; Jones and Song, 2014).

There are two broad perspectives on narrative analysis, an epistemological perspective and a political perspective (Ewick and Silbey, 1995, p. 199). The political perspective considers the study of narratives a political project, assuming that stories “have significant subversive or transformative potential” (ibid., p. 199). In contrast, the epistemological perspective suggests that the study of narratives conveys insights about aspects of the social world that would remain unseen by other methods of inquiry. The framework for analysis presented in this study primarily takes the latter perspective. The objective is to learn about the composition and content of modeled narratives to better understand how mathematical modeling can produce policy-relevant knowledge. However, the importance of such an epistemological analysis lies in the fact that these narratives can also have a political function.

3.5.2 Narrative composition

Morgan speaks of model narratives and of modeling as a form of narrative reasoning for three reasons (Morgan, 2001, p. 369). First, modeling has a temporal sequence: it starts with a question, continues with the manipulation of the model, and it ends with a new result. Model narratives trace these sequential steps. Secondly, these elements—question, changes in the model, and solution—are understood to stand in a causal relationship to each other. Thirdly, asking and answering questions about the world with the help of models requires interpretation. Through interpretation model users integrate and explain the changes happening in the model to form an argument about the world that is represented in the model.

A brief review of the literature on narratives in social research shows that Morgan's three characteristics are well in line with common definitions of narrative. Narratives are understood to have (at least) three necessary defining characteristics (Ewick and Silbey, 1995; May, 2002): (1) a narrative sets apart certain events and characters as elements of the narrative and exclude others; (2) a narrative orders the included episodes in a temporal structure, i.e. there is a beginning, a middle, a closure; (3) a narrative 'emplots' the temporal sequence of events within the narrative by making them into a coherent, meaningful, and causally conclusive whole.

Policy scholars provide a more detailed definition of the elements and qualities that define a policy narrative. Jones and McBeth (2010) suggest four central features: A policy narrative is a story that (1) is set in a particular context; (2) 'emplots' a temporal sequence of episodes in a coherent, meaningful, and causally conclusive way; (3) has three archetypal characters—heroes, villains, and victims; and (4) concludes with the moral of the story. In the following, I discuss each of these features—and adapt some of them—as they apply to policy-relevant model narratives.

External context and internal setting
For the analysis of modeled policy-relevant narratives, it is useful to distinguish between the external context in which the story is told and the internal setting of the story which is shaped by the model's mathematical structure.

First, it is important to consider the social and institutional context in which the policy-relevant models are used. Stories are always told "within particular historical, institutional, and interactional contexts that shape their telling, its meanings and effects" (Ewick and Silbey, 1995, p. 206). And people tell stories with a particular intention, interest, or purpose in mind. For stories to fulfill their purpose, they must comply with the social norms and conventions that govern the particular context they are told in (ibid., p. 207) The external context in which a narrative is told also shapes the audience's opportunities for engaging with the story by interrogating it or elaborating on it (ibid., p. 208).

Secondly, the model's mathematical structure shapes the internal setting of the stories one can tell with it. In the process of model development, modelers represent aspects of the relevant policy problem in mathematic equations, employing scientific theories and hypotheses. In doing so, Morgan (2001) points out, they link their theoretical and hypothetical knowledge about the world to the mathematical formulations of their models. When they use their models to tell stories about the world, these theories and hypotheses form an important part of the internal setting of these model stories. But of course, the internal setting of model stories is not completely and deterministically theory-driven. Modelers make numerous non-theoretical choices when developing a model, and these choices may be influenced by pragmatic considerations, technical considerations, personal interests, and modelers' worldview.[8] Moreover, modelers may interpret the existing theories differently or choose different specifications to express the same theoretical knowledge in mathematical equations—commonly, a number of different models exist of the same policy problem. Here also, the modelers' worldview, their values, and their beliefs are likely to influence their interpretation of the theory.

Plot

Model narratives do not merely describe the collection of mathematical equations that make up the model's structure, but they 'emplot' the process of manipulating that structure and putting the mathematical model resources to work in order to answer a specific question, providing that process with coherence and meaning. Mere lists of assumptions and definitions of model parameters, even if in text form, do not constitute a model narrative. Instead, narratives have a temporal structure; they have a beginning, a middle, and an end. The story begins with a question, a set of assumptions, and a particular set of model parameters. The story may then follow the temporal order of the steps in the modeling process or the calculation steps in the mathematical model, "tracing through effects of changing one thing in the model while holding others constant" (Morgan, 2001, p. 371). The story ends with a new solution and an answer to the initial question.

A narrative plot requires not only a series of temporally sequential events but also causal coherence between these events. The mathematical model exhibits causality as mathematical equations connect variables in a way that defines the direction of influence between them—from the independent to the dependent variable. The model narrative emplots these mathematical relations into the language of cause and effect, and it "also allows consideration of whether the links that occur are plausible ones" (Morgan, 2001, p. 372).

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[8] For a thorough discussion of the modeling process and the factors influencing modeling choices see articles #1 and #3 included in this dissertation.

Characters

Policy narratives typically involve three archetypal characters—a hero, a villain, and a victim (Stone, 2012). The hero is the protagonist of the story who fixes the problem that has been created by the villain and that harms the victim. The assignment of these archetypal roles in the story is indicative of the storyteller's political and ethical values (McBeth et al., 2005).

Moral of the story

Modeled narratives typically end on a normative note where they assign blame and responsibility, or they offer recommendations on whether, when, and how to respond to the modeled policy problem. The story links these model results to the world by assigning them a moral value and associating them with a call for action. The story's moral creates the most direct link between the model's internal workings and the policy world, making normative inferences from one about the other.

Narrative content

To a certain degree, the content of model stories is plastic, neither determined by scientific theory nor mathematics (Morgan, 2012). That is why one can tell different narratives with the same model, depending on which elements, assumptions, and outputs one chooses to emphasize. For example, who is the hero and who is the villain in the modeled story does not automatically follow from the models' mathematical structure, nor from the underlying theory, but it is partly a matter of the storyteller's beliefs and values regarding the problem at hand.

If the content of modeled narratives is so relative and variable, how can its analysis go beyond pure description and possibly even deliver generalizable results? The developers of the NPF argue that "meaning may be relative, [but] it is not random" (Jones et al., 2014, p. 21). They suggest that the content analysis of policy narratives should draw on established theoretical frameworks of relevant belief systems or ideologies to detect generalizable content and thus avoid relativism. For example, Jones and McBeth (2010) suggest cultural theory as a suitable framework; Jones et al. (2014) also list cultural cognition, materialism and postmaterialism, and moral psychology as appropriate options (p. 21).

3.6 An illustrative application: One model, four variations, four stories

3.6.1 Applying the analytical framework to IAMs

External context of IAM narratives

Where and how are IAM narratives told? Because IAMs exist at the intersection of science, policy, and politics, IAM stories may be produced by academics, policymakers, or interest groups. They may be documented and published in academic articles, books, policy support documents, newspaper articles or opinion pieces. Moreover, people may tell model narratives verbally in lectures, presentations, informal conversations, university courses etc. Each situation in which IAM narratives are produced and each form of publication has its own set of rules regarding narrative content and style. Within the scholarly literature (arguably the most common form of IAM story publication), the storytelling will be subject to specific disciplinary styles (McCloskey, 1990; Hyland, 2006) and the style requirements of the particular journal. More generally, to effectively produce an IAM narrative—possibly to challenge or elaborate on an existing narrative—one has to manipulate the model structure in order to alter the stories one can tell with it. This requires a certain level of expertise in order to not be considered uninformed and incoherent by the relevant community.

The motives and intentions behind IAM stories are certainly of an ambiguous nature. On the one hand, IAMs function as scientific devices, developed in the realms of scientific research to advance our understanding of the economic implications of climate change. On the other hand, it seems universally accepted that IAMs have a policy function, that their goal is to produce *policy-relevant* knowledge. In the past, integrated assessment modeling has informed policy processes at different levels of governance—international, national, and regional.[9] Therefore, is it reasonable to treat all IAM narratives as policy stories, no matter in what context they are told? The ambiguous function of IAMs—between scientific research and policy advisory—is further complicated by the fact that the current climate policy debate is highly controversial, political, and ideologically polarized. In that environment, how can any ostensibly scientific publication on climate change economics not be considered a contribution to this debate and not be 'politicized' to a certain degree? While I do not provide a complete answer to these questions, I address them again in the conclusion of this paper (Section 3.7). I do consider the policy purpose of IAMs a sufficient justification for treating them as a particular type of policy narrative.

Internal setting of IAM narratives

An IAM story's internal setting involves the assumptions underlying the theories and hypotheses of climate science and climate economics. For example, one very basic assumption about climate change policy underlying many IAM stories is that climate change is an issue that can and should be assessed with the help of cost-benefit analysis and that, consequently, cost efficiency has value. The cost-benefit dichotomy also provides a crude template for the structure of IAM narratives by defining a conflict (about the definition and valuation of these costs and benefits), assigning characters (the villains are those causing costs for the victims and the heroes are those minimizing the costs), and providing a crude general moral (minimize the net costs in order to achieve efficiency).

Another basic assumption that determines the setting of IAM narratives is the model's regional scope. Both climate science and climate economics characterize climate change as a global problem,

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[9] The Introduction to this dissertation offers a list of examples.

because GHG emissions have the same climate impacts no matter where they are produced, turning the atmosphere into a perfect example of a public good of global dimensions. A global model scope characterizes climate change as a global problem and puts the modeled story into a global setting. But climate change narratives are not necessarily global; they exist at all geographical scales and include local stories produced by communities about the weather, droughts, and floods (Daniels and Endfield, 2009).

Plot of IAM narratives

IAMs' mathematical equations define relationships between independent and dependent variables. The IAM story emplots this causal sequence—assumptions, calculations, outputs. For example, IAMs typically model carbon emissions as a function of economic activity, temperature change as a function of carbon emissions, and climate impacts as a function of temperature change. The most basic narrative explaining and interpreting these model equations is this: economic activity causes carbon emissions which lead to climate change, which at some point in time (note the internal temporal structure here!) results in damages to our economies.

Interestingly, in addition to the temporal structure that is imposed on IAM narratives by the dynamics at work in the model structure, IAM narratives also have an internal temporal structure: present and future climate change occurs due to past greenhouse gas emissions, and now is the time to make a decision about whether, when, and how to respond. Climate change is a long-term issue with significant time lags existing between carbon emissions and climate change impacts. Hence, IAM equations must include some treatment of time. For instance, an IAM may calculate outcomes at discrete time steps (e.g. of one, ten, or 50 years) into the future up to a certain time horizon.

Characters in IAM narratives

In IAM narratives, the roles of the villain, the hero, and the victim are not necessarily assigned by mathematics or by the underlying climate-economic theory. These roles may be assigned to, *inter alia*, governments of developed countries, governments of the developing countries, industry, past generations and future generations, capitalists and socialists, those who oppose action, and those who call for urgency. Even abstract concepts such as economic growth and technological progress may be either vilified as the cause of the problem or glorified as its solution.

Moral of IAM narratives

IAMs are scientific devices for advancing knowledge about climate change, but they also have the explicit purpose of generating policy-relevant knowledge. Their normative conclusions may concern the optimal stringency of emissions control measures, the optimal choice of policy instruments, or the optimal timing and trajectory of policy inventions over time. If not run as optimization models, IAMs can provide policy input through the comparison and evaluation of alternative policy proposals according to particular criteria, or they can be used to estimate the social cost of carbon.

Other morals of IAM narratives may include normative conclusions concerning future research and model development.

Content of IAM narratives

To discern the content of IAM narratives, I draw on the well-established typology of environmental worldviews by Clapp and Dauvergne (2011). The authors distinguish four perspectives on global environmental change: market liberal, institutionalist, bioenvironmentalist, and social green. Due to different values and interpretations, these four worldviews differ markedly regarding their beliefs about the causes of environmental degradation, its severity, its consequences for human and nonhuman life, and effective policy responses.

Clapp and Dauvergne emphasize that their typology is not complete and that its four categories are broad, each including a range of views with more subtle differences. The range of possible views on the environment is much wider, and any person likely holds beliefs that simultaneously reflect multiple of the four ideal types. Moreover, the authors argue, none of the four views should be considered 'correct.' The existence of numerous environmental worldviews "does not mean that there are no facts—or causality—or analysis—or statistics. [...] Rather it merely shows how different interpretations and different values [...] can shape which information an analyst chooses to *emphasize*" (italics in original) (Clapp and Dauvergne, 2011, p. 15). For example, model results showing that current global policies will fail to meet the 2°C target may be interpreted as catastrophic in one IAM narrative, and ignored in another because here, the storyteller believes that this target is arbitrary and meaningless. The typology is a helpful tool for illuminating some of these fundamental disagreements in values and interpretaions that underpin today's environmental controversy.

The following brief presentation of each worldview draws heavily on Table 1 in Clapp and Dauvergne (2011) (pp. 16-17).

Market liberals consider economic growth to be the most effective mechanism to address environmental degradation. They view economic growth as the best vehicle for achieving scientific progress, mitigating global poverty, and furthering technological innovation. Globalization and international trade are desirable as they foster economic development. Market failures may hinder economic growth and lead to pollution and inefficient resource use, but they are easily addressed through market-based policy instruments such as environmental taxation or payments for ecoservices. Any governmental interventions in the market beyond fixing market failures are not desirable as they would disturb the efficient interplay of supply and demand. According to this environmental worldview, there is no environmental crisis—on the contrary, we are on the path to green growth and sustainable development.

Institutionalists believe that strong institutions at all levels of governance are the most important weapon in the fight against environmental degradation. They hold that an environmental crisis is looming, but suggest that it can still be averted with the help of international cooperation and powerful environmental regimes. Economic growth, globalization, and international trade are not inherently harmful to the environment but they must be tightly controlled and regulated.

Bioenvironmentalists believe that the Earth's carrying capacity is finite and thus imposes absolute limits to human economic activity. Bioenvironmentalists also suggest that we have either already reached that limit or even crossed it and that the entailed environmental crisis puts the survival of human civilization at risk. Excessive economic growth, overpopulation, and overconsumption—exacerbated by globalization—are at the root of this crisis. As a solution, bioenvironmentalists propose to scale back economic activity and to show great respect for the value of non-human life. These steps may need to be forced on society by a coercive world government.

Social greens consider social injustice and global inequality the roots of environmental degradation. Large-scale industrialization and globalization have created a deep divide between the rich and the poor, the powerful and the powerless. The current environmental crisis, social greens argue, is the direct consequence of these historical processes. Hence, a solution requires the just distribution of power— away from global industries to local communities and marginalized groups.

3.6.2 Data sources and analysis

I apply the outlined framework to discern and analyze the narrative structure and content of four IAM stories. The four model structures that are used to tell these stories are all slightly altered versions of the same IAM framework, namely the DICE (Dynamic Integrated Climate Economy) model. DICE is a global model of the economics of climate change that can be used to determine the optimal path of carbon emissions reductions. DICE was first developed in the early 1990s by Yale economist William Nordhaus. Today, DICE is one of the best-known and most widely used aggregate cost-benefit IAMs.[10] The DICE model code is freely available online and thus the framework is frequently picked up and used by other modelers. The four model studies subject to this analysis are very recent examples of this practice. The producers of the four studies started their investigations from the standard DICE code, modified it based on their own assumptions, put in their own numerical values, and produced new model simulations. In other words, the modelers used the familiar structure of DICE, altered it, and used it to answer a new question and thus to tell a new story with it.

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[10] For example, DICE was one of the three models used by the US Environmental Protection Agency to calculate the official US estimate of the social cost of carbon for regulatory analysis in 2010 and 2013 (Interagency Working Group on Social Cost of Carbon, 2010, 2013). Despite its wide usage in academia and policy, the DICE model has been extensively criticized for its simplicity, its allegedly biased assumptions, and its perceived lack of reliability (see, for example, Kaufmann (1997); Pindyck (2013)). Furthermore, the introduction to this dissertation also offers an overview of common critiques of IAMs more generally.

The data sources for this analysis include, naturally, the four written publications where the new model stories are told, including three academic papers and one report published by a think tank (Dayaratna and Kreutzer, 2013; Dietz and Stern, 2015; Moore and Diaz, 2015; Dennig et al., 2015). To provide an overview of the standard DICE model framework and its standard narrative, I also draw on the official DICE manual (Nordhaus and Sztorc, 2013) and a few academic publications by the DICE developer Nordhaus (2007, 2012). These text sources were coded manually to detect first the model narratives' structural elements—their context and setting, plot, central characters, and moral—and then their content. For content analysis, I employ the typology of environmental worldviews developed by Clapp and Dauvergne (2011) as discussed earlier.

3.6.3 Results

The internal setting of the standard DICE narrative

Since the the standard DICE model is the starting point for the four model studies, and since all of the four models retain at least large parts of the original DICE code, the internal settings of these four stories are very similar to each other, and they are largely determined by the basic assumptions underpinning the standard DICE model. Here, I briefly review its key features; for a more comprehensive description see Nordhaus and Sztorc (2013).

The DICE model includes mathematical representation of the entire chain of climate-economy relations: the dependence of GHG emissions on economic activity, the dependence of climate change on GHG emissions, and the dependence of losses in social welfare on climate change.

The DICE model contains assumptions about "preferences and an objective function" (p. 6), "economic variables" (p. 8), and "geophysical sectors" (p. 15) (Nordhaus and Sztorc, 2013). The geophysical sectors in DICE include representations of the carbon cycle, radiative forcing, and climate change; this is a simplified version of the complex models used by climate scientists.

The economic variables in DICE are based on neoclassical theory of economic growth; the climate system is introduced as a specific form of natural capital. The causal chain is modeled as follows. Economic production requires energy as an input (in addition to capital and labor), and a part of the energy supply comes from fossil fuel sources. Producing energy from fossil fuels causes CO_2 emissions, which lead to rising temperatures. Warming causes damages, which reduce current economic output. These damages are modeled as a quadratic function of temperature change. An upward adjustment is made to also account for those impacts that are not monetized. But thresholds and tipping points are not considered in DICE.

In DICE, the main driver of economic growth is exogenous technological progress that increases the productivity of capital, labor, and non-fossil energy. Technical change also diminishes the carbon intensity of economic production—even in the absence of (additional) carbon mitigation policy. Total emissions from fossil fuel resources are capped in DICE, because of finite fossil fuel resources.

Investment in abatement activities can further reduce emissions from economic activity, but the cost of emissions abatement also curtails current economic output. Similar to investment in capital goods, the investment in the abatement of carbon emissions reduces consumption today, with a view to reaping the benefits of avoided damages from climate change in the future. The stringency of climate policy, i.e. the emissions-reduction rate, is the control variable in the various model experiments.

The objective function in DICE is the social welfare function. In the optimization experiment, the model determines the level of climate policy—or more precisely, the level of investment in emissions abatement—that "optimize[s] the flow of consumption over time" (Nordhaus and Sztorc, 2013, p. 7) to maximize social welfare. The carbon price that realizes this optimal emissions trajectory equals the marginal cost of carbon emissions, which is the social cost of carbon (SCC).

Social welfare is "the discounted sum of the population-weighted utility of per-capita consumption" (Nordhaus, 2012, p. 276), where consumption is assumed to include market goods such as food and housing, but also non-market amenities such as leisure, health, and environmental quality (Nordhaus and Sztorc, 2013, p. 7). Utility is a function of per capita consumption and a parameter α that is interpreted as "generational inequality aversion" (Nordhaus, 2012, pp. 276–277). The higher the value of α, the greater is the preference for smoothing consumption equally across generations. The discount factor is determined by the pure rate of social time preference, ρ, "which provides the welfare weights on the utilities of different generations" (Nordhaus and Sztorc, 2013, p. 8). These preferences, inequality aversion and pure rate of social time preference, are assumed to be exogenous and fixed.

These basic assumptions underpinning the DICE model restrict and shape the climate policy stories one can tell with it; they define the stories' internal setting. Again, since all four variations to the DICE model discussed in the following retain large parts of the DICE model code and thus many of these assumptions, I discuss here how the internal setting determined by these assumptions shapes the model stories.

The internal setting of the standard DICE narrative, as it is constituted by the basic assumptions outlined above, constructs important features of the climate change policy problem. These constructs are well-aligned with the market liberal environmental worldview for the reasons I outline in the following. This is not surprising: market liberals typically conceptualize the relationship between the economy and the environment following the logic of neoclassical economics, which is also the conceptual framework underlying the DICE model. They assume that environmental degradation is caused by adverse externalities, which cause market failures, which are best addressed by market-based solutions, i.e by pricing the externality. In line with the market liberal perspective, environmental economists consider market forces the most powerful tool for protecting the environment; the government's task is merely to set up the conditions for a functioning market by eliminating market failure.

The internal setting of the standard DICE narrative focuses on markets. The DICE philosophy is based on trust in competitive markets as the best mechanism for efficiently allocating scarce resources. For example, in the standard DICE model, both α and ρ are calibrated with reference to the interest rates and rates of return observed in the financial market. These parameters are often called 'ethical parameters' because their values express a particular perspective on intergenerational justice (for a comprehensive discussion of discounting in climate economics, see the exchange between Roemer (2011, 2013) and Dasgupta (2011)). The descriptive approach to determining the values of these ethical parameters reflects the belief that the financial markets correctly represent people's preferences about the allocation of resources over time. Another example of the market-based philosophy underpinning DICE is the treatment of finite fossil fuel resources. Markets are assumed to efficiently allocate the finite resources over time, so that, in the current version of DICE, the resource constraint is never binding (Nordhaus and Sztorc, 2013, p. 14). According to the market liberal worldview, any concerns about absolute, natural limits to economic activity appear futile: prices would always balance supply and demand. This perspective is contrary to the view of bioenvironmentalists and social greens, for whom the finite exhaustion of non-renewable resources and the Earth's carrying capacity puts absolute limits on human economic activity.

Adopting a market-centered approach the DICE framework explicitly rejects the notion of model outcomes "as the recommendations of a central planner, a world environmental agency, or a disinterested observer incorporating a social welfare function" (Nordhaus and Sztorc, 2013, p. 21). Instead, the purpose of DICE is descriptive—the model framework is meant to portray what can actually be observed in the economy. Since markets are, by default, assumed to function properly, the model's optimization algorithm should be understood as a simulation of the optimization processes performed by competitive markets—not as a normative judgment imposed from outside (ibid., pp. 21–22). While specific market failures such as externalities and spillover effects are considered to require government intervention, the philosophy of DICE is to "project from a positive perspective the levels and growth of major economic and environmental variables" (ibid., p. 8), without "judging the social desirability of existing conditions" (ibid.). This positive perspective adopted in DICE, which considers a judgment of existing conditions of the economy and environment beyond the models' scope, is starkly different from the social greens' view that environmental problems such as climate change are ultimately rooted in social injustice and global inequity and that environmental problems cannot be solved without tackling injustice and inequity first. For example, the standard version of DICE does not take into account the allocation of historical responsibility for carbon emissions among regions. Similarly, DICE's positive perspective allows no moral judgment in terms of *over*consumption or *over*population, which are standard terms in the vocabulary of bioenvironmentalists. For instance, in DICE, no distinction is made between luxury emissions from developed countries and subsistence emissions that are necessary for people in poor countries to sustain their livelihood (a distinction made by Shue (2010) and others).

Also in line with the framework's positive perspective, economic growth is not per se seen as the source of environmental degradation. Economic production enables consumption, which generates utility and thus contributes to social welfare, which is to be maximized. Therefore, once externalities are accounted for, in the optimal policy scenario produced with the standard DICE framework economic production continues to expand (Nordhaus and Sztorc, 2013, p. 25-26). However, the framework equations do not explicitly imply that economic growth works to alleviate environmental degradation either—an assumption that is core to the market liberal worldview. Specifically, in DICE, economic growth is not explicitly modeled to be a driver of technological progress (which is assumed to be exogenous) or adaptation capacity—in fact, adaptation to climate change is not explicitly considered in the model at all.

The gro-DICE narrative

The external context

This narrative was produced by two researchers affiliated with Stanford University and published in the journal *Nature Climate Change* (Moore and Diaz, 2015). The article contributes to a growing debate among climate economists about the impacts of climate and climate change on economies' long-term growth trajectories (see, for example, Hope and Hope (2013); Krakauer (2014); Hof (2015); Burke et al. (2015)).

The question

The questions that Moore and Diaz (2015) address are: How do optimal climate policy recommendations generated with DICE change if one takes into account the possibility that climate change may not only reduce economic output at the time they occur, but may lower economic growth more permanently? And how do such growth impacts affect poor and rich countries differently?

The internal setting

The authors implement a few changes to the structure of the standard DICE model structure to answer this question. They call the new model variation "gro-DICE." First, the authors disaggregate the global DICE model into two regions—poor countries and rich countries. Second, the authors modify the damage function so that temperature increases permanently affect economic growth rates via two alternative mechanisms: hotter temperatures reduce the productivity of labor and capital, and more frequent extreme weather events expedite the depreciation of the economy's capital stock. The parameters that are used to calibrate the new damage function are drawn from the empirical study by Dell et al. (2012).

The plot

The structural model changes introduced in gro-DICE allow for telling a more complex narrative that also includes a distinction between poor and rich regions as different story characters, and a conflict between two objectives—decarbonization and economic development.

The gro-DICE narrative identifies more substantial economic impacts of climate change than those identified with the standard DICE, because even small impacts on the economic growth rate are compounded over time. This effect exists although the gro-DICE narrative assumes a high capacity for adaptation, so that the permanent effects of climate change on economic growth are zero, and impacts decline at a constant rate in the short run. The SCC estimates resulting from gro-DICE are several times higher than those generated with the regular DICE. These larger projected damages justify more stringent mitigation efforts. In the gro-DICE narrative, the optimal climate policy results in the stabilization of global temperature change below 2 °C above the preindustrial level, which is, of course, commonly understood to be the threshold for dangerous climate change[11]. Regarding the timing of optimal mitigation, the gro-DICE narrative suggests that optimal climate policy may include drastic near term mitigation to slow climate change.

The victims of climate change in the gro-DICE story are the people living in poor regions. The numerical model indicates that poor countries are hit much harder by climate change impacts on economic growth, whereas people in rich regions are only modestly affected by the changes in gro-DICE. Rich countries even see a slight economic benefit from a warming climate.

The gro-DICE narrative offers two possible explanations for why climate change slows economic growth more substantially in poor regions than in rich regions. First, there is a temperature effect wherer poorer regions tend to be hotter to start with and are thus more likely to cross "biophysical temperature thresholds, beyond which warming becomes particularly damaging" (Moore and Diaz, 2015, p. 2). Second, there is a resilience effect because poorer regions tend to be less resilient to climate change, and are thus hit harder. Both effects "could explain the different sensitivities of rich and poor countries to higher temperatures observed today [but] they have contrasting implications for how climate damages might evolve over time and for optimal climate policy" (ibid.).

Over time, assuming a dynamic relationship between economic growth and temperature change, the two alternative explanations tell different stories.[12] The narrative modeled with this dynamic version of gro-DICE differs depending on which of the effects is assumed to dominate. The modelers

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[11] This definition of dangerous climate change is included in Article 2 of the United Nations Framework Convention on Climate Change from 1992. For a detailed discussion of this target's history see Randalls (2010).

[12] Naturally, they also entail different mathematical equations. For modeling the temperature effect, the growth-rate damage parameters are a function of economic growth. For modeling the resilience effect, the growth-rate damage parameters are modeled to be a function of temperature change.

therefore build both these dynamic versions of gro-DICE and tell two alternative subplots. The temperature effect implies that rich countries become more sensitive to the impacts of climate change over time as temperatures increase. Over time, the temperature effect always favors a small increase in decarbonization efforts as compared to the version of gro-DICE with a static damage function. In contrast, the resilience effect implies that poor countries become more resilient to the impacts of climate change over time with as GDP increases. This effect has an ambiguous effect on the optimal mitigation trajectory over time. While strong decarbonization is optimal in the near term to slow the rate of climate change, in the long run, strong decarbonization will slow the rate of economic growth in poor regions which will also limit their resilience.

The characters

While the victims in the gro-DICE narrative are always the people living in poorer regions, strong near-term decarbonization is not the unambiguous hero in the gro-DICE plot. The resilience effect shows that economic growth (the source of emissions) can also contribute to fixing the problem because development increases the resilience to climate change in poor countries. In fact, the central conflict in the gro-DICE narrative is the trade-off between the benefits of decarbonization in the form of avoided climate change damages and the costs of decarbonization in the form of slowed increase of resilience. Importantly, this conflict is not fully resolved—the gro-DICE model structure does not provide the necessary resources to this part of the plot. The narrative here interprets its own plausibility: "[...] the results regarding very rapid, near-term mitigation should not be over-interpreted as evidence that such a policy would necessarily be economically optimal" (Moore and Diaz, 2015, p. 3). A different version of gro-DICE that includes explicit modeling of the full effects of tight emission controls on mitigation costs and their own "persistent impacts on economic growth" (ibid.) may produce a different narrative where a more cautious decarbonisation course is found to be optimal.

The moral

The moral of the gro-DICE narrative is two-fold. First, accounting for the impacts of climate change on economic growth over time as opposed to current economic output generally justifies more stringent mitigation policies. Second, further research should be performed to remove the remaining uncertainties, in particular, those pertaining to the dynamic interaction between damages and GDP and the degree to which countries become more resilient to climate change impacts as they develop.

Content analysis

The gro-DICE narrative combines elements of multiple environmental worldviews. In important aspects the narrative expresses market liberals' values and beliefs. For example, economic growth is portrayed as a (partial) solution to the climate change problem—more explicitly so than in the standard DICE narrative. The absence of truly permanent climate impacts is explicitly justified by human capacities for adaptation. In the subplot where the resiliency effect dominates, there is the explicit assumption that economic development reduces vulnerability toward climate change damages. But implicitly, the way in which damages are modeled in standard DICE assumes perfect adaptation from one time period to another. The optimism of market liberals is still present in gro-DICE.

But the gro-DICE narrative also expresses core beliefs of the institutionalists' worldview. In particular, the modified assumptions in gro-DICE about the ways in which climate change hurts the economy also shift the narrative to incorporate a more urgent perception of a looming crisis and thus an increased need for government intervention in the form of rapid decarbonisation—despite the optimistic assumptions about adaptation. Moreover, the reference to the 2 °C target, the definition of dangerous climate change according to the UN Framework Convention on Climate Change, as a valuable goal for climate policy validates these international climate governance institutions.

Finally, the introduction of two regions based on the status of economic development—regional disaggregation could instead have been based other criteria—enable the model to tell a story about the substantially different impacts of climate change on poor and rich regions. This distinction introduces a notion of injustice: it is the poor regions in particular that suffer from the impacts of climate change on economic growth. They are more reliant on economic development and at the same time less well prepared to adapt to climate change. This aspect of gro-DICE reflects a core commitment of the social greens: that climate change is fundamentally a problem of injustice.

The NICE narrative

The external context

This IAM story was published as an academic article in the U.S. *Proceedings of the National Academy of Sciences* (Dennig et al., 2015). The modelers are all researchers at Princeton University.

This model study explicitly responds to a common perception in the literature that issues related to intergenerational justice are the most controversial ethical conflict in climate change economics. Previous IAM narratives have strongly focused on the value of the discount rate as both a key driver of model results as well as the models' most important ethical parameter. In IAMs, the discount rate is used to calculate the present value of climate damages harming people living in the future.[13] Dennig et al. (2015) provide an alternative viewpoint, arguing that intra-generational justice issues arising from the unequal distribution of climate change damages among members of

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[13] See the debate in the literature following the publication of the Stern Report in 2007, which took a new approach to determining the discount rate and altered the discourse around discounting and climate justice (Stern, 2007; Nordhaus, 2007; Weitzman, 2007; Tol and Yohe, 2009). The ethical consequences of the discount rate value are also explained in article #1 of this dissertation.

the *same* generation may be equally important in both respects.

To make this point, the modelers of this narrative use a regional version of the standard DICE framework, the Regional Integrated model of Climate and the Economy (RICE). The RICE model was first developed in 1996 by economists William Nordhaus and Zili Yang. RICE divides the globe into 12 regions, and models economic output, population, emissions, damages, and abatement at the regional level (Nordhaus and Yang, 1996). The structure of DICE and RICE are mostly analogous, except for that in RICE, each region optimizes its own social welfare function (Nordhaus and Sztorc, 2013). Essentially, the DICE framework is a globally aggregated version of RICE.

The question

The question standing at the beginning of this model narrative is: How do the optimal mitigation efforts produced with the standard RICE model change if proper accounting for subregional inequalities is incorporated in the model?

The internal setting

To answer the posed question, the authors split each of RICE's 12 regions into population quintiles based on income. In its standard version, RICE, like other IAMs, considers inequity between different generations of people via the discount rate. In addition, multi-region models such as RICE explicitly model the distribution of income and climate damages between regions. But commonly in IAMs, the income differences between people living in the same region are averaged.

The damages from climate change experienced by the different income groups depends on the newly introduced income elasticity of damage ξ. If ξ equals 0, the distribution of climate change damages is independent of income; if ξ equals 1, the distribution of climate change damages is proportional to income; if ξ equals -1, the distribution of climate change is inversely proportional to income. The authors explore only these extreme cases and do not provide an empirical estimate for ξ. A separate parameter η measures the aversion to inequality in consumption. The greater η, the greater is the loss in utility due to unequal distribution of consumption across time, as well as between and within regions. The authors leave the value of η that is assumed in RICE unchanged. They emphasize that this does not mean they approve of this assumption, but rather that this is a method to neatly isolate the effects of subregional income disaggregation on model outputs.

Other modifications of the standard RICE model are intentionally kept to a minimum, in order to strengthen the main plot line of the story by isolating the effects of the newly introduced subregional disaggregation by income. Smaller modifications include a translation of RICE from an EXCEL spreadsheet to a model version written in the programming language MATLAB, as well as changes to the assumptions on the savings rate and the modeling of sea-level rise. It is argued that these model modifications are introduced mainly for pragmatic reasons. Dennig and colleagues call this modified RICE model NICE, for Nested Inequalities Climate Economy model.

The plot

The plot of the NICE story can be summarized as follows. There are good arguments to believe that poor members of society suffer most from climate change. If that is the case, then averaging losses in utility due to climate change across income groups—a common practice in IAMs—leads to misguided climate policy recommendations, because "much of the poverty associated with high levels of vulnerability [to climate change] is masked" (Dennig et al., 2015, p. 15827). Therefore, the consequences of climate change for those who are most disadvantaged already are largely ignored. Instead, the resulting policy recommendations largely represent the needs of more affluent members of society who remain relatively unaffected by climate change damages; hence, they have relatively weak preferences for sacrificing consumption to invest in mitigation. But in the plot of this NICE narrative, this practice is neither just nor sustainable. It is not just to make policy decisions solely based on the benefits to the affluent without taking into consideration the harm inflicted on the poor by these decisions (Dennig et al., 2015, p. 15830). Neither is it sustainable to make policy decisions without the explicit acknowledgement of subregional inequity, because these policies will not guarantee that future generations of the most disadvantaged people will be able to sustain "their predecessors' level of living standards" (Dennig et al., 2015, p. 15830). That is why the distribution of climate change damages on income groups within regions matters for the optimal mitigation policy. The more the distribution of climate change damages is skewed toward poor members of society (i.e. the closer ξ is to -1), the more stringent mitigation efforts are justified. The reason is that if climate change indeed hits poor groups disproportionally hard, the overall level of inequality increases due to climate change, which reduces social welfare due to people's aversion to inequality in consumption (parametrized by η).

The NICE narrative has two sub-plots. First, the modelers suggest that their argument is reversed if future research shows that the distribution of mitigation costs across income groups is equally skewed towards the poor. Such a skewed distribution of mitigation costs would lower optimal mitigation efforts. The question motivating this subplot ('how would results change if proper accounting for subregional distribution of mitigation costs is incorporated?') is not explored using the NICE structure but only developed verbally, to conditionalize the current narrative. In this version of NICE, it is assumed that different population groups bear shares of mitigation costs proportionally to their income.

A second subplot concerns the possibility of using transfer payments to balance the uneven distribution of damages. The authors acknowledge that such transfers are the first-best solution according to economic theory. Still, they are not part of the NICE narrative, because the authors consider them politically unfeasible, and thus an implausible narrative. Here, narrative logic trumps deductive logic: the authors value the plausibility of the narrative higher than the accurate representation of economic theory. In the standard runs with NICE, any distributive transfers between regions and between different income groups within one region are deliberately excluded. But to investigate the transfer option, the authors introduce a slightly altered version of NICE that includes a “revenue-neutral constant-proportion ‘flat’ tax on the postdamage consumption levels” and assume that the “tax revenue is distributed equally, as a lump-sum basic income” (Dennig et al., 2015, p. 15830). Results indicate that, if such transfers were implemented, “the amount of redistribution that makes the usual RICE results an acceptable simplification would be very high indeed” (ibid.). Consequently, redistributive policy cannot replace stronger mitigation policy (ibid.). In other words, this new subplot produced with another, slightly altered version of NICE supports the moral of the overarching narrative.

The characters

In the NICE narrative, the victims of climate change include both the current and future poor, who need more stringent mitigation efforts (the hero) to prevent their per capita consumption from declining in the future. The central conflict underlying the NICE narrative concerns tension between the poor and the rich. These two groups within society are differently affected by climate change and therefore have differing preferences regarding mitigation policies. The common modeling practice of averaging economic variables across income groups within model regions ignores the needs of the poor, which is neither fair nor sustainable. The model innovations introduced in NICE somewhat alleviate this tension: by explicitly accounting for the distributional impacts of climate change damages in the social welfare function that is to be maximized, the achievement of economic efficiency is now dependent on the achievement of distributional fairness.

The moral

The moral of the NICE story is that the subregional distribution of climate change damages matters for optimal mitigation policy: assuming that poor people are disproportionally burdened by climate change, more stringent emissions control is justified by subregional inequality. Therefore, if we value justice and sustainability, the model innovations introduced in NICE, the authors argue, “should become new best practices in cost-benefit IAMs” (Dennig et al., 2015, p. 15830). Moreover, they conclude that future research is necessary to fully specify the distribution of mitigation costs across income groups in NICE.

Content analysis

The NICE narrative challenges the belief of market liberals that economic growth will ultimately benefit everyone and also help the environment. The NICE model narrative explicitly challenges this assumption, using the model’s mathematical resources to argue that even if the average per capita consumption is projected to continue to rise in a future with climate change, for poor people, consumption may indeed fall. While more affluent groups (today) benefit from economic growth, the least affluent groups (in the future) will suffer most from its environmental costs. The NICE narrative also introduces a more differentiated definition of the victims of climate change: it is “a common observation” (Dennig et al., 2015, p. 15827) that the most disadvantaged members of society, today and in the future, may also be the ones burdened with the bulk of its entailed environmental costs because “poorer people are more vulnerable” (ibid.).

Addressing these inequities, the NICE narrative introduces two additional objectives of climate policy—justice and sustainability—in addition to the standard utilitarian framework. The concept of justice requires “that (current) benefits to the affluent should not stem from activities that harm the (future) poor” (Dennig et al., 2015, p. 15830). Sustainability requires “that future generations be able to sustain their predecessors’ level of living standards, not only on average but also in the most disadvantaged groups” (ibid.). The value that is placed in the NICE narrative on achieving justice and sustainability is typically associated with the social green and bioenvironmentalist worldviews respectively. But social greens also consider inequity as the root cause of all environmental problems and the NICE narrative does not contain language to that effect. Hence, the NICE narrative only incorporates one direction of causality (from environmental degradation to poverty) in what the social greens identify as a positive feedback loop. Similarly, the sustainability concept promoted by bioenvironmentalists takes into account the value of the environment independent of human utility, but the NICE narrative only considers environmental sustainability to the extent that it helps maintain high and growing living standards.

The extended DICE narrative

The external context
This model study (Dietz and Stern, 2015) was published as a peer reviewed article in *The Economic Journal*. The authors are researchers at Grantham Research Institute on Climate Change and the Environment at the London School of Economics.

The authors produced this model study to respond to the perception that for global climate policy to be economically efficient it inherently must be modest and slowly phased in. This is exactly the moral of many of the stories told with the standard DICE model: that optimal emissions control should take the shape of a “climate policy ramp” (Nordhaus, 2007, p. 687), slowly tightening over time and allowing rapid economic growth to continue. In the standard DICE narrative, more rapid or stringent mitigation actions (for example, to keep within the 2 °C limit) would cause undue economic costs (Nordhaus and Sztorc, 2013).[14] Dietz and Stern (2015) set out to demonstrate that the story they tell using their version of the DICE model deviates from that narrative.

The question
The initiating question is: “[...] can the [DICE] framework support strong controls on emissions, if restrictive assumptions about growth, damage and climate risk are relaxed?” (Dietz and Stern, 2015,

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[14] In the standard DICE optimal policy scenario, global average temperature increases peak at 3.3°C in 2150, and industrial emissions continue to rise until around 2050 (Nordhaus and Sztorc, 2013).

p. 577) These restrictive assumptions, the modelers claim, “arguably lead to gross underestimation of the benefits of emissions reductions in DICE and other IAMs” (ibid.).

The internal setting

To build the model resources in DICE necessary for answering this question, the modelers modify three modeling assumptions in the standard DICE. Because they suggest two alternative approaches for each assumption, these modifications generate a large number of “extended DICE” models to compare with the standard DICE model.

First, they introduce two alternative models to incorporate permanent impacts of climate change on economic growth. The standard version of DICE only allows climate change to affect current economic output, which, the modelers argue, entails “a very narrow story of how climate change impacts on [economic] growth” (Dietz and Stern, 2015, p. 579). Instead, they argue, there are “compelling reasons” (ibid., p. 578) for assuming that climate change affects long-term growth; there is also new empirical evidence (Dell et al., 2012). To expand the scope of DICE’s narrative about the economic consequences of climate change, the modelers first implement a model of endogenous growth that considers learning effects as the crucial driver of economic development. The accumulation of capital stock is assumed to entail economy-wide learning effects, which increase factor productivity. The modelers then consider two alternative pathways through which climate change may affect economic growth in addition to its direct impacts on current economic output. The first pathway is that climate change directly impacts the size of the economy’s capital stock. The second pathway is that climate change permanently reduces the productivity of capital and labor. In both cases, climate change reduces the growth of capital accumulation and therefore affects the economy’s accumulated knowledge stock—the source of long-term economic growth.

Secondly, the modelers change the shape of the damage function in the standard DICE model to account for the potentially very large economic costs associated with more extreme temperature changes. They argue that new scientific insights—for example, regarding tipping points in the climate system—makes a more convex damage function for higher temperature changes plausible. Specifically, the modelers consider two alternative calibrations of the new damage function. The first calibration assumes that 50 percent of global economic output is lost if global average temperature increases above preindustrial levels by 6°C. The second, alternative calibration presumes that these damages occur instead at a temperature increase of only 4°C. This is termed the “high damage function.” The modelers argue that the assumptions underpinning the high damage function “may be no less plausible, to put it cautiously,” than the assumption underpinning the standard DICE damage function, which is “that [...] only 4 percent of output is lost as a result of temperatures not seen for 10 million plus years” (Dietz and Stern, 2015, p. 582). The damages determined using the extended damage function are partitioned between impacts on current output, the size of capital stock, and impacts on factor productivity.

Finally, the extended DICE models incorporate a new treatment of the climate risks that are related to the persistent uncertainties in our knowledge about the physical climate system. The standard DICE model and many other IAMs assume a single, best guess value for the climate sensitivity parameter S, but the extended DICE modelers explicitly model the uncertainty about the values of S. First, the modelers perform a sensitivity analysis including the value that the latest IPCC report considers very unlikely to be exceeded (6°C). Alternatively, they also assume a probability density function for S to enable stochastic modeling. They choose a log-logistic function because this function best fits the results from the sensitivity analysis. The log-logistic function has a medium 'fat tail', which means that very high values for S in the upper tail of the distribution have a low (but non-zero) likelihood of occurring.

The plot

The modelers run the extended DICE models numerous times, with different combinations of the alternative formulations for growth impacts, damage size, and climate sensitivity. Each of these model runs tells a different story about business-as-usual emissions, climate change, consumption losses, and the optimal policy response. The overarching narrative emerging from this multitude of stories is that the three extensions to the standard DICE model (no matter which alternative implementations are chosen) always lead to greater damages in the business-as-usual scenarios compared to the standard DICE model, and therefore also to more stringent optimal climate policies. In some of the extended models, rapid and stringent mitigation policies are optimal.

The overarching extended DICE narrative explains how the three newly introduced model modifications interact, so that "[o]verall, the scale of the risks from unmanaged climate change in this modeling framework is the convolution of these three extensions" (Dietz and Stern, 2015, p. 590). Modeling climate change to impact economic growth means that sufficiently temperature changes will induce a negative, self-regulating feedback loop: the economy stops growing due to the negative consequences of economic growth. This diminishing-growth scenario is more likely in the extended DICE because of the more convex climate damage function, which implies a loss of 50 percent of global economic output at a high temperature change. Such higher temperature changes are more likely in the extended DICE models, because they incorporate greater uncertainty about climate sensitivity and allow for higher values for that crucial parameter.

The characters

The villain in the extended DICE narrative is inertia in model development: despite improved understanding of climate-society interactions and of the associated uncertainties and risks, the relatively simple and deterministic standard DICE model has not yet been sufficiently adapted over the past 25 years.[15] The central conflict addressed in this narrative concerns the tension

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[15] This notion of inertia in model evolution over time and its causes are examined in Section 7 of article #1 of this dissertation.

between the “unrealistic” (Dietz and Stern, 2015, p. 590) assumptions underlying the DICE model and other standard IAMs and the new insights on climate change impacts, damages, and risks that allow for “relaxing” (ibid.) these assumptions. While DICE and other IAMs, over their long history, have gained authority both in policymaking and in academic research, it is now necessary to reform the models by “relaxing assumptions that have limited plausibility and possible large effects on policy conclusions” (ibid., p. 591). Uncertainty is still a crucial problem, the authors concede, but they argue that the new modeling assumptions and inputs they introduce to the extended DICE models are no less plausible than those underlying the standard DICE model. The authors are convinced that such future work, which “will need to go well beyond the choice of parameter values to consider new model structures” (ibid.), will deliver “still stronger” arguments for “strong action” (ibid., p. 592).

The moral

One moral of the overarching narrative is that optimal global carbon prices “should be in the range \$32–103/tCO_2 (2012) prices in 2015” and “should rise in real terms to \$82–260/tCO_2” within two decades (Dietz and Stern, 2015, p. 591). The “in-built assumptions” of standard DICE model “result in gross underassessment of the overall scale of the risks from unmanaged climate change” and therefore, new model extensions—going even beyond what is presented in this study—are necessary to arrive at policy recommendations that better reflect the true climate risks (ibid., p. 590). Another moral is that “[o]ne cannot and should not expect a single model to capture all relevant issues and neither should we be able to resolve all difficulties within a single framework” (ibid., p. 592). Therefore, “expanding” DICE to incorporate “different perspectives” will enhance its usefulness by providing “arguments for strong action [that] will look still stronger” (ibid.).

Content analysis

The market liberal worldview that is expressed in the standard DICE narrative is altered in important ways in the extended DICE narrative produced by Dietz and Stern. The three assumptions that are relaxed in this model study challenge some of the market liberals’ core beliefs: that economic growth is key to alleviating environmental problems, that the continuation of economic growth is secured by technological progress and human ingenuity, and that precautionary action due to uncertainty about climate change is undesirable.

The market liberal worldview suggests that environmental externalities are generally limited in scope, requiring modest government intervention. The standard DICE narrative confirms this belief. But in many of the stories told with the extended DICE model, per capita consumption starts declining because of the severe damages caused by climate change. These stories portray climate change as a serious, possibly catastrophic threat to human welfare in the near and far future. They suggest an urgent need to introduce “strong and strongly increasing” (Dietz and Stern, 2015, p. 591) emissions control.

These stories do not share market liberals' optimism. Rather, they adopt the perception of a looming crisis common among bioenvironmentalists and social greens. The overarching extended DICE narrative recognizes pervasive uncertainty about the physical and economic aspects of climate change, but argues in favor of a somewhat more precautionary approach. The concern about uncertainty and risk is reflected in the general observation that two alternative specifications are implemented for each of the three model changes, resulting in a plethora of possible stories. More specifically, the standard DICE model is extended to incorporate the "explicit and large climate risks" (Dietz and Stern, 2015, p. 578) that are associated with the lack of understanding of climate sensitivity. While most climate economy models ignore the uncertainty surrounding this crucial parameter and assume a best guess value for the parameter, the extended DICE models deliberately take into account that the climate may react more strongly to higher CO_2 concentrations in the atmosphere than previously deemed likely. In the absence of empirical evidence that would clearly constrain the choices of parameter values, the extended DICE narrative errs on the side of overestimating risk. The results from the extended DICE models with stochastic modeling of climate sensitivity are identified as "headline results", because "this exercise constitutes a fuller specification of climate risk" (ibid., p. 588).

Nevertheless, many issues that are core to the worldview of bioenvironmentalists and social greens are excluded from the extended DICE stories. The stories do not explicitly address issues related to inequity or to the institutional implementation of a global carbon price. The stories also do not address issues related to climate change impacts on non-human life. The benefits of economic growth are not fundamentally questioned in the overarching narrative—in fact, the objective in the extended DICE models is still to maximize economic growth. Neither is the general use of neoclassical economics questioned as a valid methodology for producing policy-relevant information—the introduction a global carbon tax set to the level of marginal abatement costs is still considered the optimal policy intervention.

The Heritage Foundation DICE narrative

The external context

The external context of this DICE narrative (Dayaratna and Kreutzer, 2013) gives important indications of its purpose, which in turn provides cues for the analysis of its structure and content. This DICE narrative was told in a report published by the Heritage Foundation, a conservative, U.S.-based public policy research organization. The Foundation's mission is to promote policies that are based "on the principles of free enterprise, limited government, individual freedom, traditional American values, and a strong national defense" (The Heritage Foundation, 2016). Hence, the purpose of this DICE narrative, one can fairly assume, is to function as a political instrument. The intention of telling this DICE narrative is then to support the Foundation's political mission. In particular, (Dayaratna and Kreutzer, 2013) was published in response to the release of the updated

U.S. government estimates of the social cost of carbon in summer 2013. The U.S. Environmental Protection Agency (EPA) used three IAMs, including DICE, to estimate the SCC. Dayaratna and Kreutzer (2013) start out with the standard DICE model, assuming the same set of parameter values and model inputs assumed by the EPA.[16]

The question

The question that initiates this model application is: What SCC values will the EPA DICE model deliver if a few “serious deficiencies” (Dayaratna and Kreutzer, 2013, p. 1) of the model are fixed?

The internal setting

To answer this question, the modelers alter assumptions for three model inputs that they perceive inadequate in the EPA runs: the discount rate, the equilibrium climate sensitivity distribution, and the model’s time horizon. First, the modelers produce a model run with a 7 percent discount rate, arguing that this is the rate that more accurately describes people’s behavior and preferences as reflected in “interest rates on loans and investments” (Dayaratna and Kreutzer, 2013, p. 2). The discount rates used by the EPA, the modelers argue, are too low to reflect people’s preferences, and they are therefore of a prescriptive rather than a descriptive nature. They also suggest that the 7 percent discount rate corresponds to the upper bound of the range of discount rates that the Office of Management and Budget stipulates for use by government agencies. Next, the modelers introduce a modified climate sensitivity distribution, arguing that the distribution used by the EPA was out of date. In the next model run, the modelers shorten the model’s time horizon from 2300 to 2150, arguing that no government policy should be based on forecasts nearly three centuries into the future because such forecasts are inevitably uncertain: “Therefore, it is highly suspect for the government to claim the capacity to base policy decisions on statistical forecasts extending nearly 300 years into the future” (Dayaratna and Kreutzer, 2013, p. 3). The resulting version of DICE—I call it the Heritage Foundation DICE model (HF DICE)—delivers SCC estimates of around $4—much lower than the current EPA estimate of $37.79.

The plot

Interestingly, the narrative tracing of the internal working of the model—from the newly introduced assumptions to its new solutions—is relatively brief. The internal dynamics of the DICE framework are not the main focus of this narrative plot. This may be, because the authors assume that the model is familiar to the audience, as this is somewhat of a response to an existing model study. But it may also be, because the purpose of this model narrative is to make a political statement—not to advance technical understanding of IAMs per se.

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[16] The EPA used the three models without making changes to the models’ structure. The EPA assumed input values and parameter values previously identified by an Interagency Working Group on the Social Cost of Carbon (IAWGS).

The argument at the core of the dominant plot line in this IAM narrative is that the EPA's SCC estimates are flawed and should not be used to inform regulatory impact analysis, because the model assumptions that the EPA used to generate these estimates are inadequate or not up to date with scientific knowledge. There is an implicit notion that the EPA deliberately chose to ignore some scientific evidence for political reasons; including these ignored findings—as the runs with HF DICE demonstrate—leads to much lower SCC estimates. The temporal structure of the narrative is shaped by the modelers introducing their three model manipulations in in a step-by-step fashion—first they change the discount rate, then introduce a new climate sensitivity distribution, then define a new time horizon. With each of the model manipulations, the resulting SCC estimates diminishes further and the EPA's wrongdoing is exposed further. With all these changes introduced at once, the resulting SCC estimates drop by nearly 90 percent and the narrative culminates as the authors argue that the fact that these "moderate and defensible changes" in model assumptions lead to "such large changes in the resulting estimates of the SCC" means that "the results are nowhere near reliable enough to justify trillions of dollars of government policies and burdensome regulations," and it also means that "the entire process is susceptible to political gaming" (Dayaratna and Kreutzer, 2013, p. 1).

The characters

The central conflict of the HF DICE narrative as portrayed by the modelers is between the ideal climate policy, where government responds to climate change based up-to-date and complete scientific evidence, and the actual climate policy, where the U.S. government introduces unjustified and harmful regulations on industry in the name of climate protection. The villain in this story is the EPA, which uses models with "serious deficiencies" to calculate the SCC, trying to make a "case for adding regulations to limit CO_2 emissions" (Dayaratna and Kreutzer, 2013, p. 3). The victims in this plot are the people whose preferences are ignored and not represented in the EPA's discounting assumptions, as well as "the energy sector of the U.S. economy" (ibid., p.1) that faces "burdensome regulations" as a consequence (ibid., p.1). The implicit heroes of this story are the modelers themselves, unmasking these "shortcomings in the DICE model" (ibid., p.1).

The moral

The moral of the HF DICE narrative is twofold: First, the SCC estimates that the U.S. government should use in their regulatory impact analysis equals around $4, which is a fraction of the value currently used by the EPA. Secondly, the DICE model and other IAMs should not be used to inform policy decisions because of the sensitivity of their results to even "modest and defensible" (Dayaratna and Kreutzer, 2013, p. 1) changes in assumptions makes them unreliable and vulnerable to political instrumentalization.

Content analysis

This model narrative expresses the market liberal worldview of climate change and climate policy in some respects—but not in others. The structure of the DICE model is fully maintained so that the internal setting of the story is firmly anchored in that paradigm. The manipulations that are introduced reinforce a market liberal perspective. For example, the introduction of a higher discount rate that is explained with reference to the descriptive approach is generally in line with the market liberal worldview. Similarly, the shortening of the time horizon can be interpreted as signaling trust in the wealth and technologies that future generations will have at their disposal to manage the impacts of climate change, implying that the very far future (which is highly uncertain anyway) does not need to concern today's decision-making. Finally, the inclusion of a generally lower climate sensitivity distribution contradicts both the notion of a looming climate crisis and the precautionary approach to climate change policy that is valued by institutionalists.

However, it is not absolutely clear that the worldview underpinning this narrative can be classified as an *environmental* worldview at all. At no point in the causal plot of the story is climate change explicitly portrayed as harmful to humans or the non-human environment and thus worthwhile mitigating. In this narrative, the victims are not the people affected by climate change, but the industries affected by the government's unjustified mitigation actions—the energy sector of the U.S. economy. The emphasis is on the adverse effects of assuming an unjustifiably high SCC estimate, but there is no affirmation of the general usefulness of calculating the SCC for regulatory impact analysis in the first place. Specifically, the SCC is not portrayed as the equivalent to an optimal carbon tax as suggested by the market liberals.

The question that is asked of the model is relatively one-dimensional and the new understanding of climate change and climate change policy gained from running the model with the changed inputs is relatively slim. The impacts of higher interest rates, shorter time horizons, and lower climate sensitivity sensitivity on SCC results have been previously explored in the literature. Instead, the story that is told based on this modified version of DICE is fundamentally a story about the protection of industry against unjustified government regulation. It appears that the key motivation for performing the model modifications is prove the EPA wrong and to show a lack of reliability in models like DICE. The aim of this story is not primarily to create new substantial knowledge from activating the internal workings of the model to make new inferences from model results about the content of climate policy. Its aim is to criticize this very practice: the conclusion is that DICE and other IAMs like it are not fit for informing policymaking.

3.6.4 Discussion

What does the preceding analysis of these four IAM stories using a structured analytical framework reveal about the relationship between model structure and story? What is learnt about the composition of IAM narratives, and what about their content?

The structure-story relationship

The modifications that the modelers in the four considered studies make to the standard DICE narrative allow them to change and expand the scope of the stories they can tell using the model structure. The modifications made to the standard DICE model structure range from merely varying model input values (the HF DICE) to substantial model extensions (the extended DICE).

All of the considered studies contain multiple model stories in parallel, though not all of them are fully developed. Modelers introduce subplots to the overarching narrative when they conduct sensitivity analyses (as done by the modelers of extended DICE and gro-DICE), or when they consider alternative implementations of a newly introduced aspect of the model (as done by the modelers of NICE and gro-DICE). The modelers of HF DICE set up their new model version in multiple stages and created a new subplot with each introduced modification. The subplots supplement and support the overarching modeled narrative.

Interestingly, model stories may encompass narrative elements that are not explicitly represented in the model structure. These elements may be important to the story that the modelers want to tell, but difficult or time consuming to implement in the model's mathematics. For example, in the gro-DICE narrative, it is only qualitatively acknowledged that rapid abatement policies may also have permanent growth effects. This element is important to the narrative because it affects the story's central conflict and makes its moral conditional: if the growth impacts of abatement costs are large enough, the current gro-DICE narrative becomes implausible. Similarly, Dennig et al. (2015) acknowledge only qualitatively, outside of their model calculations, that if the cost of climate change abatement disproportionally affects the poor, the NICE story changes.

The composition of IAM stories

Climate policy involves making trade-offs, and the central trade-off is between giving up current consumption to invest in emissions abatement and risking consumption loss in the future due to the damages of climate change. IAMs model this trade-off, which is why a general definition of the typical villains, heroes, and victims in IAM narratives is difficult. The gro-DICE and the NICE narratives explicitly lay out this conflict. With the current assumptions on abatement costs, the morals of these narratives recommend stringent emissions controls. But modelers recognize that these morals may invert if assumptions on abatement costs change. Correspondingly, the definition of victims may change too: people harmed by climate change may become people harmed by curtailed economic development. In the gro-DICE, NICE, and extended-DICE stories with current assumptions, the victim is the current and future global population as a whole (Dietz and Stern, 2015), poor people in all regions (Dennig et al., 2015), or people living in poor regions (Moore and Diaz, 2015). The hero is decarbonization. By contrast, in the HF narrative, the identified victims are not those experiencing damages from climate change, but the U.S. energy industry, experiencing damages caused by unjustified government regulation.

All of the analyzed narratives conclude with at least one moral, i.e. a conclusion with normative implications for future action. Based on this analysis, I distinguish three types of morals in IAM narratives: the policy moral, the science moral, and the meta moral.

The policy moral concerns the implications of the narrative on climate change policy. The policy moral most directly follows from the numerical model outputs. For example, the extended DICE narrative specifies ranges of optimal carbon prices. Both the gro-DICE narrative and the NICE narrative suggest that more stringent near-term mitigation policies may be warranted than those implied by the standard DICE narrative.

The science moral contains recommendations concerning the future scientific research agenda. The recommendations here highlight questions that remain open and that are worthy of future investigation. Such recommendations are a standard element in the concluding section of academic journal articles; their inclusion in the gro-DICE, extended DICE, and NICE narratives are therefore not surprising, nor is their exclusion from the Heritage Foundation narrative, given that this narrative is not published in an academic journal.

The meta moral of IAM narratives concerns the implications of the narratives's argument for the use of IAMs in climate policymaking and the features that an IAM should have in order to justify its policy influence. For example, in the Heritage Foundation narrative, the main purpose of the policy moral seems to be to support the meta moral. At no point do the authors recommend using the new $4 SCC value for regulatory impact analysis, but they use that numerical model result to argue that the large discrepancy between their estimate and the EPA estimate discredits the DICE model and similar IAMs from being used for policy support at all. The extended DICE narrative also ends with a rather explicit meta moral, arguing that no single model framework alone can deliver all policy-relevant information and that models in policymaking should incorporate a range of perspectives. The NICE narrative concludes that to "better inform policy making on global climate change" all IAMs should incorporate "subregional inequalities and the distribution of damage and mitigation cost" (Dennig et al., 2015, p. 15830).

Further empirical research will show whether the distinction between these three types of morals is generally useful when analyzing narratives produced with models that have the dual function of informing both science and policy.

The content of IAM stories

All of these stories fundamentally stay within the market liberal perspective of the standard DICE narrative. This is not surprising, given that the modelers retain much of the model code. The neoclassical economic theory informing the mathematical structure of the standard DICE model is the analytical framework of market liberals. Moreover, the standard DICE narrative has been well established; it has gained credibility and authority with scholars and policymakers. The modelers using the DICE model for their own research may benefit from that entrenched credibility, if they do not diverge too drastically from the standard DICE narrative in their own storytelling.[17] This finding is also in line with previous research on important narratives in international climate policy by Liverman (2009), which finds three very influential narratives that are expressions of liberal market environmentalism. The three narratives concern the policy objective to prevent 'dangerous climate change', the principle of common but differentiated responsibilities between developed and developing countries in an international climate regime, and the preferability of market-based policy responses.

Nevertheless, the modelers of the four studies considered here add markedly new flavors to the standard DICE narrative. By making small modifications to the model inputs and equations, the modelers extend the available model resources, which allows them each to answer new questions. All model narratives analyzed here (except for perhaps the Heritage Foundation narrative) use their newly created model resources to introduce certain aspects of the other environmental worldviews into the standard DICE narrative. The gro-DICE and NICE narratives problematize the link between environmental problems and economic inequality that is so important to the social greens, and the extended DICE narratives emphasize the risk of catastrophe in line with the bioenvironmentalist view.

It is obvious from the discussion of the empirical results that the Heritage Foundation narrative is different from the other three in important regards. The modifications made to the mathematical model are more modest, a larger emphasis is placed on the meta moral, and the identified values and beliefs do not indicate a strong concern for the consequences of climate change. This is the only model narrative analyzed here that is not published in the format of a peer-reviewed academic journal article, but as a report by a think tank with a clear political agenda. Hence, the purpose of telling the Heritage Foundation DICE narrative is explicitly political, and the modelers should be considered policy actors. The DICE model is used as an instrument; it is manipulated and applied with the intention of raising doubts about the practice of the EPA.

The other model narratives considered here are published in academic journal articles, written by university-affiliated professional scholars. While it is widely acknowledged that science is neither objective nor value-free, one may legitimately challenge the notion that the model stories told by Dennig et al. (2015), Moore and Diaz (2015), and Dietz and Stern (2015), are ultimately just as political as the Heritage Foundation story. These stories are not told in a primarily political context, but they do conclude with policy morals. And all modelers recognize that the purpose of IAMs, generally, is to inform policy decisions.

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[17] This phenomenon is described in great detail in article #1 of this dissertation.

3.7 Conclusions and Future Research

In this paper, I conceptually connect Morgan's theory of mathematical models, wherein they are considered as the sum of structure and story, with an analytical tool (the NPF) that was developed by policy researchers interested in the construction and use of stories in policy processes. I argue that stories produced with policy-relevant models are a particular type of policy narratives, and I suggest an analytical framework for studying their composition and content that draws strongly on the NPF (Jones and McBeth, 2010). I demonstrate the framework, by applying it to four model narratives told with variations of the DICE model, the most widely used integrated assessment model of global climate change. This explorative empirical analysis confirms an intricate but not fully deterministic relationship between IAM structures and stories as suggested by Morgan. It also illuminates the values and beliefs that underpin the composition and content of the modeled stories. Based on my conceptual discussion and the initial application of the framework, I conclude that stories are an underutilized resource for research on policy-relevant models. I argue that an appreciation of these modeled stories is essential for a full understanding of the models, of differences between models, and, importantly, of how these models are used to generate policy-relevant knowledge.

In particular, this paper lays the foundation for further research on policy-relevant modeled stories, which may contribute to ongoing debates in the governance literature. Analysis of IAM narratives may help illuminate the relationship between science and policy in the governance of science-driven policy issues such as climate change or public health where policymakers draw on mathematical models for guidance. Because of the policy purpose of models I discuss in this paper, I assumed that it is justified to use a framework for the analysis of policy narratives to study the stories produced with IAMs—even if these stories are first told in an academic context. This assumption is in line with a co-productionist approach to the study of science-policy relations (Jasanoff, 2004b,c). According to this approach, science, policy, and politics are intricately connected—to the effect that they are mutually dependent on each other. Co-production implies that IAM stories—given the function of IAMs as 'boundary objects' (Star and Griesmer, 1989; van Egmond and Zeiss, 2010) between scientists and policymakers—should never be examined as independent from the policy environment and political context they are embedded in.[18] Yet I suggest that this approach to the study of IAM stories warrants a more detailed, empirical analysis: assuming that *every* story told with a policy-relevant model automatically has a political character, how do stories published in academic journal articles still differ from modeled stories that feed more directly into the policy process? This question relates directly to the differences between the Heritage Foundation narrative and the other three DICE narratives identified in this paper. Further unpacking of these differences will contribute to the discussion about science-policy boundaries (Gieryn, 1983; Jasanoff, 1987) that is closely associated with concept of co-production. From

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[18] The introduction to this dissertation and article #1 elaborate on co-production and models as boundary objects.

this discussion one may hypothesize that modeled stories play an important role in the models' function as boundary objects between the scientific community and the policy community, with both communities interpreting them and using them to affirm their authority in the governance of the modeled policy problem.

Further, the study of model narratives may improve understanding of power and politics in the policy process by explaining why some model stories gain more authority in climate policy than others. The NPF, used in this paper to detect the values and beliefs underpinning IAM stories, can further be applied to generate testable hypotheses about the impact of different policy narratives on policy outcomes. Building on the framework employed in this paper, future studies may address the following questions: How do some model stories gain more authority in policy than others? Is it simply through repetition and endorsement? As much as model stories gain authority and shape public narratives about climate change, are they not also shaped by those same power relationships? Are model narratives that are politically non-controversial therefore more likely to gain political influence? And: whose stories about climate change are systematically excluded from IAM narratives—and thus policy? These questions relate to what Doganova (2015) calls "the politics of models" (p. 250), namely the fact that models "are devices that constrain by excluding certain questions and certain actors." Similarly, in the study mentioned earlier about key narratives shaping international climate negotiations, Liverman (2009) illustrates how these narratives both are influenced by powerful political interests and at the same time help strengthen these power structures via policy outcomes.

In addition to opening up new avenues for scholarly research, the findings of this paper may also have implications for the practical use of models in the policy process. Investigating the influence of economic models on UK economic policy, Evans (2000) finds that their influence is limited: they are used as a "rhetorical resource" in political arguments and they "function as legitimizations (and quantifications) of particular political and moral theories about the world which can be selectively invoked by policy makers" (p. 223). Assuming that, as was argued in this analysis, models are used to produce policy-relevant stories, Evans' argument implies that policymakers will pick up and promote the one model story that best fits their preconceived policy strategy and value system. (They may indeed manipulate the models to produce exactly that story.) However, a more productive use of models in the policy process, Evans argues, is to understand them as "discursive space" (ibid., p. 223) in which modelers, decision-makers, and the public come together to debate the critical assumptions, values, and beliefs that cause model stories to be different in the first place. Working with the whole range of existing models and stories instead of picking one or a small number of model narratives can help stakeholders "develop shared understandings" (ibid.) of the problem and its possible solutions. Recognizing the role of IAMs as storytelling devices rather than number-generating machines facilitates their deliberate use as discursive spaces for debate by making them more accessible to stakeholders who are less familiar with the mathematics, and by making it easier for those who are engaged in the debate to grasp where understandings and interpretations diverge in the first place.

Chapter 4

Are IAMs too arbitrary and too value-laden to be useful for policy?

4.1 Preface

This article investigates the usefulness of IAMs as tools for policy analysis. As discussed in the introduction to this dissertation, IAMs have been subject to criticism ever since they were first developed. In 2013, MIT economist Robert Pindyck (2013) argued that the models are not justified by economic theory and that their assumptions are arbitrary and biased. He concludes that IAMs have little to offer to policymakers and that their use for decision support may actually be dangerous. Pindyck's view echoes previous critiques of IAMs. But is he right?

Multiple studies of IAMs' usefulness have been produced over the past 25 years, some of which are more sympathetic to the models than Pindyck while still taking the opportunity to offer constructive criticism. In particular, the thoughtful studies by Risbey et al. (1996), van der Sluijs (2002), and Schneider and Lane (2005) offer nuanced critical discussions of IAMs. These studies served as the inspiration for this article.

My study contributes to this existing body of scholarship on IAMs by offering a new methodological approach. In particular, I do not directly evaluate the models' equations. Instead, I first use social scientific methods to investigate the features of IAM-derived knowledge. Specifically, I elicit the factors that drive modeling choices in practice—acknowledging that theory and empirical data alone cannot fully explain model development. Second, I draw on philosophy of science to normatively discuss the validity of the knowledge inferred from IAMs. Finally, influenced by a pragmatic theory of knowledge, I draw on insights from science and technology studies to infer practical recommendations on how to enhance the usefulness of IAMs as policy aids.

In sum, this study is both grounded in empirical data and attuned to the fundamental philosophical issues underpinning the criticism of IAMs. Importantly, the goal is not to 'deconstruct' individual models or particular choices in the modeling process, but to interrogate the general implications of making inferences for policy from this type of model. This study seeks to promote a constructive debate about IAMs for policy, involving practitioners, social scientists, and modelers. Importantly, while I argue in favor of a more positive view on IAMs than Pindyck, I acknowledge that continuously challenging the models and questioning their assumptions and results is crucial for quality control and scientific integrity.

In the context of this dissertation, this article directly builds on the theoretical work of article #1, providing empirical data to support some of its central arguments: that modeling choices are coupled epistemic-ethical choices, that modelers may have an incentive to only make incremental changes in the model, and that the political debate about climate change affects model development. The normative objective of this article provides closure to the three articles included in this dissertation—essentially asking the question: 'so what?'

How does this article fit into the theoretical context of this dissertation? More concretely, what does the co-productionist framework contribute to critical, normative analysis of science-policy interactions? As outlined in the introduction to this dissertation, co-production defies both the technocrat's ideal of objective and value-free scientific policy advice and the relativist's notion of scientific knowledge as fully constructed. Neither of these extreme positions is considered helpful in navigating the negotiated boundary between science and policy, between truth and power. Importantly, both of these extremes open doors to manipulation and political instrumentalization of science, and they shield scientific expertise from being exposed to scrutiny and public accountability. Working within a co-productionist framework, the existence of normative assumptions in science for policy does not automatically discredit the usefulness of scientific knowledge for decision-making. Instead, co-production enables constructive conversations about how to develop and apply adequate standards of transparency and accountability in the production of scientific policy advice. Jasanoff (2003) argues:

> "[E]xpertise has legitimacy [in policymaking] only when it is exercised in ways that make clear its contingent, negotiated character and leave the door open to critical discussion. In other words, expertise, like other forms of democratically delegated power is entitled to respect only when it conforms to norms of transparency and deliberative adequacy" (p. 160).

This article renews Jasanoff's call for developing such standards of transparency and accountability for IAMs, and it takes a first step toward that goal.

The audience I envision for this article includes primarily model developers and model users. Although this article significantly draws on philosophy, its primary target is not to further the philosophical debates, but rather to *apply* insights gained from these debates to the examination of IAMs. I imagine that model practitioners, who may be less familiar with the philosophical discourse about models, may therefore benefit from this article's interdisciplinary approach. To engage the community of practitioners, I plan to submit this article to interdisciplinary, widely read journals on climate change such as *Climatic change* or *Nature climate change.*

4.2 Overview

Integrated assessment models of global climate change have become important tools for supporting climate policy decisions. But these simulation models are also subject to scathing criticism that considers the models arbitrary and value-laden, and therefore unfit for policy use. This article provides a normative, empirically grounded analysis of these critiques. Interviews and participant observations with IAM developers reveal that, indeed, many factors other than scientific theory and empirical observations influence modeling choices. The modelers also recognize that some of their choices in the modeling process do have a partially normative character. So, do these findings validate the above critiques and disqualify IAMs from policy use? Not necessarily. Current work in philosophy of science demonstrates the need for a more nuanced approach to this question, revealing that the ideal of objectively true and value-free models is unattainable—indeed, in some aspects, even undesirable. Instead, models should be evaluated with respect to their 'fit for purpose.' Uncertain and value-laden assumptions should be addressed with transparency and conditionality. Adopting such a pragmatist perspective on IAMs, this paper concludes that IAMs are a useful, albeit imperfect, tool for assessing climate policy. Practical recommendations for how to enhance the usefulness of IAMs are provided.

4.3 Introduction

Climate change is a daunting policy challenge, where decision-makers must respond to a high-uncertainty and high-risk problem in an environment featuring a diverse multitude of stakeholders and deep-seated ideological controversy. Because of the intricate entanglement of scientific uncertainty and value disputes, the questions that climate change asks of society are of a trans-scientific nature (Weinberg, 1972, p. 209): these are "questions which can be asked of science and yet which cannot be answered by science." While scientific knowledge generated from computer-based atmospheric models has been central in bringing climate change on the political agenda (Edwards, 2010), responding to the problem involves moral and political choices that cannot be resolved by scientific research alone (Funtowicz and Ravetz, 1993, 1994).

Over the past 25 years, climate-economy integrated assessment models (IAMs) have become standard tools for the analysis and support of climate change policy, both at the national and international level (Stern, 2007; Interagency Working Group on Social Cost of Carbon, 2013; Clarke et al., 2014). IAMs are mathematical computer models that combine representations of the climate and the economic system in order to simulate their future evolution and their interactions (Weyant, 2014). This study focuses on one particular type of IAMs: global cost-benefit models.[1] These highly aggregated models represent in simplified form the full causal chain including the economic activities causing greenhouse gas (GHG) emissions, the effects of GHG emissions on climate, and the impacts of a changing climate on society. Because these models represent both the cost of climate impacts and the cost of abatement, they are used to produce cost-benefit analyses of alternative policy interventions, comparing the future cost of reducing emissions with the benefits from the avoided damages. In recent years, a primary application of IAMs has been to estimate the social cost of carbon (SCC), which measures the marginal economic damage arising from emitting each additional ton of carbon into the atmosphere.

Global cost-benefit IAMs and their use for policy support have been subject to scathing criticism. Recently, a marked increase in the latest U.S. estimates of the SCC—the average estimate went up in 2013 to $33 per ton compared to the 2010 estimate of $21—has fueled concern among businesses (Childers, 2013) and motivated a wave of new contributions to a longstanding scholarly debate about the usefulness of IAMs as epistemic devices and their suitability for informing climate policy (Pindyck, 2013; Darmstadter and Krupnick, 2013; Sterner, 2013; Posner, 2013).[2] In particular, critics suggest that the models have two major flaws. They argue that the assumptions going into the models are ad hoc and laden with normative judgments because the lack of robust theory about climate-economy interactions and scarcity of empirical data require that even crucial model formulations (e.g. the specification of economic damage functions) and parameter choices (e.g. the value of the discount rate) be left to the modelers' 'best guesses.' As a consequence, critics then argue, IAMs are vulnerable to politically motivated manipulation in order to achieve model results that support predefined policy objectives. Pindyck (2013), one of the most outspoken scholarly critics of IAMs, claims that, for these reasons, the models are "so deeply flawed as to be close to useless as tools for policy analysis" (p. 3).

Despite this tension between IAMs' influence on current policy and the fact that they have been exposed to such harsh critiques, we know surprisingly little about the development and use of IAMs in practice. Such empirical analysis is necessary to provide an informed normative assessment of their adequacy for informing policy decisions. Without such analysis, the criticism of IAMs appears as ad hoc and politically motivated as it accuses the models of being: focused on deconstructing individual model aspects and linked to advocating particular policy positions.

Addressing this knowledge gap, this study investigates the practice of IAM development with the objective of drawing conclusions regarding their usefulness in policymaking. The central question guiding this research is: Are IAMs too arbitrary and too value-laden to be adequate tools for aiding climate policymaking? I conducted interviews and participant observations with a group of selected IAM developers to learn about the modeling process firsthand. The results reveal

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[1] As discussed in the introduction to this dissertation and in article #1, various types of IAMs exist that differ regarding their conceptual framework, model scope, level of detail, and their applicability for policy-analysis.

[2] The introduction to this dissertation provides a historical overview of this debate.

that, indeed, many factors other than scientific theory and empirical observations influence the modelers' choices. The factors include epistemic norms, technical constraints, limited availability of time and money, political factors, career considerations, intuition, and personal preferences. The empirical analysis also shows that modelers generally recognize a partially normative character of some modeling choices, although different modelers vary in where they draw the line between positive and normative choices. It appears that, for the modelers, the boundary between positive and normative modeling choices is not clearly defined, but rather that there is a continuum between the two.

I analyze and evaluate these empirical findings drawing on two relevant debates in philosophy of science. I turn to philosophy because underpinning the IAM critiques are fundamental philosophical issues. The first debate concerns the role of computer simulation models (such as IAMs) as tools of inquiry; the second debate concerns the role of value judgments in scientific research and scientific modeling. I find that the partial dissociation of IAM development from scientific theory and observable empirical data is a common feature of computer simulations in science, and that it is thus not necessarily a convincing reason to dismiss the conclusions inferred from these simulations as unscientific, unreliable, or untrustworthy. I also find that the partially normative character of IAMs is not automatically a compelling reason to write them off as inadequate for policymaking. The value-free ideal in scientific research is neither achievable nor desirable.

I conclude that, although the empirical research produced for this study partly validates central points in condemning IAM criticism, we should not write off IAMs as useful policy aids. Climate change is—and will always be—complex and uncertain, and climate policy will always require making normative value choices. And yet, decisions about whether, when, and how to act are urgently required. IAMs are not perfect tools for informing these decisions but it would be wrong to conclude from these findings that IAMs are generally unfit for policy-making. I draw on pragmatist philosophy to support my argument; pragmatism judges the outcomes of scientific inquiry primarily based on their practical usefulness for solving societal problems—not their 'truth.' Also, pragmatism does not assume that scientific inquiry is value-free. To improve the usefulness of IAMs for policymaking I suggest that we (1) define criteria by which we evaluate the relative quality of different IAMs with reference to their purpose, (2) develop a strong "knowledge infrastructure" (Edwards, 2010, p. 432) for IAMs to continuously monitor and challenge their development and use; (3) invest in the primary research that informs IAMs; (4) explore alternative decision-support tools outside of mathematical simulation modeling; (5) provide models with stable funding; and (6) further investigate the relationship between the positive and normative aspects of the climate change problem.

The paper is structured as follows:

- Section 4.4 illuminates the methods and materials used in this study.
- Section 4.5 presents the results of the empirical inquiry.

- Section 4.6 links my empirical findings to the current scholarly debates about the epistemology of computer simulation models and about the role of values in scientific research.
- Section 4.7 concludes by highlighting practical implications for assessing the usefulness of IAMs as tools for informing policy.

4.4 Materials and methods

4.4.1 Data collection

This study was designed to investigate the practice of integrated assessment modeling, both empirically and theoretically, in order to provide a well-informed response to critics' claims that IAMs are arbitrary and value-laden and thus unfit for supporting policy decisions. Data sources for this study include an extensive literature review, analysis of primary documents, in-depth elite interviews with the developers of three influential IAMs, and participant observations with one of these modelers.

The bodies of literature reviewed herein include philosophy of science and science and technology studies (STS), with a focus on knowledge generation via models and computer simulations and the role of values in science for policy respectively. Primary documents include IAM manuals and documentation as well as IAM-based studies.

The five informants interviewed for this study hold an elite status in the academic community of climate-economic modeling.[3] Three of the interviewees are senior modelers, all affiliated with universities, who have developed and maintained the three IAMs that have arguably been the most influential on the academy, public policy, and public discourse. The two other interviewees are modelers at earlier stages of their academic career (also working at universities), who use one of the three models for scientific research or have used them in the past. To protect the interviewees' anonymity, I refer to them as modelers A, B, C, D, and E when quoting them verbatim.[4]

The interviews took place in the time period between May 2015 and April 2016. The semi-structured interview guide consisted of three 60-minute segments that could be shortened or combined depending on the participants' time availability. Two interviewees were only available for a 1-hour interview each, while I spoke for several hours with others. Also, interviewees were given the opportunity to raise additional issues or comments during the interview. All interviews except for two were tape-recorded. In total, I collected around 12 hours worth of recorded interview material.

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[3] Elite interviews "involve[s] talking to people who are especially knowledgeable about a particular area of research" (Gillham, 2005, p. 54). This interview type poses particular challenges on the researcher, for example, related to gaining access to elite interviewees and the imbalance of expertise and power between researcher and interviewee. Resources I drew on to prepare myself for the interviews conducted for this study included: Gillham (2005), Stephens (2007), Harvey (2011), and Mikecz (2012).

[4] One modeler I approached for an interview declined my request.

The two interviews that were not recorded were documented in written notes.

In addition to the interviews, I also conducted participant observation sessions with one of the interviewed model developers over the course of a month. The observation sessions allowed me to learn about modeling practices and routines firsthand. Observations were recorded in written field notes.

I acknowledge limitations to my methodology. Regarding the interviews, the number of study participants is small. This is largely due to the fact that the number of aggregate cost-benefit IAMs is small and that these models are commonly not produced by large modeling teams but by individual researchers. Also, the length of the interview varied across participants because I was dependent on the limited time that participants were available. Moreover, the interviewed modelers may have incentives to bias their interview responses. In particular, they may have an interest in presenting themselves and their work in the best light in order to promote their credibility with policy-makers, academic peers, or the public at large. Where possible, I used document analysis and the data obtained through my participant observations to corroborate evidence from interviews.

4.4.2 Data analysis

For the content analysis of the interview transcripts and field notes, I used the qualitative data analysis software NVivo. I initially applied structural coding based on my interview guide. For a second coding cycle, I combined two coding techniques: descriptive coding and versus coding. Descriptive codes summarize in a word or a short phrase the key topic of a piece of qualitative data (Saldana, 2013). This coding technique was useful for identifying and ultimately grouping the various factors that drive modeling decisions. Versus coding involves identification of dichotomous or binary terms that describe a conflict between individuals, groups, processes, concepts etc (Saldana, 2013, p. 115). This technique is well suited to elucidate the modelers' views on the dual function of IAMs in science and policy, as well as the trade-offs and dilemmas that this dual function creates in their modeling work.

4.5 The practice of Integrated Assessment Modeling

4.5.1 Uncertainty dominates the modeling process

The modelers interviewed for this study recognize that integrated assessment modeling requires the constant management of uncertainty: both the theories and the empirical data feeding into the models are incomplete and contested. Most interviewees identified a high level of uncertainty about our knowledge regarding the systems represented in IAMs, and they find that uncertainty is, to some degree, irreducible. One modeler specified three key loci of uncertainty in IAMs. First, the inherent unpredictability of people's future behavior means that projections of future emission trajectories are uncertain. Secondly, our incomplete understanding of the dynamics of physical climate change entail uncertainty about the impact of emissions on climate. Thirdly, the unpredictability of people's future preferences means that the valuation of future impacts of climate change is unknown (and unknowable). This modeler recognized that more research may reduce uncertainties at these three loci, but likely not substantially.

IAM simulations serve as a substitute for traditional methods for empirical data collection such as experiments and observations. As one interviewee (B) pointed out, "we haven't seen 5 degrees temperature rise. We don't know what that is going to look like; we have to make projections of it." This modeler argued, that the lack of empirical data increases our need for IAMs, in order to demonstrate how that uncertainty affects model outputs and to illustrate which of the many uncertainties have the most effect on policy recommendations and thus should be prioritized in research.

Modelers recognized that uncertainty increases the degrees of freedom in the modeling process, which requires them to make choices in model construction. Interviewees acknowledged that a certain degree of leeway is inherent in any modeling process independent of uncertainty—after all, models are "products of human minds and human efforts" (C), and not of automated processes. What factors influence the creative act of building integrated assessment models? The empirical research conducted for this study reveals multiple factors, which are discussed in the following sections.

4.5.2 Epistemic norms

Interviews and observations reveal that modelers draw on traditional epistemic norms for guidance in their modeling choices. The norms alluded to by the modelers include honesty, reproducibility, and transparency, as well as compliance with the norms of reason as defined by their scientific peer community. Modeler D explained: "So the model quality should depend on the inputs of the model, [...] what comes out [...], if you then don‘t like it you have to go back to your assumptions. But [...] you can't go data mining and say 'oh no, I wanted a different number'." A good modeling practice, according to the interviewees, also involves ensuring that the model is free from coding errors and running stably.

The modelers said that they turn to peer-reviewed literature first for input and guidance on modeling choices. Since multiple disciplines feed into IAMs, the modelers (who are typically not experts in most of these disciplines) often need to "spread yourself very thin and just make sure that what you've done represents a reasonable approximation of the state of the art in all the different areas" (C). If available, modelers turn to the literature and other model studies as an objective benchmark to inform their modeling work. However, this benchmark is absent when modelers introduce a model innovation, i.e. when they incorporate a new aspect into the model or when they introduce a novel way of modeling a familiar aspect. In these cases, modelers rely more strongly on their intuition and expert judgment.

In return, modelers put out their own models for peer review and public scrutiny to detect errors or gaps in their simulations. One modeler in particular recounted multiple incidents when model users have detected errors in the model code. Two interviewees indicated that there are emotional aspects to this step. One said it was not easy because they may “embarrass” (C) themselves; another one said that they want to make sure that “the scientists and the economists won’t laugh at you” (B). Modelers take different approaches to the publication of their modeling code. One modeler has made the open sharing of code an explicit part of their model philosophy, encouraging others to use it and experiment with it. Another modeler makes their model available, but only in connection with a consulting contract that grants the modeler a degree of control over how the model is used. Yet another interviewee is more protective, arguing that making the model too easily accessible is irresponsible, because non-qualified users may use the model in an inappropriate way. But overall, the need to share the model code to ensure debate and scientific integrity is recognized. Modeler C said: “It’s a trillion-dollar problem. Trillion-dollar problems should have people testing and prodding and probing and trying alternatives.”

4.5.3 Technical factors

IAMs are computer simulation models and are thus dependent on computer technology. Technical constraints are imposed by the syntax and the capabilities of the programming language used, as well as the computational power available to solve the model. The use of computers enabled the development of the first IAMs in the late 1980s, and advancement in computer technology continues to enable model innovations today. The interviewees still considered computational capacity as an important constraint to their modeling work that influences their decisions on model complexity and choices about what functionality should be granted priority. For example, one interviewee explained that full uncertainty treatment in the model demands a lot of computational capacity, possibly requiring a trade-off with other computationally demanding model functionality such as optimization or a high degree of regional disaggregation (see Section 4.5.9).

At least in the short term, modeling choices are also constrained by the programming language in which the IAM is built. IAMs can be written in various software languages such as EXCEL, C++, and GAMS. The three case study models are all written in different languages, and one model exists in various languages in parallel. Each programming language has its own strengths and weaknesses, affording certain functionalities while disabling others. Hence, the seemingly technical choice of a programming language may shape the substantial content of the model and the type of results that the model can produce. For example, certain languages are better suited to run optimizations, while others are better able to model uncertainty. In the long run, the software infrastructure may be changed to better accommodate modelers' changed priorities about model scope and/or complexity. But transferring the models from one programming language to another is labor intensive, especially if it requires the modeler to learn the new syntax.

Finally, modeling choices may be influenced by technical factors in more subtle ways. First, integrated assessment modelers are typically not trained software developers. However, writing code and dealing with technical issues constitutes a key part of the model development process—and it is a part that is particularly prone to errors. Once the model is set up, it requires maintenance and 'debugging'—tasks that are necessary, but not academically interesting. Secondly, as was mentioned earlier, modelers commonly make their model code public, enabling other researchers, policy actors, and decision-makers to use the model. The programming language chosen and the complexity of the code determine the technical capacities and the level of expertise that are required for users to run the model, as well as the ease with which they can adjust model inputs to produce their own experiments. This, in turn, then influences the degree of peer review exposure that the model is experiencing—which in turn may influence the course of model development over time.

4.5.4 Other resource constraints

As for all scientific research, limited availability of time and money influences IAM developers' choices. The aggregate 'simple' models subject to this study are the products of small modeling teams led primarily by the models' original developers. Some of the funding and time constraints these developers face result from a deliberate choice to work primarily alone or with only a few collaborators at a time, rather than in a large modeling team. Interviewees mentioned their own time as one of the most important constraints on what they can do with the model. They also recognized that they are not experts in the various disciplines represented in their models, and that a larger modeling team, possibly including such experts, would enable more frequent model updates and a larger volume of research output. However, the reason for not developing larger teams, as two interviewees explained, is that they had no interest in spending more of their time on fundraising than on the actual modeling, which would be necessary to sustain a large team. Instead, a smaller model can be sustained through university funding in combination with some external funds. One interviewee also mentioned that dependence on external money may compromise academic freedom.

4.5.5 Career considerations

Interviews reveal that, over the course of a modeler's academic career, the objectives they pursue with their modeling and the incentives that drive their model work may change. For example, as professional academics, modelers publish their work in academic journals and thus subject their models to the scrutiny of editors and peer reviewers. Because of the applied and interdisciplinary character of IAMs, two interviewees argued that it can be difficult to publish IAM-based studies in top-tier disciplinary journals; they are more likely to be published in applied journals which are typically of a lower academic reputation. One modeler mentioned that the inter-disciplinary character of integrated assessment modeling may moreover slow promotion in disciplinary university departments. On top of that, model developers spend much time on rather mechanical 'non-publishable' activities such as model maintenance and coding, as opposed to more substantive activities such as model innovations and model experiments.

4.5.6 Political factors

The interviewed modelers are aware that their work stands in the centre of a heated political debate and is thus subject to not merely scholarly, but also public scrutiny. They recognized that their models may be used by policy makers and interest groups to mobilize support for or against certain policy interventions, either by exploiting or by challenging the established credibility of IAMs.[5] One interviewee explained that IAM studies often recommend introducing a carbon tax, but typically not a very high one, and thus they are likely to attract criticism from all political sides. Another interviewee called integrated assessment modeling "a big-leagues and rough sport", where modelers "have to be prepared for the fact that you'll get beaten up, that you'll get used and misused" (C). Yet the degree to which modelers feel constrained in their work by the polarized political process varies across modelers. It depends on whether their motivation to work with IAMs is based purely in "academic interests" or in the intention to "make a certain point" (A)—in other words, what they define their role to be at the intersection of political activism, policy advisory, and scientific research. This definition, the interviewee explained, may change with age and over the course of a career.

One interviewee also explained that political heat may be one reason why many younger academics involved in integrated assessment modeling tend to steer away from addressing controversial questions in their modeling research and instead write, in their opinion, "very arcane and technical papers" (A) exploring narrow methodological questions. They work with the existing model code of well-established IAMs without having to justify—epistemically and politically—all of the underlying assumptions going into it.

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[5] The Heritage Foundation study analyzed in article #2 of this dissertation is an example of the latter.

4.5.7 Subjective factors

Interviewees acknowledged that some choices in the modeling process are inevitably subjective, even if modelers intend to follow the objective guidance of peer reviewed literature. In fact, one modeler (B) considers all modeling choices subjective, to varying degrees. Some choices may be informed by "lots of data" (though they are still not 'objective'), while others only rely on "gut feeling" and the limited studies available. Intuition and gut feeling are particularly dominant in modeling choices that are new, because no literature yet exists to provide guidance. Some of the interviewed modelers indicated a greater comfort with the degree of subjectivity in integrated assessment modeling than others.

I asked some of the interviewees whether they consider IAMs more similar to a piece of art or a product of mechanical engineering. The most common answer was that IAMs contain elements of both. In the modelers' view, the modeling process is more structured than a purely creative process but less objective and formulaic than the implementation of an engineering task. The artistic element in constructing IAM simulation has to do with the importance of intuition, expert judgment, experience, and personal modeling style. Like artists, the modelers suggested that they themselves are the primary judges of the quality of their work and that they are primarily accountable to their own conscience. They then expose their work to the scrutiny of their academic peers by publishing papers and sharing their model code.

4.5.8 Inertia and path dependence

Interviews and observations indicate that path dependent processes may occur both in the evolution of one model over time and in the evolution of the entire model fleet.[6] Within one IAM, initial choices that were made when the model was first developed may shape the trajectory of future model development because of incrementalism and inertia. Initial modeling choices (for example, about the number of model regions) may have been influenced by the constraints on computer power that existed at the time. Although these constraints may no longer be binding today, the initial choice has now manifested in legacy code that is expensive to change. Making fundamental model changes costs time and money, and it is easier to only make incremental changes. Another reason for incrementalism may be that modelers, when calibrating new model components, may consider large deviations from previous model results to be suspicious.

The initial invention of IAMs happened in a particular time and place. One interviewee recounted how, around 1990, multiple developments coincided to make available the different parts required for building IAMs: progress in climate research and research on economic growth, the improvement of the mathematical algorithms that were used in energy modeling, and software

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[6] Theoretical treatment of this issue is offered in Section 7 of article #1 included in this dissertation.

innovations. In addition, the emerging interest in global climate policy, illustrated by the establishment of the UN Framework Convention on Climate Change in 1992, created a receptive environment for climate-economic modeling. Another interviewee pointed out that the scope of IAMs today is still partly determined by the scope and substance of the primary research that was available when IAMs were first developed. For example, there was abundant research on energy economics (on the mitigation side) and agriculture (on the impacts side). In contrast, there was little primary research available on mitigation in transport and agriculture and impacts on migration and conflict. The effects of this initial imbalance are still visible in today's models, and new research in the traditionally neglected fields is still slow to catch up.

Over time, some interviewees indicated that there is a tendency for those IAMs that survive to converge, i.e. to become more similar to each other in assumptions and results.[7] One interviewee used the analogy of an "ecology of models" (C) to describe inter-model dynamics. This analogy indicates that the modeler perceives a degree of competition between models and that models that are not competitive will disappear. This selection process exists because modelers are generally rewarded for building models that deliver results that are roughly in line with those from already established, trusted models. The established models set the benchmarks against which future model developments are evaluated by scientific peers and policymakers. Policymakers prefer peer reviewed models with academic clout, and models used once for policy assessments are likely to be used again because they are familiar and their results more predictable. Conversely, consistent outliers are unlikely to be published in academic journals, although there is often no evidence that these outliers are substantially wrong. A related point that emerged from the interviews is that the models slowly shape the policy discourse over time and thus the demand for further modeling analysis. As a concrete example, IAMs promoted the emergence of SCC estimates as relevant input for policy in the early 2000s. Today, interviewees agreed, policymakers need SCC estimates, and these estimates are one of the key outputs that IAMs can deliver. So, if models want to stay policy relevant and competitive, they must be able to deliver SCC estimates. Also, as mentioned before, one interviewee explained that young scholars often pick up one of the established models to investigate only a specific methodological aspect of it. Instead of challenging or advancing the entire model, they use it to investigate a narrow question, benefiting from the model's established credibility, which relieves them from having to justify the larger framework. Once they have published a number of papers, they tend to leave the model behind and move on. This pattern, the interviewee (A) concluded, may lead to a "fake consensus" among models in the literature—the fundamental disagreements between the different model frameworks have not been addressed or resolved but they simply ceased to be a subject of debate.

There is general agreement among the interviewees that maintaining diversity among models is important as different models serve different purposes: "[T]he good thing is that there are many

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[7] This is a matter of interpretation: another interviewee suggested that convergence is not occurring and that the models that are currently most in use deliver significantly different results.

models there. They have different structures [and] different scales, and the biggest challenge is to use the right model for the right purposes" (E).

4.5.9 Modeling requires trade-offs

Modeling choices are complex, and in practice they are likely influenced by multiple of the factors discussed above at the same time. Trade-offs may exist between the various factors, requiring modelers to prioritize. How to make these trade-offs is not determined by the underlying theories, nor by the available empirical data; these trade-offs only emerge in the process of transforming theory and data into computer simulations. For illustration, I briefly discuss two important decisions in the modeling process that emerged from my interviews and observations.

Trade-offs are required in decisions about model scope. Climate change is a complex issue with unclear boundaries. A vast number of human activities contribute to greenhouse gas emissions, and climate change impacts are expected to affect nearly all aspects of society. Which aspects of the climate problem should be included in IAMs and which ones left out? The global cost-benefit models considered in this study generally aim to represent the total costs and benefits of climate change. But choices about model scope, of course, have to be made in the face of finite computational capacity, other resource constraints, and—importantly—the limited availability of primary research in the relevant disciplines. Regarding aspects of climate change where no or very little primary research exists (possibly due to historical conditions), modelers face a trade-off between two epistemic norms, namely model completeness and model reliability. One such problem area that two interviewees explicitly recognized in current models is the impact of climate change on migration and conflict. Modelers consider the costs related to this impact potentially significant, but quantitative research that can be scaled to feed into a global model is scarce. If modelers decide to include this impact type in their models based on the limited knowledge available, the representation would be highly uncertain and largely based on intuition and the modelers' 'best guess.' But the impact type is represented, at least—if only with a placeholder. Conversely, if modelers decide not to include the cost of climate-induced wars and migration but to wait until more robust primary research is available, they risk missing potentially significant costs. This trade-off naturally raises questions about whether there is also a political dimension to this decision. One modeler explains that observers often think that there are political motivations behind not including certain aspects in the model, while in fact the reason is simply a lack of primary research. Finally, subjective preferences may come into play as well in this decision; modeling aspects for which very little prior research exists likely requires more subjective judgments by the modelers, and not everyone may feel equally comfortable with making these judgment calls.

Trade-offs also are required in decisions about the appropriate degree of model complexity. The interviews reveal that modelers generally value simplicity in their models for various epistemic, technical, and political reasons: simple models are more accessible to non-experts, less prone to coding errors, easier to implement technically, and quicker to run. For example, a high degree of regional aggregation frees computational capacity to perform optimization calculations and/or to model uncertainty stochastically. As explained above, optimization and comprehensive uncertainty representation often compete for limited computer power. But interviewees also agree that there is a delicate balance to strike between simplifying a complex problem to make it more accessible and avoiding undue over-simplification that fails to adequately represent the problem's complexity. A model that is too simple, one interviewee argued, becomes non-transparent because higher degrees of aggregation typically require more wide-reaching implicit assumptions. More complex models, on the other hand, require more elaborate coding, which is more prone to errors and less accessible to model users. One modeler expressed a strong preference for minimizing the time it takes to run the model in order to enhance practicality. This individual preference entails that computational power ultimately determines the model's degree of complexity: "The equations that you use, you will have this balance between things that are a reasonable representation of what you really think is going on in the world and something which you can fit into a simple modeling form that is going to be run 10,000 or 100,000 times to get results" (B). Finally, very complex models need larger modeling teams and are more expensive to maintain. These requirements, however, may clash with modelers' ideas about how they want to spend their time—managing and fundraising vs. modeling. Over time, decisions about model complexity may become costly to change, and thus they may remain unchallenged and manifested in the model's 'legacy code' for a long time.

4.5.10 An epistemology of IAMs—from the modelers' perspective

Recognizing the omnipresent uncertainty surrounding the modeling process as well as the diversity of factors that come to influence the choices made necessary by that uncertainty, the interviews illuminate the modelers' perspectives on the kind of knowledge that IAMs generate and how that knowledge should be used. First, interviewees emphasized that the contribution of IAMs to the advancement of knowledge about climate change lies in enabling consistent and well-structured integration of existing knowledge that is dispersed across various disciplines. The modelers pointed out that by way of integrating original research from multiple disciplines, IAM simulations only have a limited capacity to generate new primary knowledge—or reduce the uncertainty—in any of these contributing disciplines. Instead, the new knowledge that IAMs create concerns the interactions between the different pieces of the system that are studied in various disciplines.

Secondly, due to uncertainty in theory and empirical data, the interviewed modelers argued that IAM simulations should not be treated as generators of 'predictions' or 'truth.' Instead, the information that IAM simulations provide, they argue, should always be considered conditional upon the specific set of assumptions that underpin model construction. In other words, IAM simulations explore 'what-if' scenarios: if one believes the assumptions, then this is the result.

Modelers emphasized that the advantage of running models over writing static reports about climate policy is that models allow for changing these underpinning assumptions relatively easily when exploring the implications of a variety of viewpoints: “And I think it’s a benefit of having a model that can handle those things explicitly and work everything out under different values [...] And then you have got some new information there rather than just somebody saying ‘oh, it should be this number’ and somebody else saying ‘no, it should be that number’ ” (B). Hence, modelers thus emphasized the function of IAMs as frameworks for discussion of uncertain assumptions—in particular, normative ones. The mathematical rigor with which IAMs translate assumptions into outcomes is seen to enable a “structured debate” (D) about the desirability of alternative policy responses assuming different normative positions: “You can ask why: what is it in the model that you think is not being captured or which number is wrong? It doesn’t become so arbitrary. It is more substantive and transparent, I think, the discussion around it” (D).

Thirdly, the modelers considered policy support a key purpose of IAMs, and they found that the models are, overall, useful for that purpose. In particular, the models’ capacity to estimate the SCC renders them very important for policymakers, according to the interviewees. One modeler said that the alternative to using integrated assessment modeling to learn about the costs and benefits of climate change policy is to “toss a coin” (B). Another one argued that the models enable to go from not “having any idea” to having a ”sophisticated intuition” (C).

4.5.11 Normative model assumptions: “a treacherous field”

Asked about the purpose of IAMs, the interviewees’ responses reveal two central purposes; one interviewee (C) called them the “upstream” and the “downstream” purpose. Upstream, IAM simulations contribute to scientific research by increasing our understanding of issues in climate policy. Downstream, IAM simulations illuminate policy-relevant trade-offs and provide input to decision-making. In particular, all informants considered SCC estimates to be a crucial input to policymaking that only IAMs can deliver.

Modelers agreed that the key achievement of IAMs is that they illuminate and quantify the trade-offs inherent in climate policy. Modeler A explained that the primary trade-off in climate policy is between two different risks. If policies for curbing emissions are not stringent enough, we risk significant damages from climate change in the future. But if measures to cut emissions are too stringent, we risk the consequences of an unnecessary halt in economic development, particularly in developing countries. Making this trade-off, modeler A acknowledged, “is what ethics is about” and it is the task of public policymakers, “and in that sense public policy is just ethics, applied ethics.”

I inquired with the modelers whether it is possible for IAMs to highlight the trade-offs that are inherent in climate policy without making them. Put differently, I wanted to know: is all integrated assessment modeling inherently ethical in nature? The responses reveal that the boundary between highlighting the policy-relevant trade-offs and making these trade-offs is not always clear-cut.

Interviewees perceived some elements of IAMs to be of a purely empirical nature. Examples include observable values, such as rates of substitutability, and the projections of model variables such as economic growth and emissions. Modelers also saw other model elements as requiring normative assumptions. Yet they did not agree on a universal demarcation between positive and normative choices in model construction. Interviewees differed in their views on the extent to which some (or all) modeling choices manifest normative positions on the trade-offs inherent in climate policy. One interviewee recognized that in practice, it makes no difference to them: "I don't know what the correct discount rate should be and I don't know what the correct climate sensitivity should be. So I am going to apply ranges to both of them." Another interviewee explicitly recognized that there is a "continuum of normative versus positive aspects to problems" (C) rather than a clear boundary, and that there are "grey elements" (C) between the two.

Based on the interviews, I distinguish different types of normative choices in integrated assessment modeling. First, at the most fundamental level, multiple modelers pointed out that the decision to invest limited research time and resources on integrated assessment modeling is inherently a normative choice. Climate change is not the only complex problem facing global society today, and there are many other problems whose solution would generate great benefits for humanity. Allocating investment into research on how to address climate change is thus an ethical value judgment.

Secondly, modelers recognized that choosing economics as a decision-making framework in IAMs has ethical implications, because there are strong normative judgments intrinsic to economic methodology.[8] In particular, utilitarianism is the default starting point for evaluating social welfare in economic theory—and the interviewed modelers recognized that utilitarianism implies a powerful ethical position. Economics moreover incorporates a commitment to respecting individuals' revealed preferences. This commitment, which puts the economist into the role of an observer who describes the choices people make, rather than a judge who evaluates these choices, is often referred to in arguments about the appropriate valuation of climate change impacts.[9] The logic of economic methodology asks for eliciting people's preferences as revealed, for example, in market prices. But there is inherent ethical judgment in choosing any approach to making these modeling choices that involve assumptions about people's values. As modeler C put it: "That‘s a very, very large set of moral or ethical judgments behind that [norm]. I am comfortable with saying that I will assume that. If someone wants to argue with it, that is a good argument." One example of a modeling choice about people's values where that logic is often applied concerns the value of

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[8] See Hausman and McPherson (2006) for a comprehensive discussion.

[9] For example, climate-economist Martin Weitzman states: "An enormously important part of the 'discipline' of economics is supposed to be that economists understand the difference between their own personal preferences for apples over oranges and the preferences of others for apples over oranges" (Weitzman, 2007, p. 712).

the discount rate in IAMs. The issue is whether or not it is ethically defensible to use market interest rates to guide that choice.[10] The point is that modelers explicitly recognized the normative assumptions implicated by choosing economics as an organizing framework for IAMs because economic methodology takes controversial approaches to eliciting people's values.

Thirdly, the interviewed modelers also offered their perspectives on how to address the 'grey elements' in integrated assessment modeling—the implicitly normative judgments that may become manifested in modeling choices. The interviewees considered effective communication about model assumptions and an appropriate framing of model outputs as important measures to manage and even to mitigate the normative character of their models. Multiple interviewees stressed that model results should be presented as 'if-then' statements rather than unconditional recommendations for policy action. The latter, interviewee C explained, "most definitely is a normative kind of judgment" and "a treacherous field because of the implicit assumptions." Regarding the modeling decisions on the continuum between positive and normative, modeler C stated: "[Y]ou could say those [decisions] are normative, or you could say they are positive, or you can just say what you are doing. I am doing this and I am doing that. This is no moral judgment." Another modeler (A) suggested that what may be unethical about integrated assessment modeling is when modelers fail to make their ethical assumptions explicit: "But there are of course also models that adopt a particular ethical standpoint and present that as optimal without discussing ever what they really mean when they say optimal. And if you do that, knowing that what you are saying is a particular viewpoint without making it clear, then you can indeed call that unethical." Yet another modeler emphasized the distinction between the default version of their model, which contains their 'best-guess' assumptions, which can be easily changed, and *the model*, i.e. the hardcoded model equations that provides the stable framework for others to experiment with their own assumptions. This interviewee emphasized that there is sometimes a misunderstanding about the distinction between the model framework and the default model, and that the assumptions they make in the default settings should always be seen as flexible. Still, this modeler recognized that certain judgments may be made and hardwired in the model framework.

No matter the extent to which modelers explicitly acknowledged normative aspects in integrated assessment modeling, they tended to oppose the notion of imposing their own normative judgments on their models, and by extension, on society. Instead, they see their job as eliciting and representing the judgments of others, including other scholars, decision-makers, and society at large. The modelers' expressed goal is to build a model that is a descriptive framework useful for simulating the policy implications of alternative value judgments. Speaking about the value of the discount rate, modeler D explained: "People reveal how they trade off the future. And I don't feel that as an economist I am the one to say 'oh no, I think you should do this.' [...] [I]f we as a society make

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[10] Numerous papers by both economists and ethicists discuss the parameter's entanglement with concepts of intergenerational justice, including Page (1977), Dasgupta (2008), and Roemer (2011). This issue is also extensively discussed in the introduction to this dissertation as well as in articles #1 and #2.

a decision that we want to do that, that's fine, but [...] my job as an economist is not to make that judgment. But my job is to say what will it cost."

4.6 Discussion: Too arbitrary and too value-laden?

4.6.1 No model is objectively true

The empirical results presented in the previous section show that, indeed, IAMs are not built from theory and empirical data alone. A number of other factors such as resource constraints, intuition, and political considerations influence how model decisions are made in practice.[11] Since theory and empirical observations are the traditionally trusted elements of scientific inquiry, for which accepted epistemological conceptions of 'truth' and 'objectivity' exist, do the findings of this study validate critics in their dismissal of IAMs? Are IAMs useless because they involve choices that are not dictated by theory and empirical data? This question requires a more nuanced discussion of the purpose of models in science. While a full review of the literature on models in philosophy of science is beyond the scope of this paper, I focus more specifically on the growing body of research investigating the epistemic status of knowledge generated from one specific type of model: computer simulations.

The arrival of digital computers has enabled researchers to construct mathematical models capable of simulating the evolution of complex systems over time (Winsberg, 2003). For example, IAMs simulate the future interactions between two complex systems: the Earth's climate and the economy. Computer simulation is a process of inquiry that employs mathematical models to study complex systems (Winsberg, 2015). Simulation models are run on digital computers and "the evolution of dependent variables on the computer is said to 'simulate' the evolution of the system in question" (Winsberg, 2003, pp. 107-108). The process of simulation modeling involves "building, running, and inferring from computational models" (ibid., 107) as well as the visualization and interpretation of simulation results (Winsberg, 2015). In other words, the computation of numbers is only one part of simulation modeling; equally important parts are making inferences from these numbers about the modeled system and assessing these inferences in terms of their reliability. One may use computer simulations for heuristic purposes, i.e. as a practical method to represent, better understand, and communicate a complex problem. However, one may also use computer simulations to predict past and future data, either in the form of point values, qualitative 'ballpark' estimates, or an explicit range of values (ibid.).

Winsberg argues that the distinct features of computer simulations require new strategies for

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[11] These results broadly confirm findings from the empirical STS literature on the influence of social and technical factors on the practice of modeling in science and scientific practice in general (Latour and Woolgar, 1979; Knorr-Cetina, 1999; Shackley et al., 1999; Shackley and Wynne, 1996; Shackley et al., 1998; Lahsen, 2005).

justifying the knowledge inferred from them, because traditional mechanisms of justification do not apply.[12] The reason, Winsberg argues, is that inferences from computer simulations have three specific features: they are downward, autonomous, and motley. First, computer simulations are constructed in a *downward* fashion with an established theory as the starting point. Computer simulations apply existing theories in that they "transform theoretical structures into specific concrete knowledge" about the modeled systems (Winsberg, 1999, p. 275). Hence, justifying inferences from computer simulations is not about establishing theory (a traditional concern of philosophy of science), but justification of a specific *application* of that theory. At the same time, the downward character of computer simulations also implies that the knowledge inferred from these simulations cannot be automatically justified by reference to the underlying theory because it is partly autonomous from that theory.

Secondly, computer simulations create knowledge that is also partly autonomous from observable empirical data. Sanctioning model assumption and simulation results by comparing them with observable data is often impossible as computer simulations are commonly employed as a substitute for scarce or missing observations (Winsberg, 2015). That is why Morrison and Morgan (1999) describe models as partly autonomous from both scientific theory and empirical data.

Thirdly, Winsberg (2009) argues that inferences from computer simulations are motley, because constructing computer simulations is a creative and contingent process that involves various ingredients aside from scientific theory and empirical data, including "the blood, sweat, and tears of much trial and error" (p. 837). The translation of scientific theory and empirical observations into a set of mathematical equations and, ultimately, a string of solvable computer code does not follow a deterministic formula. The motley character of the model-building process has been recognized by other philosophers of science as well. Boumans (1999) compares economic modeling to the act of "baking a cake without a recipe", because it requires mixing together various ingredients including theory, empirical data, pragmatic considerations, mathematical techniques, idealizations, intuition, and computer hardware. The diverse model ingredients are held together by the unifying language of mathematics. Sometimes, constructing a solvable computer simulation may even require a deliberate deviation from the truth. For example, Winsberg describes processes of parametrization in physical models that are necessary to construct a solvable mathematical model, but that resemble "pieces of fiction" rather than empirically substantiated scientific facts (Winsberg, 2010). He argues that such incorporation of untrue, fictional model assumptions does not inherently imply that the inferences from simulation results are not valid or trustworthy. In fact, such assumptions may be necessary to "structurally enhance poorly constrained data into models displaying coherent structures" (Norton and Suppe, 2001, p. 86).

The question that arises is whether computer simulations, due to their partial autonomy from

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[12] Winsberg's declared need for a separate epistemology of computer simulations is challenged by Frigg (2009), who argues that the existing epistemologies of modeling and mathematics are sufficient to explain knowledge generation from computer simulations. See also Parker (2013) for a discussion of this issue.

theory and empirical data—for which reliable standards of credibility exist—can ever generate trustworthy, reliable results. They indeed can, according to Winsberg (2010), who argues that simulation models derive their reliability from the credibility of the model-building techniques employed in their construction (p. 122). Modeling techniques establish credibility over time as they build a track record of successful applications. The application of particular modeling techniques or assumptions is a success, when these techniques or assumptions "produce results that fit well into the web of our previously accepted data, our observations, the results of our paper-and-pencil analyses, and our [...] intuitions" (Winsberg, 2010, p. 122). Over time, modeling techniques come to "carry with them their own credentials" (ibid., p. 45). Hence, we can speak of some simulation results being more reliable than others and modeling techniques growing in reliability over time.

What emerges from this brief review of the scholarly discussion is that seeking for truth—the traditional criterion for evaluating the quality of scientific research—proves to be less relevant for the evaluation of IAMs in their role as decision aids for policy. While a track record of successful applications makes modeling techniques reliable, it does not make them true. But importantly, "[r]eliability, unlike truth, comes in degrees" (Winsberg, 2010, p. 134). It is well understood that scientific models never exclusively emerge from established theory and empirical data. Hence, a general verdict on the usefulness of IAMs based on the argument that their assumptions are untrue, according to the standards of truth applied to evaluate theories and observations, should be replaced by a more nuanced assessment of individual models' relative reliability. From a similarly pragmatic perspective, Knuuttila (2009) argues that modeling is a performative rather than a representational act. This means that we gain knowledge about the world from models because of the model's performance in mimicking the relevant phenomena—not due to its exhaustive representation of the target system: "I suggest that models should not be treated at the very outset as representations of some definite target systems. Instead, they could be conceived of as purposefully constructed independent objects, epistemic artifacts, whose cognitive value is due to their epistemic productivity" (ibid. 206). Models' epistemic productivity lies in providing "external scaffolding to our thinking" (ibid., p. 222) about complex and uncertain problems. In practice, model building in the face of uncertainty requires modelers to "try to make use of what is already known and understood, what provides the rationale for using as-if reasoning, analogies, familiar computational templates, and other constructive techniques" (ibid., p. 228). What Knuuttila's argument suggests is that, at any point in time, the relative reliability of a model is to be evaluated also with respect to the "ingredients" available to modelers at that point in time.

4.6.2 No model is value-free

The empirical results also show that some choices in integrated assessment modeling are vulnerable to implicit normative judgment. Again, this finding raises the question: should IAMs indeed be discredited from providing policy advice because they are not value-free and thus open to bias and manipulation? Again, I turn to current literature in philosophy of science to explore this question. In particular, I am interested in the discussion of implicit, unexamined value judgments in science and scientific modeling in particular.

Conducting scientific research (such as building an IAM) requires scientists to make choices at different times in the process. The way in which scientists address the choices they face in their research tells us something about their values—what they consider to be important or significant about the topic (Machamer and Wolters, 2004a, p. 2). Often, a distinction is made between epistemic values such as objectivity, accuracy, and honesty. Epistemic values are concerned with bringing us closer to true knowledge. In contrast, non-epistemic values include political, emotional, and ethical values. There is general agreement among philosophers of science that non-epistemic values inevitably influence two types of choices in scientific research: choices about what research questions are worthwhile asking, and choices about how to use research results (Machamer and Wolters, 2004a). Indeed, as discussed earlier, the modelers interviewed for this study clearly identified these two types of choices as normative choices in the modeling process.

There is less consensus among philosophers regarding the types of values that drive the numerous choices that occur within the scientific process itself—on the way from research question to research results.[13] Those who defend the idea of a value-free science argue that this process can—and should—be exclusively driven by epistemic values. Opponents of this value-free ideal suggest that scientific practice can never be free of the influence of non-epistemic values; some scholars even propose that, in certain cases, the application of non-epistemic values in policy-relevant science is necessary and desirable (Longino, 2004; Douglas, 2009).

Douglas (2009, p. 103) argues that researchers investigating policy-relevant issues have a moral obligation to take the social implications of their work beyond academia into consideration when assessing the certainty of their claims. Specifically, researchers must be aware of the consequences of erring in their assessment of uncertainty. For example, if climate economists underestimate the likelihood of extreme climate events in their models, this may lead policy-makers to reject more ambitious mitigation and adaptation policies. The lack of policy ambition may then have harmful consequences if these extreme events actually occur. Douglas assigns moral responsibility to scientists to consider the risks associated with being wrong in their research decisions, recognizing that this is a moral issue that must be assessed using moral, rather than epistemic, values: "But we must keep in mind that the judgment that some uncertainty is not important is always a moral judgment" (ibid., p. 85). The quality of the available evidence should be subject to an open, naturally value-laden debate about "where the burdens of proof should lie" (ibid., p. 113).

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[13] The philosophical debate about the adequate role of value judgments in scientific research dates back to the infamous exchange between Rudner (1953) and Jeffrey (1956) in the 1950s. A comprehensive review of the literature on the topic produced since then is beyond the scope of this paper, but is provided elsewhere (see, for example, the contributions in Machamer and Wolters (2004b)). Here, I briefly review a few recent contributions to the debate, with a particular focus on the influence of values on decisions in the development of simulation models to inform policy-making.

While Douglas explicitly acknowledges that science is never value-free, because values influence our judgment of uncertainty (and rightly so), she also argues that “unacceptable, politicized science occurs when values are allowed to direct the empirical claims made by scientists” (Douglas, 2009, p. 113). Scientists must not ignore evidence or manipulate empirical evidence to align their findings with their political leanings. Like Machamer and Wolters (2004b), Douglas argues that values should only have a *direct* influence in the very early stages of the scientific process (in choices of research questions and ethical research methodologies) and at its very end (the decision about how to use scientific findings).

In direct response to Douglas, Betz (2013) defends the value-free ideal in science for policy, arguing it is generally desirable and often achievable in practice. Betz claims that transparency about uncertainty and careful articulation of research findings eliminate the necessity of consulting non-epistemic values in research choices. He suggests that researchers should openly acknowledge the limited empirical data and theoretical understanding that their work is based on, e.g. by working with ranges of observational input data and running alternative models in parallel (Betz, 2013). Researchers should also explicitly communicate the uncertainty surrounding their research findings, report ranges of output values rather than point estimates, and possibly frame their findings in conditional ‘if-then’ statements. Hedging uncertain results through such epistemic qualification and conditionalization, Betz argues, does not compromise the results’ policy relevance but eliminates risks associated with being wrong in the assessment of uncertainty. Transparency, epistemic qualification, and conditionalization relieve researchers of the need to apply social values in that assessment because their “hypotheses are sufficiently weak, or can be further weakened, so that the available evidence suffices to confirm them beyond reasonable doubt” (ibid., p. 214). Presented with such “hedged hypotheses” (ibid., p. 212), it is the policy-makers’ task to make the normative value judgments about the acceptable level of risk. But Betz admits that, in practice, “[s]cientists may lack the material or cognitive resources to identify all uncertainties [in their research], make them explicit and carry out sensitivity analyses” (ibid., p. 219).

Addressing the occurrence of value judgments in climate modeling, Winsberg (2012) argues (similarly to Douglas) that modeling under uncertainty inevitably involves social values. He suggests that, due to uncertainty, numerous methodological modeling choices are ‘unforced’ on purely epistemic grounds, which means that, based on theory, empirical data, and epistemic values alone, no unambiguous choice can be made. “Rather, most choices will be better in some respects and worse in other respects than their alternatives, and the preference for one over the other will reflect the judgment that this or that respect is more important” (ibid., p. 130). In these cases, social values are drawn on to fill the void, preventing models from succumbing to complete arbitrariness. Winsberg emphasizes, however, that modelers commonly make these value judgments unconsciously, implying that a clear separation between epistemic and normative choices in the modeling process is impossible.

Parker (2014) disagrees with Winsberg for two reasons. First, Parker argues that pragmatic factors rather than social values will govern epistemically unforced choices in model development. For example, modelers may choose methodologies that they are more familiar with, are easier to implement, or are more highly respected in the peer community (ibid., p. 27). Second, Parker also argues that, given that uncertainty prevents precise probability estimates, it is common practice to use coarser verbal uncertainty measures such as 'likely' vs. 'unlikely' when presenting model results instead of "artificially precise" (ibid.) quantitative estimates. Even if non-epistemic values influence modeling choices, Parker argues, results that are expressed in such coarse uncertainty categories are unlikely to change much as a consequence considering that model outputs are so uncertain in the first place. In other words, social values may feed into the modeling process but their impact on results is likely negligible relative to all other uncertainties. And yet, Parker eventually suggests that non-epistemic values will still influence choices about how to model uncertainty and how to communicate uncertain model results. In particular, Parker recommends exercising caution in statements about the (un)certainty of model results, which will give modelers confidence to fully own their findings: "In more general terms, the source of the difficulty here seems to be that sometimes experts are willing to *offer* uncertainty estimates that they nevertheless are not willing to fully *own*, i.e. that they would agree are (in one or more ways) inaccurate depictions of the extent to which current understanding can constrain their expectations about future climate change" (ibid., pp. 29-30).

In short, all authors reviewed here generally agree that, in practice, value-laden judgments are to some degree inevitable in the production of policy-relevant science—some argue that they are even desirable. Both Betz (2013) and Parker (2014) moreover recommend transparency about assumptions and a cautious presentation of results as effective responses to the acknowledgment that value-laden modeling choices are to some degree inevitable. Douglas (2009) calls for an open discussion of value-laden decisions about uncertain evidence and its social, moral, and political implications. In the context of IAMs, these demands for transparency, caution, and deliberation assume that modelers are aware of when non-epistemic values influence their modeling choices or when modeling choices have moral, political, or social implications beyond academia. Such awareness is certainly present for some modeling choices, as the interviews illustrated, but there may be other implicit value-laden choices that are not easily detectable. In her work on the topic, Tuana (2010) speaks of these choices as intrinsic, coupled epistemic-ethical choices[14], and she recommends closer collaboration between researchers in policy-relevant fields and philosophers of science to create greater sensitivity for implicit, intrinsic normative judgments.

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[14] Article #1 in this dissertation identifies and discusses a number of concrete examples in IAMs.

4.7 Conclusion: A pragmatic assessment

This study investigates the usefulness of IAMs for informing climate policy. The empirical research conducted for this study indeed indicates that IAM development is influenced by various factors outside of established scientific theory and empirical observations. My findings also show that modelers generally acknowledge that there is no sharp dichotomy between positive and normative modeling choices. Do these discoveries prove the critics right and disqualify IAMs from policy use? Not necessarily. The criticism is implicitly based on the expectation that, to be fit for policymaking, models must be 'objective' in that they are exclusively based on established theory and empirical data. And they must also be 'value-free', which means that they must be independent of non-epistemic value judgments. But in the context of current debates in philosophy of science, these high expectations from IAMs appear unjustified. Because our knowledge about climate change and its interaction with human life is uncertain, all scientific models of these phenomena necessarily involve ingredients outside of theory and empirical data. And since scientific uncertainty about climate change is moreover paired with controversies about the how to evaluate the limited knowledge we have, such models are also necessarily influenced by non-epistemic values. These features of models are not exclusive to IAMs and—from a pragmatic perspective—do not make IAMs inherently useless for policymaking.

The purpose of IAMs is to provide information that is useful for practical decision-making on climate change policy. Since climate change is a problem that is uncertain and complex, and that possibly leads to catastrophic consequences for human society, practical responses to climate change will inevitably involve the management of risks and uncertainty as well as significant ethical judgment and complex political negotiations. Our knowledge about climate change, in terms of both the theories describing its causal processes and empirical observations, are incomplete and will likely remain so. Moreover, climate change is a moral and political issue and the value conflicts and political disputes linked to climate policy decisions will likely persist. Yet, despite these challenges, there is pressure on governments to respond (even if that response is to not take action at this point) and policymakers need information to make these decisions. Independent of the chosen method, generating policy-relevant information about climate change will have to manage the existing gaps in our knowledge as well as the moral and political dilemmas associated with climate change. These features of the problem inherently entail a degree of freedom and valueladenness in policy-relevant evidence. Any alternative methods for generating policy-relevant knowledge will not be immune to these challenges—there is no way around the difficult questions that humanity is facing. It would therefore be naive and misleading to hold on to the technocratic ideal of disinterested scientists delivering certain and value-neutral information to representative policymakers (Edenhofer and Kowarsch, 2015).

For pragmatists in the tradition of John Dewey, Charles Sanders Peirce, and William James, these epistemological observations apply to all scientific knowledge; pragmatism never considers knowledge to be infallible or everlasting, and it rejects a clear dichotomy between facts and values (Hookway, 2016). Due to limited space, I focus on a brief review of the key features of pragmatist philosophy that are most relevant in the context of this argument. I particularly draw on Dewey's account of scientific inquiry.[15] In Dewey's account, scientific research is problem-oriented; the process of inquiry begins with the identification of a problem and it ends when an actionable solution to that problem is found. Hence, the goal of scientific research is never merely to better understand a problem, but to actively *change* the undesirable situation. Having identified the problem, the process of inquiry then continues with a detailed definition of the problematic situation, which enables the proposition of hypotheses for addressing it. The problem definition, Dewey recognizes, is not value-free; it is inevitably shaped by the culture and social life that the researcher is embedded in. Once the possible solutions to the problem are identified, the most intellectually challenging step in Dewey's process of inquiry follows, namely the critical and careful consideration of these hypothetical solutions with regards to their potential direct and indirect consequences. Ultimately, a choice is made about the appropriate course of action, and the chosen solution is put into practice. For socio-political inquiries, this means the introduction of policy. Particularly in situations where disputes exist about which course of action to take, these choices involve making trade-offs between conflicting values. Such trade-offs, Dewey's pragmatism contends, should be made "entirely on the basis of their consequences" (Brown, 2012, p. 299). Considering that the problem definition already is not value-neutral, the choice of a solution is not free of value judgments either. In fact, according to Dewey, a clean separation between facts and values in scientific inquiry is impossible. Instead, he sees fact-value distinction as a gradual matter: "[t]here are, of course, relatively more or less practical judgments in which evaluation plays a major or minor, explicit or implicit role" (ibid., p. 300). The final step of inquiry is the evaluation of the implemented solution—how well has the problem been resolved? The assessment of a particular solution is always relative to the specific inquiry and subject to change over time. Yet the outcome of scientific inquiry can still be considered a "warranted assertion" (Dewey (1938) p. 16-17, seen in Brown (2012), p. 297) if it was indeed determined via a careful and thorough reasoning process. In sum, Dewey's theory of inquiry proposes to judge the results of scientific research not based on their 'truth' but based on the *process* through which they were obtained. Moreover, the 'warranted assertions' generated from research are not universal, but relational, situated, and not immune to being challenged and replaced over time. Since the results of scientific inquiry inevitably lead to change in the world and involve judgments about future actions, inquiry is never value-free. Where values collide about the appropriate response to an identified problem, pragmatism suggests that the alternative options be evaluated based on their practical implications.

Applying these insights from pragmatist epistemology to IAMs, it becomes clear that the purpose of IAMs, arising from the need for making decisions on climate policy, must be considered in the evaluation of the models and their results. Put differently, because the purpose of IAMs

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[15] The following owes much to the insightful interpretations and discussions of Dewey's logic of inquiry by Brown (2012) and Kowarsch (2016).

is to contribute to practical problem-solving—and not to produce infallible true knowledge—the adequacy of IAMs must be evaluated in the light of that purpose. In line with this pragmatic approach, Edwards (2010) argues that comprehensive models of climate change will never be "a perfect image" of reality and we should therefore stop "trying to make them so" (p. 354). Despite the uncertainty, policymakers are now making decisions that may markedly influence the trajectory of climate change far into the future, and in these choices, Edwards argues that the "models give them the best information they are likely to get" (ibid., p. 435) as they "offer the only practical way to discern the effects of policy choices about climate change" (Edwards, 2001, p. 63). IAMs may be imperfect and flawed, but they are available now and they do achieve their intended purpose: in practice, they provide evidence to inform action on climate change. Of course, both modeled evidence and the chosen course of action are subject to change over time. IAMs also offer a framework for a public debate about the implications of the available evidence, as called for by Douglas (2009), as well as an opportunity for natural scientists, social scientists, and philosophers to come together and unpack the multilayered judgments underpinning modeling choices, as suggested by Tuana (2010). Evans (2000) introduces the metaphor of models as "discursive spaces" in his argument in favor of using models in policymaking—despite their inherent biases and their inability to provide unambiguous numerical solutions. In particular, when multiple different models are used, Evans argues that these models come to function as discursive spaces in which the public can come together to discuss the different value judgments and assumptions that make the models diverge. In contrast, "announcing that nobody really knows what's going on," Edwards (1996) argues, "is defeatism, masquerading under the guise of populist democracy, that will at best only perpetuate the status quo" (p. 556). Actors opposed to making any deliberate decisions on climate change action may exploit any doubt raised about the reliability and trustworthiness of the available methods for generating knowledge about climate change. As such, criticizing IAMs may become part of a political strategy aiming to discredit any climate policy. Interestingly, Pindyck (2013), in his devastating review of IAMs, also ultimately comes to the conclusion that his criticism of the models must not be seen as a justification for non-action.

Pragmatism also implies a focus on the process of reasoning in the assessment of IAMs. This focus is of course reflected in Winsberg's approach to establishing reliability of computer simulations referenced in this article (Winsberg, 2003, 2010). Winsberg argues that computer simulations gain credibility vicariously through the credibility of the techniques used in their construction, meaning that the process of choosing construction techniques for these simulations has important implications for the trustworthiness of the model results. Winsberg is well aware that, again in line with pragmatic philosophy, a positive track record does not mean that modeling techniques are true or infallible—simply that they are relatively reliable for the time being. A pragmatist focus on process is also reflected in the empirical component of the present article, which explicitly aims to learn more about the modeling process and the factors that shape it as a means to better understand the merit of model outcomes. Interestingly, the modelers interviewed for this study do not advertise their models as 'truth-machines' either, but see them as devices for thinking through ‘what-if’ scenarios, thus providing a framework for discussion. Also in line with a pragmatist perspective, the modelers do not hold a view of their models as value-free. But they acknowledge, if to varying degrees, the inseparability of empirical and normative modeling aspects.

In sum, IAMs are an imperfect and provisional solution to a complex problem. And while this study did not identify ‘red flags’ to the use of IAMs for policymaking, multiple challenges associated with the development of IAMs have been diagnosed, that may prevent the models from providing legitimate ‘discursive spaces’ for deliberating climate policy. The challenges include funding issues, unexamined path-dependence in model development, and a lack of clarity and transparency around positive vs. normative modeling choices. Having argued that, in principle, knowledge generated from IAM simulations should not be outright dismissed as invalid for policymaking, it is important to invest in addressing these challenges. To this end, I conclude with a non-exhaustive list of practical recommendations.

(1) Define criteria for evaluating and comparing the ‘fit for purpose’ of different IAMs for policy support. Adopting a pragmatic approach, it is clear that the absolute ‘truth’ criterion is inappropriate. Instead, model usefulness is a gradual and relative performance measure. *Relative* model objectivity and *relative* value-neutrality may be appropriate indicators, but the results of this study imply that transparency and caution in the communication of model assumptions and results may be equally important evaluation criteria. Cash et al. (2003) suggest credibility, salience, and legitimacy as general quality criteria for the evaluation of integrated assessments. Kowarsch (2016) extends this list, arguing that scientific policy advice should be (1) based in sound science, (2) policy-relevant, (3) effectively communicated, and (4) politically legitimate (p. 26) These generic lists may not be conclusive; there may be other and more refined criteria with regards to IAMs in particular. Moreover, the appropriate criteria may change over time as we gain additional knowledge about the problem.

(2) Develop a strong “knowledge infrastructure” for IAMs. Instead of aiming to prove the truth of models (an elusive goal), according to Edwards (2010), we should build a robust “climate knowledge infrastructure” (p. 432) by strengthening the mechanisms that make models more trustworthy as instruments for knowledge generation: peer review, the integrity of scientific discourse, and institutions for the governance of science (such as the IPCC) that promote “controversy within consensus” (ibid., p. 427). A strong knowledge infrastructure should help the community to build the successful track-record of model-building techniques that Winsberg (2010) proposes as the key mechanism for building model reliability. But it should also constantly challenge these apparent accomplishments to prevent occurrence of inertia and path dependence and to ensure that the models’ ‘warranted assertions’ are not mistaken for universal truths. Risbey et al. (1996), Schwanitz (2013), Kloprogge et al. (2011), and Jakeman et al. (2006) contribute to establishing such a knowledge infrastructure for IAMs. These practical approaches focus on developing standardized procedures in the modeling and simulation process, enhancing transparency, and establishing sys-

tems of accountability toward academic peers and other stakeholders. For example, Risbey et al. (1996) argue that quality control requires modelers to apply greater scrutiny when "anchoring [new model outputs] on past results" (p. 392) in order to avoid path dependence. The authors also recommend a diversification of funding sources and of disciplines involved in IAMs. They further consider the establishment of "informal fora for open discussions of problems that arise in IA modeling" (ibid., p. 393) as effective means for identifying common quality standards. Schwanitz (2013) develops a practical framework for evaluating the robustness and trustworthiness of IAMs based on a seven-step evaluation hierarchy: (1) setting up an evaluation framework, (2) evaluation of the conceptual model, (3) code verification and documentation, (4) model evaluation, (5) uncertainty and sensitivity analysis, (6) documentation of the evaluation process, (7) communication with stakeholders. Schwanitz moreover suggests that the existing Integrated Assessment Modeling Consortium (IAMC) is an appropriate forum for developing community wide standards for modeling and evaluation. Jakeman et al. (2006) present a list of basic steps that should guide environmental modeling practice. The authors emphasize that open communication with stakeholders at every step of the modeling process may create important learning opportunities for all parties involved.

(3) Invest in the primary research that informs IAMs. My empirical research indicates that a lack of primary research limits the scope of IAMs and increases the degrees of freedom in the modeling process. Enhancing comprehensiveness and reliability of the underpinning theories and empirical data will help.

(4) Provide models with stable funding. This will enhance their intellectual independence and enable model updates when new knowledge from primary research, rather than new funding, becomes available. Moreover, adequate funding for model development can create incentives for diversifying approaches and for experimenting with different assumptions.

(5) Investigate the 'grey elements' between positive and normative modeling choices. To uncover the implicit normative assumptions made in IAM development, Tuana (2010) suggests involving philosophers of science in the model development and simulation process.

(6) Explore alternative decision-support tools outside of mathematical simulation modeling. Pursuing a portfolio of alternative methods for generating policy-relevant knowledge may help grasp the full complexity of the problem and inform the society-wide discussion about the substance of values that should inform any assessment of global climate change (Jamieson, 2010). Alternative methods include *inter alia* alternative quantitative models such as agent-based models (e.g. Nannen and van den Bergh (2010)) and co-evolutionary models (e.g. Crépin et al. (2011)); qualitative assessment methods such as structured qualitative comparisons of costs and benefits (e.g. van den Bergh (2004)) and qualitative scenario-building (e.g. Stern (2013)); and informal methods such as expert panels as well as heuristic principles such as the precautionary principle (e.g. Iverson and Perrings (2012)) and the minimax regret principle (e.g. van den Bergh (2004)). Parson (1997) also mentions policy exercises, simulation-gaming, and scenario exercises as deliberative alternatives to

representational modeling.

Chapter 5

Conclusion: Modeling climate change impacts at the science-policy boundary

5.1 Summary of findings

This dissertation provides an innovative, interdisciplinary examination of the various inputs and outputs of climate-economic integrated assessment models.

Regarding the inputs, the three articles highlight that integrated assessment modeling—far from being a deterministic procedure—follows its own logic. It is a contingent and negotiated process, situated in a particular time and place. I disentangle the numerous factors influencing model development and driving modeling decisions. From a largely theoretical perspective, article #1 outlines the epistemic, ethical, and political contexts in which IAMs are developed and that shape modelers' choices. Based on empirical data, article #3 elaborates in greater detail on what these contexts look like, identifying a set of specific factors that influence modeling choices: epistemic norms, technical factors, other resource constraints, career incentives, political factors, and subjective factors. While previous model studies, the existing literature in the relevant fields, and the general norms of good scientific conduct provide modelers with some parts of a recipe, intuition and expert judgment still play an important role. Importantly, these findings indicate that individual model choices are likely shaped by a mix of various factors. My findings also suggest that the various factors influencing modeling choices in IAM development are not independent of each other. In fact, article #1 suggests that the epistemic, ethical, and political contexts in which modeling choices are made are interrelated. Similarly, in article #2, I identify the environmental worldviews that become manifested in models, where an environmental worldview is defined as a coherent combination of epistemic beliefs and ethical values regarding environmental change. Moreover, article #3 illustrates that some modeling choices require modelers to make trade-offs between the various factors. Examples are decisions about model scope and the degree of model complexity. Technical constraints imposed by programming language and computational capacity specifically contribute to triggering such trade-off situations in the modeling process.

Regarding model outputs, this dissertation investigates how the effects of IAMs on policy and politics may reach beyond the mere delivery of numerical model outputs in response to specific policy design questions. Article #2 illustrates how IAMs are used for telling stories about the policy problem of climate change and its possible solutions. Examining these modeled stories and the environmental values and beliefs underpinning them represents a new and necessary approach to studying how models influence policymaking—whether they are IAMs or models of public health, or the economy.

But ultimately, I find that a clear separation of model inputs from model outputs is not as straightforward as it may seem. Articles #1 and #3 highlight that positive feedback loops may create path dependence. Here, past modeling choices establish epistemic benchmarks, ethical norms, and expectations from editors and policymakers, which incentivize modelers to make similar or only incrementally different modeling choices in the future. Hence, modeling choices reinforce the same benchmarks, norms, and expectations that motivated them in the first place. For example, the stories told with four versions of the DICE model examined in article #2 promote the market-liberal perspective on the policy problem of climate change. This perspective favors carbon pricing as a policy solution. Implementation of such measures would in turn increase the demand for studies produced with the very same type of models. Such path-dependent dynamics may constrain the evolution of individual models over time and also lead to convergence within the entire fleet of IAMs. However, as argued in #3 it is important to withstand these tendencies and keep the modeling process as open as possible in order to appropriately represent the high level of scientific and ethical uncertainty in the field. Uncertainty calls for a large variability in modeling approaches to optimally inform decisions on climate-policy.

These results seem to underscore the inherent flaws of IAMs—their arbitrariness and value-ladenness. Many critics of the models' use as policy aids base their criticism on these two points. Yet this dissertation also provides an argument in favor of continuing the investment in IAM research in the future. From philosophy of science, we know that models are never objective, as they are never exclusively based on established theory and empirical data. We are also aware that models are never value-neutral. Instead of striving unrealistic ideals, I suggest—in line with pragmatism—to 'work with what we have', which means to use our knowledge of the imperfections of IAMs to constructively work on improving the usefulness of the models as decision aids. We need investment both in the improvement of the models as well as in our *meta*-understanding of how the models are developed and used. This dissertation, of course, contributes to the latter research program.

The concept of co-production serves as the central analytical framework of this dissertation. IAMs appear in this account as both a product and an instrument of co-production. They are a product of a particular favorable interplay in the late 1980s between progress in computer technology, increasing momentum in international climate policy, and progress in the underlying sciences as well as in mathematics. Conversely, IAMs are also instruments of co-production, because they stand in the centre of mutually interdependent subsystems of society—science, policy, and politics. While climate policy and politics, together with technology, influence model construction, the modeled evidence feeds back into the policy process and thus may become an instrument in climate politics.

5.2 Where next?

Reflecting on my findings, I recognize that this dissertation raises many questions without resolving them. I am tempted to use this final chapter to muse at length about the many fascinating dissertations still to be written about IAMs, and policy-relevant scientific models more generally. Instead, I focus on three issues I consider particularly interesting and fruitful subjects for future research. These three issues also show how this dissertation contributes to the three main bodies of research informing it: political science (vis-à-vis the science-policy interface), STS (policy-relevant scientific models), and moral philosophy (climate change ethics).

Different models, similar issues

The first research project I suggest relates to the transferability of the insights gained in this dissertation to other scientific models used in other policy areas. Such areas include economic governance, governance of global environmental change (other than climate change), and health governance. While the role of computer models in the former two is comprehensively discussed elsewhere (den Butter and Morgan (2000), MacKenzie (2006), Morgan (2012) and Beven (2009)), here, I focus on mathematical modeling in health governance. Specifically, I refer to a recent book on the topic, written by the social scientist Erika Mansnerus, as a concrete example for outlining a future research project that applies and expands the findings of this IAM case study to examine policy-relevant models in public health governance.

The work by Mansnerus (2014) concerns the development, use, and evaluation of "[m]athematical models and simulation techniques [that] have been developed and used to predict, prevent, and study infectious risks" (p. 2). For example, these models and techniques are employed to predict pandemic outbreaks, simulate the spreading of diseases, and calculate the effects of preventive vaccination programs. Like IAMs, these models are multi-disciplinary and computer-based, and they provide decision-relevant information on a topic that is characterized by a high level of scientific uncertainty, high risks, and value disputes. Also like IAMs, the outputs from these models are used as substitutes for unavailable empirical data points. Finally, like IAMs, these models have inherent limitations. For example, both IAMs and the models studied in Mansnerus' work fall short in representing social, qualitative aspects of the respective problem, as "they at best predict the future by modelling the past" (ibid, p. 4). Her overall perspective on models is critical: "Yet, the limitations of model based evidence have not been fully explored. We remain impressed by their fluency and forget to examine how *the uncertain* becomes *certain* through this computational machinery" (ibid., p. 2, italics in original). The author's aim with her book is to "critically assess what lies underneath their authority" (ibid., p. 5). In that sense, this dissertation and Mansnerus' work have many common interests: both investigate the double function of computer models as investigative devices in research and policy aids. Yet, I do not believe that these similarities render the two streams of research redundant.

I see great opportunities for these bodies of research to complement each other in future research endeavors, partly because the works use mostly different analytical frameworks, often work at different scales of analysis, and provide complementary insights on the evolution of models over time. While the guiding framework for this dissertation is the idiom of co-production of science and policy, Mansnerus uses the metaphor of the 'life cycle' of mathematical models in epidemiological research as an overarching organizing concept for her book. Accordingly, she studies the models' origins, their 'forefathers' in biology and chemistry, their early development, the relationships between 'family trees' of models, the models' 'working life' as decision aids in public health policy, and ultimately, the models' retirement when they cease being useful. Within the 'life-cycle' analogy, Mansnerus explains how pieces of modeled evidence are re-used in other models, creating a 'kinship' of models that involve many shared elements coming from common roots. This notion, of course, is reminiscent of the concept of modeling 'archetypes' suggested by Risbey et al. (1996) that is referenced in this dissertation by way of explaining path dependence dynamics in model evolution. Again, I believe that a reconciliation of insights here would be a fruitful exercise. While both Mansnerus' research and this dissertation work with the notion of story-telling models (drawing on the work by Morgan (2001, 2012)), and the idea that modeled stories become policy stories, Mansnerus focuses less on particular stories told with specific models, their composition, and their content. Applying the analytical framework developed in article #2 may complement the work by Mansnerus in that regard, providing a more fine-grained discussion of, for example, the different stories of propagation of an epidemic produced with different models. Similarly, Mansnerus investigates the drivers and constraints in model development, but is overall less concerned with the details of individual modeling choices or 'model ingredients', but rather examines the evolution of models over time. In that sense, one can say that this dissertation and Mansnerus investigate the issue at different scales—and that they therefore have the potential to build on each other, establishing a critical body of research on the role of modeled evidence in policymaking. Considering their policy influence, an improved understanding of how policy-relevant scientific models are developed and used, of their advantages and limitations, is indispensable.

The 'demand side' of modeled evidence

The second question is a rather obvious one: while my dissertation investigates the 'supply side' of IAMs as a tool for climate policy appraisal, a future project may take a closer look at the 'demand side' in order to find out how this information is picked up, interpreted, and employed in national and international policymaking. Taken together, the two projects would illuminate the complete end-to-end process of producing and applying models to inform in climate-change policymaking.

Canada's current federal climate policy is a timely and local example of the relevance of this research program. After years of stagnation and political stalling on climate change, the then newly elected liberal government adopted a progressive negotiating position at the Paris UN global climate summit in December 2015, and in that context also expressed a commitment to grounding their Paris climate action in "fact-based decision-making and robust science" (Government of Canada, 2016). With IAMs being standard tools for producing such 'robust' policy-relevant science, were model studies produced to inform the government's Paris position? Were IAMs run to inform the subsequent announcement in October 2016 of a pan-Canadian carbon tax regime obliging the Provinces to implement a carbon price of at least $10/t in 2018 and increase it to at least $50/t in 2022? How were these floor prices determined? What models were used to inform these decisions, and how were they selected? Who run them and with what parameter values? What policy-relevant stories were told with the models?

Current research in policy studies warns against over-estimating the influence of scientific evidence on policy outcomes (Jasanoff, 1990; Cairney, 2015). Numerous empirical studies by policy researchers show that the translation of that evidence into policy is more complex than suggested by the technocratic model: policymakers do not exclusively draw on scientific evidence to make informed decisions, but in practice, numerous actors are involved in the interpretation and application of the evidence, including researchers, bureaucrats, lobbyists, and elected politicians. All of these actors use heuristics and shortcuts to deal with complexity and resource constraints; they respond to institutional, economic, and political pressures; and their decisions may easily be influenced by their pre-existing beliefs and pre-conceived judgments. Some scholars argue that the technocratic model falls short even as an aspirational goal, as drawing exclusively on science to inform policy implies that other types of knowledge, such as community knowledge and indigenous knowledge, which may legitimately shape policy, are excluded from decision-making (Bäckstrand, 2003; Owens et al., 2004; Blowers et al., 2004). The last point is particularly interesting to me, as referenced at multiple points in this dissertation.

IAMs have inherent limitations: they assume a particular narrative of the climate problem, they likely exclude aspects of the problem that are important to some stakeholders, and they are vulnerable to manipulation. Therefore, granting models a privileged influence on policy outcomes (in line with the objective of evidence-based policymaking) relative to other kinds of knowledge entails giving priority to some stakeholder ideas and interests over others. This may create tension with another important governance objective: inclusiveness. To what extent and how does the use of models crowd out more deliberative and participatory approaches to creating knowledge, such as public consultations or participatory integrated assessment (Rowe and Frewer, 2000; Salter et al., 2010)? How can the use of models in climate policymaking be democratized to reconcile the two objectives (Ravetz, 2003)? These questions are addressed in greater detail below.

The research project I suggest as a logical follow-up to this dissertation would empirically examine the employment of policy-relevant scientific models such as IAMs in decisions on national and international policy. It would also include an evaluation of the use of these models as a means of evidence-based policymaking in relation to the objective of achieving an inclusive decision-making process. While I mentioned Canada as a specific example, a comparative approach would be particularly interesting, considering previous research on cultural differences between states regarding the integration of science into public decision-making in practice (Jasanoff, 1990, 2005). For optimal complementarity, the empirical findings would be discussed and integrated using the same co-productive framework adopted in this dissertation.

The difficult questions

This final entry point for future research is likely the most challenging—and arguably the most urgent. It concerns the value disputes and ethical controversies that are inherently entangled with the construction of IAMs. If we, as recommended in article #3, continue to use IAMs as one of multiple instruments for informing climate policy, then we cannot avoid the question: how should these value disputes be resolved in the models? For example, how should decisions about model parameters that are explicitly labeled ‘ethical’, including the social discount rate and equity weights, be made? (This is, of course, just the most obvious example; as illustrated in article #1, there are many other implicitly ethical modeling choices.) It was mentioned at multiple points in this dissertation that there exist two key approaches to setting the value of the discount rate, namely the descriptive approach and the prescriptive approach. But which is appropriate? How should this ethical uncertainty ultimately be resolved in the model?

In article #1, I illustrate that ethical uncertainty surrounding climate change is commonly classified as ontological in nature. This means that empirically measurable answers that would eliminate all ethical uncertainty, if only we knew them, do not exist. What are the implications of this classification for choosing a value or a range of values for the social discount rate? Ultimately, it requires moral relativism in order to be valid—of the metaethical kind, to be precise. Metaethical moral relativism implies that there is no absolute justification of moral judgments, but that this justification is always relative to some group of people, their traditions, convictions, and practices (Gowans, 2012).[1]

In the context of climate change, heterogenous stakeholder groups disagree about the valuation of future climate change damages. In the absence of one absolute moral truth and normative consensus, many inherently equally legitimate moral positions exist. Lockhart (2000) argues: “If

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[1] In contrast, descriptive moral relativism refers to the *empirical* observation that moral views vary significantly across different societies (Gowans, 2012). Metaethical moral relativism does not necessarily follow from descriptive moral relativism, because there may be rational resolutions to substantial normative disagreements (see Gowans (2012) for a full discussion).

fundamental moral quandaries and disagreements occur because 'moral truth' is a matter of individual or societal determination, then there are no preexisting, objective moral facts about which we can be uncertain" (p. 17). In this case, he continues "[m]oral uncertainty is a misnomer that misleads us into thinking that there is objective moral truth that we can, at least in principle, discover. We must understand that moral uncertainty is to be resolved by decision rather than by rational inquiry. And posing the problem as one of rational decision-making under moral uncertainty perpetuates the misrepresentation" (Lockhart, 2000, p. 17). If one accepts the view that moral rightness is neither universal nor rationally derivable, one has to deal with the question of what and whose moral views are and should be manifested in IAMs—hence, one has to deal with the processes through which societies legitimize certain views over others.

An intuitive response may be to call on experts—moral philosophers, welfare economists—for help. Since no absolute moral truth exists, it is not clear that these experts' judgments are any more 'right' than those of lay persons, but they understand the ethical implications of various choices and have expertise in elucidating and communicating them. This involves a review of the available evidence on the issue at hand, assessment of that evidence, and its reconciliation with alternative methods of moral reasoning (Singer, 1972).[2] A couple of examples of expert elicitations with regards to the social discount rate exist, but these surveys focus exclusively on economists. Weitzman (2001) presents the results of a survey among 2,160 economists, which comes out in favor of 'gamma discounting', a declining social discount rate over time. Similarly, in 2011, twelve economists came together for a workshop hosted by the independent research organization *Resources for the Future* to advise the US government on choosing a discount rate for evaluating the costs and benefits of climate change (Arrow et al., 2012). The voice of philosophers is missing in these assessments, despite the fact that some philosophers have published extensive discussions on climate ethics, including the discount rate issue (for example, see Chpt. 8 in Broome (2012)). Indeed, multiple authors cited in this dissertation advocate for a greater involvement of philosophers in the modeling process—or more generally, in the process of policy-relevant scientific knowledge production. Briggle and Frodeman (2016) call on philosophers to collaborate with scientists in policy assessments—not necessarily to *make* value judgments, but to force others to justify the value judgments they make. Similarly, Tuana (2010) calls for an extension of the notion of research ethics to encompass intrinsic and extrinsic dimensions (see article #1 for a more comprehensive discussion). She also demands a closer integration of philosophers in policy-relevant scientific research to help identify hidden value assumptions and ethical implications of choices in the research process. Yet the question remains whether the elicitation of experts to address the difficult value judgments in IAMs is the adequate means to resolve this issue. Or is it, in fact, a manifestation of the 'bad' side of technocracy—resulting in lack of social legitimacy? Does turning the issue over to a different set of experts really solve the problem? Maasen and Weingart (2005b) argue that the real question in normative discussions on science-policy relations is "[...] how can epistemically

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[2] It should be noted that the existence and meaning of moral expertise is not uncontroversial. See Singer (1972), Hills (2009), Weinberg et al. (2010), and Driver (2013) for a discussion of these issues.

and ethically sound decisions be achieved without losing democratic legitimacy?" (p. 3).

In order to establish democratic legitimacy, an alternative may be to leave these difficult ethical questions for elected governments to resolve, based on the scientists' presentation of alternative options. This approach is essentially pursued by van Asselt and Rotmans (2002), referenced in article #1. Here, the authors run an IAM assuming various worldviews (based on cultural theory) that determine the values of ethical parameters and they present all the options in order to enhance transparency about the implications of ethical uncertainty. Such an approach is also in line with the idea of integrated assessment modelers as 'honest brokers' as portrayed in Pielke (2007). Edenhofer and Kowarsch (2015) make an explicit call for direct participation of decision-makers and other interest groups in the assessment of climate change, as a form of 'extended expertise' (Maasen and Weingart, 2005b) or 'extended peer review' (Funtowicz and Ravetz, 1993). A large body of theoretical literature investigates the relationship between science and democracy and the democratization of knowledge production (Laird, 1993; Turner, 2001; Maasen and Weingart, 2005b; Lengweiler, 2008), and a growing body of applied research focuses on the advantages, disadvantages, and practical challenges of participatory policy assessments, and participatory modeling in particular (Lemos and Morehouse, 2005; Stirling, 2008; Salter et al., 2010; Voinov and Bousquet, 2010; Voinov et al., 2016). Drawing on recent contributions in both literatures, I will briefly address important philosophical questions underpinning the debate, as well as some practical issues pertaining to the implementation of stakeholder participation in the production of modeled knowledge.

From a theoretical perspective, the democratization of the science-for-policy process via the inclusion of stakeholders is widely considered to have important potential benefits. It can help build trust in science among citizens through greater accountability, it can improve the procedural justice of the decision-making process, and it can lead to substantively better policy decisions (Wolgar, 2000; Owens et al., 2004; Stirling, 2006). Nevertheless, Maasen and Weingart (2005b) mention a potential drawback: does a greater involvement of citizens as 'extended experts' in the assessment of climate change risks illegitimately diffuse responsibilities away from central government and onto the individual? The authors argue that "extended peer review [should] not lead to extended technocracy by way of skillfully putting citizens into service of solving the irresolvable dilemmas at the interface of science and politics" (Maasen and Weingart, 2005b, p. 16). Increased emphasis on participation may work to shift the responsibility for managing climate change onto the individual, and away from central government. This requires great, perhaps unrealistic, knowledgeability from the lay individual (O'Malley, 1996).

What may participatory integrated assessment modeling look like in practice? In the case of discount rates, the descriptive approach—observing people's preferences about inter-temporal trade-offs as manifested in market interest rates—can be considered a form of stakeholder participation in IAM building. Lynam et al. (2007) refer to this type of stakeholder interaction as 'extractive use', where researchers simply obtain and synthesize information about stakeholders knowledge, values, or preferences. ‘Co-learning’ describes a more interactive approach to involving stakeholders and citizens in knowledge production with a view to consensus building. Here, stakeholders and researchers together build a common understanding of the issue before developing and synthesizing the required knowledge (Lynam et al., 2007). Working together on IAMs (and other forms of integrated assessment) in an iterative process, both groups learn from each other and thus engage in a very explicit and intentional form of science-society co-production (Lemos and Morehouse, 2005): scientists and citizens (with the help of ‘boundary objects’ that provide them with a common language) literally co-produce scientific representations that, conversely, work to co-produce science and society.

Of course, the effectiveness of participatory modeling in terms of substantive outcomes, procedural justice, and enhanced credibility will crucially depend on *who* participates and *how* and *when* they are involved in the assessment process. Salter et al. (2010) and Voinov and Bousquet (2010) provide comprehensive reviews of experiences with participatory modeling. Potential participants include modelers, researchers from various disciplines, interest groups, citizens, and policymakers. Participants may be involved through individual or group exercises, including in-depth interviews or focus groups. Participation may be take place in one-off workshops or in a more permanent engagement. Social media and crowd-sourcing of information opens new and exciting doors for public involvement (Voinov et al., 2016). As best practices, the authors identify participatory modeling efforts that are iterative, open, representative and balanced in terms of who is invited to participate, and designed to include participants as early in the process as possible. To reap the benefits of participatory modeling, it is important that the process of knowledge production is truly ‘opened up’ to accommodate the non-expert views of participants (Stirling, 2008).

What are the challenges in participatory modeling? First, experience shows participatory exercises of this kind are best used in local contexts (Salter et al., 2010), and that may be one reason why the IPCC, for example, has not yet featured them in their reports. Participatory modeling is also resource intense; it requires a lot of time, money, and cognitive labor by all participants. Non-expert participants are often required to absorb a lot of new information and to invest a significant amount of time and effort to become familiar with the model, the computer technology, the mathematics involved, and the modeling process (Yearley, 1996). Some people may frame the problem or their views of the future in ways that are not conducive to a mathematical representation at all. Hence, as the review of the literature by Salter et al. (2010) indicates, some participatory modeling projects included qualitative components such as storylines and worldviews into the modeling experience to facilitate the participation of non-experts. But then, the mathematical integration of the qualitative information on values into models may pose a new challenge (Salter et al., 2010). Finally, participatory modeling does not necessarily prevent biased modeling choices—even if participants are well-chosen and the process is well-managed. “Confirmation bias, framing biases, steady-state bias, creeping normality, binary bias, cognitive discounting, causality bias, jumping to conclusions [...], belief in human exceptionalism and separatedness from ‘nature’, are all examples of biases that can negatively affect the pursuit of human knowledge and that need to be considered in PM [participatory modeling]" (Voinov et al., 2016, p. 211).

The latter point, in particular, relates to an emerging discourse among some scientists, described by Stehr (2013). Some climate scientists and other observers question the ability of democratic systems to adequately respond to complex and long-term global environmental problems such as climate change. They argue that ethical uncertainty and sociopolitical concerns should be given less weight in decision-making—the scientific facts alone should be considered sufficiently unambiguous to tell us what to do. Stehr (2013) discusses this controversial claim and he does indeed identify a fundamental conflict between the lack of public understanding of the complex problem on the one hand, and the illegitimacy of unquestioned expert rule in democracies on the other. Is it true that people would agree to take action on climate change if only they had a better understanding of the issue and its large decision stakes? These questions directly relate to the three models of science-policy relations discussed in the introduction to this dissertation. To what extent can and should science dictate policy? In the current climate debate, given the slow political progress at the international level and in key national governments toward setting emission reduction targets that are in line with what even the more conservative IAM-based studies recommend it may not be surprising to hear calls for a greater shift of authority from voters to experts. Technocracy as a normative vision may be experiencing a revival (Jasanoff, 2003; Maasen and Weingart, 2005b; Stehr, 2013).

Future research will be required to explore the options for meaningful participation in integrated assessment modeling. Participation of stakeholders and citizens would, of course, dramatically change the epistemic, ethical, and political contexts in which modeling choices are made. Theoretically, it would provide opportunities for model innovation and for a better appreciation of ethical uncertainty in the models, but its practical implementation would impose important challenges. In the eyes of technocrats, democracy is 'inconvenient', because despite our knowledge of the existential risks related to climate change and our understanding—incomplete but certainly adequate—of what we have to do to prevent them, democratic implementation is slow, cumbersome, and ineffective. Nevertheless, Stehr (2013) concludes: "In short, the alternative to the abolition of democratic governance as the effective response to the societal threats that likely come with climate change is more democracy and the worldwide empowerment and enhancement of knowledgeability of individuals, groups and movements that work on environmental issues" (p. 60). I agree—and hope that this dissertation makes a modest contribution to meeting this great challenge ahead.

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