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Map-makers and navigators of politicised terrain: Expert understandings of epistemological uncertainty in integrated assessment modelling of bioenergy with carbon capture and storage

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ABSTRACT

Bioenergy with carbon capture and storage (BECCS) has recently risen to international prominence due to its modelled potential to allow a mid-term temperature overshoot compensated by large, long-term removal of carbon dioxide from the atmosphere. The technology, however, is far from commercial. Therefore, BECCS is a suitable entry point for exploring how modellers identify, manage and communicate uncertainties. By applying framing analysis to 21 interviews with researchers working directly or closely with integrated assessment models (IAMs), three prevalent cognitive frames are identified: Climate scenarios as (1) talking points to discuss possible futures, (2) fundamentally political prescriptions that foreclose alternatives, and (3) distortions of pure science. The discourse around IAMs has entered a phase of critical reflection about their performative, political dimensions, both inside and outside of the IA modelling community. This phase is marked by modellers grappling with the responsibilities that are perceived to come with simultaneously providing maps of possible futures and standards by which these maps are to be evaluated.

1. Introduction

The Paris Agreement of 2015 has been viewed by experts, policymakers, NGOs and media reporters as a sign that industrialised and industrialising countries are finally ready to tackle the responsibility of dealing forcefully with climate change. At the same time, however, it stimulated an intense critical discussion within the scientific domain about the scientific validity of the ambitions stipulated in the agreement, especially the reliance on carbon dioxide removal (CDR) technologies and net negative emissions, such as bioenergy with carbon capture and storage (BECCS), to limit warming to well below 2 °C, aspiring to hold it at 1.5 °C. In fact, most scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) can reach neither the 1.5 °C nor the 2 °C targets without a temporary temperature overshoot that is balanced by CDR during the second half of the century (Anderson & Peters, 2016; Creutzig et al., 2015; Geden, 2015).

At the centre of the critical debate are integrated assessment models (IAMs), a form of advanced computer modelling that

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integrates and links energy, economic and climate systems in order to produce results of high policy relevance (Anderson & Peters, 2016; Laude, 2019). IAMs have long been prominent in climate science and the IPCC is paying close attention to what the scientific literature has to say about IAMs and climate scenarios (Beck & Krueger, 2016; Schneider, 1997). The critical post-Paris discussions have revolved around whether these models rest on unrealistic or arbitrary assumptions, whether the IA modelling community's close association with the policymaking sphere is opening up the models to political influence, and whether the inclusion of negative emissions technologies (NETs) such as BECCS in a substantial number of scenarios constitutes a moral hazard (e.g. Anderson & Peters, 2016; Ellenbeck & Lilliestam, 2019; Geden, 2015).

This critique is in fact a continuation of a critical discussion about the specific problems associated with IAMs that has been ongoing for at least two decades, and in which IA modellers themselves have often taken part in critical self-evaluation (Beck & Krueger, 2016; Creutzig et al., 2015; Fuss et al., 2014). Due to the complexity of integrated modelling, IA modellers must handle a multitude of uncertainties concerning evaluation, boundary conditions, parameterisations, input values and feedback representation. At the same time, choices about such aspects have ethical and political implications (Ellenbeck & Lilliestam, 2019; Friman & Strandberg, 2014), which grow in importance as IAMs become increasingly influential.

Beginning with the understanding that, despite their prevalence in policymaking contexts, IAMs are still under-researched both theoretically and empirically in the social sciences (Beck & Krueger, 2016), the aim of this paper is to explore and analyse understandings of uncertainty in modelling and the relation between modelling and climate policy among IA modellers, climate, energy and earth system modellers, and other researchers who have worked closely with IAMs. The study contributes empirically through interviews with 21 researchers, and identifies and analyses views on uncertainty, scientific validity and researchers' responsibility for communicating uncertainties in their interactions with policymakers, especially in relation to BECCS since it recently has become an important component in IAM and the construction of climate stabilisation scenarios. We will also discuss how these differences among the researchers can be understood in terms of three idealised cognitive frames. In the concluding section we will reflect on how the prevalence of political issues in experts' sense-making of IAMs indicates that the field is leaving what Hamilton et al. (2015) characterise as the maturity phase and instead has entered a new politicised phase.

We use the concept of the 'cognitive frame' to capture the notion of such understandings, which are individually held, but drawn from a common repertoire of social representations upon which individuals can create their own understanding of an issue (see also Ellenbeck & Lilliestam, 2019). Cognitive frames, in this understanding, are a structuration of meaning in relation to a specific issue, i.e. "a central organizing idea or story line that provides meaning" (Gamson & Modigliani, 1987, p. 143; see also Goffman, 1974). The notion of cognitive frames that give meaning to the world of IAMs is helpful for two reasons: First, it captures the active practice of cognitive structuring and restructuring that can be expected to follow from the vocal problematisations of IAMs in recent years. Secondly, it indicates the social nature of representations, as something that can be held by several individuals, and the possibility for individuals to shift between different frames. While the models are inscribed with the social representations held by individuals and specific expert professional cultures, these models will be influential in forming the wider representation of climate change and how societies could act upon it. We will return to this complex and potentially dilemmatic relation in the method section and also in the concluding words of the paper.

2. Background

This chapter provides a brief background to IAMs and their prominent position in the IPCC context, presents different perspectives on IAMs and critique that has been forwarded within the social sciences. The second section narrows down to the current debate on how BECCS is included in IAMs. Several of the topics presented here also surface in the interviews and are developed further in the analysis.

2.1. Integrated assessment models in general

The IPCC describes integrated assessment as a method of analysis that "combines results and models from the physical, biological, economic and social sciences and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it" (IPCC et al., 2014). Further, it states that:

> Integrated models explore the interactions between multiple sectors of the economy or components of particular systems, such as the energy system. In the context of *transformation pathways*, they refer to models that, at a minimum, include full and disaggregated representations of the energy system and its linkage to the overall economy that will allow for consideration of interactions among different elements of that system. (IPCC et al., 2014).

Hence, the IAM activity is distinguished from conventional disciplinary research by both its purpose of informing policy and decision-making and its interdisciplinary character.

In 2014, more than 20 IAMs existed worldwide, of different levels of complexity and aggregation, ranging from simple cost-effectiveness models to full cost-benefit models and even more complex policy optimisation models (Weyant, 2014). In a review from 2013, three IAMs were seen as dominating the literature: the Dynamic Integrated Model of Climate and the Economy (DICE), the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and the Policy Analysis of the Greenhouse Effect (PAGE) (Beck & Krueger, 2016). In more recent work, in the context of Shared Socioeconomic Pathways (SSPs) within the IPCC, five IAMs are applied, AIM/CGE, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND-MAgPIE and WITCH-GLOBIOM (Riahi et al., 2017). The academic critique of IAMs is widespread and also expressed from within the IA modelling community itself; however, according to Beck and

Krueger (2016), the community primarily deals with epistemic dimensions, neglecting external aspects such as the influence of policy communities.

Beck and Krueger (2016) argue that the policy-advising ambitions of the IA modelling community should entail a sense of responsibility for the potential political impact of model results, but that the transfer of issues from political contexts into seemingly neutral scientific models may instead lead to depoliticisation. Shackley et al. (1998) argue that climate change issues then become subject to the implicit and socially contingent judgements of experts, rather than a wider political discussion among numerous and heterogeneous stakeholders. Ultimately, modelling decisions may prematurely narrow the content of policy deliberations (see e.g. Friman & Linnér, 2008).

This practice risk confining the evaluation of crucial issues to the scientific sphere, instead of making them subject to a wider political debate where they ought to be treated. However, as Veenman and Leroy (2016) point out, it is difficult to outline different normative futures and it is consequently often avoided. The ambition to provide policy-relevant results also carry with it the challenge of maintaining independence and scientific integrity in the configuration of models, so as to allow for politically unpalatable results. Krueck and Borchers (1999) have described IA modelling as a balancing act with the aim of maintaining credibility in the scientific, political and research-funding realms simultaneously. Modellers who do not manage to deliver ‘reasonable’ or palatable results face the risk of not being involved as experts and eventually also putting their access to funding at risk. Therefore, according to Stirling (2010), the model–policy co-production can lead to a lock-in of sub-optimal assumptions, practices and even entire sets of models.

Pindyck (2013) is of the view that IAMs have crucial flaws and that they black-box uncertainties, resulting in climate scenarios giving a false impression of precision. He emphasises the impact of sometimes arbitrarily chosen discount rates and other important parameters (see also Beck & Krueger, 2016; Stanton et al., 2009), the uncertainties surrounding climate sensitivity and the inability to satisfactorily deal with major discontinuities (see also Stanton et al., 2009; Pindyck, 2013; Weitzman, 2008) and threshold effects (see also Stanton et al., 2009), and concludes that a modeller can tweak parameters to obtain almost any result. Pindyck’s (2013) claim that parameters are arbitrarily chosen is challenged by Ellenbeck and Lilliestam (2019). In a study of energy models results, with a similar theoretical approach as ours, Ellenbeck and Lilliestam (2019) maintain that the parameters are not arbitrarily selected, instead they are normative and reflect the modellers understanding of society, science, tools and theories, hence they are shaped by the discursive contexts the modellers are related to.

2.2. Integrated assessment models and bioenergy with carbon capture and storage

Vaughan and Gough (2016) led an expert assessment exercise of IAMs and pinpointed several assumptions that were *both* highly uncertain *and* had a strong influence on modelling the future mitigation potential of BECCS. Among these were land availability, future yields, technology uptake, policy frameworks, storage capacity and social acceptability. The complexity adds up when considering the entire life-cycle and impacts on other parts of the ecosystem and the interactions between the uncertain variables. Vaughan and Gough (2016) conclude that the IAM scenarios often apply unrealistic assumptions concerning crucial aspects such as the availability of biomass and societal support structures. While they deem such models to be inherently inaccurate in certain respects, they still encourage more research into the uncertainties associated with these key assumptions. At present, several groups of IA modellers that include NETs are working on enhancing their models and are also cooperating in model inter-comparison projects (e.g. Keller et al., 2018).

Fuss et al. (2014) claim that, for many IAMs, the assumptions of achieving negative emissions in the future are not based on thorough technological or political assessments. Instead, they are an outcome of a purely economic optimisation of emissions reduction with conventional methods, and do not satisfactorily capture the complexities and challenges of implementing BECCS. This observation is partly in line with Geden’s (2015) argument that modellers must include net negative emissions in their models and scenarios in order to even theoretically deal with the likely temperature overshoot. Thus, in Geden’s view, scenarios stabilising temperature increase at less than 2 °C are at risk of creating a false sense of optimism and undermining the integrity of climate science, whether intended or not. The phenomenon of modellers adjusting models in line with what is politically palatable has, according to Geden (2015), gradually led to less realistic and less plausible model outcomes.

Several aspects crucial to the understanding of BECCS are arguably inherently uncertain. Nevertheless, since many policymakers, national climate plans and international climate politics already rely on the future delivery of net negative emissions, modellers must manage these uncertainties in their models by applying various methods or strategies (Haikola et al., 2019). This management can take many forms and shapes, from excluding BECCS from the models’ technology portfolio to constraining biomass availability or applying conservative cost estimates. However, many crucial conditions are not being investigated thoroughly enough according to Anderson and Peters (2016), and they add that policymakers need a much more complete picture of BECCS than what is currently possible to deliver.

3. Method

This paper is based on 21 interviews with experts on IA modelling and its relation to climate policymaking. The qualitative interview method provides excellent opportunities to gather in-depth information, elaboration of complex issues, and also a flexibility to pursue new relevant topics as they surface. The informants are either currently working directly with IAMs or have done so in the past, or they are developing data to be used as input to IAMs, or they work closely with the IA modelling community. We conceive of the interviews as something more than a method for accessing the reality of our respondents’ professional activities. On the basis of

Silverman's claim (1985) that "interview data […] reproduce and rearticulate cultural particulars grounded in given patterns of social organization" (p. 157), we believe that the perspectives articulated by experts about the world of IA modelling are, in a wider sense, important aspects of how models are enacted in the world. Put differently, the way experts speak of models contribute to how models are perceived in other contexts, as well as feeding into modelling practices through the dialectic relationship between the material world and its social representation (Berger & Luckmann, 1966). In the case of IAMs this dialectic relationship is especially intricate, since the models themselves are social representations of climate dynamics, societal development, and climate policy.

The interviews ranged between 30 and 60 min in length and were performed over Skype or in person, between March 2017 and March 2018. They were semi-structured, meaning that we constructed an interview guide that still allowed us to follow informants in their reflections and ask follow-up questions that were not planned beforehand. A few of the respondents requested that their statements be depersonalised. For the sake of consistency, therefore, all interview data has been depersonalised. We do, however, list all informants and their affiliations in Appendix A. Every informant has randomly been attributed a number between 1 and 21 and references are made to these numbers throughout the result chapter.

The interview guide (see Appendix B) was developed on the basis of the brief literature review presented in the previous chapter, in which we surveyed critical literature that has grown up around IAMs over the last few decades, as well as on the patterns we have noticed in our previous research concerning the debate among researchers in international mass media about BECCS and IAMs that followed the Paris Agreement in 2015 (Haikola et al., 2019). More concretely, the concerns derived from Vaughan and Gough's (2016) expert assessment exercise of IAMs, which is also partly summarised in the previous chapter, guided the interview questions on the theme "identifying uncertainties and unknowns". The theme "reflections on the communication of uncertainty and the scientist's role" was inspired by the findings in Haikola et al. (2019). Haikola et al. (2019) observed a strong critique against modellers for lack of open deliberation with an extended peer community, black-boxing important values and facts and for not maintaining their integrity in relation to policy makers. The final themes, "extra questions" and "dealing with uncertainties in models and the role of unknowns", evolved from the open-ended discussions with the first informants. These themes were subsequently integrated into the interview guide.

The interviews were recorded, and we conducted a clean verbatim transcription of the sections we considered most relevant for the results and analysis and took notes on sections with background or contextual relevance. As we analysed the interviews, we developed two groups of categories into which respondents' statements could be sorted: first, substantive issues of how uncertainties are identified and managed, and, second, disciplinary belonging as well as the general view (positive/moderately critical/explicitly critical) of respondents on the role of IAMs in policymaking. While admittedly coarse, this latter distinction was analytically important for us to make sense of how perspectives were ordered and related to each other.

We qualitatively identify and describe the different patterns of meaning that occupy the discursive space surrounding IAMs in relation to the identification, management, and communication of uncertainties. Following Gaskell (2001), we take such patterns of meaning, or social representations, to be produced in an interplay between individuals and their surrounding culture. Hence, certain social representations are more readily available in a particular social setting, such as an academic discipline, which makes it pertinent for us to distinguish between disciplinary belongings in our analysis. The use of direct quotations is motivated by our wanting to establish the existence of certain typical social representations of IAMs. Thus, the quotes should be understood as representative of a commonly occurring perspective and they could, in most cases, be easily substituted with another, similar quote.

4. Result chapter

4.1. Perspectives on uncertainty

4.1.1. Epistemological progress

Experts' perceptions of uncertainties in IAMs with BECCS can be divided into two groups, separated according to view on epistemological progress. For those we would term the epistemological optimists, uncertainties can and will be significantly reduced as science progresses. They are, however, divided on the issue of how well suited IAMs are to incorporate these reductions in uncertainty. For some, all of them working in or closely with the IA modelling community, there are no inherent limitations as to how detailed IAMs may get in terms of uncertainty reduction. This view can be illustrated by one natural scientist (17)[1] who is working closely with the IA modelling community:

> So I think we could do that [improve biogeochemical and economic parameters], we already have the tools do that, we only have to start bringing together the communities. IA modellers tend to look at land competition relatively well, but they are not so good at knock-on effects on, for example, food prices and so on. The capacity is there in the models to do that, it's only a question of bringing together already-existing models.

Likewise, two IA modellers (5, 6) express a belief that all kinds of uncertainties may be adequately handled through probability distributions or supplementary bottom-up studies, while another argues that "we will eventually be able to quantify everything" (7).

Other epistemological optimists, however, not associated directly with the IA modelling community, regard IAMs as more or less incompatible with significant uncertainty reduction, because the models tend to over-simplify complex processes. In the view of one natural scientist (3) critical of IAMs, for example, the rate of uncertainty reduction through field experiments is effectively outpaced

[1] Every informant has been attributed a unique number.

by the increase in uncertainties that occurs as the models grow more complex.

The other group harbours those who take a distinctly more pessimistic or agnostic view on how much more accurate the IAMs may become in modelling BECCS. In this group, it is common to claim that IAMs should be viewed primarily as exploratory tools (e.g. 1, 9, 11, 19, 20, 21). One of the more senior IA modellers (18) reflects on his/hers initial, optimistic belief that integrated modelling would open radically new possibilities in the field of forecasting. This belief has foundered on his realisation of how much uncertainties increase with model complexity. One climate physics modeller (8), specialising in uncertainty reduction, believes that uncertainties pertaining to physical aspects of climate sensitivity have not been reduced over the last 30 years:

> I wouldn't say we haven't made any progress […] but the range of uncertainties is still basically the same. As we continue to push the boundaries of the models, we continue to see more complexities than we were thinking back then. There are now papers that are saying that the feedbacks are not constant over time, that you cannot take climate sensitivity in the 20th century and make projections into the future based on that. Because when the pattern of warming changes, it alters the feedback in different regions. The sensitivity you may estimate from the 20th century may be quite different from future warming when aggregated globally. So there are fundamental uncertainties in energy-balance arguments, so overall I would say the uncertainties are pretty much the same, it hasn't really decreased substantially. I couldn't say if that's because they are the same uncertainties or if it's because we have removed some and added new ones. It may change as we go forward but it will take a long time.

One modeller of energy systems (15) and a earth system modeller (9) argue that the key uncertainties that will determine the feasibility of BECCS are cost and acceptance, and these are fundamentally "impossible to evaluate through models" (15).

4.1.2. Uncertainty in fundamental assumption

There is no discernible correlation between perspectives on epistemological progress, on the one hand, and general attitudes towards IAMs on the other. Put differently, the informants within the IA modelling community and those working closely with it harbours both epistemological optimists and pessimists/agnostics. Both forms of epistemological perspectives are also found among those moderately and explicitly critical of IAMs. Common to many, both those working with and those critical of IAMs, is the view that the most important uncertainties are not related to specific parameters (storage capacity, transport costs etc.), but rather to basic assumptions about everything from biophysical and atmospheric science to socio-political aspects and costs. One earth system modeller (9) opines that "the main uncertainties are not parameter related" but lie rather in the premise that large-scale BECCS is at all feasible (also expressed by e.g. 12). A climate science expert (2), who is an outspoken critic of the employment of NETs in IAMs, regards parameter uncertainty as relatively unimportant compared to the bias that goes into the basic setting of the models: "The boundaries are hugely subjective, so what we get is objective analysis within subjective, and hugely simplistic, boundaries" (similarly expressed also by e.g. 1).

Parameter uncertainty may often be handled through sensitivity analysis, whereas certain fundamental assumptions are inherently unknowable. One IA modeller (10), for example, expresses the view that "there are so many uncertainties over socio-economic and human development, when you think about 2050 and beyond, that we use different baseline scenarios to start from, and this creates in its own right a very big uncertainty because your starting points are so different." Another IA modeller (4) says that there is a "huge, crucial uncertainty that has nothing to do with BECCS, but with [the development of] other, competing technologies." Yet another IA modeller (7) regards the decision about which limiting factors to include in models as a "very human process where subjectivity might sneak in". This informant also reflects upon the rather strange fact that his/her work is devoted to finding cost-optimal solutions based on simple assumptions, when he/she privately believes that "history has never chosen the most cost-optimal solution" (7).

4.1.3. Uncertainty in relation to model purpose

Thus, both those explicitly or moderately critical of IAMs and those positively inclined to IA modelling express similar views on epistemological progress as well as on how uncertainty is built into models. The important difference between the IA modelling community and its critics instead lies in their views on the purpose of models, that is if they should be seen as predictive or exploratory tools. Either view is related to specific assumptions about what political and social influence is wielded by IAMs, and consequently how uncertainty can be managed when translated into scenarios.

For most IA modellers, and those working closely with them, deep uncertainty does not preclude the possibility of satisfactorily validating model results through qualitative analysis or model inter-comparisons. Indeed, such retrospective analysis of model results is often identified as a more important task for IA modellers than the quantification and reduction of parameter uncertainty. "It is not about reducing uncertainties but understanding the behaviour of the system", as one IA modeller explains his/her work (4), which is also in line with Enserink et al.'s (2013) observations. Accordingly, significant uncertainties are not in themselves a hindrance to the production of policy-relevant scenarios, given that IAMs are not supposed to copy the world but to facilitate the evaluation of different alternatives (1, 4, 5, 11). The climate physics modeller (8), quoted at length above, is adamant that the vast and perhaps irreducible uncertainties in climate models do not preclude their usefulness. The climate physics modeller's view is that criticism of IAMs in the context of BECCS could probably be explained by a misunderstanding of what the models are: not an attempt to promote a specific technology, but a "'what-if' exercise that is agnostic as regards the probability of different scenarios" (also e.g. 1, 4, 11, 13, 20).

4.1.4. Uncertainty management

Those informants who take a more or less explicitly critical stance from the outside of the IA modelling community tend to believe

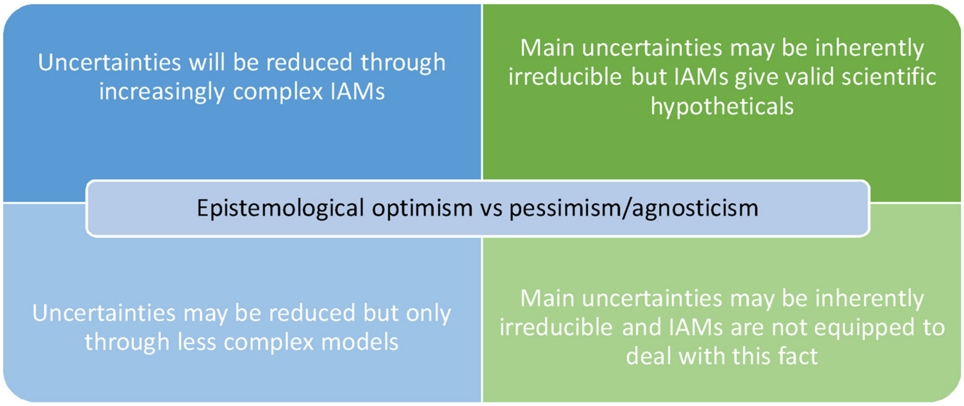

Fig. 1. The relation between experts' views on epistemological progress and the management of uncertainties in IAMs.

that the only way of adequately dealing with uncertainties in IAMs is to disaggregate them, making them less complex but more detailed (e.g. 2, 3, 14, 15; see Fig. 1). This view is related to the belief that IAM results are too infiltrated by fundamental uncertainties – uncertainties that are, as noted, often acknowledged by the IA modellers as well – to be regarded as legitimate scientific input.

The optimistic attitude to uncertainty management is most common among informants in and close to the IA modelling community, while those sceptical of such management mostly work outside of the community. However, there are exceptions to this pattern. One earth system modeller (9) close to the IA modelling community expresses disillusionment with the possibility of dealing with uncertainties in IAMs because of interdisciplinary boundaries:

> I'm working in between two communities – working group I, the physicists, and working group 3, the economists – and it's quite amazing to see how the physicists just don't question what the economists say. There are some scenarios, some model, and the physicists just take the results and say 'ok, let's do that!' No questioning, no criticising. It has nothing to do with intellectual capacity but with time. The same phenomenon is apparent in the literature, where you can see different communities using radically different methods to answer the same questions, in a way that makes it difficult to compare or communicate.

Apparently, this quote implies a questioning of the very basis of the integrated modelling approach and relates to the question of how model uncertainties can and should be communicated. We will turn to this in the following.

4.2. Communication of IAMs and uncertainty

Central to the critique of IAM scenarios in the context of the Paris Agreement has been the notion that modellers have failed to sufficiently highlight and communicate uncertainties around the feasibility of large-scale BECCS. In our conversations with experts, we have found some, both within and outside the IA modelling community, holding the opinion that large-scale BECCS presents certain uniquely complex problems in modelling terms, due to its multidimensional uncertainties relating to both technological development and land-use (e.g. 18, 21). This, however, does not always translate into a view that uncertainties surrounding BECCS are uniquely difficult to communicate (e.g. 12). For most of the experts we have talked to within and close to the IA modelling community, the differences in IAMs' results as regards BECCS deployment are only marginal in the context of the main message that drastic mitigation measures are needed. All informants stress that BECCS should never be perceived as anything more than a complement to other mitigation measures, but many acknowledge that the message has been distorted.

There is a near total agreement among the informants that scientific uncertainty is inherently difficult to communicate to stakeholders outside the scientific community. However, several of the interviewed experts (4, 5, 7, 11, 20) that work with IAMs have a positive view on the possibility to communicate important messages to high-level policymakers involved in climate policy. There is also a general agreement in the IA modelling community that the main role for all kinds of climate modelling is to deliver the central message that drastic mitigation measures are needed immediately. All IA modellers we have interviewed regard this message as external to the models themselves, in the sense that model runs can never deliver any other conclusion but only variations on the same main message.

While all the experts we have talked to agree that BECCS in itself is not the key factor in the scientific communication of IAM results, there are important differences in their view of how the main message is transformed through IAM scenario production. One important dividing line runs through perceptions of how well uncertainties are understood and communicated within the scientific community itself. While some experts hold inter-disciplinary communication about IAM uncertainties to be relatively unproblematic, others hold the view that disciplinary boundaries make communication even within the scientific community difficult (6, 8, 9, 11, 17). Two of the earth system modellers (9, 13) explain that the economists and the physicists in the joint projects often take the other discipline's "results without questioning" (9). From this latter perspective, the very act of complex modelling by necessity involves the suspension of uncertainties because their origin becomes impossible to trace – in practice if not in theory – through retrospective analysis (2, 3, 9, 14). The difference between these two perspectives can be translated into a difference in perception about whether integrated modelling creates certain *unique* uncertainties that make communication to the outside world particularly problematic.

Most IA modellers and several modellers who work closely with the IA modelling community adopt the position that there are no unique uncertainties pertaining to integrated modelling. This correlates to a view that IAM results can, in principle, be communicated just as well as any other kind of scientific result, and that integrated modelling is just one way among many of illustrating the main message of mitigation urgency to policymakers. Communicating uncertainty in IAMs is therefore seen as a matter of communication strategy, just as science communication in general. In the words of one earth system modeller working closely with the IA modelling community: “You shouldn’t over-communicate your uncertainties because then people will lose faith in your results. This is a model, so the result is always going to be uncertain” (13).

This view does not preclude a self-critique among IA modellers of their communicative performance so far. While stressing the fact that scientific uncertainty is inherently difficult to communicate, many IA modellers also express a concern that they, as a community, have neglected their role as interpreters of what the central message should be. According to this perspective, this neglect could have led to BECCS being awarded an unreasonably large role in policymaking (13, 18).

The alternative perception is that integrated assessment modelling *does* create unique uncertainties. Here it is held that IAMs produce a special kind of uncertainties that separates IAM knowledge claims from classic Popperian scientific knowledge. Communicating IAM uncertainty is not seen as a matter of communication strategy, but as something inherently impossible.

This is a view held primarily by experts outside of the IA modelling community. In this view, the dilution or distortion of the central message cannot be explained primarily as the result of poor communication. Instead, it is a result of the way knowledge is produced in the models. According to experts adopting this perspective, given that scientists themselves are unable to adequately evaluate the complex layering of uncertainties, it would be naïve to expect policymakers and other recipients to do so. One climate science expert (2, and also 12), for example, perceives IAMs as black boxes of uncertainties and hidden assumptions that are precarious to translate into policy advice:

> [IA] modellers continually insist that policymakers are aware of uncertainties [concerning BECCS] but when I talk to politicians, they always say they haven’t got a clue.

One earth system modeller (9) believes that the reason that BECCS has been awarded such importance in climate policy is the difficulty in communicating between scientific disciplines within the institutional order of the IPCC. One energy system modeller (21), likewise, believes that while one group of scientists might reasonably be expected to adequately communicate uncertainties pertaining to their own specific discipline, integrated modelling means that uncertainties will travel unchecked between disciplinary boundaries. In this view (also 15), then, IAMs are themselves an important reason why the message becomes diluted, because the scenarios they create give the illusory impression of valid alternatives.

A further distinct perspective exists, which similarly regards IAMs as a unique form of scientific knowledge, but from a more positive angle. Unlike previously mentioned perspectives, it puts considerably less emphasis on the importance of IAMs contributing to the communication of a central message. Instead, it sees the role of IAMs as to construct a wide array of alternatives, regardless of whether they can be deemed realistic or not. This perspective, which is adopted by those working within and close to the IA modelling community, is rarely expressed as a consistent approach to modelling but rather occurs as a shift in modellers’ descriptions of their own work (1, 4, 7, 11, 13, 20). Through this shift, model scenarios are construed as unique scientific knowledge with a value in itself. Accordingly, to this perspective, it is the proliferation of different alternatives showing the world as it possibly could be, rather than the consistent formulation of a key message, that makes integrated modelling a uniquely valuable scientific operation (see Fig. 2). This perspective implies a special way of looking at the IAMs’ status and relation to the outside world, and we will turn to this in the following.

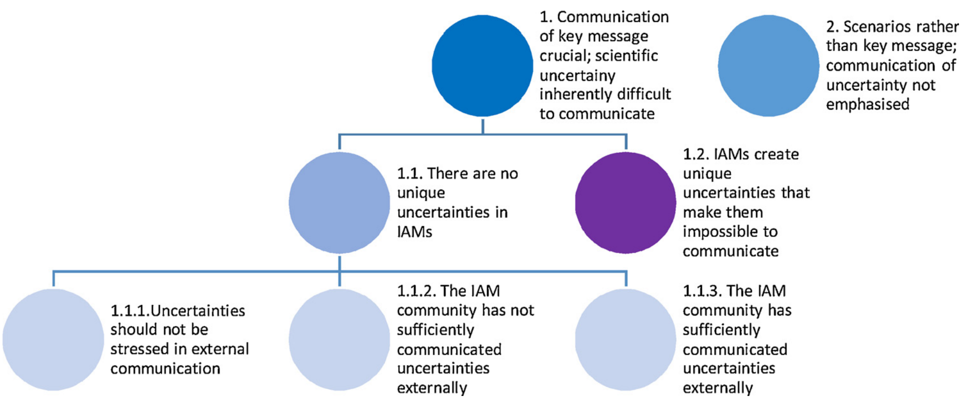

Fig. 2. Experts’ perspectives on how uncertainties in IAMs can and should be communicated, and how they have been communicated historically. When uncertainty in IAMs is not seen as unique, uncertainty communication is a matter of choosing communication strategy (1.1.1; 1.1.2; 1.1.3). When IAMs are regarded as a distinct species in the realm of scientific knowledge production (1.2; 2), uncertainty communication is either seen as an insurmountable problem (1.2), or as not important at all (2).

Fig. 3. Experts' views on how IAMs relate to the real world on a scale from representing reality to providing purely hypothetical experiments.

4.3. Model relation to reality

There are noticeable differences among experts in terms of how they perceive the function of IAMs in translating scientific knowledge about the world into scenarios.

These views can be understood as shifting across a scale, from the view of there being a relatively direct relationship between IAMs and the real world, to a view of the models being to a large extent detached from reality (13, 20; see Fig. 3).

Most informants shift across this scale, and sometimes express views that place them at both ends of the scale. A clear minority of those we have interviewed (6, 10, 17), all of them working either within or close to the IA modelling community, are firmly placed to the left of this scale, and view IAMs as having relatively direct access to the world as understood through a scientific lens. From this perspective, computer processing power is the primary limiting factor on modelling of real-world scenarios. IAMs are therefore close to being the ideal device for integration of best available, relevant science.

A clear majority of the informants, however, tend to regard IAMs as somewhat detached from real-world constraints, to a greater or lesser extent (e.g. 1, 5, 7, 11, 12, 19). For some, this detachment is an asset, as it allows modellers to move beyond certain limiting factors in the real world, to explore possibilities that may or may not be politically feasible. A view expressed by several IA modellers in the study is that, precisely because uncertainty is ubiquitous, the experimental and hypothetical nature of models is important in order to illustrate future possibilities. One IA modeller, for example, argues that "You shouldn't make only totally realistic scenarios, because who knows how the climate will be in the future?" (20).

These views shift from the notion that IAMs provide the means for a scientifically grounded exploration of possible futures, to the notion that IAMs are uniquely equipped to capture and experiment on the dynamics of the climate system/society interaction. In the former view, IA modellers derive rough but scientifically robust assumptions from current state-of-the-art scientific knowledge, and use the models to project fictitious but plausible development paths into the future. In the latter view, however, IAMs do more than project current knowledge into the future. Rather, they are seen to generate a special form of knowledge that could not be gained through more traditional, compartmentalised science. By tapping into the complex, dynamic interrelations between climate, economy and society, IAMs can allow for unique insights into the world as it could be.

Several informants within the IA modelling community or working in its vicinity, regard IAM experimentation with different temperature targets as a productive source of knowledge in its own right (e.g. 13). While the boundary is far from clear-cut, there is an important difference in perspective between, on the one hand, regarding the model as primarily a projection device and, on the other, viewing it as an experimental micro-cosmos.

Others reflect on the relative detachment of IAMs as more of a potential problem than an asset. It is not uncommon for respondents from the IA modelling community who place great value on the experimental dimension of the models to also express concern that the importance awarded to BECCS by the models may prove to be problematic. Some IA modellers (e.g. 12, 18), for example, see NETs as having evolved in IAMs through a dynamic triggered by modellers' ambition to simply explore possible worlds, into a policy option that risks distracting from other, more reality-based mitigation alternatives:

> The fact that models like NETs is not surprising, but the number is staggering, I would have to say. It's not that we didn't realise that from the start, we knew this was a special type of emissions reduction, but we were focused in the beginning on how we could go to two degrees, and then we were charged with going to 1.5 degrees […] Originally, many of the mitigation scenarios were way too high to be relevant to that target, and we responded to policymakers by exploring what was necessary to reach that target […] And I don't think anybody has really done anything wrong, but with hindsight, if you look at the literature as a whole, there are too many scenarios with NETs and too few without them. (18).

Several modellers outside of the IA modelling community express similar concerns. One modeller (14) believe that IAMs risk prioritising options like BECCS over more practical and cheaper mitigation measures due to algorithms no one has really yet deciphered, and that the mere practice of modelling BECCS constitutes a dangerous distraction. One modeller of energy systems (15), speaking from his/hers close association with IA modellers, reflects:

I'm concerned that everything becomes so focused on modelling results that are totally theoretical and detached from reality […] I assume that every value [in IAMs] by itself has an objective foundation, but the end result may still lack realism.

One biophysical modeller (3), one climate modeller (12) and two energy and earth system modellers (1, 9) argue along similar lines that modellers sometimes are insufficiently reflexive around the fact that their purely hypothetical scenarios may be read as policy-prescriptions.

To conclude, the three aspects we have highlighted here – view on uncertainty, communication and model relation to reality - all concern whether or not IAMs create a unique way of relating to the world, and the political consequences that follow from this understanding. In the concluding discussion, we will delve further into this issue.

5. Discussion: mapmakers and navigators

This chapter brings the discussion to a more general level. It leaves the specificities of BECCS and instead discusses the above perspectives on uncertainty, communication and models' relation to the real world and how they can be analytically construed as three separate, idealised cognitive frames, each forming a specific view of how IAMs relate to the world, to the politics of today, and to the future (for other analytical schemas of strategies for managing or viewing uncertainty at the science–policy interface, see Funtowicz, 2006; van der Sluijs, 2006, 2012; Veenman & Leroy, 2016). These frames should be seen as discursive formations rather than individually consistent viewpoints, in the sense that one person may move between these frames. It is indeed common for respondents to express opinions that straddle the boundary between these idealised frames. Neither should these frames be understood as mutually exclusive or completely incompatible, but rather as differences in emphasis and general view of the problems that have been discussed in the interviews. These kinds of inconsistencies do not only appear in conversations, but also in thoroughly reviewed scientific reports. Veenman and Leroy (2016) have observed that framing of issues and epistemological positions can shift from post-normal into positivist frames within IPCC reports, for example. In our discussion here, we will borrow the metaphor of the mapmakers (scientists) and the navigators (policymakers) from one of our informants (Informant 8, see also Edenhofer & Kowarsch, 2005), to make sense of these cognitive frames as perspectives on IAMs and their function in the world.

5.1. Frame one: integrated assessment models as talking points or possible futures

The first perspective, which is also the dominant one in our study, regards IAMs as a heuristic device for understanding different societal development options at a highly generalised level. Scenarios, from this perspective, are talking points for scientists and policymakers rather than attempts to realistically model the future, since decisions about the future must always be taken from a standpoint of imperfect knowledge. Uncertainty, while ubiquitous as a precondition for modelling, is therefore somewhat peripheral to this understanding of how models function in the world, which also means that a lack of solid science as a basis for a certain parameter does not necessarily preclude the production of scenarios as talking points. This understanding of uncertainty, as a premise rather than a methodological problem, means that this perspective lies close to the notion of 'issue-driven', 'post-normal' science that Funtowicz and Ravetz (1993, p. 740) prescribe as the way in which science may be used to inform policy-making under circumstances of great complexity, uncertainty and high stakes. In post-normal science, the legitimate response to uncertainty cannot be inaction, since there is an urgent imperative for science to inform critical policy issues. Hence, IA modellers, in this perspective, are perceived to respond to the policy community's call for scientific input by supplying a palette of alternative development paths based on a crude approximation of the best available knowledge, issued on the premise that they be interpreted as talking points rather than policy prescriptions.

This perspective is complicated, however, by the acknowledgment that IAMs are in themselves highly complex black boxes that do not merely act as a bridge of translation between historic conditions, the present and the future, but are themselves in need of being translated. If end users are to understand the model outputs, i.e. the climate scenarios, they need extensive knowledge of how to understand the production software, i.e. the IAMs. Thus, IA modellers must fulfil a mediating role between the scenarios and the policymakers, as interpreters and communicators of the translations made by the models. Many of the IA modellers express self-critique as to how they have performed in this role so far, while others adhere to the view that science communication is not about highlighting each and every caveat, but to get a central message across and make sure it does not become blurred (see also van der Sluijs, 2002, for an analysis of miscommunication and the role of perceptions of uncertainty).

Complicating the view that IAMs need to be translated by modellers into legible policy advice is the acknowledgment that models have grown increasingly complex. Modellers, who ought to be best equipped to provide guidance on how to understand IAMs, are working in ever-larger collectives, with individuals often lacking an overview of the IAM they are working with. IAMs have reached a stage where modellers find themselves devoting an increasing amount of time to disentangling and investigating the world of the models in attempts to understand why they yield certain results. Hence, there is uncertainty about the extent to which the models are actually anchored in scientific knowledge of the real world, and the extent to which they operate free of real-world constraints, as worlds in themselves. There is thus some ambiguity concerning whether the models are merely providing descriptive analyses for policymakers to decide upon, or whether they are in fact active agents in the creation of possible futures.

However, the distinction is not always maintained because the status of the models and their relation to the world and to the future shifts, making the IA modellers appear as both mapmakers and navigators. Similar to Shackley et al.'s (1998) 'pragmatist' type, this frame stresses the worth of models that may inform policy, despite their flaws. However, unlike the pragmatist in Shackley et al.'s terminology, who sees a "need for a model which can provide answers about anthropogenic climate change" (p. 19), frame one does not emphasise 'answers' so much as the construction and presentation of alternative possible worlds. Unsurprisingly, many IA modellers take up this position, but it is not exclusive to them, and neither do they remain fixed there.

5.2. Frame two: integrated assessment models as political machines

The second perspective emphasises the performative role that models can have in relation to policy-making, and views them as fundamentally 'political machines' (Barry, 2001, see also Veenman & Leroy, 2016). It is crucial, from this perspective, that their machinery is scrutinised and held up to light. Such scrutiny has been severely lacking in IAMs and, instead, uncertainties have been allowed to aggregate, with the result that models have become black boxes detached from reality. IAMs are therefore operating detached from reality but, fatally, they are very much connected to the future, influencing political decisions in the present through their creation of new imaginary worlds.

According to this perspective, a thorough scrutiny of IAMs would show them to be premised on arbitrary or normative assumptions regarding technological development, economics and political structures (Ellenbeck & Lilliestam, 2019; Pindyck, 2013; van Sluijs, 2002). As IAMs are set to reach cost-optimal results according to, for example, a theoretical discount rate or learning rate for technologies, they often have a built-in bias towards 'techno-fixes'. This set-up makes them 'political machines' in the double sense described by Barry (2001): they are machines that influence politics, and at the same time they are inscribed with a distinctly technical kind of politics, a kind that takes "technical change to be the model for political intervention" (p. 2). Thus, while the first perspective would consider IAMs to *open up* the future by revealing alternative paths for development, this second perspective would argue that, on the contrary, they *foreclose* possibilities by being locked into a very narrow set of basic assumptions.

It follows from this perspective that the increasing complexity of the models is a problem not primarily because the results become difficult to interpret correctly, but rather that the complexity hides their political core. Thus, merely disaggregating the models to verify the validity of their component parts, as suggested through frame three (see section 5.3), is not enough, as the whole machine would need to be disassembled to reveal its political assumptions. From this perspective, then, the distinction between navigator and mapmaker is impossible to uphold. The problem with IAMs in their current form is not that they fail to uphold the distinction between science and policy, but that they give the erroneous impression that it exists. While this perspective is most pronounced outside of the IA modelling community, many inside it also reflect on what they perceive as a potential problem with the political dimensions of IAMs.

5.3. Frame three: integrated assessment models as contaminated

The third perspective resonates with the 'purist' type identified by Shackley et al. (1998). It is premised on the need to keep science clean from interference, be it political considerations or faulty data. It maintains a fundamental scepticism towards IAMs, both because of their orientation towards policy relevance, which from this perspective carries the risk of allowing political interference with good science, and because of their interdisciplinary approach, which brings the risk of oversimplification or misinterpretation.

From the 'purist' perspective, the core purpose of scientific modelling is to model biophysical and atmospheric reality as realistically as possible, from as detailed a set of data as possible. The notion of models being designed for the purpose of creating talking points rather than creating an exact approximation of real-world phenomena is dangerous, because it risks giving scientific legitimacy to modelling results that cannot pass for sound science. The consequence might be that purely theoretical modelling scenarios appear as 'possible futures', a shift in conception that undermines the legitimate relationship between science and policymaking.

Since modellers, from this perspective, should strive to create as detailed and accurate depictions of reality as possible, the integration of data sets from different disciplines necessitates a weakening of the scientific basis for the model results. This is not only due to limitations in data capacity, but also to limitations in the human ability to validate the results when highly diverse disciplines are brought together in one model. What one gains in scope through IA modelling, one loses in resolution and, from the purist perspective, the reverse order should have priority. This attitude does not mean that the value of policy-oriented modelling is disregarded, but rather that it is based on the belief that diminished resolution has the tendency to transform into outright errors when models become increasingly complex. In contrast to the first frame, reducing uncertainty in the models is key here. Once an integrated model has become contaminated with errors, uncertainties will aggregate as layers of complexity are added, resulting in a black box that yields implausible results. The only means to reinstate scientific rigour is to disaggregate such black boxes, making them less complex in terms of their disciplinary breadth but increasingly complex in terms of their resolution.

In contrast to the second frame, which sees IAMs as being inscribed at their core with a specific set of problematic political premises, the third perspective is not anchored in a political critique. Instead, it holds that the models' *general* openness to politics, rather than their openness to a *particular kind* of politics, makes them problematic. From the third perspective, then, there is a very clear distinction between navigators and mapmakers that must be upheld. Scientific modellers should concern themselves only with drawing the maps, as accurately as possible, for the navigating policymakers to use. This perspective is most pronounced among modellers working outside of the IA modelling community, but it also occurs among people working closely with the IA modelling community.

6. Concluding words: the politicisation of integrated assessment models

In all three of the discursive positions we have sketched above, views on how to handle and communicate uncertainty in IAMs, normative views on sound climate science, and views on the relation of IAMs to the real world relate to specific ways of regarding the political dimensions of the models. The two ideal types, 'purists' and 'pragmatists', identified by Shackley et al. (1998) among climate modellers, are still very much present, but they are not sufficient to account for the highly politicised perspective, i.e. frame two identified in this article, which influences the whole discussion in a palpable sense. Most, if not all, respondents have firm and often well-thought-through opinions on the political dimensions of IAMs, and IAM modellers themselves reflect critically upon the role their models have played at the science–policy interface in recent years, in a way that goes beyond the rather limited, epistemic-oriented self-critique found to be most prominent in the IA modelling community by Beck and Krueger (2016).

To us, this could be seen as a new, politicised phase in the historical development of IAMs, to add to the four identified by Hamilton et al. (2015). The most recent phase according to this chronology, which Hamilton et al. (2015) date to around 2010, saw IAMs reach a state of maturity in which more sophisticated topics such as good modelling practices and uncertainty management were addressed. The politicisation phase, then – which would not necessarily mean a decisive end to the maturation phase – could be seen as a continuation of such self-examination from within the IA modelling community, as well, of course, as a response to outside criticism, which has grown in tandem with the political influence of IAMs (see also Enserink et al., 2013). This would be in line with the observation within the sociology of science, that the scientific debate tends to become politicised when policymaking informed by science occurs in a context of high stakes (e.g. Irwin, 2001; Jasanoff et al., 1995; Jasanoff & Wynne, 1998), and Friedrich (2011) observation that official climate science has embraced a post-normal science condition.

Two ironic aspects of this politicisation can be noted. The first relates to criticism associated with frame two, that IAMs are locked into unrealistic techno-fixes and foreclose the option of other, more conventional but drastic forms of mitigation. This criticism often takes aim at the simplified assumptions about technological change, most especially in the form of NETs and BECCS, and amounts to an accusation that the role of policy is neglected in favour of technicalised, depoliticised utopias. What could be said to be forgotten in this critique, however, is the fact that such assumptions about technological development actually presuppose just the sorts of drastic political actions in the form of support for R&D, infrastructure investment and global carbon pricing mechanisms – that the IAMs are criticised for neglecting. From this perspective, it seems more accurate to describe IAMs as harbouring "an ambivalence to both the possibilities of the present and the potential of the future" (Edwards & Bulkeley, 2018, p. 352).

The second irony relates to the self-critical evaluation of the models' political influence in recent years from within the IA modelling community itself. The irony lies in the fact that IAMs are designed explicitly with the purpose of speaking science to power. Thus, self-critique could be a response to the fact that the community has been successful in reaching the level of policy influence it has sought from the outset.

We might hazard to trace such hints of self-reflexive doubts among IA modellers to their perception of IAMs as hybrid objects. There is a contradictory relationship between, on the one hand, the view of the models as replicas of the world and, on the other, the view of models as independent worlds of their own. When models risk appearing detached from reality, separate entities with a value in themselves, their value as policy-informing devices would seem to become questionable, dependent as that is on its relation to the real world.

This hybridity can be said to originate in the double functioning of IAMs as both producers of imaginaries, a certain way of visualising both the present and possible futures, and at the same time supplying tangible policy advice. This double function was identified by Edwards (1996) twenty years ago, when he argued that the aggregated, global and simplified way of imagining the world fostered by IAMs would lead to the creation of an "epistemic community" (p. 150), thus giving the models *political* influence even if they failed to find concrete *policy* application.

In the post-Paris world, IAMs seem to have come a long way in gaining ground in both respects: the epistemic community fostered by integrated modelling is well established in the global climate political arena, while IAMs' climate scenarios also form an important basis of climate policymaking. IAMs have thus attained a unique role in that they simultaneously provide the maps for the future and the standard by which these same maps are to be evaluated. This realisation, disconcerting to some, may explain the politicisation of IAMs that we have noted in this paper, as experts struggle with themselves and each other about how to make sense of the role that these models should and do play as producers of imaginaries and in relation to policy-making.

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Appendix A. Informants

- Anderson, Kevin. Zennström professorship at Uppsala University, Tyndall Centre, University of Manchester, Sweden/UK, 23/03/2017.
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- Boysen, Lena. Department of The Land in the Earth System, Max Planck Institute for Meteorology, Germany, 02/11/2017.
- Daioglou, Vassilis. Department of Climate, Air and Energy at Energy at PBL Netherlands Environmental Assessment Agency, The Netherlands, 07/11/2017.
- Etsushi, Kato. Senior Research Scientist, Institute of Applied Energy (IAE), Japan, 11/10/2017.
- Fuss, Sabine. Head of working group Sustainable Resource Management and Global Change, The Mercator Research Institute on Global Commons and Climate Change (MCC), Germany, 14/03/2018.
- Gasser, Thomas. Research Scholar, Ecosystems Services and Management Program (ESM), The International Institute for Applied Systems Analysis (IIASA), Austria, 25/10/2017.
- Harmsen, Mathjis. Copernicus Institute of Sustainable Development, Environmental Sciences, The Netherlands, 09/11/2017.
- Johansson, Daniel. Associate Professor, Department of Space, Earth and Environment, Physical Resource Theory. Chalmers University of Technology, Sweden, 13/10/2017.
- Knutti, Reto. Professor at Institute for Atmospheric and Climate Science, Department of Environmental Systems Science, ETH Zürich, Switzerland, 24/10/2017.
- Kram, Tom. Programme Manager Integrated Assessment Modelling – IMAGE, Department of Climate, Air and Energy at Energy at PBL Netherlands Environmental Assessment Agency, The Netherlands, 13/11/2017.

- Kravitz, Ben. Climate scientist in the Atmospheric Sciences and Global Change Division at the U.S. Department of Energy's Pacific Northwest National Laboratory, USA, 2017-10-09.
- Kriegler, Elmar. Vice chair of the Research Domain “Sustainable Solutions” at the Potsdam Institute for Climate Impact Research (PIK), Germany, 20/12/2017.
- Muri, Helene. Department of Energy and Process Engineering, Norwegian University of Science and Technology, Norway, 03/11/2017.
- Möllersten, Kenneth. Senior Scientific Advisor, Swedish Energy Agency, Unit for International Climate Change Mitigation, Sweden, 06/10/2017.
- Peters, Glen. Research Director at Center for International Climate Research (CICERO), Norway, 13/10/2017.
- Schellnhuber, Hans Joachim. Professor in Theoretical Physics at Potsdam University, Director of Potsdam Institute for Climate Impact Research (PIK), Germany, 19/12/2017.
- Smith, Pete. Professor of Soils & Global Change, School of Biological Sciences, University of Aberdeen, UK, 03/10/2017.
- Tavoni, Massimo. Associate professor at the Department of Management, Politecnico di Milano and Fondazione Eni Enrico Mattei (FEEM), Italy, 12/12/2017.
- van Soest, Heleen. Department of Climate, Air and Energy at PBL Netherlands Environmental Assessment Agency, The Netherlands, 02/11/2017.
- van Vuuren, Detlef. Professor in Integrated Assessment of Global Environmental Change at the Faculty of Geosciences, Utrecht University and senior researcher at PBL Netherlands Environmental Assessment Agency, The Netherlands, 10/11/2017.

Appendix B. Interview guide

Background

1 Your academic background, briefly?
2 How long have you been involved in BECCS or related issues and in what capacity are you involved?
3 How were you involved in the XXX study, can you briefly describe its context and background?

Identifying uncertainties and unknowns

4 Can you list the most important assumptions and parameters that may impact how BECCS is deployed in climate scenarios?
5 Among these assumptions, which are the greatest uncertainties for deployment of BECCS in accordance with the climate scenarios?

LIST OF POSSIBLE ELEMENTS TO DISCUSS:

i
  - i Land area used for biomass production (ha)
  - ii Future yields (t/ha/year)
  - iii Climatic response to massive reductions in CO2 atmospheric concentration levels
  - iv Maximum CO_2 storage capacity (t CO_2) (not so high influence on results)
  - v Technology uptake (GW/year) (not so high influence on results[A1])
  - vi How (net) negative is BECCS[A3]? (aimed at getting to the heart of the basic premise behind the use of BECCS to deliver negative emissions.)
  - vii Policy framework
  - viii Social acceptability
  - ix Net negative emissions (accounting and verification)

ii Could you reflect specifically on how technology learning curves for BECCS affect climate scenarios?
iii What is your view of how discount rates are deployed and what it means for BECCS in climate scenarios?
iv How do you view the possibility of modelling future technological development? What assumptions regarding technological development are reasonable when modelling BECCS?
v Has any of the uncertainties become significantly more easily quantifiable in later years, and has uncertainties been reduced? [I.e., has our knowledge of it improved?]
vi Are you aware of uncertainties that cannot be quantified adequately at the moment but might be in the future?
vii Are you aware of uncertainties that probably never can be quantified accurately?

LIST OF POSSIBLE ELEMENTS TO DISCUSS:
Social unrest

i Tipping points, nonlinear dynamics
ii International politics
iii Other social factors that would not fall under the label ‘social acceptability’ or ‘policy framework’

iv land/water use

Dealing with uncertainties in models and the role of unknowns

12 Are or can the uncertainties be dealt with satisfactorily in the models?
13 Is there a fundamental difference between modeling BECCS and modeling fossil CCS on the one hand and other kinds of technologies included in scenarios on the other hand?

Reflections on the communication of uncertainty and the scientist's role

14 Who are the main stakeholders with whom you communicate your results?
   a Can uncertainties around BECCS be communicated satisfactorily and do you take extra measures to communicate these uncertainties to your end users?
15 How would you like your results to be interpreted by policy makers, the public and the media?
16 What responsibility do you believe modellers and climate researchers should feel for how their work is interpreted and used in climate governance?
17 Has your own view on the feasibility of deploying BECCS as well as the possibility to realistically model BECCS future deployment changed as you've been working with it over the last couple of years?
18 Do you believe your choice of assumptions and methods have been influenced by the political aspirations of limiting global warming well below 2 °C?

Extra questions: Reflections on the limitations and policy relevance of models

19 Will we reach a more accurate understanding of the feasibility of BECCS (or other CDR technologies) through more modeling? Are the models becoming increasingly realistic as they become more complex?
20 How do you believe that the scientific community generally communicates uncertainties around BECCS?
21 How do you handle surprises in modeling results?
22 What role do you believe your models have in the context of global climate governance and policy-making?

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