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Decision making in contexts of deep uncertainty - An alternative approach for long-term climate policy

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ABSTRACT

The majority of global emissions scenarios compatible with holding global warming to less than 2 °C depend on the large-scale use of bioenergy with carbon capture and storage (BECCS) to compensate for an overshoot of atmospheric CO_2 budgets. Recent critiques have highlighted the ethical and environmental risks of this strategy and the danger of building long-term climate policy on such speculative technological scenarios emerging from integrated assessment models.

Here, we critically examine both the use of BECCS in mitigation scenarios and the decision making philosophy underlying the use of integrated assessment modelling to inform climate policy. We identify a number of features of integrated assessment models that favour selection of BECCS over alternative strategies. However, we argue that the deeper issue lies in the tendency to view model outputs as objective science, capable of defining "optimal" goals and strategies for which climate policy should strive, rather than as exploratory tools within a broader policy development process. This model-centric decision making philosophy is highly sensitive to uncertainties in model assumptions and future trends, and tends to favour solutions that perform well within the model framework at the expense of a wider mix of strategies and values.

Drawing on the principles of Robust Decision Making, we articulate the need for an alternative approach that explicitly embraces uncertainty, multiple values and diversity among stakeholders and viewpoints, and in which modelling exists in an iterative exchange with policy development rather than separate from it. Such an approach would provide more relevant and robust information to near-term policymaking, and enable an inclusive societal dialogue about the appropriate role for carbon dioxide removal within climate policy.

1. Introduction

The Paris Agreement seeks to hold the increase in global average temperature '*to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels*' (Paris Agreement, 2015). Unfortunately, meaningful action to stabilise, or even slow the rate of increase in global greenhouse gas (GHG) emissions is continually delayed (Jackson et al., 2017). The longer this delay persists, the more aggressive the action needed to get emissions back on a trajectory aligned to the Paris Agreement's goals (Masson-Delmotte et al., 2018). Recent explorations have considered the need to pursue both deep cuts in GHG emissions, and the possibilities for a substantial net *removal of* CO_2 from the atmosphere - starting in the coming decades, and likely scaling and persisting well into the 22nd century (IPCC, 2018).

This need has been most apparent in the results of global integrated assessment models[1] (IAMs) that are used to characterise emissions pathways consistent with meeting temperature goals. Out of the 400 IAM-based mitigation scenarios compiled in the IPCC's 5th Assessment Report that have a better than 50% chance of limiting warming to 2^{0}C, 86% depend on large-scale deployment of "negative emissions technologies" in the 21st century (Anderson, 2015). Under the more recent generation of deep mitigation scenarios harmonized under a framework of policy assumptions known as the Shared Socio-economic Pathways (SSPs) (Riahi et al., 2017; Rogelj et al., 2018), 95% of unconstrained scenarios which limit warming to 2^{0}C, and 100% of those which

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[1] Integrated Assessment Models referred to throughout this paper are Global.

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achieve 1.5⁰C, involve both negative emissions and 'net negative' global carbon emissions in the second half of the century. Alternative scenarios that purposely limit or exclude the use of negative emissions in meeting a 1.5⁰C pathway instead require unprecedented rates of reduction in fossil fuel use (Holz et al., 2018; Grubler et al., 2018 and van Vuuren et al., 2018), with widespread energy efficiency, electrification and renewable energy deployment. Holz et al. (2018) note that efforts to limit reliance on negative emissions will require societies "to investigate rates of CO_2 reductions well outside of what is currently deemed plausible" (Holz et al., 2018, p.10).

IAM scenarios rely on Carbon Dioxide Removal (CDR) to generate negative emissions at a significant scale - with a median value of 12 $GtCO_2$/yr in 2⁰C compatible pathways (Anderson and Peters, 2016), and 15 Gt CO_2/yr for 1.5⁰C by the end of the century (Rogelj et al., 2018). Where emissions peak later in the century, there are scenarios that rely on up to 1200 $GtCO_2$ of cumulative 'negative emissions' to 2100 (Rogelj et al., 2018), equivalent to nearly thirty years of current global emissions (Le Quéré et al., 2018).

In such scenarios, negative emissions are predominantly achieved through the use of a technology called Bioenergy with Carbon Capture and Storage (BECCS) (Fuss et al., 2018; Williamson, 2016), - see Fig. 1. In principle, BECCS captures carbon emitted as CO_2 during bioenergy conversion, which itself has been absorbed from the atmosphere by growing biomass, and securely sequesters it in geological or other reservoirs. Other removal approaches include various biological pathways, such as biochar, soil carbon sequestration, afforestation and reforestation, and chemical pathways such as direct air capture and enhanced silicate weathering (Griscom et al., 2017). However, only afforestation, reforestation and BECCS are typically modelled in IAMs with < 0.1% of all simulations representing alternative CDR technologies.

The scale of BECCS envisioned in emissions scenarios is monumental, requiring up to 1100 Mha of land dedicated to energy crops (Rogelj et al., 2018). Yet, with the exception of afforestation and reforestation, at the time of writing, neither BECCS nor any other CDR approaches have been developed at any substantial scale (Fuss et al., 2018), and the inclusion of CDR at such a magnitude in modelled scenarios is subject to controversy (Larkin et al., 2017; Anderson and Peters, 2016; Dooley et al., 2018). There is concern that a dependence on CDR is being baked into emissions targets without a public debate about their use (Van Vuuren et al., 2017) and that initiatives to seek a better understanding of technologies for removals in the real world are still very limited (Minx et al., 2018). There is a growing body of literature highlighting the mismatch between the level of removals required by emissions pathways and the enormous real-world challenges associated with their scale up, as well as major ethical and sustainability considerations related to their deployment (Fuss et al., 2014; Heck et al., 2018; Boysen et al., 2017; Dooley and Kartha, 2018).

Here, we critically examine both the use of BECCS in emissions scenarios and the decision-making philosophy which underlies the use of integrated assessment modelling as tools for creating policy targets. We find that the widespread selection of BECCS in these scenarios reflects a series of assumptions and structural features within IAMs as much as its value as a mitigation technology. However, the controversy around the role of CDR arises from a deeper error: the interpretation of IAMs as predictive solution-finding tools that can independently define optimal policy goals, rather than as exploratory tools within a richer policy development process. We advocate the need for an alternative approach that embraces multiple policy values, viewpoints and possible futures, and in which modelling exists in an iterative exchange with policy development rather than being separate from it. Such an approach would support more relevant and robust near-term policy-making, ensure greater transparency and facilitate a more productive dialogue on the role of these little understood technologies.

Section 2 reviews the reasons why BECCS has become so deeply embedded in integrated assessment modelling, and the implications of this for climate policy. Section 3 investigates the assumptions and decision-making philosophy underpinning the current use of IAMs in developing climate policy, and argues that their use is currently not supporting robust and effective climate policy. Section 4 proposes an alternative philosophy of policy design that explicitly recognises the uncertainty, multiple values and multiple actors associated with long-term climate policy.

2. The consequences of carbon dioxide removal technologies in Integrated Assessment Models

As several existing critiques have highlighted, the large-scale reliance of IAM scenarios on CDR via afforestation and BECCS is problematic for a number of reasons. In this section we explore the features of BECCS that favour its selection in model runs, and the implications that this has had on the climate policy discourse.

2.1. The allure of Bioenergy with Carbon Capture and Storage

In spite of being what some have called a speculative technology (Beck and Mahony, 2018), BECCS has been rapidly introduced as *the* removal technology in IAM scenarios compatible with 2 °C and 1.5 °C mitigation pathways. Table 1 reviews some recent landmarks in the integration of BECCS into modelled scenarios and the real world status of BECCS development. From this brief chronology it is clear that BECCS appears to have become widespread in modelling in the 2000s while remaining technologically immature - see Fig. 2 (Lomax et al. (2015a)). Indeed, it has been described as a "technological imaginary", meaning the technology does not exist other than in the minds and models of those seeking to make the CO_2 budget balance to reach climate goals (Rayner, 2012). Yet the assumed long-term availability of BECCS in mitigation scenarios has implicitly given the impression that a

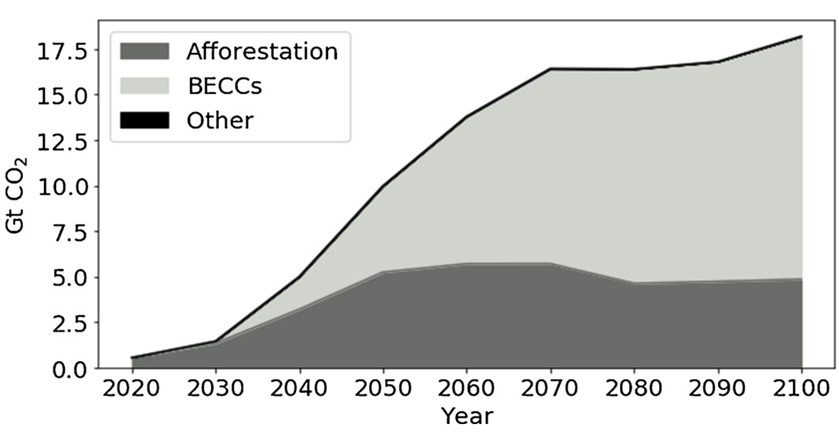

Fig. 1. Total median $GtCO_2$ scale of carbon dioxide removal in Integrated Assessment Modelled scenarios compatible with a 1.5⁰C temperature limit (RCP1.9). Proportion of removals achieved via Bioenergy with Carbon Capture and Storage (light grey); afforestation /reforestation (dark grey); and other (e.g. Direct Air Capture) (black). Less than 0.1% of IAMs include CDR technologies other than BECCS and afforestation. *Data from IIASA 1.5 scenario explorer, accessed May 2019.*

Table 1
The 18-year history of BECCS development in the commercial, scientific and policy spheres (based on Hickman, 2016).

1998:	BECCS Concept Born: *Eco-Restructuring* (Williams, 1998).
2001:	BECS Modelled: *Negative Emissions from Bioenergy use, carbon capture and sequestration* (Mollersten et al., 2003).
2002:	Economics of BECCS modelled: suggested as potentially more cost effective than many conventional mitigation (emissions reduction) technologies, but with questions over scale and sustainability (Rhodes and Keith, 2019).
2003:	Use in very low stabilisation targets: *Not an excuse to do nothing* (Azar et al., 2006).
2005:	BECCS important for Low emissions scenarios (van Vuuren et al., 2007).
2007:	IPCC 4th Assessment Report: BECCS prevalent in low carbon trajectories (IPCC, 2001).
2009:	Royal Society (2009) Report on Geoengineering - BECCS low cost, moderate and predictable environmental impacts.
2010:	`Key assumption in most modelling - if CDR at significant scale not possible then options for meeting targets substantially constrained' (UNEP Gap Report, 2010).
2011-13:	Comprehending Scale Workshop `Opportunities and Challenges' associated with CDR technologies. (Tavoni and Socolow, 2013).
2011-12	Five BECCS operations in existence, three in USA (operational in 2009), one in Canada (operational in 2012), and one in the Netherlands (operational in 2011). All are fermentation plants producing ethanol from agricultural products. For two of these, dedicated storage of CO_2 in geological formations is ongoing or planned, whereas the other three supply CO_2 for enhanced oil recovery (OECD/IEA, 2016).
2014:	IPCC (2014) 5th Assessment Report: Large scale use of BECCS and net negative global carbon emissions in 2nd half of century.
2015:	Paris COP21: the 1.5°C target explicitly included as an overall objective (Paris Agreement 2015, Article 2.1), and BECCS-reliant pathways included in mitigation pathways (Dec.1/CP21, para 17).
2017:	Illinois Basin Decatur BECCS Project: operational from 2011- 2014 (see above) - scaled up to capture and store 1 MtCO2/year, under the Illinois Industrial CCS Project (IICCSP) (IEA, 2016).
2018:	IPCC Special Report on 1.5°C: 95% of Shared Socio-economic Pathways unconstrained scenarios which limit warming to 2°C, and 100% of those which achieve 1.5°C, involve both negative emissions and 'net negative' global carbon emissions in the second half of the century, relying predominantly on BECCS (Riahi et al., 2017 and IPCC, 2018).

more modest rate of near-term mitigation can effectively achieve the goals of 2°C (Schellnhuber, 2012).

BECCS is a centrally deployed technology that requires high capital investment to set up and sustain. It is economically competitive in cost optimisation models as it produces electricity or other energy products, typically assumed to be carbon neutral, as a co-product of carbon removal (McGlashan et al., 2012). More generally, enabling net removal of carbon from the atmosphere makes available two unique possibilities that contribute to the favoured role of BECCS in IAMs:

- By capturing CO_2 from the atmosphere, it decouples mitigation from the source of emissions in space (McGlashan et al., 2012). Large-scale removal options thus offer a tool to address emissions that are otherwise very costly or difficult to reduce or capture at source, such as the aviation sector. This can reduce the need for other new and expensive technologies, and thus reduce overall mitigation costs; and
- Perhaps more importantly, it also decouples emissions from mitigation in time, creating the possibility of "overshoot" scenarios where CO_2 levels exceed target concentrations before being returned to lower levels by removals in the second half of the century (Lomax et al. (2015b)).

While BECCS is the most prevalent example, the same is true of other CDR technologies deployed at sufficient scale. Studies that have modelled direct air capture technologies have found they play much the same role (Obersteiner et al., 2018).

Large-scale carbon-dioxide removal has thus become key to reconciling the short-term political and technological barriers to phasing out fossil fuels with long-term success in meeting climate targets, by enabling future ambition to make up for sluggish near-term progress. Dooley et al. (2018) observe this delay is included in the Paris Agreement, where the supporting decision 1/CP.21, paragraph 17 refers to the need for below 2 °C pathways to reduce emissions to 40 $GtCO_2$ by 2030, a pathway consistent with 500–950 $GtCO_2$ cumulative removals this century. However, a number of recent commentators have highlighted the substantial risks inherent in this exchange, and its potential for negative implications for both CDR development and climate policy

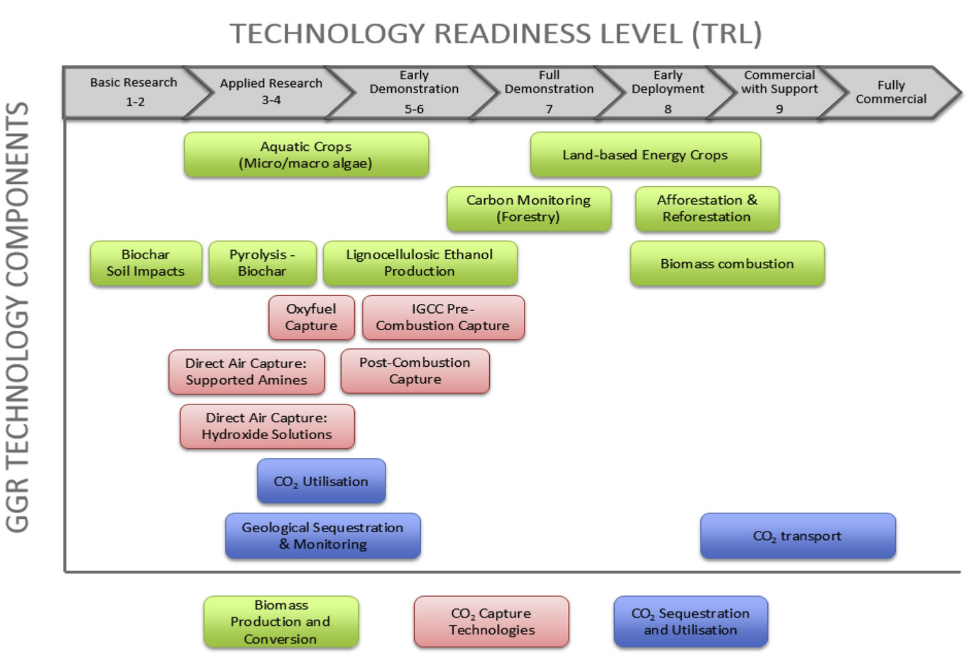

Fig. 2. the technological state of development from TRL 1 to 9 (horizontal axis) of selected Carbon Dioxide Removal technology components (vertical axis) required in the Bioenergy Carbon Capture and Storage value chain: Biomass Production and Conversion (top three rows); CO_2 Capture Technologies (next three rows from top) and CO_2 Sequestration and Utilisation (bottom two rows). Apart from land-based options, all technologies are immature, including CO_2 capture, utilisation and sequestration technologies. Reproduced from Lomax et al. (2015a), 2015b.

in general.

2.2. Climate policy implications of an overreliance on Bioenergy Carbon Capture and Storage

The overwhelming dependence of successful mitigation scenarios on the use of BECCS, and in particular of overshooting CO_2 concentration targets, raises a number of serious risks.

First, there is a serious risk that BECCS and similar technologies turn out to be unfeasible or extremely costly at the scales envisaged (Dooley and Kartha, 2018; Hansen et al., 2017; Bednar et al., 2019). Of the CDR approaches considered in modelling, none but afforestation and reforestation have been developed at scale (Field and Mach 2018). If global human society follows a path that assumes large-scale availability of CDR, and such capability turns out not to be available, we would be locked into a path that greatly overshoots required carbon budgets (Dooley and Kartha, 2018; Shue, 2018).

The scale of CO_2 removal currently envisaged in IAM scenarios compatible with 2 °C and 1.5 °C pathways would require substantive land-use change, with a potential increase in energy crop area of 150–1100 Mha (Rogelj et al., 2018). Such an enormous land-use change risks severe negative implications for food security, land rights and conversion of natural ecosystems, impacting multiple sustainable development goals and potentially surpassing planetary boundaries (Dooley et al., 2018; Heck et al., 2018). The net emissions from such extensive land-use change, soil preparation, and fertilizer required for energy crops could be substantial, potentially resulting in a net *increase* of emissions from the use of BECCS (Wiltshire and Davies-Barnard, 2015; Harper et al., 2018). Land use emissions embedded in BECCS pathways can be large, potentially offsetting the mitigation benefits of BECCS in situations of poor governance where soil erosion, land degradation or indirect land-use change occur as a result of BECCS (Wiltshire and Davies-Barnard, 2015; Vaughan et al., 2018).

More broadly, the reliance of modelled scenarios on BECCS risks developing a technological path-dependency (Rogers, 2003). The apparent simplicity of BECCS deployment ducks politically contentious issues such as the governance and sustainability challenges of land use at the massive scales assumed, as well as hindering exploration of alternative strategies. The ubiquity of BECCS in modelled scenarios has obscured the risks and complexities of reliance on a this particular technology (Fajardy et al., 2019).

The inclusion of BECCS at gigatonne-scale in IAM emission pathways has also created a polarised discourse around the role of CDR technologies. To some, the prevalence of BECCS in IAMs has enabled a lack of ambition (Shue, 2018; Dooley and Kartha, 2018, Hansen et al., 2017) and crowded out exploration of other pathways and technologies to reach 2 °C, including other CDR approaches (Lomax et al. (2015a)). For others, the reliance on CDR in the form of BECCS is seen as a necessity for achieving deep decarbonisation scenarios (Riahi et al., 2017; van Vuuren et al., 2007; Luderer et al., 2018), albeit the need for other CDR options and a 'portfolio of approaches' is more recently acknowledged (Minx et al., 2018). This polarisation is exacerbated by the framing of the debate around multi-gigatonne deployment of BECCS late in the century, where uncertainties are high, potential harms are immense and near-term action can be postponed.

In the worst case, this polarisation could hinder progress on developing both CDR and alternative strategies. If BECCS remains implicitly embedded in near-term climate targets, but a constructive debate about appropriate governance and development of CDR is not allowed to develop, the world could be faced with the imperative to deploy BECCS or other technologies at massive scale without having developed the policies and governance safeguards to do so responsibly. Thus there is a good chance that a lack of dialogue (Weaver et al., 2013) on the appropriate role of CDR use could result in the very concerns that it's most worried opponents are seeking to avoid (Vaughan and Gough, 2016).

In Section 3, we explore the roots of these issues in the use and interpretation of IAMs. We find that they are not an inevitable result of including BECCS in modelled scenarios, but rather reflect deeper aspects of how these models are structured, and how they are being interpreted.

3. The use and misuse of Integrated Assessment Modelling

At the heart of the issues identified above is the role of integrated assessment modelling in shaping the discourse around long-term climate policy and global emissions pathways.

IAMs are simplified, parametric representations of complex technical, socio-economic systems, typically used to explore least-cost packages of climate change mitigation solutions (Haikola and Hansson, 2018). IAMs contain several key assumptions and structural features that favour the selection of BECCS or other large-scale carbon removal approaches later in the century, many of which have been criticised as unrealistic or as introducing systemic bias favouring carbon removal over other mitigation approaches. However, we argue that it is also the framing and interpretation of IAM results in the current policy discourse, rooted in a "predict-then-act" decision making philosophy, that has allowed these outcomes to dominate the discourse at the expense of a richer dialogue and solution mix (Lempert et al., 2013).

3.1. Criticisms of Integrated Assessment Models

Recent criticisms of the use of IAMs have highlighted several factors that favour the deployment of BECCS in goal-oriented scenarios at the expense of alternative strategies. Prominent critiques are that the selection of BECCS at large-scale is premised on flawed assumptions about the feasibility of assumed technology roll-out (Anderson and Peters, 2016), key omissions in input assumptions provided (Rosen and Guenther, 2016), and lack of consideration of the environmental and social impacts of key mitigation options (Vaughan and Gough, 2016). Rapid development, scale-up and global diffusion of technology is assumed, yet the feasibility of BECCS at the scale assumed in IAMs is well beyond historical rates of energy technology diffusion (Vaughan et al., 2018), and CCS deployment rates are currently lagging well behind expectations (Peters et al., 2017).

IAMs have also been critiqued on a macro-economic basis – specifically for calculating the costs of climate mitigation, but failing to include the economic benefits of limiting temperature increase to below 2 °C (Rosen and Guenther, 2016). The economic discounting of future costs at a relatively high real discount rate of 5% per year further biases the macro-economic analysis in favour of postponing mitigation action (Rosen and Guenther, 2016). This structural feature of IAMs promotes late-century carbon removal over near-term mitigation, in spite of the fact that the latter has lower absolute costs and higher relevance to today's decision-makers.

The modelling community has responded to calls to address these limitations by excluding BECCS or overshoot scenarios (Holz et al., 2018); by widening the solution set explored in IAMs (e.g. demand-side strategies - Grubler et al., 2018); and by improving representation of dynamics not addressed in conventional IAMs (e.g. technology diffusion and political constraints – van Vuuren et al., 2018). However, we argue that such changes will have only limited success in making IAM results more relevant to today's decision makers/policymakers[2] unless complemented by a parallel shift in how model results are used in the policymaking process.

[2] The decision makers/policymakers referred to in this paper are those analysts, decision makers and negotiators responsible for agreeing national or international emissions targets, both domestically and through the UNFCCC processes'.

3.2. The use of IAMs in the climate policy discourse

IAMs have been critiqued as misleading by providing a veneer of scientific credibility to their results despite irreducible uncertainties in underlying assumptions (Pindyck, 2017; Dooley et al., 2018). Pindyck (2017) suggests IAMs are insufficiently explicit about the constraints applied to derive goals or about foundational assumptions, thereby giving a false impression of precision and objectivity.

Modellers argue that such criticism is misplaced because IAMs are not intended to make scientific predictions, but to embrace uncertainty through modelling the behaviour of a wide range of hypothetical scenarios (Haikola and Hansson, 2018). Futher to explore uncertainty by the IAM community (e.g. Marangoni et al., 2017; Price and Keppo, 2017). By seeing IAMs as a tool to explore hypotheticals rather than predictions, IAMs can be used to ask a set of "what if?" questions around future possible technology developments and their role in climate mitigation. Far from the moral hazard critique that is regularly levelled at IAMs, modellers argue that viable future technologies and alternatives must be envisioned in order to be enacted (Haikola and Hansson, 2018).

However, such a philosophy is at odds with the prevailing way IAMs are now used in the climate policy discourse (Haikola and Hansson, 2018). Historically, model-based scenarios in climate research were used to determine potential future emissions under a given storyline or set of assumptions about the future (Moss et al., 2010; Marangoni et al., 2017). In the IPCC 5th Assessment Report, a different approach was adopted where different Representative Concentration Pathways (RCPs) were set for atmospheric greenhouse gases, and IAMs were used to determine what future policy and technology measures combine to produce the pathway to each 'target' atmospheric concentration. The introduction of the RCPs thus saw a shift from IAMs as descriptive to prescriptive, representing a critical change in the use of climate models as decision-making tools (Girod and Flüeler, 2009).

Such normative, goal-orientated solution seeking scenarios are particularly attractive to decision makers because they describe coherent packages of measures to achieve fixed goals, for example a future limit in global temperatures. The weakness of tasking models with selecting "optimal" solutions is that alternative scenarios and measures which fail to deliver the goal within the model framework, or which perform less well on the chosen metrics, can be ignored entirely. Indeed, there are recent modelling exercises whereby ambitious climate targets are missed which are not yet given the prominence in the climate policy discourse as might be warranted (Pye et al., 2019; Winning et al., 2018). Far from exploring a wide range of hypothetical scenarios, IAMs have become increasingly 'solution-chasing' as the advance of more stringent climate targets and tighter carbon budgets has been solved by introducing ever greater quantities of CDR to attain targets. Despite the "mass production" of IAM scenarios using different assumptions and modelling frameworks (Haikola and Hansson, 2018), most of those that meet desired climate targets share similar characteristics and dependency on CDR. Unless multiple model runs are conducted with a wide range of input assumptions and alternative solutions, such an approach will provide only a partial view of measures available to achieve a given goal. Furthermore, technologies or policy strategies that meet the goal within the model world may be favoured regardless of whether they are technologically or politically feasible in reality[3] .

In practice, this seems not to have led to dramatically increased investment in BECCS as a technology (Haikola and Hansson, 2018). Its chief negative impacts instead have been in legitimising near-term political inaction in the face of ambitious targets agreed to by world governments, and in hampering exploration of alternative strategies. Investments in renewable energy, while far exceeding investments in BECCS, remain well below those indicated in IAMs; such investments would need to be higher still if BECCS were not considered feasible at scale (Haikola and Hansson, 2018).

The use of IAMs as prescriptive tools also denies a core reality of the policymaking process: it models decision-making as occurring at a global level with a single uniform set of goals defined by the technical modelling community (Dooley et al., 2018). In practice, there is always a need for policies to meet multiple goals and gain support from different stakeholders (Dooley et al., 2018). Models generally fail to accommodate for political will and social acceptance to derive goals (Sovacool et al., 2015), even though social acceptability is likely to be the most critical and most challenging prerequisite of any development of a CDR sector on the scales mooted in IPCC scenarios.

Yet to the extent that policymakers view IAM results as "objective science", it is natural for such least-cost prescriptions to be interpreted as feasible or even preferred targets for climate policy. That is, they are used as scientific evidence in themselves rather than a way of discussing, assessing and organising scientific evidence. Examples of this can be seen in national-level policy setting, with the inclusion of 50–70 $MtCO_2$ removals via BECCS in recent advice to the UK government on its 2050 net-zero target (CCC, 2019), and the US strategy for 80% GHG reductions by 2050, in which 20–40% of GHG emissions are removed through BECCS and land sinks (The White House, 2016).

The dominance of BECCS in IAM outcomes and international and national policy discourse belies the claim that they are seen primarily as tools to explore hypothetical futures. Instead, we argue that this interpretation reflects a mindset that seeks to find optimal solutions to policy challenges: what Lempert et al. (2013) refer to as a "predict-then-act" framework. The tendency for policy-makers to frame problems in a predict-then-act framework when using modelled outputs leads to the seemingly precise characterisation of imprecise possible futures, hindering the exploration of the full range of available measures to mitigate climate change.

4. Broadening the climate policy toolkit

The above sections have outlined how the current use of IAMs give a false sense of certainty for something that is inherently deeply uncertain, despite clear communication of this uncertainty from the modelling community (Dooley et al., 2018; Haikola and Hansson, 2018). The "predict-then-act" mindset is rooted in the "Expected Utility" hypothesis of classical decision theory and economics. This approach assumes that we can make good predictions of the future, or at least reliably characterise the probabilities of different outcomes, and then select a course of action that yields the optimal outcome (i.e. expected utility). However, when the conditions of the problem being looked at have high levels of uncertainty, such prediction-based decision analysis is problematic. This has been called ignorance (Funtowicz and Ravertz, 1993) or "Deep Uncertainty" (Lempert et al., 2003) in the literature, defined as: "*circumstances when the parties to a decision do not know - or agree on - the best model for relating actions to consequences or the likelihood of future events*".[4] Under this framework, the long-term

[3] In the 1,184 modelled scenarios reviewed for the IPCC 5th Assessment Report only 12% don't include negative emissions and 69% are normative in that they address prescribed emissions targets – see IIASA AR5 Scenarios Database: https://tntcat.iiasa.ac.at/AR5DB/dsd?Action=htmlpage&page=about [Accessed 28th March 2018]

[4] Deep uncertainty *is defined as a circumstance where analysts do not know, and/or the parties to a decision cannot agree on: (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future; (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes. In particular, the long-term future may be dominated by factors that are very different from the current drivers and hard to imagine based on today's experiences.*' (Lempert et al., 2003).

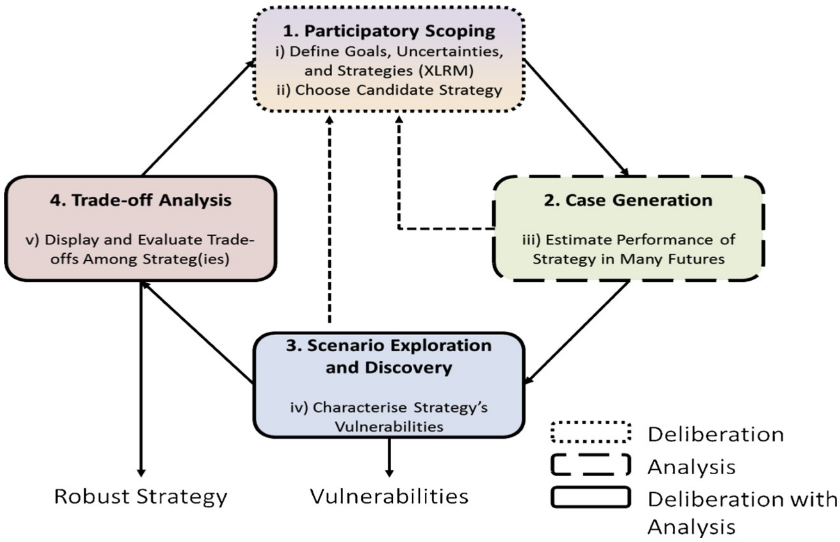

Fig. 3. The Iterative, Participatory Steps (1–4) which characterise Robust Decision Making Analysis. An explanation of each component of the process is also outlined. (Lempert et al., 2013).

evolution of societies, technologies and the climate falls clearly into the realm of Deep Uncertainty, and thus requires a different approach to decision-making.

4.1. The role of modelling in policy development

The classical decision-making approach, exemplified by the interpretation of IAMs described above, fails on three primary counts:

1 Outcomes can be highly sensitive to flaws in input data or assumptions;
2 Results typically optimise for one or two criteria (e.g. cost efficiency), rather than seeking acceptable trade-offs between multiple values; and
3 Decisions are assumed to be taken at a global level in accordance with a global goal, rather than through negotiation between many actors with different values and interests.

How should we instead seek to develop informed and coherent climate policy in a world of deep uncertainty, where no single model is able to provide optimal solutions? We argue that the chief change required is a shift to the use of models primarily as exploratory tools that are embedded within the policymaking process, rather than separate from it. This will require policymakers to be more directly engaged in framing questions, assumptions and possible strategies explored by such models, and even in co-development of model structure (Strachan et al., 2016). The upcoming IPCC Working Group III Sixth Assessment Report, with a greater apparent focus on the Paris Agreement and national actions, could present an opportunity to align modelling with national-scale policymaking (IPCC, 2017). Such an approach must have at its core a recognition that the future is inherently unpredictable, and that complex models should be used to understand the behaviour of a system and the relationships between assumptions and outputs. In short, models are "meaning making" (Klein et al., 2006) rather than providing answers.

Used wisely, models can help decision makers compare the performance of policies and strategies, generated through dialogue, co-creation and negotiation, across multiple futures and criteria without resting on any one assumption or prediction. Several structured methods and tools have been developed to achieve this change in the realm of Decision Science, including Robust Decision Making, Info Gap Theory, Real Options, Multi-Criteria Tools, Conflict Analysis and others (AU4DM Network, 2018). These methods contrast with rational choice decision theory methods which assume decision-making actors as being economic optimisers, having access to perfect information, with values aligned with constituents and broader society e.g. Anderson, 1997.

We briefly review an alternative framework, Robust Decision Making (RDM) which falls within the suite of Scenario-Focused Decision Analysis methods, as a case study of the principles and processes that could help models be used more effectively to inform climate policy.

4.2. Robust decision making: a case study in managing deep uncertainty

RDM is a structured process of evaluating the performance of considered strategies under conditions of uncertainty, with a goal of identifying those that are "robust" across many possible futures, rather than optimal under a single future. "Robustness" here also includes an anticipatory and adaptive element: as the future unfolds, learning and feedback can occur, enabling adaptation of strategies to better suit the unfolding conditions. Building adaptability into decisions thus reduces the potential cost of being wrong in initial predictions. This re-planning is a key part of how we actually think under deep uncertainty.

Quantitative system modelling is a core tool in RDM, but its use differs in three key respects from the prevailing interpretation of IAM outcomes, focusing on development of robustly performing strategies without prediction or optimisation.

First, the orientation of the analysis is said to be reversed (Lempert et al., 2013). Rather than seeking to define what the future might be (possibly from a range of scenarios) and optimise a solution to that future, RDM begins with a candidate strategy and tests how that strategy performs across a wide range of scenarios, using large numbers of model runs. The goal is to identify vulnerabilities: the key features or assumptions that differentiate scenarios where the plan succeeds from those where it fails. This avoids the convergence of strategies on a single optimised outcome which requires a specific set of conditions to succeed, and guides decision makers to ask how proposed policies may be adapted to succeed over a wider range of futures.

Second, the modelling exists in an iterative exchange with strategy development, continuing until a good enough solution can be found. This differs from the more unidirectional relationship between IAMs and climate policy today, in which modelling is done by a technical community outside the policymaking process (Dooley et al., 2018). This iteration facilitates the development of more refined policy strategies, while also ensuring model design and scenario choices are maximally relevant to decision making. Fig. 3 outlines this iterative process for conducting RDM analysis in more detail.

The third feature is clear visualisation of the results and engagement of multiple stakeholders. Outputs are integrated into a multi-criteria candidate strategy testing process and presented to stakeholders via various visualisation techniques (e.g. parallel plots, multi-dimension surfaces). This allows all stakeholders to evaluate performance and trade-offs using their own values and metrics (Simon, 1959). This engagement of stakeholders and broader audiences forces an anthropological choreography between analysts, decision makers and stakeholders, allowing co-creation of solutions better acceptable to all parties. How models, RDM / Scenario-Focused Decision Analysis methods more broadly and their components elements might be integrated into international climate policy processes in the context of the Paris agreement with it bottom up nature will need to be the subject of future research.

Incorporating these three principles into the use of complex modelling of climate futures, and into deliberation and creation of long-term climate policy, would greatly open up the space of possible solutions, values and stakeholders considered. We call for the policy community to broaden the philosophy and tools by which it sets its goals and develops long-term strategies for meeting global climate targets, in order to assess a much broader range of possible strategies and technologies against possible future scenarios - more so than is today (Haikola et al., 2019). The use of these tools should evaluate options for developing and scaling BECCS and other carbon-dioxide removal technologies across a wide range of possible futures and against multiple criteria, as well as alternative pathways for achieving climate targets. We believe that to do so could reveal a much broader range of options, pathways and robust near-term decisions for the global policy community.

5. Conclusion

Global emissions pathways currently deemed compatible with holding global temperatures to well below 2 °C rely overwhelmingly on large-scale carbon-dioxide removal, generally through BECCS, in the second half of the century. Such a strategy could carry serious unintended consequences, including weakening of mitigation efforts in the short term and the potential for large-scale environmental and social damage in the long term. This dependence on BECCS has emerged predominantly in the integrated assessment model scenarios that are used to characterise possible global mitigation scenarios.

We highlight structural features of integrated assessment models that appear to favour the use of BECCS over other deep mitigation strategies in-spite of the high uncertainties associated with such an approach. However, we argue that the real root of the issues above lies not in the structure or assumptions of IAMs, but rather in the philosophy of policy development that underpins how IAMs are interpreted. Specifically, there is a strong tendency to view IAMs as providing objective analysis that can define the optimal goals and strategies for which climate policy should strive. However, this philosophy of decision making implicitly embeds the following assumptions that are inappropriate in the context of long-term global action on climate change:

1 Key parameters such as the feasibility, cost and deployment rates of technologies can be characterised with reasonable confidence on a multi-decadal timescale.
2 Optimal technology choices can be defined at a global level based on simple metrics such as marginal abatement cost.
3 Aspects not typically captured in models, such as negative environmental, social or political implications of technologies, are secondary to those included in the model framework, and can be managed at a later stage in the policy process.
4 Appropriate goals for climate policy in a given context can be defined ex ante by a single community, rather than being agreed by dialogue between multiple stakeholders.

We therefore articulate the need for an alternative approach that explicitly embraces deep uncertainty, multiple values and diversity among contexts, stakeholders and viewpoints, and in which modelling exists in an iterative exchange with policy development rather than separate from it. Such an approach would provide more relevant and robust information to near-term policymaking, and enable an inclusive societal dialogue about coherent paths forward in climate policy, including the appropriate role of carbon dioxide removal. Opening up the discussion in this way will force societies to confront the reality that keeping global average warming to well below 2 °C, let alone 1.5 °C, is probably unobtainable without transformative change in all elements of society, the impacts of which could be unequally distributed. The inclusion of diverse stakeholders, viewpoints and value-sets in policy making is therefore imperative.

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