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Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling

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ABSTRACT

How are novel energy, technology, and land-use systems strategies for limiting climate change judged to be 'feasible'? Controversy has arisen around the research community behind integrated assessment modeling (IAM) scenarios used in the Assessment Reports of the Intergovernmental Panel on Climate Change. This regards the role played by an unproven component in projected energy systems—a coupling of bioenergy generation with carbon capture and storage techniques (BECCS)—that allows IAMs to achieve ambitious temperature targets since adopted by the Paris Agreement. We engage members of the IAM community and a multidisciplinary range of critical experts to interrogate how the 'feasibility' of BECCS—or other novel technologies—is assessed within modeling, and use 'boundary work' to show how the kind of expertise—and by extension, the authority—held by the IAM community is being challenged. We find that the competing judgments of BECCS's feasibility, between the IAM community and its critics, reflect and reinforce different understandings of the freedom of scientific inquiry, the mutual influences of science and policy, the shape of science communication, and the necessity of reform. We ask what these claims signal for future activity in this space, and conclude with a call for 'reflexive' modeling approaches to bridge perspectives.

1. Introduction

If there is a narrative at the heart of climate policy, it is this: 'It is five minutes to midnight, but we can still make it, if we start to act now' [1]. The pairing of urgency and feasibility around the reform of energy systems and the achievability of a livable climate—of the threat of disaster and the promise of avoiding it—keeps climate change politics as currently practiced alive.

The 'feasibility' component of this narrative—that 'we can still make it'—is functionally backed by key pathways of mitigation strategy featured in the resonant Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). These scenarios, tackling the difficult and acute question of future energy, technology, and land-use systems, are the efforts of an expert community built around the use of integrated assessment models (IAMs). Over the last decade, IAM expertise has become authoritative in IPCC mappings of options for achieving (or avoiding) future climates [2]. By extension, the ability of IAMs to mark the terrain between today's carbon economy and ambitious temperature targets as 'feasible' provides an important degree of scientific upholstering for climate policy.

One approach whose scope has been rapidly expanded consists of 'negative emissions technologies', or NETs: programming into models the assumption that increasing amounts of carbon can be removed from the atmosphere through the innovative expansion of carbon sinks. One particular approach—a coupling of bioenergy generation with carbon capture and storage, or BECCS—is currently attractive within modeling parameters because it simultaneously does two things that models seek to optimize: generate energy and reduce carbon dioxide (CO_2) concentrations. Its large-scale deployment features prominently in scenarios simulating temperature rises of no more than 2 °C, underpinning the Paris Agreement's targets [3,4].

Yet, for all its prominence in modeling, BECCS exists only at the pilot stage; like all novel NETs, it requires the bridging of considerable technical and societal uncertainties in order to be deployed at the envisioned scale. BECCS' seeming appearance as a stop-gap towards otherwise improbable climate targets has provoked vigorous criticism in academic channels: not only regarding barriers to implementation, but on the uses and limits of IAMs, the roles of research communities

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built around them, and efforts of the IPCC to navigate the politics of climate assessment [5–9]. Yet, critique only illuminates part of the picture. Members of the IAM community argue that they have consistently warned about excessive reliance upon these approaches, while pointing out uncertainties and research agendas [10–15].

Following scholarship in science and technology studies (STS), we see these exchanges as an example of 'controversy', in which differing values, forms of expertise, and understandings of how science and policy should relate to each other become visible when intra-scientific processes are exposed to criticism [16]. To access these understandings, our study inquires after the lodestone of that controversy: how the 'feasibility' of BECCS is understood, calculated, and communicated. Why does this matter? 'Feasibility' is an amorphous concept that allows for interpretations amenable to different demands. We find that judgments of BECCS's feasibility are proxies for wider worldviews, tied up with different understandings of the freedom of scientific inquiry in policy-driven assessments, the proper relationship between science and policy, and the shape of appropriate science communication. In turn, these understandings underpin different ideas for the reform of IAM assessments, with repercussions for how future mitigation strategies will be mapped—and perhaps, executed.

Section 2 introduces critical literatures in which our analysis is grounded. Section 3 explains our research method, in which we map the argumentation strategies of members of IAM groups involved in the construction of BECCS-heavy pathways, and contrast their responses with those of a multidisciplinary grouping of experts critical about the role of IAM activity in recent climate assessment. Section 4 presents our interview results, revealing diverging understandings of BECCS' feasibility and the scope of IAM work. Section 5 explores how feasibility judgments are co-produced with longer-running perspectives on the proper relationship between science and policy in (climate) governance, and questions what implications they hold for future research. Section 6 reflects on attempts to put perspectives into conversation, with an eye to process reform, in future modeling.

2. Literature and theory

In climate governance, where data on an unformed future is produced through simulations of climatic and societal trends, modeling constitutes a legitimized form of speculative research. IAMs are heterogeneous assemblages of climate, land-use, economic, and energy systems models that underpin Working Group III assessments of mitigation options [17]. Since 2006 (for eventual incorporation into AR5), IAM work has undergone a community-wide shift to a 'matrix architecture', where scenarios are developed by varying three kinds of parameters: radiative forcing, socioeconomic development, and policy. The first is covered by the Representative Concentration Pathways or RCPs; for this study's purposes, the RCPs constitute the only relevant framework, as they house the results included in AR5's assessment of mitigation pathways.[1] Scenarios within the RCP framework calculate emissions trajectories that correspond to ranges of radiative forcing (or likely temperature increase) in 2100 [18]. Depending on the 'target' posed, these emissions pathways implicate profound changes in technological and societal systems (the mitigation options), of which BECCS deployment is only one example [3].

[1] This nuance is not trivial. The matrix architecture that appears to have prioritized the RCPs also includes two other parameter frameworks: the Shared Socioeconomic Pathways or SSPs (which vary societal and political landscapes) and the Shared Policy Assumptions or SPAs (which vary policy configurations). The RCP scenarios were intended to be cross-referenced with the societal and policy dimensions of the SSPs and SPAs to form more well-rounded scenarios – but crucially, the latter frameworks had not been fully developed in time for inclusion in AR5 (around 2013), and are now coming fully into play as bounding parameters for IAM work. For a rapidly proliferating range of SSP-informed scenarios, see the database at http://www.iconics-ssp.org

Our study joins a growing literature that acts both as a post-mortem on the appearance of BECCS in IAMs and as a prospectus for the use of IAMs in the future, encompassing a number of dimensions. The technical opacity of the internal structure of IAMs, as well as their imperfections as a platform for climate policy, are historically well-documented criticisms in economic modeling literature; Gambhir et al. [19] reviews such critique through the lens of BECCS. Our work leverages studies grounded in critical social sciences. Recent works, for example, reflect upon policy narratives embedded in scenarios [20] and the value judgments buried in ostensibly technical modeling choices [21]. Ethnographic studies of IAM-deploying institutions are growing. Hughes and Paterson [22] highlight an elite cluster of economist-heavy research groups based in the global North, while Cointe et al. [2] trace the emergence of the IAM community itself—in particular, the 'repertoire' of projects, procedures and philosophies that now underpin its authority within the IPCC. Further analogues emerge in the wider modeling ecosystem. Beck and Krueger [17] and Hulme and Mahony [23] document lively exchanges between climate modelers and their critics on the political dimensions of climate models: the agendas and responsibilities of modelers in shaping simplified but resonant depictions of future climatic impacts, while under pressure from supposed policy imperatives, funding incentives, and disciplinary demands.

Rather than map the landscape of IAM research groups and users, our study maps perspectives that marshal the efforts of modelers and critics. Haikola et al. [24] represents a recent example; unlike this study, we focus on boundary work [25] and boundary objects [26] as an explanatory framework for the contestations witnessed in participants' attempts to navigate and resolve controversy. Boundary objects—an iconic example in the modeling space is the definition of 'uncertainty' in GCMs, in Shackley and Wynne [27]—act as a discursive totem around which (expert) communities can engage. At the same time, stakeholders advance their separate areas of authority by defining the objects and terms of debate in ways responsive to their own expertise and agendas—this is boundary work.

Branches of STS have theorized how scientific controversies are navigated in varying, intersecting ways—for example, as a competition of 'interpretive flexibility' over facts ('social construction of technology', [28]), or the coming together of things, ideas, and people in relationships ('actor network theory', [29]). We reference the 'co-production' framework of Jasanoff [30,31], which defines boundary work as contestations over scientific knowledge and its appropriate relationship to policy that reflect and reinforce different conceptions of social order. Following a co-productionist perspective on boundary work allows us to reach beyond intra-scientific processes of social construction or network-building, and to understand controversies as revolving around competing political worlds that contain distinct representations of the role of scientific inquiry in society. Leveraging these literatures, we apply the concepts of boundary work and objects to 'feasibility' as an entry point to understanding how the authority of IAM-based definitions and forms of expertise are contested.

3. Methods

13 participants (anonymized, Table 1) were chosen according to three criteria: a roughly even divide between modeling and other disciplinary backgrounds, inclusion of senior figures in the IAM community, and demonstrated engagement with the emergence of BECCS in IAMs. It was not our intention to create a 'mini-public', or to comprehensively map disciplinary perspectives. Rather, we chose to capture controversy at a moment in time amongst a cohort of engaged actors.

We categorized participants into four groups: (1) four self-identified members of the integrated assessment modeling community (IAMs), (2) four with varying modeling backgrounds, who have worked with but do not identify as part of the IAM community (Models), (3) two from science and technology studies (STS), and (4) three in global climate policy (Policy).

Table 1
Study participants.

Background	Position/Institute	Engagement with BECCS debate
IAMs	Professor, University	IAM technical literature
IAMs	Professor, University	IAM technical literature; societal challenges
IAMs	Senior research leader, Global environment research institute	IAM technical literature
IAMs	Senior researcher, Global environment research institute	IAM technical literature
Models (Economic)	Senior research leader, Global environment policy institute	Technical and societal challenges; future research agendas
Models (Economic)	Senior research leader, Global environment research institute	Technical and societal challenges; critique of climate assessment structure
Models (Land-use)	Professor, University	Technical and societal challenges
Models (Vegetation)	Scientist, Global environment research institute	Environmental challenges
Science & Technology Studies	Senior researcher, Sustainability research institute	Critique of climate assessment structure
Science & Technology Studies	Lecturer, University	Critique of climate assessment structure
Policy	Researcher, Sustainability research institute	Societal challenges; governance structures
Policy	Senior research leader, Global policy institute	Technical and societal challenges; critique of climate assessment structure
Policy	Director, Global environment research institute	High level analysis of global climate policy

Our process consisted of two rounds of engagement. The first was an online survey (Round 1) to which participants typically gave paragraph-length answers.[2] Following the principle of inter-rater reliability, the authors assessed the answers for themes that reflected agreement or contention. Care was taken to see if themes could be identified along disciplinary lines, and particularly ones demarcating understandings between modelers and critics of BECCS in IAM work; as well as co-occurrences between themes that might indicate larger constructs of reasoning. This was followed by individually conducted, semi-structured interviews (Round 2) that honed in upon themes established in Round 1. The refined themes of the Round 2 interviews form the results presented in Section 4.

Finally, a note on positionality. The authors come from an STS background, as do many observers critical of BECCS in IAM scenarios. The reader will note that a sensibility grounded therein informs our analysis, but we hope that this will not be misread as unsympathetic to IAM work. Our intent is to map the arguments of defenders and detractors with equal focus, and to understand diverging perspectives with an eye to bringing them into productive conversation with each other.

4. Results

Six themes emerge—we list these below as question sets. They reflect areas of inquiry fleshed out in conversation, rather than exact phrasings posed to participants.

(A) How should the feasibility of BECCS—or novel technologies in general—be defined or calculated?
(B) What constraints or incentives shape researchers' agency when asked to investigate pathways towards ambitious climate targets (2 °C and 1.5 °C)?
(C) Do the results of modeled pathways present options for achieving various climate targets neutrally, or make certain strategies appear more necessary than others? Where do responsibilities lie in applying results?
(D) How does the IAM community communicate on or provide access to modeling processes and results, and how do members of that community and other actors understand these efforts?
(E) What would participants describe as constructive critique of IAM processes and results?
(F) What concrete reforms should be made to the processes by and contexts within which IAMs operate?

These themes serve as anchor points along which argumentation diverges, reflecting differing epistemologies and agendas. But while the construction of feasibility anchors our inquiry, it cannot be the sole focus. Rather, what one thinks of feasibility reflects different ways of thinking about process, authority and science-policy interactions, as represented in the other themes. This is the essence of boundary work, and the subject of more detailed discussion further on.

To explore these, we must begin in Section 4.1 with the 'feasibility' of BECCS, for which no clear, multidisciplinary consensus could be found, and to which only a technical definition could provide a common basis for conversation. The credibility of the technical definition, then, comes attached with understandings that diverge imperfectly along disciplinary lines in two rough blocks, and demarcate competing judgments on the value of IAM expertise for providing a base of knowledge in climate strategy.

The first block is coherently driven by the understandings of participants from IAM groups—we label this an *'incumbent'* perspective (Section 4.2). Responses that reflect a critical analysis of certain aspects of IAM work are characteristic of the second block, supported by a more multidisciplinary spread of participants with backgrounds in different kinds of modeling, STS, and policy—this, we label a *'critical'* perspective (Section 4.3). We present these views in a form that walks the line between data and narrative, and even where they are presented in the rhetorical form of factual statements, they should be read as representing the positionality of the interviewees. However, the juxtaposed perspectives should not imply that participants can be sorted without nuance into 'for' and 'against' camps—the reader can consult Tables 2 and 3 to note the diversity of participants speaking to each theme or component position.

4.1. The technical definition of feasibility

All participants agreed to engage with the IAM community's technical definition: Feasibility is a function of model solvability. The concept can be applied either to the technologies that exist as options for modeling pathways to particular temperature targets, or to the scenarios laying out pathways of deployment. However, feasibility is only indirectly calculated: groups operating particular models pose constraints upon technological options or scenarios, which determines whether, and in what amount, a technology emerges. The focus is on technical and economic dimensions, and social and political aspects are not explicitly considered (see footnote i). The shape of constraints relies upon the judgment of contributing experts, and processes vary with regard to different technologies. IAMs are often 'optimization' models, calculating the most efficient pathway(s) towards particular temperature targets. If a model—given aforementioned constraints—cannot 'solve' for a target, that result goes unreported [32].

In sum: what is 'feasible' is *de facto* what is computationally possible, given initial constraints that are based on interdisciplinary and not uniformly codified expert judgments, and that change from model to model. A scenario is feasible if the model can solve for a temperature target, and a technology is feasible if it was made available as an option at all. Scenarios that are highly implausible in reality, or that produce alternative pathways to the same goal, are all technically feasible.

[2] The survey from Round 1 can be accessed at: goo.gl/F1KZBb

4.2. A modeling-based 'incumbent' perspective

A. Feasibility is contained within the reality of modeling

For many with (integrated assessment) modeling backgrounds, the large-scale inclusion of BECCS in ambitious pathways is justifiable because IAM work does not seek to produce direct representations of reality. IAM participants spoke of having two notions of feasibility: the technical version that is part of their shared professional equipment, and a second that appears more personally defined by intuition and experience with climate policy. And while most admitted to personal misgivings about BECCS, or certain scenarios, or climate targets, all emphasized the professional definition when confronted with criticism (e.g. that the 2 °C target is functionally supported by BECCS). Modelers labeled IAM work as an 'explorative' space for mapping alternative mitigation strategies at a systemic level, under experimental assumptions. Modeling constraints are malleable and can produce unintuitive outcomes, but 'outliers' are contextualized within a wider range of results from multiple models, targets, options, and assumptions to guard against arbitrariness—this is the logic of model inter-comparisons, which underpin the production of all IPCC pathways. Nor is the internal complexity of IAM work prohibitive. Models must navigate a tension between usability (which calls for simplicity) and reflection of reality (which calls for complexity); moreover, complexity is supposed to produce emergent insights—simplistic calculations would not require models. Finally, many modelers pzointed out that all emissions reductions measures—any number of fledgling sociotechnical systems—have to be triggered to their full potential to achieve ambitious emissions pathways, and BECCS is being unfairly singled out by critics.

B. Agency is the duty to assess policy options and targets by scientific standards

Underpinning this depiction of IAM work as 'explorative' is the perception that responsibility for determining climate targets or using scenario insights for policy is a matter for decision-makers and society, not the IAM community. Novel options (e.g. BECCS) or targets (2 °C or 1.5 °C) have to be 'taken as given' and cannot be prejudged without assessment; personal intuitions about feasibility or desirability are irrelevant. Potential misuse should not deter explorative research, but be prevented or preempted by increasing basic literacy in modeling intents and limitations amongst those who might use its results.

C. Modeling maps the solutions space

Accordingly, IAM participants emphasized the advisory, 'map-making' function of their work: scenarios provide decision-making support, and are neither predictions of the future nor prescriptions for a particular climate target or raft of mitigation measures. Many referenced the 'policy relevant but not policy prescriptive' mission statement of the IPCC. Some pointed out that scenarios exercise no discernable influence in propping up ambitious climate targets or driving a rush towards BECCS development, and that optimal pathways have historically failed to inspire the scale of mitigation efforts that they model. IAM participants also argued that policymakers are capable of understanding the complexities of scenario construction, and that senior modelers are aware of the contexts surrounding policymakers.

D. Communication requires improved model and scenario documentation

Given skepticism that IAM work has inherent potential for self-fulfilling prophecies, many with modeling backgrounds expressed confusion regarding criticisms of the IAM community's outreach and openness, which they judge is being conducted to a reasonable, if improvable, degree. Scenarios are made available in databases [33,34]; modelers are improving model documentation [35,36] and collaboration to improve basic literacy in IAMs [37,38]. Modelers admitted that co-authorship is a standard request made of those who use code and data, but this is not gate-keeping—some quality control is needed to navigate the trade-off between external verification and misuse for perverse scientific and political positioning.

E. Critics misunderstand 'explorative' IAM work

These reasonings coalesced revealingly when IAM participants addressed what they saw as the major misconceptions that critics had about their work, and as the objectives of useful critique. Modelers were eager to clarify two perceived misconceptions: firstly, that the IAM community prescribes the eventual deployment of BECCS or negative emissions; secondly, that IAM work is predictive rather than explorative. Present critique unfairly implies a disproportionate burden on the IAM community, and other disciplinary communities seeking to be valuable should help broaden understanding of the barriers to BECCS rollout, or explore the consequences of and alternatives to not deploying BECCS.

F. Reform as 'reality checks' and scenario diversity

IAM participants were receptive to exploring new metrics and common languages for feasibility, citing that 'reality checks' with industry professionals, ecosystems scientists, and social scientists should be expanded, and applied not only to assessment of scenarios, but to assumptions that shape scenarios. At the same time, some IAM participants emphasized the merits of a bounded, technical definition of feasibility fit to modeling purposes, warning that efforts to expand the definition and the objects of inquiry, while worthwhile, could result in nebulousness and inapplicability. Greater scenario diversity was also cited as necessary, highlighting societal values, technological options, and policy configurations that move beyond the current depiction of BECCS as a stop-gap. For many with modeling backgrounds, these efforts would serve to improve calculations of feasibility, underpinned by the collective value of scenario ranges and model inter-comparison for increasing confidence in results. Finally, enhancing engagement was considered necessary, with many calling for new incentive structures that prioritize wider consultations and interdisciplinary collaboration, and highlighting in particular the role of funding bodies. Time and resource constraints in the transitions between IPCC Assessment Reports—particularly between AR5 and the Special Report on 1.5 °C—were also mentioned as obstacles; here, the IPCC was called upon to mandate and convene spaces for reform. IAM participants emphasized that policymakers have strong responsibilities regarding these spaces of exchange, reasoning that stronger modeling literacy amongst climate delegates allows an appropriate division of labor between science (informing options) and policy (setting objectives, and executing options).

Table 2
'Incumbent' perspective.

Name	Ascribed to participants from: IAMs (out of 4)	Models (4)	STS (2)	Policy (3)
A: Feasibility is not a direct representation of reality.	2	3		1
Model constraints form experimental conditions to test alternatives.	4	2		1
BECCS is unfairly singled out.	3	2		
Model and scenario diversity contextualize outliers.	2			1
IAMs navigate the tension between simplicity and complexity, and produce emergent insights.	4	2		
B: Research is 'explorative' - policy has to be taken as given.	4	3		1
Potential misuse should not deter explorative research.	4	2		
C: 'Map-making' widens the solutions space.	4	3		1
Policymakers and researchers are capable of mutual understanding and collaboration.	3	1	1	
D: Quality control navigates need for verification and potential for misuse.	4	2		
Modelers are working to close information gaps.	4	2		
E: Critics misunderstand 'explorative' work; constructive criticism needed on BECCS barriers.	4	2		
F: Try to improve feasibility in modeling inputs, and there are benefits to technical definition.	4	2		
Greater scenario diversity underpinned by modeling logics.	3	1		
Policy makers have responsibilities in understanding modeling limits.	2	2		

4.3. A multidisciplinary 'critical' perspective

A. Feasibility is undefinable, but requires a stronger fidelity to reality

From critical viewpoints, the technical judgment of BECCS' feasibility influences political perceptions of the 2 °C target's feasibility. When asked to provide an alternative definition of 'feasibility' to that of the IAM community, critics implicitly conflated it with 'reality'—but otherwise struggled to define either concept or the relationship between them. Some mentioned biophysical, technical, and sociopolitical dimensions of feasibility by turns; others named adjoining concepts of robustness, credibility, or legitimacy of evidence, referencing the 'confidence statements' used in IPCC Assessment Reports [39]. But critics tended to bracket the definitional issue, focusing instead upon the implications of logics based in modeling practice for political actions in reality. Some highlighted the malleability of model inputs as problematic—overly optimistic assumptions can result in fledgling technological systems acting functionally as backstops for reaching targets, with the heavy presence of nuclear technology in earlier scenarios raised as an analogy [40]. Others noted that 'outlier' results can be used as 'silver bullets': in this case, scenarios that present perceived possibilities for maintaining the carbon economy will be inevitably adopted by opportunistic actors. The internal complexity of IAMs, moreover, makes it difficult to trace the calculations of those outcomes. Finally, inter-comparisons do not necessarily keep the modeling enterprise honest; rather, they often harmonize (unfeasible) assumptions across models.

B. Agency is the responsibility to take the politics of scientific assessment seriously

Many critics argued that 'taking policy as given' therefore reflects a false objectivity. Research is a choice; there has to be responsibility in gauging one's political impacts. Claiming a neutral stance towards novel areas of research, or that results are conditional upon model, scenario and assumptions, simply allows the IAM community to distance themselves from their own choices, and by extension, from criticism. Some speculated on motivations, constraints, and incentives: privileged authority in the present structure of IPCC assessments (where IAM networks form the backbone of Working Group III), or funding and publication opportunities presented by emerging areas for model application, or the tribalism of disciplinary communities, that prioritize further model application ahead of more fundamental reforms of model structure. Critics from policy and STS backgrounds tended to note that policy objectives increasingly drive, structure, and evaluate climate assessments. For example, in the current mode of IPCC work, modelers are asked to generate pathways towards politically negotiated targets (an example of 'regulatory' science, see [30]).

C. Modeling shapes the solutions space

Whatever their intent, scenarios contain signals and have functional effects. Research does not simply 'map'; it actively adjudicates between options by creating criteria and storylines on their benefits and risks (a potential also highlighted by IAM participants). STS-grounded participants, in particular, described BECCS-heavy scenarios as 'performative', with others joining them in arguing that these functionally prop up the viability of ambitious temperature targets and heighten the potential for the hijacking of BECCS (as a silver bullet) by actors beholden to the carbon economy. Policy-grounded critics argued that the IAM community does not adequately grasp the perversities of politics. The promise of eventual carbon removal may allow policymakers to placate competing constituencies—strong climate targets satisfy greens, while continued carbon dependence satisfies certain economic interests. Alternatively, decision-makers want to appear informed, and generating this impression requires funding research whose results are largely cosmetic. And with key exceptions, modelers (or researchers in general) were argued to be driven more by curiosity than how research is subject to political context and messaging.

D. Communication requires interrogation of IAM practice, not only results

Given the potential of explorative research being politicized to drive perverse outcomes, and the seeming lack of awareness to this danger, critics expressed dissatisfaction with what they saw as the IAM community's technocratic, insular nature and routine efforts at outreach. The availability of scenario results, highlighted by the IAM community as an example of openness, was argued to be trivial if processes—model structure, and the internal workings of the community—remain closed. Some critics also speculated that members of the IAM community communicate different messages (regarding the feasibility of BECCS, or IAM practices) to different constituencies, with seeming intent to maintain the coherence of their community in the face of external criticism.

E. Modelers misunderstand critique

Critics claimed to understand that IAMs are intended to be explorative, and that BECCS is not an intentional political agenda, but a model-derived stopgap. The IAM community, rather, misunderstood a subtler set of observations—that modeling BECCS circuitously allows the IAM community to reap the rewards of policy-relevant work, that there is inadequate feedback from users of modeling results in modeling processes, that there are dangers of a purely enabling stance towards BECCS research, and that choices made by researchers can have prescriptive effects for politics where there is a close coupling between policy-making and scientific advice—here, through IPCC Working Group III activity. At the same time, most critics admitted that their efforts were 'big picture' analyses that did not truly penetrate the internal politics of IAM research groups, and some mentioned comparisons to the structure of the climate modeling community as an analogous entry point.

F. Reform as addressing equity and structural change

Critics suggested corrective measures comparable to those suggested by IAM participants such as new metrics for feasibility, greater scenario diversity, and more innovative engagement and transparency—but with different emphases. The technical definition of feasibility was repeatedly highlighted as inadequate for grappling with its unintended political consequences, but critics understood reform in more diverse ways. Most emphasized the need to source new technological, ecological and political dimensions of feasibility to improve modeling design as a first step; others also saw improving feasibility as part of a larger reevaluation of the IAM mode of modeling-for-targets. A more plural spread of scenarios and pathways was phrased as 'extended peer review', underpinned by the need to make explicit the performative influences of IAM work. And while IAM participants noted the role of decision-makers in increasing transparency, for some critics, it is the IAM community who must grapple with a disproportionate influence in framing the viability of novel options and climate targets, and should take the appropriate responsibility for communicating modeling practice through measures more innovative than peer-reviewed publications, model documentation, or conventional policy outreach.

authority.

Let us begin with the 'feasibility' of BECCS. Most participants share a personal sense that BECCS, as modeled, is questionable—there is some misalignment with BECCS' assumptions, scales, and timelines, and what the participant believes about the real world. But adherents to the 'incumbent' perspective emphasize the definition most amenable to modeling practice: Model solvability, with alternative depictions of the techno-economic and biophysical requirements and implications of roll-out at scale. Modelers phrase the improvement of feasibility as a 'reality check', in which technical (and to a lesser degree, sociopolitical) uncertainties can be fleshed out by adding dimensions to the barriers and implications of deployment. This attempt to align 'feasibility within models' and 'feasibility in reality' represents a well-worn debate within IAM practice [19,24], and only relates to mitigation options and scenarios. The critical perspective, however, stretches the IAM community's coverage of feasibility to include (however inadvertently) key climate targets. If BECCS is judged feasible by way of inclusion in 2 °C and 1.5 °C pathways (however BECCS is qualified and bracketed technically), then the IAM community has contributed to a depiction of those temperature targets as feasible.

Defining what feasibility can be applied to (e.g. BECCS, wider mitigation strategies, or climate targets) and how it can be calculated (via the methods of integrated assessment modeling or by other methods), comes about as part of establishing what IAM expertise speaks to, and should speak to. This is the 'boundary': the demarcation between what matters for modeling in IPCC assessments, and for science in policy, that establishes where researchers are responsible—as well as what lies outside of their purview and influence, where failures do not erode their authority. Following Sundqvist et al. [41], this boundary is a demarcation between the (albeit idealized) worlds of science and politics, in which judgments on the proper shape of scientific advice depend on how one observes—and secondly, desires—a stronger separation or entwining of those worlds. IAM argumentation proposes a division of labor between IAM mappings (i.e. science) and climate targets and strategies (i.e. policy and politics). Critics attempt to dissolve the boundary; to introduce secondary, external repercussions into the purview of IAM work by highlighting the inevitably political nature of scientific policy advice. These efforts can be seen in several areas.

Table 3
'Critical' perspective.

Name	Ascribed to participants from: IAMs (out of 4)	Models (4)	STS (2)	Policy (3)
A: Feasibility requires fidelity to reality.		2	1	2
Modeling constraints are malleable enough to achieve any conclusions.		1		2
New technologies can over-perform (e.g. nuclear).	2	2		1
Outliers can be used as 'silver bullets'.	1	1		3
Internal complexity makes results inexplicable.		2		1
Inter-comparisons may not improve model practice.	1	1	1	1
B: Research has to be a choice.	1	1		2
Claiming neutrality avoids criticism.		1		2
Financial incentives constrain agency.	1	2	1	1
Policy objectives constrain agency.			2	2
C: IAMs frame viability and desirability.	2	1	2	2
Modeled BECCS has performative effects.	1	1	2	2
Researchers do not grasp policy-making.		1		3
BECCS fulfills cynical political and policy functions.			1	2
D: IAM community focuses communication on results, not research process.		2	1	1
E: Modelers misunderstand critique; IAM work has to recognize its driving effects.		1	1	1
F: Redefining feasibility has to reflect some new understanding of IAM influences.		1	2	1
Greater scenario diversity underpinned by equity concerns; implicates structural change at IPCC.		1	2	
Modelers have primary responsibilities in engagement; co-design of modeling needed.		1	2	

5. Analysis: Defining 'feasibility' reflects boundary work

The exchanges above represent boundary work, in which contestations over an ostensibly common frame of reference—in this case, 'feasibility'—are co-produced with diverging understandings of what is, and what ought to be, the proper relationship between science and policy. In less disciplinary terms: When defining feasibility, actors are speaking to what they see as the proper relationship between modeling and climate policy in particular, and science and society writ large. From this, their arguments establish competing depictions of the authority—some arguable capacity to set certain terms of debate—that IAM expertise wields in IPCC assessments, and the propriety of that

The first regards the freedom of inquiry and its relation to responsibility in policy-relevant science. Critics question whether the centrality of the IAM community to the IPCC's mappings of mitigation options constrains their research questions, such as taking 2 °C and 1.5 °C as targets for pathway modeling—and in a more circuitous way, led to the emergence of BECCS. Indeed, some critics harken to what STS refers to as 'regulatory' or 'mandated' science, where scientific work is structured by relationships, and even quid pro quos, with policy [25,30]. Critics call for discretion—framed as 'choice' or 'responsibility'—in the conduct of IAM work. Many of modeling backgrounds, rather, rejoin that science is defined by the very absence of personal politics. These, then, are competing attempts to define elements of responsible research. For critics, it is the agency to question the propriety of research; for most modelers, it is the duty to conduct and evaluate that research by disciplinary standards, regardless of political premise. The modelers' view, by extension, highlights that responsibility is more properly defined by the use (rather than conduct) of research, and crucially, this lies outside of the purview and control of scientists.

A second area is the implications of modeling results on climate policy, touching upon what STS literatures refer to as 'performativity'—things, by way of existence, have effects. Critics argue that BECCS has set numerous effects in play: the stabilization of 2 °C and 1.5 °C ambitions in climate governance, the normalization of BECCS or some alternative form of carbon removal, and the crowding out of alternative mitigation and adaptation strategies (for further context external to our study, see [7,42]). IAM and modeling participants, in response, invoke the 'policy relevant but not policy prescriptive' IPCC mandate, and emphasize that the intent of IAM work is 'neutral mapping'. A smaller number of modelers acknowledge that IAM work can have effects incongruous to intent. But they also help demarcate a safe space for modeling by questioning if 'performativity' is too general a concept to be helpful to scientific practice, and is best left to the communication of research results rather than interrogating the conduct of research itself.

A third area revolves around the appropriate shape of critique. Critics attempt to shift the terms of debate to the politicization of science though references grounded in critical social sciences: for example, 'regulatory science', 'external peer review', organizational theory on the calculus of policy makers [43], ethnographies of climate modeling groups as a template for the IAM community [27], and the heavy deployment of nuclear power in previous IAM work as an analogue for BECCS's role as a model-derived stop-gap [40]. For IAM participants, these arguments shifted the bounds of conversation into such an unfamiliar shape that all their initial responses showed a misunderstanding of such critique, which they viewed as accusations that the IAM community supports BECCS deployment, and that models do predictive work. They then fell back upon a characterization of the proper relationship between climate science and policy based on dispassionate investigation, institutional independence, and a purely advisory role. No modeler gave formal naming to this self-identification, but it reflects the tenets of Merton's [44] resilient characterization of scientific expertise as 'on tap' in supplement to politics 'on top', and by extension, a separation between scientific authority and those of laypersons. By invoking the 'not policy prescriptive' IPCC mandate in characterizing the rationale and effects of IAM results, and by linking the feasibility of those results to the experimental nature of model structure, modelers emphasize that how decision-makers use science matters more than how science structures the bounds of possibility.

5.1. What implications might boundary work have for future IAM activity?

To be clear: it is not our intent to imply condemnation of IAM epistemology and practice. Rather, boundary work helps us to clarify the IAM community's sense of misplaced culpability. At the same time, we must recognize that boundary work has real consequences for the future shape and direction of the IAM enterprise, and we can see this particularly in proposals for reform. Participants arrived at corrective measures that were comparable at a high level, but the details conformed to preceding arguments that privileged particular perspectives.

Firstly, modelers saw improving feasibility as 'nudging' existing IAM processes, by adding real-world perspectives to modeling parameters (e.g. costs, technology diffusion rates). Critics, however, saw improving feasibility as part of a wider 'judging' of the IAM community's supposed capacity to legitimize unproven sociotechnical systems. In a second example, IAM participants rationalized the need for a greater spread of scenarios as a way to increase the 'solutions space' and confidence via further model application and inter-comparison. Some critics, by contrast, saw it as an opportunity to ask who is in the room to do the mapping, and increase confidence via inclusion, reflection, and objectives alternative to those posed by the RCPs.

Finally, emphases emerged on the shape of process transparency—this time, driven by differing conceptions of the role of scientists in politically charged research. IAM participants framed engagement as a clearer cautioning to policy makers in IPCC-UNFCCC interfaces that IAMs map rather than shape options, and as documentation of scenarios (and to a more limited degree, the structure of different models) via various databases. The first framing reinforces the boundary between IAMs as information providers and end-users as decision-makers; the second reflects a traditional mode of science communication where results rather than process are the objects of attention. Some critics, driven by perceptions of the technocratic and performative nature of IAM work, called for more fundamental re-designs—not just the scenarios themselves, but objectives, (non-expert) participants, model structure, and the relationship between IAM work and climate policy.

The former conception of critique and reform, then, is about expanding the research agenda: Delivering experimental but actionable evidence about various socio-technical approaches for tackling climate change by fine-tuning and increasing model application. This is borne out by the contextual literature: Critical assessments of BECCS and modeling work led by (integrated assessment) modelers tend to be review articles combined with prospective research agendas for widening the dimensions of BECCS' feasibility, where the limitations and variabilities of model structure are either hinted at but not interrogated [10,11,13–15] or where reform is contested by perspectives internal to modeling practice [19]. One partial exception calls for public debate on the policy options generated within assessments to feed back into refining the front-end of modeling [45]. Yet, the object of critique here would be proposed strategies like BECCS, or emerging implications such as food security—not the IPCC Working Group III's structure of solution-oriented assessment.

The latter conception of reform, rather, is about interrogating the research mode: Questioning the motivations and structures of evidence-production upon which this research agenda is built. This difference is noteworthy. Within the former mode, activities thought by its proponents to be critical and self-reflective can proliferate, and will not endanger the system of knowledge production and the perceived relationship between science and policy represented by IAM activity in IPCC assessments. This reflects conclusions drawn by Shackley and Wynne [27] regarding the interrogation of modeling on the physical science of climate change: operators of those models understood critique and reform within their existing practices, reinforcing rather than eroding the centrality of their work to climate assessment.

In turn, the mode of research has implications for how mitigation strategies will be mapped and framed. Ideas for more comprehensive reforms of IAM and WGIII activities are heterogeneous and remain at a high level of abstraction. But what might some effects be if the 'incumbent' modeling perspective remains inertial? The narratives and discursive structures of IAM work would make for rich study [20,21], and it is already clear that research and discourse—e.g. exploring barriers to rollout, ambitious climate targets, 'overshoot' of global carbon budgets, normalization of carbon removal proposals, language framed around 'Net Negative' or 'Net Zero' emissions—is being shoehorned into futures shaped or reinforced by the presence of BECCS in scenarios that were meant only to be 'explorative' [7,46]. But it is not simply the products of modeling—BECCS, the promise of negative emissions, or the IPCC pathways that incorporate them—that might be performative, but the system of production as well.

One concern centers on the expansion of the space that IAMs could possibly map, alongside a shift from the original objectives and coherence of the IAM community's restructuring of its work prior to the AR5 (see footnote i). The expansion of the 'scenarios space', seen as necessary to map the 'solutions space', may lead to a spread of new climate and sustainability targets, new technological and societal strategies, new framing assumptions and parameters, new expert communities to engage, new models to deploy. One can accept that a shifting scenario space is part of the evolving nature of climate assessment, but we must also be wary that this is not accompanied by an increasingly tenuous grasp of the overall content and direction of the literature. The Shared Socioeconomic Pathways (SSPs), representing variations on sociopolitical conditions, has since the release of AR5 resulted in hundreds of new studies [34], and overarching analyses have yet to be conducted—although this would likely have to be produced in the course of preparing the IPCC's Sixth Assessment Report. There have also been explorations of the value of reorienting the RCP-SSP framework for biodiversity assessments [47]. What would happen if IAMs were purposed to map strategies to achieve the UN's benchmark Sustainable Development Goals?

Another concern follows the example set out by BECCS: that speculative technologies deployed in IAMs as back-stops for reaching ambitious targets become normalized due to a lack of credible alternative visions. Recall that this has been argued to follow a template once occupied by nuclear energy [40]; our discussion need not be restricted to novel carbon sinks, but to innovations in energy systems, behavioral systems, carbon budgets, and other components that can be programmed into modeling as well. Is the next move to expand into IAMs other land-based approaches for negative emissions [13]? What would happen if the capacities of terrestrial carbon removal are exhausted in modeling work—does modeling then incorporate negative emissions approaches based in the marine environment, or technologically-grounded 'direct air capture' approaches, or methods for reflecting sunlight ('solar radiation management', SRM), on a similarly 'explorative' basis?

6. Conclusion

We echo calls to develop 'reflexive' or 'participatory' approaches to modeling as a pragmatic step to bringing diverse perspectives into conversation with each other. McLaren [48] notes: 'Modeling should experiment with … designing trans-disciplinary research programs that genuinely engage with political, social and cultural dimensions of climate policy, not merely seeking to abstractly model the political and social alongside the scientific' (p. 218). Salter et al. [49], through 'participatory integrated assessment', go further, highlighting modeling not only as a technocratic area of knowledge production in need of upstream stakeholder engagement, but as a tool capable of bridging the expertise of modelers and the concerns that drive users. Nose-to-tail engagement with a particular modeling process—as tool, political objective, project design, and dissemination—can teach modelers and decision-makers something about each other, and decisions will be more robust for it. In the short term, this dovetails with modeling proposals to introduce stakeholder feedback into the evaluation of modeling content, and connect these to designing a diversity of objectives and scenarios [45].

In the long run, reform would require re-evaluation of model structure, as there is sufficient debate within and external to economic modeling on the suitability of the current structure of IAMs for their stated mapping purposes [19,21,50]. Reform would also implicate the major institutions that manage the boundary between climate science and climate policy—the IPCC, in particular, cannot remain untouched [7,51]. For the near future, individual projects might serve as expositions of the possibilities that such modeling affords, offering opportunities for learning and experimentation with different formats and approaches. We must note, in this vein, recent initiatives generated by modelers themselves. For example, the SENSES [37] and DIPOL [38] projects—housed at the Potsdam Institute for Climate Impacts Research, host to much resonant IAM work—organize collaborations between scientists and end-users to explore the front-end of modeling, and to produce needs-relevant scenarios.

It is laudable that efforts to proactively grapple with concrete alternatives are not only undertaken by modelers, but have come to adopt the language of critics. We must ensure that these do not embody fringe initiatives that neither reflect, nor will be able to shift, the inertia of the IAM enterprise. We can observe this evolving space through the lens of boundary work, and look for the lurking presence and effects of different animating understandings of what the purposes and processes of reform should be. If modelers and critics of various disciplines see increasingly common frames of reference like 'co-production', 'scenario diversity', or the coordinating role of the IPCC, much like 'feasibility', through the prisms of their own worldviews, then we must navigate misunderstandings that could emerge once we scratch the surface of the reforms posed, due to the presence of different political projects that are still unfolding.

The emergence of BECCS has thrown a spotlight on IAM work, and both hope and caution are due in observing recent developments on the embrace of greater inclusivity. Our study points out the need—accompanied, promisingly, by some desire and action—towards a shared ethos and process between creators, translators, and users of these depictions of possibilities for mitigating climate change. And in future collaborations, we must recall that despite their resonance, IAMs are but one corner of climate governance, and remain wary that we do not treat improving model structures and scenarios as a proxy for inquiring more creatively and comprehensively after the kind of climate and society that we wish to have.

Declaration of Competing Interest

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

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