Special issue

Techniques in Science Advice: Modelling for Policy and the Politics of Models

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ABSTRACT: Computational models have become indispensable in policy-making across many domains, from environmental regulation, to trade policies and public health. Yet their role as techniques in science advice remains underexplored. This article discusses models through three interrelated analytical dimensions: as boundary objects coordinating different social spheres; as sites where authority is enacted, negotiated, and contested; and as performative devices that actively constitute policy realities. Drawing on social science scholarship and empirical cases, the article demonstrates how models entangle epistemic, technical, social, and political dimensions within advisory assemblages. It concludes with a discussion of responsible modelling, emphasizing inclusion, transparency, and communication.

KEYWORDS: computational models; science advice; boundary objects; authority; performative power

SUMMARY: 1. Introduction: Models as Parts of Advisory Assemblages – 2. Models as Boundary Objects: Coordinating Social Worlds – 2.1. Conceptualizing Models as Boundary Objects – 2.2. Analytical Perspective: Models as Mediators – 2.3. Normative Perspective: Conditions for Success – 3. Models as Sites of Authority: Credibility, Legitimacy and Contestation – 3.1. Epistemic and Social Sources of Authority – 3.2. Contesting Authority: Instrumentalization and Counter-Modelling – 3.3. Structural Limits: Opacity and Uncertainty – 4. Models as Performative Devices: Enacting Political Realities – 4.1. Framing Issues: Defining Problems and Solutions – 4.2. Inscribing Values: Embedding Assumptions in Design – 4.3. Materializing Imaginaries: Technical Affordances and Governance Visions – 4.4. Constituting Futures: Legitimizing Actions Under Uncertainty – 4.5. Reproducing Hierarchies: Expertise, Power, and Exclusion – 5. Conclusions: Towards Responsible Modelling for Policy.

1. Introduction: Models as Parts of Advisory Assemblages

When discussing science advisory systems, the focus is frequently on institutions and actors, such as advisory organisations and experts, and questions regarding their various forms, ways of mediating between science, politics and publics and factors for effective policy advice.[1] This emphasis is also reflected in the various contributions to this Special Issue. Yet while people

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and institutional mechanisms receive considerable attention in reflections on science-policy interactions, the techniques for producing and mediating expertise often gain less attention. In this contribution, I reflect on a technique that is becoming increasingly important in science-policy interactions: computational modelling.

Computational models[2] have become ubiquitous across policy domains. In energy and climate policy, models serve to explore transition pathways and inform international assessments like the Intergovernmental Panel on Climate Change (IPCC).[3] In trade and economic governance, models project macroeconomic effects and evaluate policy options.[4] Models increasingly guide environmental regulation, risk assessment, and resource management, from chemicals registration, oil spill risk management, to water planning.[5] The COVID-19 pandemic demonstrated models' crucial role in public health crisis response.[6] These exemplary applications show how models increasingly inform policies by anticipating trends, sketching scenarios, and developing and testing socio-political actions, thereby gaining considerable authority in informing public action.

Why, then, are models less frequently the focus of discussions about scientific policy advice than advisory institutions or experts? This imbalance may be due to the persistent understanding of models as neutral analytical tools that are free from politics.[7] This understanding is consistent with the modernist paradigm, which is based on the much-criticised but still dominant linear model of policy advice and assumes that decision-making can benefit directly from information and analytical techniques, both in terms of content

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[1] See for example, J. LENTSCH, W. PETER, *The politics of scientific advice. Institutional design for quality assurance*, Cambridge, 2011.

[2] Very basically, computational models (synonyms: computer models, computer-based models) "are mathematical models that are simulated using computation to study complex systems. […] The parameters of the mathematical model are adjusted using computer simulation to study different possible outcomes." See: https://www.nature.com/subjects/computational-models (last visited 19/10/2025).

[3] See for example, B. COINTE, C. CASSEN, A. NADAÏ, *Organising policy-relevant knowledge for climate action: Integrated assessment modelling, the IPCC, and the emergence of a collective expertise on socioeconomic emission scenarios, in Science & Technology Studies,* 32(4), 2019; S. PFENNINGER, A. HAWKES, J. KEIRSTEAD, *Energy systems modeling for twenty-first century energy challenges, in Renewable and Sustainable Energy Reviews,* 33, 2014; M. CHANG, J. Z. THELLUFSEN, B. ZAKERI, B. PICKERING, S. PFENNINGER, H. LUND, P. A. ØSTERGAARD, *Trends in tools and approaches for modelling the energy transition, in Applied Energy,* 290, 2021.

[4] See e.g., M. A. R. ESTRADA, D. PARK, *The past, present and future of policy modeling, in Journal of Policy Modeling* 40, 1, 2018; M. A. R. ESTRADA, S. F. YAP, *The origins and evolution of policy modeling, in Journal of Policy Modeling,* 35 (1), 2013.

[5] See e.g., H. BOULLIER, D. DEMORTAIN, M. ZEEMAN, *Inventing prediction for regulation, in Science & Technology Studies* 32, 4, 2019; T. PARVIAINEN, S. KUIKKA, P. HAAPASAARI, *Enhancing science-policy interface in marine environmental governance: Oil spill response models as boundary objects in the Gulf of Finland, Baltic Sea, in Marine Policy* 135, 2022; B. D. TRUMP, D. HRISTOZOV, T. MALLOY, I. LINKOV, *Risk associated with engineered nanomaterials: Different tools for different ways to govern, in Nano Today* 21, 2018; R. ALBA, T. KRUEGER, L. MELSEN, J.-P. VENOT, *Modelling water worlds, in Water Alternatives,* 18(2), 2025.

[6] See for example, J. HÄLTERLEIN, *Conflicting values in epidemiological modelling, simulation, and dashboard-design, in Digital Culture & Society* 9, 2, 2023; T. RHODES, K. LANCASTER, *Making pandemics big: On the situational performance of Covid-19 mathematical models, in Social Science & Medicine,* 301, 2022.

[7] E. FISHER, P. PASCUAL, W. WAGNER, *Understanding environmental models in their legal and regulatory context, in Journal of Environmental Law* 22, 2, 2010; T. UDREA, A. BAUER, *Between control and independence: computational modelling within EC's trade sustainability impact assessments, in Impact Assessment and Project Appraisal,* 41(1), 2023.

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and procedure, and regardless of the context in which the knowledge is produced. This notion is, for example, clearly reflected in the use of models in the European Commission's Impact Assessments. When models are addressed in guidance and literature, discussions predominantly revolve around technical aspects of modelling, their refinements, data access, or practical modelling choices.[8]

As social science scholars have long demonstrated, models serve not as objective tools for prediction or insight, but as techniques that coordinate different actors, actively shape policy outcomes, contribute to shared understandings and imaginaries of socio-political issues and futures, and lend legitimacy to decisions and regulatory actions.[9] Hence, models cannot be understood in isolation from the political and social contexts in which they operate. Instead, we can conceive of models as key elements within "advisory assemblages", understood as the relationally constituted configurations of actors, institutions, techniques, discourses, and infrastructures that together compose and authorize policy advice.[10] Within these assemblages, institutions, people, and techniques of expertise enable and shape each other, are mutually dependent, and together contribute to the enactment and maintenance of their authority in science, policy, and society. For example, energy systems models, energy systems modellers, research institutions providing the needed infrastructures, scenario-based energy transition strategies, and actors in energy planning all constitute and legitimize each other.

This article discusses computational models from three interrelated analytical angles, each illuminating different dimensions of how models function within advisory assemblages. First, I discuss models as boundary objects, examining their hybrid nature and role in coordinating diverse social, political, and scientific domains (section 2). Second, I discuss how models acquire, maintain and lose authority (section 3). Third, I examine their performative power, i.e., how models enact realities (section 4). These dimensions are mutually reinforcing. How models function as boundary objects depends on their authority, which in turn enables their performative power to constitute what counts as real, calculable, and actionable in policy contexts. Concludingly, I reflect on how these insights can inform practices of "responsible modelling" (section 5).

The discussion synthesizes social science literature on modelling, selected contributions from key modelling domains (including energy modelling, economic modelling, risk assessment, water management), my own published research on modelling for policy,[11] as well as two unpublished case studies on modelling

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[8] As an example, see L. NILSSON, *Reflections on the economic modelling of free trade agreements*, *in Journal of Global Economic Analysis,* 3(1), 2018.

[9] See for example, C. SCHUBERT, *The social life of computer simul*ations, in N. J.SAAM, M. RESCH, A. KAMINSKI (ed.), *Simulieren und Entscheiden* ,2019; J. OOMEN, J. HOFFMAN, M. A. HAJER, *Techniques of futuring: On how imagined futures become socially performative*, *in European Journal of Social Theory*, 25(2), 2022; R. ZEISS, S. VAN EGMOND, *Dissolving decision making? Models and their roles in decision-making processes and policy at large*, in *Science in Context*, 27(4),2014.

[10] For a general understanding of assemblages, see B. LATOUR, *Reassembling the social. An introduction to actor-network-theory*, Oxford, New York, 2005; S. C. AYKUT, *Reassembling energy policy*, in *Science & Technology Studies* 32 (4),2019; E. MCCANN, K. WARD*, Policy assemblages, mobilities and mutations: Toward a multidisciplinary conversation*, in *Political Studies Review,* 10(3), 2012.

[11] A. BAUER, L. CAPARI, D. FUCHS, T. UDREA, *Diversification, integration, and opening: developments in modelling for policy,* in *Science and Public Policy*, 50(6), 2023; A. BAUER, D. FUCHS, *Modeling for nano risk assessment and management: The development of integrated governance tools and the potential role of technology assessment*, in *TATuP - Zeitschrift für Technikfolgenabschätzung*, in *Theorie und Praxis*, 32(1), 2023; T. UDREA, A. BAUER, *op. cit*; T. UDREA, L. CAPARI, A. BAUER, *The politics of models: Socio-political discourses in modeling of energy transition and transnational*

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for energy transition.[12] By foregrounding models as techniques within advisory assemblages, this article complements the institutional and actor-focused contributions in this Special Issue. It demonstrates that a comprehensive understanding of science advisory systems also requires critical attention to the techniques through which expertise is produced, mediated, and authorised.

2. Models as Boundary Objects: Coordinating Social Worlds

Understanding models as part of advisory assemblages requires reflecting their position at the science-policy interface. Rather than treating models as neutral, apolitical devices that simply transmit scientific findings into policy contexts, social science scholarship has characterized them as active mediators, including as "techniques of futuring",[13] "vehicles of expertise",[14]and, most prominently, as "boundary objects".[15]

2.1. Conceptualizing Models as Boundary Objects

The concept "boundary object", originally introduced by Star and Griesemer,[16] describes artifacts, practices, representations, and technologies that link and coordinate elements of different "social worlds" (such as science, policy, and practice) while allowing these worlds to maintain their stability.[17] This requires interpretative flexibility, indicating that models can hold distinct meanings for different groups and may serve diverse epistemic and socio-political interests while maintaining a recognizable structure for all involved actors.[18]

The idea of models as boundary objects has been invoked in two complementary ways across scholarly and practitioner debates. The analytical perspective treats all policy models as boundary objects by virtue of their position at the science-policy interface, examining how they mediate between different social worlds regardless of how successfully they do so. The normative perspective focuses on the conditions under which models function effectively as boundary objects, evaluating their success in enabling coordination, deliberation, and knowledge mediation. These perspectives are not mutually exclusive but

trade policies, in *TATuP - Zeitschrift für Technikfolgenabschätzung*, in *Theorie und Praxis*, 32(1), 2023; D. Fuchs, A. Bauer, *Anticipatory practices in risk governance: Affordances and politics of computational models*, in *Futures*, 175, 2026.

[12] *Project CoMoPA – Computational Modelling in Policy Advice (2018-2020),* funded by the Innovation Funds of the Austrian Academy of Sciences.

[13] M. A. Hajer, P. Pelzer, *2050—An energetic odyssey: Understanding "techniques of futuring" in the transition towards renewable energy,* in *Energy Research & Social Science,* 44, 2018.

[14] C. Landström, S. J. Whatmore, S. N. Lane, *Learning through computer model improvisations,* in *Science, Technology, & Human Values,* 38(5), 2013.

[15] E. Fisher, P. Pascual, W. Wagner, *op. cit;* S. C. Aykut, D. Demortain, B. Benbouzid, *The politics of anticipatory expertise: Plurality and contestation of futures knowledge in governance — Introduction to the special issue,* in *Science & Technology Studies,* 32(4), 2019; A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit;* T. Udrea, A. Bauer, *op. cit;* R. Zeiss, S. van Egmond, *op. cit;* P. G. Taylor, P. Upham, W. McDowall, D. Christopherson, *Energy model, boundary object and societal lens: 35 years of the MARKAL model in the UK,* in *Energy Research & Social Science,* 4, 2014.

[16] S. L. Star, J. R. Griesemer, *Institutional ecology, "translation" and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39,* in *Social Studies of Science,*19(3), 1989.

[17] See also, T. Parviainen, S. Kuikka, P. Haapasaari, *op. cit;* A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit;* R. Zeiss, S. van Egmond, *op. cit.*

[18] S. L. Star, J. R. Griesemer, *op. cit;* A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit.*

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emphasize different dimensions of the same phenomenon: all policy models occupy boundary positions (analytical perspective), yet their effectiveness in coordinating heterogeneous actors and transforming knowledge varies significantly (normative perspective).

2.2. Analytical Perspective: Models as Mediators

From an analytical perspective, policy models are intrinsically hybrid and function as boundary objects by virtue of their position, regardless of their success. They inhabit multiple social worlds and mediate between different scientific disciplines, between science and policy, and between science and publics.[19] This descriptive conceptualization holds true even when models remain opaque and are difficult for non-experts to understand or use. The analytical focus is on the different ways in which models occupy this hybrid space, how they coordinate different actors, and with what effects.

The use of models in the European Commission's Trade Sustainable Impact Assessments (SIA) illustrates how the same model can simultaneously occupy boundary object status while varying in functional effectiveness. When the European Commission shifted economic modelling, which is the main analytical component of SIAs, from external consultancies to its own in-house modelling team.

the socio-technical arrangements of modelling changed significantly in terms of interactions between consultants and DG Trade, consultations with stakeholders, and relationships with other modelling work. As a result of this shift, economic modelling became simultaneously external to the SIA analyses and central to the SIA as a whole, serving as input for further analyses, as a basis for making the case for trade agreements in stakeholder consultations, and as the main content of SIA reports. The scope for deliberations between the EC, consultancies, and stakeholders was reduced, and models became less transparent. The discussion around this reorganization revealed the interpretative flexibility inherent in models as boundary objects. Different actors, including modellers, consultancies, DG Trade, and stakeholders, ascribed different roles and functions to the models. The in-house shift was consistent with an understanding of models as rational and neutral analytical tools that provide clear, largely unambiguous results and thus guide and legitimize policy choices. However, this shift became problematic for those who understood models as a "structured framework for discussion" that prioritizes deliberations around modelling over a focus on outcomes.

This example demonstrates that models can connect multiple social worlds (DG Trade, consultants, stakeholders, the public) while simultaneously failing as effective boundary objects by limiting participation, reducing transparency, and constraining the space for deliberation. The case also shows how these inclusions and exclusions are not necessarily determined by the model itself but depend on actors' understandings of models and their functions, as well as on institutional arrangements. Who conducts the modelling, how results are presented and integrated into policy assessments and consultations, and what mechanisms exist for review and critique directly shape both coordination potential and, as we will see in section 3, model authority.

[19] R. ALBA, T. KRUEGER, L. MELSEN, J.-P. VENOT, *op. cit.*

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Special issue

2.3. Normative Perspective: Conditions for Success

From a normative perspective the focus is on the specific attributes and processes that are required for models to function successfully as boundary objects. This approach emphasizes coordination and knowledge management, highlighting that not all models automatically achieve effective boundary object status. In this reading, the boundary object concept serves as a normative model for how to design and use models at the science-policy interface. Models as successful boundary objects then align with a characterization of modelling as an analytical-deliberative process rather than merely a method for generating truth,[20] i.e., models are understood as processes for helping to frame and understand issues, potential pathways and actions, thereby aiding analysis, deliberation, and solution finding. This perspective has also informed practitioner debates about participatory modelling and stakeholder engagement.

The development of Portugal's Roadmap to Carbon Neutrality (RNC2050, 2017-2019)[21] exemplifies such a deliberate approach, giving the model centre stage in deliberations on carbon-neutral futures. In this process, modellers and domain experts, policy-makers representing different areas and a range of stakeholders from the energy industry and civil society were brought together to collaborate on developing scenarios for a low-carbon strategy. The process incorporated stakeholder input through multiple feedback loops and enabled negotiations over modelling choices and assumptions. By this process controversies, for example on how many new dams the country would need, how oil prices should be set, or what role agriculture could and should play in achieving carbon neutrality, were identified and addressed at an early stage. Participants considered the process to be highly valuable and goal-oriented, maintaining strong trust in the modelling. The model-based scenario process thus produced not only quantitative figures but also shared visions and relations that aligned with the political context and objectives.

Similarly, the MARKAL energy model's longevity in UK energy policy has been attributed to its successful functioning as a boundary object, providing shared understandings of energy policy problems across a variety of departments and stakeholders.[22] Notably, the institutional arrangements of how the model is integrated in the policy process differs from the Portuguese case as the model was developed by academia but since has been firmly integrated into administrative structures and procedures. Hence, these cases illustrate that there is no one-size-fits-all approach to successful boundary management but that different arrangements can facilitate genuine coordination across different communities, when they create spaces for deliberation, and when they enable a joint production of knowledge and policy visions.

However, functional success is not guaranteed. For instance, as discussed by Parviainen and colleagues,[23] operational models in marine risk governance showed limited capacity as boundary objects, failing to translate knowledge across semantic (shared meaning) and pragmatic (action orientation) boundaries and remaining instrumental tools rather than platforms for exploring alternative framings.

In sum, all policy-facing models are boundary objects by position, but successful ones only when they achieve coordination and knowledge mediation across communities. Yet models' capacity to coordinate

[20] E. Fisher, P. Pascual, W. Wagner, *op. cit.*

[21] This discussion is based on an unpublished case study from the project CoMoPA.

[22] The discussion of Markal is based on P. G. Taylor, P. Upham, W. McDowall, D. Christopherson, *op. cit.* and an unpublished case study in the project CoMoPA.

[23] See T. Parviainen, S. Kuikka, P. Haapasaari, *op. cit.*

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diverse actors depends fundamentally on their authority, i.e., how they gain, maintain, and lose credibility and legitimacy across different contexts.

3. Models as Sites of Authority: Credibility, Legitimacy and Contestation

Computational models have an authoritative position in modern governance, functioning as far more than analytical tools; they are socio-political instruments that structure knowledge, define actionable futures, and legitimate policy decisions. This authority is not inherent or universally accepted, but is continually enacted, negotiated, and contested.[24] Understanding the dynamics of this authority requires analysing its multiple sources, the mechanisms of its contestation, and the structural challenges to authority.

3.1. Epistemic and Social Sources of Authority

Models' authority stems from both epistemic characteristics and social standing, continuously enacted and contested through interactions among actors.[25]

On an epistemic level, authority stems from the models' rooting in accepted scientific knowledge, practices, and long institutional history.[26] For complex issues like climate change and trade policy, models gain credibility by embedding established scientific practices and disciplinary consensus. Computable General Equilibrium (CGE) models in trade analysis,[27] the long-established MARKAL energy model in the UK,[28] and General Circulation Models (GCMs)[29] in climate science exemplify how conventional approaches strengthen epistemic authority within their domains.

The shift toward computational modelling in science over the past seventy years has reinforced an objective, numerical, and anticipatory scientific culture, granting models authority by complementing traditional sources of knowledge like observation and experimentation.[30] Models abstract and generalize place-based knowledges, enabling comparison across geographical regions and temporal scales.[31] Unlike observation and measurement, models offer access to remote places and futures, allowing them to "travel between contexts" with apparent universal relevance.[32] The IPCC scenarios exemplify this: Integrated Assessment Models produce socio-economic emission scenarios that serve as the basis for assessing climate policy options globally.[33]

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[24] A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit.*

[25] M. Hulme, *How climate models gain and exercise authority*, in K.Hastrup, M. Skrydstrup (ed.), *The social life of climate change models: anticipating nature,* New York and London 2013.

[26] C. Landström, S. J. Whatmore, *Virtually expert: Modes of environmental computer simulation modeling,* in *Science in Context* 27(4),2014; M. Hulme, *op. cit.*

[27] T. Udrea, L. Capari, A. Bauer, *op. cit.*

[28] P. G. Taylor, P. Upham, W. McDowall, D. Christopherson, *op. cit.*

[29] J. C. Hochsprung Miguel, M. Mahony, M. S. A. Monteiro, *"Infrastructural geopolitics" of climate knowledge: the Brazilian Earth System Model and the North-South knowledge divide,* in *Sociologias* 21, 2019.

[30] A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit.*

[31] R. Alba, T. Krueger, L. Melsen, J.-P. Venot, *op. cit.*

[32] Ibid.

[33] B. Cointe, C. Cassen, A. Nadaï, *op. cit;* C. Miller, *Climate science and the making of a global political order,* in S. Jasanoff (ed.), *States of knowledge. The co-production of science and the social order,* London 2004.

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Special issue

This anticipatory capacity is particularly valuable in policy contexts where decisions must be made about uncertain futures.[34] In these contexts, models gain credibility because they are constructed from components that themselves possess epistemic authority, such as accepted theories or scientific observations and data[35]. This genealogy of credibility allows models to maintain particular epistemic authority even when they are recognized as incomplete and simplified representations of the world.[36] The proliferation of modelling approaches and tools consolidates their epistemic standing, as models are progressively becoming a standard method of evidencing.[37]

Beyond epistemic foundations, models derive social authority from public visibility and performance and their institutional standing.[38] Models' social authority is strongly backed by the deep-seated "trust in numbers" embedded in Western cultures.[39] Quantification provides evidence in seemingly concrete and objective numbers, presenting governmental actions, especially controversial ones, as resulting from an impartial and impersonal calculation.[40] In public health crises like the COVID-19 pandemic, models and their quantified projections acquired significant authority, leading to the enactment of a "model society" that responds to uncertainty through calculated evidence.[41]

The reputation and institutional standing of the organizations and researchers involved significantly confer authority upon a model.[42] For the Integrated Assessment Modelling (IAM) community, their central position within the IPCC Working Group III and the establishment of coordination bodies like the IAM Consortium enhance their authority and legitimacy.[43]

The relationship between models' and institutions' authority is reciprocal, meaning that models lend legitimacy to institutions, and, conversely, their continued use by institutions reinforces their own authority. In the case of global agricultural models, an institution's capacity to shape evidence-based policy depends directly on its link to a dominant model. For example, the International Food Policy Research Institute (IFPRI) benefited from the legitimacy of its IMPACT model to secure influence over agricultural policies.[44] Conversely, the ability of a model to function successfully often depends on its capacity to become institutionally authoritative.[45] For example, the PEARL model (Pesticide Emission Assessment at Regional

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[34] D. Fuchs, A. Bauer, *op. cit.*

[35] A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit;* R. Alba, T. Krueger, L. Melsen, J.-P. Venot, *op. cit.*

[36] J. Trombley, *Assembling, channelling, and orienting watershed management: The performative roles of computer models in environmental management institutions*, in *Water Alternatives,* 18(2), 2025; R. Alba, T. Krueger, L. Melsen, J.-P. Venot, *op. cit.*

[37] A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit.*

[38] M. Hulme, *op. cit.,* 33.

[39] T. M. Porter, *Trust in numbers: The pursuit of objectivity in science and public life,* Princeton, 1996.

[40] F. Molle, B. Lankford, R. Lave, *Water and the politics of quantification: A programmatic review,* in *Water Alternatives,* 17(2), 2024; A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit;* S. C. Aykut, *op. cit.*

[41] T. Rhodes, K. Lancaster, M. Rosengarten, *A model society: maths, models and expertise in viral outbreaks,* in *Critical Public Health,* 30(3), 2020.

[42] F. Molle, B. Lankford, R. Lave, *op. cit;* L. Cornilleau, *Magicians at work: Modellers as institutional entrepreneurs in the global governance of agriculture and food security,* in *Science & Technology Studies,* 32(4), 2019.

[43] B. Cointe, C. Cassen, A. Nadaï, *op. cit;* L. van Beek, M. Hajer, P. Pelzer, D. van Vuuren, C. Cassen, *Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970,* in *Global Environmental Change,* 65, 2020.

[44] L. Cornilleau, *op. cit.*

[45] The following discussion is based on R. Zeiss, S. van Egmond, *op. cit.*

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Special issue

and Local Scales) in Dutch pesticide regulation achieved a high degree of authority by becoming an "obligatory regulatory point of passage" with a legal status in pesticide. In contrast, the LARCH model (LAndscape ecological Rules for the Configuration of Habitat), which informed deliberation without providing binding results, had not attained this same degree of authority in its domain. This suggests a functional hierarchy in the status and influence of different models within regulatory systems.

Consequently, model authority is heavily influenced by the networks, discourses, and institutional contexts surrounding them. However, models must continually demonstrate their utility and legitimacy within actual social processes and political contexts,[46] meaning that social authority is not permanently secured but must be actively maintained.

3.2. Contesting Authority: Instrumentalization and Counter-Modelling

Model authority, however established, faces constant challenges. Disputes about models increasingly appear in political debates, media discourse, and legal proceedings.[47]

One of the most profound challenges to models' legitimacy is their instrumentalization, often referred to as "policy-based modelling".[48] Policy-based modelling implies that models are used to provide technical justification for policies that have already been decided upon on other reasons and sources.[49] Political actors may commission modelling work specifically to generate results that justify a predetermined ambition level or policy choice.[50] When political agendas clash, the modelling landscape can become a contested terrain where opposing political coalitions commission contradictory studies to support their arguments. This phenomenon, sometimes referred to as the "War of the Models",[51] highlights how major political struggles play out through competing quantifications, with different models making competing claims to authoritative knowledge.[52] The political discussions around the now-halted Transatlantic Trade and Investment Partnership (TTIP) free trade agreement (EU-USA) provide a compelling illustration of this dynamic.[53] In this case, there were highly opposing political positions and highly charged debates, in which specific model studies were heavily criticized. Due to the political significance of the topic, a wide range of alternative modelling studies was conducted. Most pointed in the same direction (indicating slightly positive effects) as the EC commissioned studies, but there were studies, such as Capaldo's,[54] which showed negative impacts of the negotiated agreement. Depending on the political stance, the relevant

[46] C. Schubert *op. cit.*

[47] E. Fisher, P. Pascual, W. Wagner,*op. cit.*

[48] D. Süsser, A. Ceglarz, H. Gaschnig, V. Stavrakas, A. Flamos, G. Giannakidis, J. Lilliestam, *Model-based policymaking or policy-based modelling? How energy models and energy policy interact,* in *Energy Research & Social Science,* 75, 2021.

[49] H. Strassheim, P. Kettunen, *When does evidence-based policy turn into policy-based evidence? Configurations, contexts and mechanisms,* in *Evidence & Policy,* 10(2), 2014.

[50] S. Royston, C. Foulds, R. Pasqualino, A. Jones, *Masters of the machinery: The politics of economic modelling within European Union energy policy,* in *Energy Policy,* 173, 2023; D. Süsser, A. Ceglarz, H. Gaschnig, V. Stavrakas, A. Flamos, G. Giannakidis, J. Lilliestam, *op. cit.*

[51] Y. Varoufakis, *Adults in the room: My battle with the European and American deep establishment,* New York, 2017.

[52] S. Royston, C. Foulds, R. Pasqualino, A. Jones *op. cit;* S. C. Aykut *op. cit.*

[53] This discussion is based on T. Udrea, A. Bauer *op. cit.*

[54] J. Capaldo, *The Trans-Atlantic Trade and Investment Partnership: European disintegration, unemployment and instability,* in *GDAE Working Papers,* 2014.

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modelling study was then used as a basis for argumentation, while the credibility of opposing studies and the validity of their methodology were undermined. In this case, the modelling studies served less as guidance and more as argumentative tools for supporting specific political positions, with each side questioning the credibility and legitimacy of the models of the other. This illustrates how authority may become contested in political struggles. This instrumental use of models threatens their perceived independence and credibility, exposing them to criticism.

Counter-modelling may also be used by marginalized groups to challenge hegemonic models.[55] This involves constructing alternative narratives supported by different scientific approaches, assumptions, and values. Nabavi,[56] for example, shows how upstream modellers in the Zayandeh-Rood River Basin in Iran challenged the dominant model's claim of an upstream water surplus, thereby seeking to gain scientific authority and legitimize their own claims for environmental justice. This shift positioned counter-modelling not merely as technical critique but as a "tool of resistance".[57] Yet this example also shows that while counter-modelling challenges the authority of dominant models, it may strengthen the overall authority of models as a policy (advisory) technique.

The authority of a model depends heavily on who conducts the modelling and how it is integrated into policy processes. As discussed in Section 2, the European Commission's shift to in-house modelling for Trade SIAs enhanced control but challenged perceived independence and legitimacy, illustrating how institutional arrangements shape authority.[58]

3.3. Structural Limits: Opacity and Uncertainty

Beyond their direct contestation through politicization, models face inherent limitations and systemic pressures that structurally challenge their claims to epistemic and social authority.

First, models tend to be opaque or "black-boxed".[59] They are often written in specialized programming languages and rely on complex approximations and assumptions that are not easily comprehended by non-experts, or even some experts.[60] This opacity limits political, public and sometimes even scientific scrutiny and reinforces modelling as a domain reserved for technical experts.[61] This black-boxing can protect underlying assumptions and worldviews from critique, reinforcing models' epistemic authority.[62] However, it also reduces the scope for deliberation and hinders models' potential role as effective boundary objects, thereby undermining their social legitimacy. Opacity accelerates with the tendency towards ever more complex integrated models. While epistemic authority might increase with more complex

[55] L. Cornilleau, *op. cit*; E. Nabavi, *Modelling as intervention technology: Science, politics, and water conflicts*, in *Water Alternatives,* 18(2), 2025.
[56] E. Nabavi, *op. cit.*
[57] Ibid.
[58] T. Udrea, A. Bauer, *op. cit.*
[59] See for example, A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit*; E. Fisher, P. Pascual, W. Wagner, *op. cit.*
[60] R. Alba, T. Krueger, L. Melsen, J.-P. Venot, *op. cit.*
[61] S. Low, S. Schäfer, *Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling*, in *Energy Research & Social Science*, 60, 2020; A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit.*
[62] S. C. Aykut, *op. cit.*

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models as they better represent physical or social systems, their social authority might be challenged when consistency, comprehensibility, transparency, and clear accountability are compromised.[63]
Second, models operate under high uncertainty, especially when they aim for projections.[64] This is particularly acute in emergency situations: The COVID-19 pandemic illustrated how models provide a necessary "bridge to knowing" yet are constrained by limited empirical data.[65] This environment of uncertainty provides grounds for political instrumentalization and selective use of model outputs, as also frequently observed in climate policy debates.[66]
In summary, modelling has acquired substantial authority as a standard evidencing technique. Yet this authority remains contested and continuously negotiated in political and social debates. This authority, however contested, is inseparable from models' performative power.

4. Models as Performative Devices: Enacting Policy Realities

Models actively shape the socio-political realities in which they are embedded.[67] This performative power, the capacity to enact rather than merely represent, is realized through organizing knowledge, coordinating actors and communities, structuring debates, and defining legitimate actions.[68] Performative power thus transcends all stages and levels of policy-making, from initial problem definition to the reproduction of social hierarchies.

4.1. Framing Issues: Defining Problems and Solutions

Models play a crucial role in shaping political and societal agendas by identifying policy problems, constructing the urgency of those issues, and framing the acceptable range of solutions.[69] Decisions must be made regarding the boundaries of the system or processes to be modelled, the degree of abstraction, the theories implied by the model, assumptions about parameters, and so forth. These are not merely neutral

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[63] A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit*; M. A. R. Estrada, S. F. Yap, *op. cit*; N. Gilbert, P. Ahrweiler, P. Barbrook-Johnson, K. P. Narasimhan, H. Wilkinson, *Computational modelling of public policy: Reflections on practice*, *in Journal of Artificial Societies and Social Simulation*, 21(1), 2018; R. Zeiss, S. van Egmond, *op. cit*.
[64] E. Fisher, P. Pascual, W. Wagner, *op. cit;* S. C. Aykut *op. cit;* S. Pfenninger, A. Hawkes, J. Keirstead, *op. cit;* A. Saltelli, G. Bammer, I. Bruno, E. Charters, M. Di Fiore, E. Didier, W. Nelson Espeland, J. Kay, S. Lo Piano, D. Mayo, R. Pielke Jr, T. Portaluri, T. M. Porter, A. Puy, I. Rafols, J. R. Ravetz, E. Reinert, D. Sarewitz, P. B. Stark, A. Stirling, J. van der Sluijs, P. Vineis, *Five ways to ensure that models serve society: a manifesto,* in *Nature,* 582, 7813, 2020.
[65] T. Rhodes, K. Lancaster, *op. cit.*
[66] M. Lahsen, *Seductive simulations? Uncertainty distribution around climate models,* in *Social Studies of Science,* 35(6), 2005.
[67] See, for example, E. Svetlova, *On the performative power of financial models,* in *Economy and Society,* 41(3), 2012; S. Beck, M. Mahony, *The politics of anticipation: the IPCC and the negative emissions technologies experience, in Global Sustainability,* 1, 2018; A. van der Heide, *Model migration and rough edges: British actuaries and the ontologies of modelling, in Social Studies of Science,* 50(1), 2019; A. Nadaï, C. Cassen, F. Lecocq, *"Qualculating" a low-carbon future – Assessing the performativity of models in the construction of the French net zero strategy,* in *Futures* 145, 2023.
[68] A. Loconto, R. Rajão, *Governing by models: Exploring the technopolitics of the (in)visilibities of land,* in *Land Use Policy,* 96, 2020; S. C. Aykut ,*op. cit;* E. Nabavi, *op. cit.*
[69] S. Royston, C. Foulds, R. Pasqualino, A. Jones, *op. cit.*

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technical matters; they are simultaneously scientific and political in nature,[70] determining which aspects of reality are considered worthy of investigation and debate and which are sidelined or downplayed.[71] Models reduce complex socio-political challenges to manageable technical problems by making decisions about relevance, assumptions, and categories. While these decisions are shaped by underlying values, ideas, and worldviews, they are often rendered invisible in the modelling process. This dynamic contributes to the "epistemisation of politics",[72] i.e., the pervasive tendency in modern governance to reformulate inherently political conflicts and societal value disputes as matters of scientific or technical knowledge. The reliance on models during the pandemic vividly illustrates this process, as political decisions sought legitimacy through scientific findings. Similarly, global flood risk models frame floods primarily as technical challenges, thereby depoliticizing the issue and omitting how social, economic, and political structures shape vulnerability and risk.[73]

In other cases, the questions that models seek to answer are deeply embedded in policy discourses, simultaneously drawing on and reinforcing them. For instance, different modelling approaches and tools within the domain of energy system modelling relate either to the discourse on climate change or to the discourse on energy access and security in energy-poor regions.[74] Such framing has consequences for which elements of the energy system are considered relevant, which pathways are explored and how model outputs are interpreted. Thus, agendas of policy communities are referred to in scientific communities as justifications for modelling exercises and in return, these scientific commitments stabilize the policy goals that motivated them initially.[75]

Also, the choice of the modelling approach, for example between ex-ante projections (exploring future outcomes based on current trends) or an ex-post backcasting (designing pathways to achieve a pre-set goal, such as net zero emissions) is a politically charged framing decision.[76] This normative choice directly shapes what counts as feasible or necessary policy action.

4.2. Inscribing Values: Embedding Assumptions in Design

Model construction involves methodological decisions that determine how reality is represented and what constitutes knowable facts. Choices about parameters, boundary conditions, and structural assumptions are value-laden, necessarily excluding elements deemed irrelevant, and thereby rendering them invisible.[77] This goes beyond transparency; model developers often rely on implicit epistemic and normative considerations, making it impossible to fully articulate all values and assumptions driving their choices.[78]

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[70] D. Demortain, *Expertise, regulatory science and the evaluation of technology and risk: Introduction to the special issue,* in *Minerva* 5(2), 2017.

[71] A. Loconto, R. Rajão, *op. cit;* E. Fisher, P. Pascual, W. Wagner, *op. cit.*

[72] See: J. Hälterlein, *op. cit.*

[73] J. Cohen, A. Mdee, M. A. Trigg, S. Singhal, S. Cooper, A. N. Alemu, E. Seifu, *A politics of global datasets and models in flood risk management,* in *Water Alternatives,* 18(2), 2025.

[74] T. Udrea, L. Capari, A. Bauer, *op. cit.*

[75] D. Demortain *op. cit;* S. Shackley, B. Wynne, *Global climate change: the mutual construction of an emergent science-policy domain,* in *Science and Public Policy,* 22(4), 1995.

[76] S. Royston, C. Foulds, R. Pasqualino, A. Jones, *op. cit.*

[77] E. Winsberg, S. Harvard, *Scientific models and decision making,* in *Elements in the Philosophy of Science,* 2024; A. Loconto, R. Rajão, *op. cit.*

[78] E. Winsberg, S. Harvard, *op. cit.*

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For example, conventional Computational General Equilibrium (CGE) models embed assumptions such as "perfect markets" or "economically rational actors".[79] These seemingly technical structural assumptions have major implications for model outputs, but more fundamentally, they enact economic reality in particular ways, making market-based solutions appear natural and necessary while rendering alternative economic arrangements unthinkable within the model's framework. Ultimately, economic processes are altered toward conformity with the model's initial, sometimes flawed, often criticised, assumptions.[80] Hence, these assumptions privilege certain worldviews and interests, not through bias but through the very ontology they enact.

4.3. Materializing Imaginaries: Technical Affordances and Governance Visions

Models materialize governance imaginaries through their technical affordances, i.e., the specific capabilities they offer users as computational artifacts.[81] Therewith models serve as key sites where governance visions are translated into actionable technologies.[82]

In the context of nano risk governance, for example, integrated modelling tools entail specific affordances for risk assessment and management.[83] These affordances are neither accidental nor purely technical but are the intentional result of negotiated design choices that reflect both scientific possibilities and curiosity as well as regulatory demands. The Sustainable Nanotechnologies Decision Support System (SUNDS), for instance, affords anticipatory practices for industrial risk assessment and management. By integrating mechanisms to weigh environmental and health risks against social and economic benefits, the tool technically manifests a bias toward innovation and sustainable manufacturing. This imaginary prioritizes market introduction, supporting particular applications like industrial decision-making while side-lining others, such as societal reflections on risks. Simultaneously, the tool also incorporates broader expectations and visions about future regulatory and governance needs, for example, by opening the possibility to assess and weigh social effects. Thus, the tool envisions future regulatory regimes in its technical design, making certain questions and assessments possible while foreclosing others.

4.4. Constituting Futures: Legitimizing Actions Under Uncertainty

Models make futures knowable and actionable under uncertainty by producing quantified scenarios and enabling virtual experimentation with policy options.[84] This anticipatory function is crucial in emergencies, providing a "bridge to knowing" amid crises.[85]

A key performative function of models is their capacity to constitute what counts as legitimate, rational, or necessary action even under conditions of high uncertainty and diverse values. In highly contentious areas like climate policy, models calculate the economic viability of politically negotiated goals, such as

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[79] S. Royston, C. Foulds, R. Pasqualino, A. Jones, *op. cit.*
[80] E. Svetlova, *op. cit.*
[81] D. Fuchs, A. Bauer, *op. cit.*
[82] M. A. Hajer, P. Pelzer *op. cit;* A. Bauer, D. Fuchs, *op. cit.*
[83] The following discussion is based on D. Fuchs, A. Bauer, *op. cit.*
[84] B. Cointe, C. Cassen, A. Nadaï *op. cit;* N. Gilbert, P. Ahrweiler, P. Barbrook-Johnson, K. P. Narasimhan, H. Wilkinson, *op. cit.*
[85] T. Rhodes, K. Lancaster, *op. cit.*

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the social cost of carbon, thereby translating normative policy goals into seemingly technical facts.[86] When policy is supported by a dominant model, its authority serves as a shield against possible resistance.[87] Performative power operates through seemingly technical constraints. When a model shows that a particular policy is "too expensive" or "economically inefficient", it constitutes that policy option as illegitimate not through political argument but through technical calculation. The model performs a world in which economic efficiency is the primary criterion for legitimate action, naturalizing this value hierarchy. Models can thus diminish political discussion not by suppressing it but by transforming political questions into technical ones.

4.5. Reproducing Hierarchies: Expertise, Power, and Exclusion

Lastly, the performative power of models can be traced in their role in shaping and reproducing social groups, distributing power and resources among them.

Models function as boundary objects by coordinating different actors (including modellers, domain-specific scientists, policymakers, and stakeholders). In doing so, models do not simply coordinate pre-existing social worlds but contribute to their negotiation and stabilization.[88] Thus, models define what counts as expertise and who can claim expert status. They confer political influence on expert communities that control the "means of anticipation".[89] Conversely, models may side-line non-experts and lay publics from meaningful engagement and exclude marginal or critical voices and alternative perspectives.[90] For example, in the previously discussed case of integrated risk assessment models, we observe how technical experts and industrial stakeholders gained authority while social scientists and civil society actors (for example environmental or consumer groups) were marginalized.[91]

Models might also reproduce geopolitical asymmetries. Infrastructural asymmetries regarding computational power limit which countries can contribute authoritative knowledge, forcing others, to rely on external models and inputs, thus structuring global power relations.[92] The majority of modelling capacities and activities is located in the Global North (e.g., in climate and energy modelling) which perpetuates the North-South knowledge divide and challenges the Global South's epistemic sovereignty.[93]

In summary, models' performative power manifests across multiple dimensions: framing problems, inscribing values, materializing governance imaginaries, constituting legitimate futures, and reproducing social hierarchies. Performativity is intrinsic to modelling as choices about boundaries, assumptions, and representations inevitably constitute particular realities while rendering others impossible. The challenge

[86] A. Saltelli, G. Bammer, I. Bruno, E. Charters, M. Di Fiore, E. Didier, W. Nelson Espeland, J. Kay, S. Lo Piano, D. Mayo, R. Pielke Jr, T. Portaluri, T. M. Porter, A. Puy, I. Rafols, J. R. Ravetz, E. Reinert, D. Sarewitz, P. B. Stark, A. Stirling, J. van der Sluijs, P. Vineis, *op. cit;* R. S. Pindyck, *The use and misuse of models for climate policy,* in *Review of Environmental Economics and Policy,* 11(1), 2017.

[87] A. Saltelli, A. Puy, *What can mathematical modelling contribute to a sociology of quantification?,* in *Humanities and Social Sciences Communications,* 10(1), 2023; R. Zeiss, S. van Egmond, *op. cit.*

[88] S. C. Aykut, D. Demortain, B. Benbouzid*, op. cit.*

[89] S. C. Aykut, *op. cit;* S. Royston, C. Foulds, R. Pasqualino, A. Jones, *op. cit.*

[90] D. Fuchs, A. Bauer, *op. cit;* E. Fisher, P. Pascual, W. Wagner, *op. cit;* S. Royston, C. Foulds, R. Pasqualino, A. Jones, *op. cit.*

[91] A. Bauer, D. Fuchs, *op. cit.*

[92] J. C. Hochsprung Miguel, M. Mahony, M. S. A. Monteiro, *op. cit;* R. Alba, T. Krueger, L. Melsen, J.-P. Venot, *op. cit.*

[93] J. C. Hochsprung Miguel, M. Mahony, M. S. A. Monteiro, *op. cit;* T. Udrea, L. Capari, A. Bauer, *op. cit.*

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for democratic governance is not to eliminate performative dimensions but to make them visible, debatable, and accountable. This requires recognizing that debates about models' assumptions or outputs are not merely technical but are political struggles over which realities will be brought into being through modelling practices.

5. Conclusions: Towards Responsible Modelling for Policy

Models have become established elements of advisory assemblages, entangling the epistemic, technical, social, and political across domains.[94] This article has discussed models as socially embedded techniques through three interrelated dimensions: as boundary objects that coordinate heterogeneous actors and knowledge systems, as sites where epistemic and social authority is negotiated and contested, and as performative devices that actively constitute policy realities. Throughout these reflections, the focus has been on socio-technical arrangements, interpretative flexibility, epistemic and social authority, discursive embedding, and power relations.

As boundary objects, models mediate between different social worlds, yet their success in coordination depends on design choices, institutional arrangements, and opportunities for engagement. As sites of authority, models manifest and reproduce social trust in quantification, but are also subject to political instrumentalization, credibility battles, and challenges through counter-modelling, revealing that their authoritative status is continuously negotiated rather than naturally given. As performative devices, models do not simply represent systems or processes but play active roles in constituting and shaping the social worlds in which they are embedded. Through their design choices, structural assumptions, and deployment in governance, models might reinforce and consolidate existing power structures and policy paradigms, or they might open up space for transforming the possible repertoires for action.

Recognizing the hybrid nature, contested authority, and performative power of models calls for a rethinking of how they are designed, deployed, and governed in democratic societies. Addressing these questions requires moving beyond purely technical solutions toward a more reflective engagement with modelling practices themselves. In recent years, scholarly and practitioner debates have increasingly emphasized the notion of "responsible modelling",[95] which directs attention to the processes of model development as well as to issues of transparency, reflexivity, and communication.

Responsible modelling includes a general reorientation from modelling outputs to modelling processes. Rather than devices for generating definitive results, modelling should be understood as part of an analytical-deliberative process that enables coordination between diverse actors, ideas, and demands.[96] Successful boundary work depends on inclusive processes that balance interpretative flexibility with coherent frameworks for collective action. Such an approach counteracts the systematic exclusion of critical voices

[94] S. JASANOFF, *States of knowledge. The co-production of science and the social order,* London, 2004.

[95] See, for example, F. SQUAZZONI, J. G. POLHILL, B. EDMONDS, P. AHRWEILER, P. ANTOSZ, G. SCHOLZ, &. CHAPPIN, MILE, M. BORIT, H. VERHAGEN, F. GIARDINI, N. GILBERT, *Computational models that matter during a global pandemic outbreak: A call to action,* in *Journal of Artificial Societies and Social Simulation,* 23(2), 2020; A. SALTELLI, A. PUY, *op. cit;* T. RHODES, K. LANCASTER, M. ROSENGARTEN, *op. cit;* N. GILBERT, P. AHRWEILER, P. BARBROOK-JOHNSON, K. P. NARASIMHAN, H. WILKINSON, *op. cit.*

[96] E. FISHER, P. PASCUAL, W. WAGNER, *op. cit;* N. GILBERT, P. AHRWEILER, P. BARBROOK-JOHNSON, K. P. NARASIMHAN, H. WILKINSON *op. cit;* T. UDREA, A. BAUER, *op. cit;* A. SALTELLI, A. PUY, *op. cit.*

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and lay publics.[97] A participatory modelling process can also contribute to greater legitimacy by incorporating multiple perspectives and creating a sense of shared ownership over model assumptions and results, as demonstrated by examples such as Portugal's Roadmap to Carbon Neutrality.

To counter the pervasive problem of models as black boxes, responsible modelling requires openness and transparency.[98] Openness demands comprehensive disclosure, including data, methodologies, documentation, open-source code where possible.[99] This commitment supports independent scientific verification and allows users to better assess the trustworthiness and potential limitations of models. In legal and regulatory contexts, this relates to the reviewability of model-based decisions. Beyond documentation, transparency also requires reflexivity. Modellers and other actors must address underlying values, possible stakes, assumptions, biases, and overlooked narratives and worldviews.[100] The most reflexive approach involves articulating a desired future before using models to assess interventions and feasibility.[101] However, transparency alone is insufficient if models remain incomprehensible to broader ranges of stakeholders. Accessibility must accompany transparency, fostering genuine deliberation rather than merely technical compliance.[102]

Finally, responsible modelling requires honest communication which acknowledges the inherent limitations and uncertainties, resists pressures to present model outputs as more definitive than warranted and avoids instrumentalization to justify pre-determined positions..[103] This is especially critical when model outputs inform legally binding regulations, where the distinction between model-generated evidence and established facts may become blurred. In media discourses, complex results are often simplified into accessible narratives, sometimes even in sensationalized figures.[104] This communication strategy can obscure the complexity and inherent limitations of the work, reducing important nuances and policy implications.[105] Responsible communication must actively counteract simplifications to ensure public debate is accurately informed.[106]

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[97] T. Parviainen, S. Kuikka, P. Haapasaari, *op. cit;* P. G. Taylor, P. Upham, W. McDowall, D. Christopherson, *op. cit;* J. Trombley, *op. cit.*

[98] A. Saltelli, G. Bammer, I. Bruno, E. Charters, M. Di Fiore, E. Didier, W. Nelson Espeland, J. Kay, S. Lo Piano, D. Mayo, R. Pielke Jr, T. Portaluri, T. M. Porter, A. Puy, I. Rafols, J. R. Ravetz, E. Reinert, D. Sarewitz, P. B. Stark, A. Stirling, J. van der Sluijs, P. Vineis, *op. cit;* A. Bauer, L. Capari, D. Fuchs, T. Udrea ,*op. cit;* D. Süsser, A. Ceglarz, H. Gaschnig, V. Stavrakas, A. Flamos, G. Giannakidis, J. Lilliestam, *op. cit.*

[99] S. Pfenninger, L. Hirth, I. Schlecht, E. Schmid, F. Wiese, T. Brown, C. Davis, M. Gidden, H. Heinrichs, C. Heuberger, S. Hilpert, U. Krien, C. Matke, A. Nebel, R. Morrison, B. Müller, G. Pleßmann, M. Reeg, J. C. Richstein, A. Shivakumar, I. Staffell, T. Tröndle, C. Wingenbach, *Opening the black box of energy modelling: Strategies and lessons learned,* in *Energy Strategy Reviews,* 19, 2018; A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit.*

[100] S. Royston, C. Foulds, R. Pasqualino, A. Jones, *op. cit;* E. Winsberg, S. Harvard, *op. cit;* A. Saltelli, A. Puy, *op. cit.*

[101] S. Sgouridis, C. Kimmich, J. Solé, M. Černý, M.-H. Ehlers, C. Kerschner, *Visions before models: The ethos of energy modeling in an era of transition,* in *Energy Research & Social Science,* 88, 2022.

[102] A. Bauer, L. Capari, D. Fuchs, T. Udrea, *op. cit.*

[103] A. Saltelli, G. Bammer, I. Bruno, E. Charters, M. Di Fiore, E. Didier, W. Nelson Espeland, J. Kay, S. Lo Piano, D. Mayo, R. Pielke Jr, T. Portaluri, T. M. Porter, A. Puy, I. Rafols, J. R. Ravetz, E. Reinert, D. Sarewitz, P. B. Stark, A. Stirling, J. van der Sluijs, P. Vineis, *op. cit;* E. Winsberg, S. Harvard, *op. cit;* N. Gilbert, P. Ahrweiler, P. Barbrook-Johnson, K. P. Narasimhan, H. Wilkinson, *op. cit;* F. Squazzoni, J. G. Polhill, B. Edmonds, P. Ahrweiler, P. Antosz, G. Scholz, &. Chappin, mile, M. Borit, H. Verhagen, F. Giardini, N. Gilbert, *op. cit.*

[104] T. Rhodes, K. Lancaster, M. Rosengarten, *op. cit.*

[105] A. Saltelli, A. Puy, *op. cit;* T. Rhodes, K. Lancaster, M. Rosengarten, *op. cit.*

[106] N. Gilbert, P. Ahrweiler, P. Barbrook-Johnson, K. P. Narasimhan, H. Wilkinson, *op. cit.*

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Concludingly, the call for responsible modelling is not simply a call for better science, but a requirement for robust democratic governance rooted in inclusion, transparency, reflexivity, and communication. Modellers, policymakers, and other stakeholders involved in modelling for policy are continuously tasked with critical engagement with models, their role as boundary objects, their authority and performative power. This requires sustained attention to how models serve different epistemic and socio-political interests,[107] how they are negotiated across heterogeneous networks, how they are represented in public discourses,[108] and how science-policy boundaries are managed in their development and implementation.

[107] T. RHODES, K. LANCASTER, *op. cit.*

[108] R. M. CHRISTLEY, M. MORT, B. WYNNE, J. M. WASTLING, A. L. HEATHWAITE, R. PICKUP, Z. AUSTIN, S. M. LATHAM, *"Wrong, but useful": negotiating uncertainty in infectious disease modelling,* in *PloS one,* 8(10), 2013.

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