Open Models Are Not Enough. Advancing Energy System Modelling Towards Practical Usefulness

Francesco Lombardi, Diana Süsser, Frauke Wiese, Johan Lilliestam, and Stefan Pfenninger

1 INTRODUCTION

Energy system models are tools used to support deliberation around energy transition strategies. For instance, they are used to explore the economic and environmental impact of alternate energy policies[1] or to

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[1] Rodrigues et al. (2022).

F. Lombardi (✉)
Technische Universiteit Delft, Delft, The Netherlands
e-mail: F.Lombardi@tudelft.nl

D. Süsser
Institute for European Energy and Climate Policy (IEECP), Amsterdam, The Netherlands

F. Wiese
Department of Energy and Environmental Management, Europa-Universität Flensburg, Flensburg, Germany

J. Lilliestam
Research Institute for Sustainability, University of Potsdam, Potsdam, Germany

S. Pfenninger
Technische Universiteit Delft, Delft, The Netherlands

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reveal trade-offs between equally feasible carbon–neutral energy system configurations.[2] In the last decade, models have experienced major developments, reaching unprecedented spatial and temporal resolution and technical detail.[3] Increasingly, modellers make the underlying code and data publicly available[4] to foster transparency, reproducibility and trust.[5] Nonetheless, disagreements persist about where the usefulness and real-world relevance of energy system models lies,[6] for a number of reasons.

First, models still tend to represent only one specific (techno-economic) worldview and ignore other possibilities.[7] In other words, models make strong assumptions on what is useful or important to consider and what is not.[8] Such normative assumptions are commonly hidden from view, even though they affect model outputs and their meaning.[9] A prominent example is that sufficiency options to achieve the energy transition are largely underrepresented in the energy modelling literature[10] compared to efficiency measures and deployment of renewable energy technologies.[11]

Second, even models whose data and code are made publicly available with an open licence are not necessarily transparent and perceived as trustworthy by users. The effort for ever-higher realism and complexity can make models and the underlying assumptions too complicated to understand, even when they are open.[12]

Third, models are still too often used as a tool by which modellers, as ‘holders of the truth,’ provide answers, rather than as a platform for a broader societal debate.[13] In other words, models are mainly used

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[2] Tröndle et al. (2020).

[3] Prina et al. (2020).

[4] Pfenninger et al. (2018).

[5] Pfenninger et al. (2017).

[6] Süsser et al. (2022a).

[7] Lombardi et al. (2020).

[8] Braunreiter et al. (2021).

[9] Ellenbeck and Lilliestam (2019).

[10] Zell-Ziegler et al. (2021).

[11] Wiese et al. (2022).

[12] Süsser et al. (2022a).

[13] Ibid.

unidirectionally, for modellers to provide ‘solutions,’ without suitable mechanisms to bring stakeholder knowledge into the modelling process. Yet, this currently lacking co-creation may be key to generate model-based insights that align with real-world needs and questions.[14]

Increasingly, those who use such models or the modelling outputs for decision-making, perceive these shortcomings.[15] It is thus urgent to discuss these problems in depth and provide new perspectives on how to improve the quality and usefulness of modelling approaches.

The remainder of the article is structured as follows. In Sect. 2, we review and discuss each of the shortcomings identified above, providing practical examples from the most recent literature. In Sect. 3, we move on to proposing possible solutions to mitigate these shortcomings and discuss how to implement them in practice. We conclude the text with a reflection on the implications of our findings for the broader energy modelling community and policymakers.

2 Shortcomings of State-of-the-Art Modelling Approaches

Strong, Hidden Assumptions Arbitrarily Restrict the Window of Possibilities

Energy system models are grounded in a positivist, techno-economic worldview. Most of them seek cost-minimal energy system configurations that fulfil exogenously determined boundary conditions.[16] In energy transition research, these boundary conditions are typically: a greenhouse gas emissions target, e.g. net-zero emissions by 2050; a spatial scope, such as the borders of a country or the EU; and the engineering or physics constraints of the system components. Only occasionally do models consider further objectives[17] or limits.[18]

Because of this techno-economic, optimisation-centred nature of energy models, modellers often struggle with the handling of ‘political’ or

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[14] Pickering et al. (2022).

[15] Süsser et al. (2022a).

[16] Chang et al. (2021).

[17] Lombardi et al. (2020), Sasse and Trutnevyte (2020).

[18] McKenna et al. (2021), Koecklin et al. (2021).

'normative' issues.[19] As they try to unravel techno-economically optimal energy transition strategies, modellers often leave non-techno-economic matters aside. Consequently, although such models generate technically consistent scenarios, the window of possibilities these scenarios explore is significantly constrained. Many alternative options to achieve carbon neutrality remain entirely uninvestigated[20] because modellers disregard socially relevant factors as 'political' or 'normative'. In other words, when relying on the results of most state-of-the-art modelling analyses, we look at an implicitly but strongly limited option space, which hides from view many feasible ways to attain carbon neutrality. And possibly, we never realise that and why it happened.

In practical terms, every addition of a constraint to a (cost-) optimisation model, such as limiting transmission interconnection capacities, increases the cost of the modelled system because it reduces the model's degrees of freedom. Hence, up to a point,[21] a larger and more interconnected energy system design is cheaper and hence results generated under the cost-optimisation paradigm suggest that large, continentally integrated systems are the *best* option. However, this is the necessary outcome—rather than an actual finding—of the decision to optimise costs under the only constraint of carbon neutrality, in disregard, for instance, of the social acceptability of the infrastructure entailed by such a large, interconnected system design.[22] This hidden normative assumption has significant real-world consequences, since it prevents other, more expensive but equally viable options in the model from being considered in policy discussions.[23] In current European energy policy debates, energy system strategies based on large, Europe-wide interconnection are indeed dominant, supported by model results exploring such options in detail.[24] And yet, policymakers, citizens and other stakeholders also discuss entirely different options,[25] corroborating the fact that cost-optimality is not the only driver of energy and climate policy. Some such alternative

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[19] Ellenbeck (2017).

[20] Lombardi et al. (2020), Trutnevyte (2016).

[21] Reichenberg et al. (2022).

[22] McKenna et al. (2021).

[23] Ellenbeck and Lilliestam (2019).

[24] Tröndle et al. (2020).

[25] Xexakis and Trutnevyte (2021).

options depart strongly from the cost-optimisation paradigm, which is why modellers rarely consider them, despite their societal prominence.[26] Two examples are degrowth-leaning strategies, such as sufficiency ones, and the reliance on more decentralised system designs.

Sufficiency limits production and consumption to a sustainable level by changes in social practices and societal organisation.[27] As this would reduce the energy demand, it may be a supportive option for reaching climate neutrality.[28] Moreover, Creutzig et al. find that demand-side solutions to climate change mitigation are consistent with high levels of well-being.[29] Despite its benefits and potential, sufficiency options are rarely captured by current quantitative tools or process indicators,[30] although many and diverse sufficiency policy options exist.[31] One reason for that is that demand reduction by policy interventions and behavioural change does not fit into the rigid structure of cost-optimisation models, and that reducing GDP does not match energy-economic models' search for reducing emissions while maximising economic growth.

A decentralised system would likely be more expensive than a continental, centralised system as it lacks the economies of scale brought about by larger units and the sharing of flexibility options across regions and countries.[32] And yet, it may still be attractive in practice, for example, due to higher regional value creation and energy independence, and because of the lower institutional and political complexity. A standard cost-optimising model is unlikely to deliver such an option due to the higher overall cost, regardless of any benefits (including economic ones) that may play out on a more local, policy-relevant scale.[33]

Decentralised and sufficiency-centred strategies for carbon neutrality are just two examples of the many options that implicit normative model assumptions hide from view. As modellers tend not to communicate their implicit normative assumptions, and by extension, which options they

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[26] Zell-Ziegler et al. (2021).

[27] Jungell-Michelsson and Heikkurinen (2022).

[28] Grubler et al. (2018).

[29] Creutzig et al. (2022).

[30] Mundaca (2019).

[31] Best et al. (2022).

[32] Tröndle et al. (2020).

[33] Sasse and Trutnevyte (2019).

arbitrarily exclude, users of model results are left with the misleading impression that such alternative options simply do not exist.

Open Data and Code Do Not Automatically Entail Understandability

Many modellers and model users agree that model transparency, data reliability, reproducibility of the modelling results, and open-source licencing of models are important conditions for and improve the quality of the modelling process.[34] And indeed, the open release of model code and data and the open-access publication of the related studies have increasingly become standard practice.[35] Simultaneously, we also increasingly see that they alone are not enough to address the opacity of energy modelling processes.[36]

First, recent work[37] has shown that the mere release of code and data on public repositories is often not enough to ensure understanding and re-usability of those across different modelling teams, let alone non-expert users. Without proper documentation tailored to specific target user groups, also an open model will remain largely non-understandable.[38] This is particularly true for models that are becoming increasingly large and complex as they seek to cover as many energy transition challenges as possible at once.

Second, numbers and equations do not provide all the critical pieces of information. For instance, the normative assumptions discussed in subsection 2.1 are not explicit because they are omitted already at the model design stage. Therefore, an inspection of data and code is unlikely to reveal them. This represents a critical issue. On the one hand, every model is designed to explore specific research questions under specific assumptions. There is no guarantee that the same model can meaningfully explore and answer an entirely different set of questions and assumptions.[39] On the other hand, open models are intended to foster re-usability by many users, including users with no relationship

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[34] Chatterjee et al. (2022).

[35] Pfenninger et al. (2018).

[36] Pfenninger (2023).

[37] Chang et al. (2021).

[38] Pfenninger (2023).

[39] Ellenbeck and Lilliestam (2019).

with the original developers.[40] If the assumptions under which a given model design is sensible and useful are not explicitly communicated, as is typically the case, there is a high risk that the model is improperly applied outside of the initially conceived scope, affecting the quality and legitimacy of the results.[41]

In summary, while open data and code are necessary conditions to ensure transparency and understandability of an energy modelling process, they are not sufficient. There is a need for further advancements to strengthen the translation of the theoretical benefits of openness into practical ones and extend the concept of openness to also include 'open assumptions.'

Models are Used Unidirectionally, Overlooking Stakeholder Needs

Ideally, energy system models are 'thought experiments' by which users can explore energy transition options and understand the trade-offs as a starting point for further discussion.[42] And ideally, modellers aim for such a discussion to support real-world policy decisions.[43] But for this to occur in practice, model outputs and user-interaction options should match real-world stakeholder questions and needs.[44] Instead, modelling analyses are often perceived as unidirectional 'exercises' in which modellers use their 'truth machines' to provide precise answers to the questions that they themselves deem relevant,[45] disregarding the subjectivity inherent to the modelling process and the plurality of stakeholder information needs.[46]

The importance for users to be able to contribute to the modelling process actively is closely related to our previous discussion on the issue of hidden assumptions and worldviews (see Sect. 2.1). Different worldviews are a prominent example of aspects that different users or stakeholders may want to include in the analysis of alternate options for the resulting insights to be relevant. Professional networks typically share

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[40] Pfenninger et al. (2018).

[41] Pfenninger (2023).

[42] Pickering et al. (2022).

[43] Silvast et al. (2020).

[44] Süsser et al. (2022a), Xexakis and Trutnevyte (2021).

[45] Braunreiter et al. (2021).

[46] Süsser et al. (2022a).

a common perception of the energy system and its future, leading to 'cognitive monopolies.' Other worldviews are difficult to integrate until such networks are expanded to a broad range of stakeholders.[47] Furthermore, stakeholders may help quantify the value of some parameters, suggest which metrics to explore across alternate system configurations or inform on which variations to scenarios are most relevant.[48] In other words, they have the potential to enrich the process with pieces of knowledge that modellers cannot access by themselves. For instance, recent work by McGookin et al. showed that 'authentic' involvement of stakeholders in the modelling process facilitates understanding the 'messy reality' within which energy systems operate.[49] Such an understanding allows for better defining modelling approaches and aligning modelling tools to local needs and developments. Similarly, McKenna et al. showed that crowd-sourced stakeholder considerations about which landscapes are scenic, and thus more worth protecting, can be used to adjust the values assumed for the socially acceptable wind generation deployment potential across the regions of a country.[50] When accounting for real-world stakeholder input, the optimal configuration of wind generation capacity deployment may change dramatically compared to when running the analysis only based on state-of-the-art techno-economic parameters. Moreover, recent work[51] has shown that, even when explicitly generating multiple energy transition alternatives for societal discussion instead of a single 'solution', integrating stakeholder views in the process is highly advisable. In fact, although the decision alternatives that models can generate are virtually infinite, modellers tend to provide only a tiny subset of options for the sake of computational tractability. Only iterations with stakeholders can ensure that the generated option space reflects real-world stakeholder and decision makers' needs.

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[47] Midttun and Baumgartner (1986).

[48] Campos et al. (2022), Xexakis and Trutnevyte (2021).

[49] McGookin et al. (2022).

[50] McKenna et al. (2021).

[51] Pickering et al. (2022), Lombardi et al. (2023).

Modellers often claim to value stakeholder engagement.[52] In most cases, however, such engagement is limited to feedback at the beginning or the end of the modelling process.[53] Moreover, engagement is often circumscribed to policymakers or to a small community of high-level stakeholders that, rather than helping challenge the status quo and the ‘cognitive monopolies’ mentioned above, lead to technology-policy-reinforcement feedback.[54] This reinforces the status quo rather than seeking new solutions. Recent analyses[55] argued that failing to include inputs from a broader range of stakeholders in the modelling process is among the main reasons for user distrust and lack of relevance in the outcomes of the process. In fact, planning for the energy transition is a typical post-normal science issue[56]: beyond policymakers and system operators, a multitude of actors—virtually every citizen—is affected by and potentially interested in the outcomes of the process.[57] If only modellers or a few high-level stakeholders lead the process, the energy transition options they explore are based solely on parameters, constraints and scenarios that they deem relevant. With such a limited ‘elite’ stakeholder involvement, results fail to inform and support deliberation on the aspects that are important to most stakeholders and decision makers.

3 Possible Solutions to Improve the Quality of Modelling Approaches

Previous work and efforts to improve the quality and usefulness of energy modelling particularly emphasised the need to advance from ‘black-box’ to open and transparent models.[58] Some have referred to this first wave of efforts and advancements as ‘energy modelling 2.0’.[59] Here, we argue that a number of further advancements are essential in light of the above-mentioned shortcomings, if the aim is to make models fit as advice tools

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[52] Süsser et al. (2022a).

[53] Süsser et al. (2022a).

[54] Sgouridis et al. (2022).

[55] Braunreiter et al. (2021)Sgouridis et al. (2022).

[56] Sgouridis et al. 2022.

[57] Lombardi et al. (2020).

[58] Pfenninger et al. (2017), Pfenninger et al. (2018).

[59] Müller et al. (2018).

for societal and political processes. First, the standard provision of a list of assumptions and deficiencies alongside each publication. Second, the preference for modular, multi-model approaches—a *cosmos of models*—in opposition to the growing ‘one-size-fits-all’ trend to face the complexity of energy transition questions. Third and most important, a concerted effort towards co-creative, participatory modelling approaches that integrate stakeholders in an extended peer community. We call this set of advancements ‘energy modelling 3.0’, building on previous work that tentatively proposed the same terminology with a focus on stakeholder engagement alone.[60] In the next subsections, we discuss in depth each of the proposed advancements.

Standardising Explicit and Understandable Lists of Assumptions and Deficiencies

In subsection 2.2, we argued that open data and model code are necessary preconditions for transparent and understandable models, but also that providing all data and code along with a scenario study is not sufficient. The overwhelming amount of data and code that characterises state-of-the-art energy system models makes it difficult or impossible to get a clear overview of a given study’s most relevant drivers and potential shortcomings. This is not only true for people outside the respective modelling team: modellers themselves are in danger of becoming unaware of the deficits of their models as the models’ scope and complexity increase through time.[61] Further, data and code do not provide an immediate understanding of the normative assumptions underlying a given study. As discussed in subsection 2.1, understanding these implicit normative assumptions is critical for evaluating the usefulness of results.

We thus propose to standardise the practice of publishing an ‘assumptions and deficiencies statement’ along with each model or scenario publication. Such a statement would include a list of the model assumptions that are most impactful on the results, with a particular reflection on normative assumptions. It would also list the main deficiencies and how they restrict the scope for which the results are valid. In other words, it would summarise what the resulting numbers can tell us and what they

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[60] Müller et al. (2018).

[61] Pfenninger (2023).

cannot, which normative assumptions underlie the input (and hence the output), and what key factors may have been excluded from the model despite being potentially relevant for the research question.

Some of the elements above do occasionally appear in the discussion section[62] or even in a dedicated 'limitations'[63] or 'critical appraisal' (sub)section[64] of energy modelling publications. Yet, even when authors provide such reflections, a more structured statement at a prominent spot of the article could significantly improve the outreach of such critical information, for at least three reasons. First, it would allow modellers to think about the deficits of their work in a systematic, structured way. Second, it would provide the readers and recipients of the results with an overview of what the results can be helpful for. Third, it would help establish a 'deficiency-discussion' culture among the energy systems modelling community. Making an 'assumptions and deficiencies statement' a standardised and harmonised practice would make the open communication of a modelling exercise's limitations a less daunting task and help the modelling community identify the open research gaps in their work.

Moving Away from One-size-fits-all Models Towards a Cosmos of Models

The scope and size of models are constantly increasing. This is not only due to increasing advances in computational power but also to the need to deal with complex, systemic challenges of the energy transition. For instance, taking into account sector coupling, high temporal and spatial resolutions,[65] environmental implications[66] or social drivers and constraints[67] that affect the potential and speed of the transition is necessarily both code- and data-intensive. However, the need to move beyond single-sector or purely techno-economic modelling carries the risk of models becoming too complex: too complicated for modellers to be

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[62] Pickering et al. (2022), Lombardi et al. (2020).

[63] Sasse and Trutnevyte (2019), Victoria et al. (2022), Schwenk-Nebbe et al. (2022), Sepulveda et al. (2021).

[64] Neumann (2021), Parzen et al. (2022).

[65] Chang et al. (2021).

[66] Süsser et al. (2022b).

[67] Krumm et al. (2022).

aware of all the implicit assumptions, or too intransparent for users to understand where the modelling results come from.

To mitigate such problems, we argue that it is advisable to move away from trying to cover as many aspects of a problem as possible with large, individual models. A better approach would be to create and use a 'cosmos of models' that interact in a modular and adaptable way. For example, some models could deal with the details and maximise technical complexity. Others may look at the 'bigger picture', including potential societal disruptive events such as pandemics and wars, or at non-mainstream worldviews, such as those focusing on sufficiency, autarky or grassroots-driven futures. These models would need to be interoperable, with interlinkages across models either existing from the onset or easy to set up at need.[68]

Another advantage of such a cosmos of energy models would be that smaller models within the cosmos may allow for a first, quick response to unforeseen real-world issues and challenges that impact energy policy. Let us consider the current challenge of rapidly rising gas prices in Europe following the reduction of gas supplies from Russia amid the Russian invasion of Ukraine. European countries are faced with an unforeseen trade-off between pursuing their pathways to carbon neutrality, building on gas as a bridging fuel and ensuring energy security and affordability in the short term. Each country is reacting differently, for instance, discussing changes to nuclear power plans, building new re-gasification terminals or reactivating retired coal power plants. At the same time, the European Commission quickly designed the REpowerEU plan, which sets out the need to reduce energy consumption, expand renewable energy and diversify fossil fuel resources for all member states.[69] Large, monolithic models take time to set up in such a way to analyse all these issues at once, and may be unable to find radically new solutions, also because of their built-in assumptions. Instead, a modelling cosmos could allow for a quick but robust investigation of specific issues in depth, for instance, looking at options for avoiding blackouts, replacing natural gas or reducing energy poverty. Such specific insights could be then harmonised to provide a comprehensive picture.

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[68] Bollinger et al. (2018).

[69] European Commission (2022).

For example, the Horizon 2020 project ‘Sustainable Energy Transitions Laboratory’ (SENTINEL) is one recent effort to start building such a modelling cosmos. The project connects modelling tools from across different modelling communities and paradigms. The experiments performed during the SENTINEL project demonstrate the value of smaller, interlinked modelling tools. The project has successfully soft-linked various tools and used them to answer research questions co-created with stakeholders, including questions related to an energy transition without Russian gas.[70]

It is worth noting, however, that this project encountered a higher-than-anticipated difficulty of achieving such interlinkages in practice: the involved modellers found it difficult to align model assumptions and scenario runs to truly link existing modelling tools.[71] One key reason: the difficulty for teams to understand implicit assumptions embedded within a model coming from a different discipline. So our first recommendation could also make our second recommendation more possible and doable. Albeit beneficial in terms of quickness, flexibility and comprehensiveness of the response to real-world challenges, setting up a frictionless modelling cosmos entails a more substantial collaboration effort between different modelling teams.

Co-Creative, Participatory Modelling with Stakeholders in Extended Peer Communities

In Sect. 2.3, we discussed the pitfalls of unidirectional modelling approaches that fail to integrate stakeholder knowledge and perspectives. Today, there is growing demand for stakeholder involvement in research as a new way of knowledge production and decision-making[72]—so much that it is now even a requirement for many research projects.[73] Nonetheless, there are different types of stakeholders that can be involved and different ways to do so, with different degrees of impact on the produced knowledge.

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[70] Stavrakas et al. (2021), Michas et al. (2022).

[71] Michas et al. (2022).

[72] Lang et al. (2012).

[73] European Commission. Horizon (2020).

Stakeholders can represent different groups who are affected by the research results or have a concrete interest in the research outcomes, ranging from citizens, civil society organisations, industry and policymakers to consulting and academia, from local to international level. Stakeholder engagement can come in many different forms and intensities, such as information sharing, consultation, cooperation, collaboration and empowerment.[74] As we argued in Sect. 2.3, an ideal involvement of stakeholders includes a broad base of stakeholders rather than a few high-level ones, and involves these stakeholders repeatedly throughout multiple phases of the modelling process. When this occurs, there is the potential for co-creation to happen.

Co-creative or participatory approaches[75] have been successfully applied in many fields to integrate the available knowledge,[76] create ownership for problems and solutions and a consensus about paths forward,[77] develop practically relevant and actionable solutions to complex, real-world problems[78] and increase policy impact.[79] And yet, co-creative approaches in energy modelling and planning are still rare.[80] The common practice remains for modellers to unidirectionally inform a specific target group about their modelling outcomes.

To foster a wider adoption of co-creative approaches in the energy modelling community, there are several possibilities for involving stakeholders along the modelling process to tailor models and model runs to the specific needs of specific cases and contexts:

1. *Research design*. Co-defining the problem, the modelling needs (including which models to use and which not) and the research questions.
2. *Model assumptions*. Discussing and co-defining qualitative storylines, quantitative assumptions and input data.

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[74] Schneider and Buser (2018).

[75] Lawrence et al. (2022).

[76] Lang et al. (2012).

[77] Waisman et al. (2019), Cuppen et al. (2021).

[78] Fazey et al. (2018).

[79] Süsser et al. (2021).

[80] McGookin et al. (2021).

3. *Model development*. Jointly developing a model's (new) features and constraints. Or directly shaping the criteria or numbers in the model's objective.
4. *Model results*. Discussing modelling results and their meanings (what they do and do not mean) in the on-the-ground context.
5. *Model communication*. Leveraging stakeholder knowledge in the co-design of communication materials and in the communication of the research outcomes. Involving stakeholders in publications and in advocating for the open-access release of models, data and results.

Involving stakeholders along these five steps (Fig. 1) enables a two-way, interactive exchange of knowledge and a joint exploration of the solution space for future energy systems. Establishing feedback loops between the various stages of the modelling process is also possible, which may lead to a re-designing of model assumptions and mathematical formulation.[81] Such deep stakeholder involvement allows moving away from the idea of modellers as holders of the truth that provide answers to society, towards the opposite concept of 'extended peer communities' in which modellers and stakeholders, or society more generally, co-create knowledge to solve societal problems. Furthermore, it is a practical way to ensure that the modelling results are useful to the users and eventually more policy relevant. For instance, co-creating models with stakeholders allows assessing if, for a given research question, it makes more sense to push for technical detail at the expense of higher diversity of worldviews and larger solution space, or vice versa.

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[81] Lombardi et al. (2023).

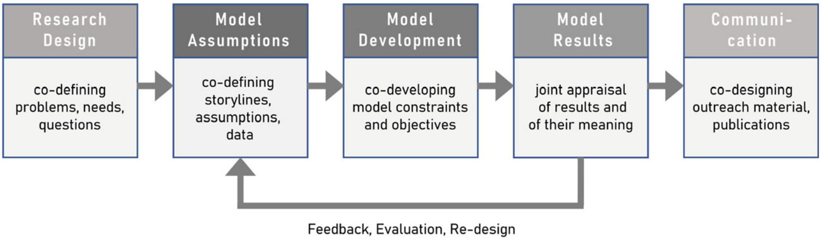

Fig. 1 Graphical summary of the ways and stages in which stakeholder involvement can occur along the whole modelling process chain (© Francesco Lombardi)

4 Conclusion

We have discussed how, despite valuable efforts in the last decade to bring the energy system modelling community into a more open and transparent 'modelling 2.0' state, a number of critical shortcomings remain to be addressed to strengthen the quality, usefulness and real-world relevance of energy modelling processes. These include the presence of hidden normative assumptions; the discrepancy between openness and understandability; and the unidirectional use of models that reinforces cognitive monopolies and biases.

To address these problems, we propose the following advancements:

- The focus on openness and transparency should go beyond code and data to include 'open assumptions', prioritising the understandability of the released material. As regards open assumptions, we propose that every modelling analysis be accompanied by an explicit, visible list of both assumptions and aspects left outside of the model despite potentially relevant for a given research question.
- Instead of trying to fit all the challenges of the energy transition into all-encompassing, monolithic models, modellers should strive to work with a cosmos of modular models. Technically detailed, complex models should be combined at need with simpler models that can allow for a clearer understanding of the interdependencies between inputs and outputs and can explore other practically relevant questions, such as the impact of different worldviews or disruptive events.

- Modelling should be, to the extent possible, a co-creative, participatory approach involving many stakeholders. Stakeholder knowledge can add value across several stages of a modelling process and is key to choosing the right (combination of) models for the right research questions, maximising the benefits of openness and transparency.

Although they are far from effortless, we argue that such advancements are key to achieve the next step in the quality and usefulness of energy modelling analyses. Bringing the energy modelling community into such a 'modelling 3.0' phase is critical for it to be able to adequately support the urgent task of planning for the energy transition.

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