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Better suited or just more complex? On the fit between user needs and modeller-driven improvements of energy system models

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Declaration of Competing Interest

We declare that we have no known competing financial and personal relationships with other people or organisations that could have appeared to influence the work reported in this paper.

Note:

- colour should be used for all figures online

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Highlights

- Modellers refine models, but unclear if that makes models more useful for users
- Common need for better representation of environmental impacts and higher transparency
- Users seek ways to better represent social and behavioural factors
- A better understanding of user needs is imperative to *improve* energy system models
- Co-creative modelling is one possibility to enhance common understanding and impact

Abstract

Energy system models are advancing rapidly. However, it is not clear whether models are becoming *better*, in the sense that they address the questions that decision-makers need to be answered to make well-informed decisions. Therefore, we investigate the gap between model improvements relevant from the perspective of modellers compared to what users of model results think models should address. Thus, we ask: *What are the differences between energy model improvements as perceived by modellers, and the actual needs of users of model results?* To answer this question, we conducted a literature review, 32 interviews, and an online survey. Our results show that user needs and ongoing improvements of energy system models align to a large degree so that future models are indeed likely to be *better* than current models. We also find mismatches between the needs of modellers and users, especially in the modelling of social, behavioural and political aspects, the trade-off between model complexity and understandability, and the ways that model results should be communicated. Our findings suggest that a better understanding of user needs and closer cooperation between modellers and users is imperative to truly *improve* models and unlock their full potential to support the transition towards climate neutrality in Europe.

Keywords: energy systems modelling, energy transition, user needs, energy policymaking, climate neutrality, European Union

1 Introduction

For more than twenty years, the European Union (EU) has been a global leader in fighting climate change [1]. This effort was recently strengthened by the EU's commitment to become the first climate-neutral continent by 2050 [2]. This requires profound decarbonisation across key sectors, including the energy sector. Because real-world experimentation with entire economic sectors is impossible, energy system modelling supports decision- and policymakers by providing knowledge about possible futures, effects and trade-offs between different decarbonisation strategies or energy policy options [3].

Energy system models are advancing very rapidly, adding sectors, details, complexity and growing ever larger, constantly remaining at the frontier of what is computationally feasible. However, it is not clear whether models are becoming *better* in the sense that they address the questions that model users need to be answered, in ways that are useful to them. We define *model users* as individuals, who use modelling results for their work, including both commissioning modelling studies (e.g., a ministry requesting model consultancies) and reading findings from academic or consultancy modelling studies. The *modellers*, in contrast, are the individuals developing and running the models. To increase the chance that modelling results are relevant for and used by potential model users, models must be tailored to the users' needs [4–7]. Indeed, there is some evidence for a gap between what modelling provides and what users need, especially when it comes to specific policy questions and modelling of political or societal paradigm changes [8–11]. Because user needs are rarely considered explicitly when developing or refining models [5,12,13], most research on model improvements and key modelling challenges is based on what modellers think are the most relevant areas in which their models should advance [14,15].

In this article, we investigate the possible gap between model improvements relevant from the perspective of model developers and what users of model results think the models should address. By doing so we on the one hand analyse modellers' needs to improve and further develop energy models and, on the other hand, we identify the needs of individuals who use modelling results in their day-to-day work but who do not model themselves – the *model users*. The main research question guiding this study is: *What are the differences between energy model improvements and adjustments as perceived by modellers, and the actual needs of users of model results?*

To answer this question, we derived four analytical categories of possible user needs[1] from literature, and we conducted interviews with modellers and users in five European jurisdictions, in addition to a Europe-wide survey. We approached both modellers and model users in policy, energy industry, NGOs, consulting, and academia; among users, researchers are represented stronger than other categories. Our findings show that users and modellers agree that models need to better perform ex-ante policy measure assessment and become more transparent. We also show that they disagree on the right balance between simplicity and interpretability on the one hand and complexity and detail on the other, both in terms of the model itself and regarding the way model results are analysed and communicated. Overall, we identify key modelling gaps and research priorities that energy modellers should focus on when developing and improving existing modelling tools in support of the European transition to climate neutrality.

[1] We define as 'needs' all demands and requirements for modelling and model improvements, as well as questions for which users need answers.

2 Background: user needs and energy systems modelling

Modellers are developing more advanced and complex tools to improve the overall quality of energy modelling, which is often understood as a scientific exercise. Nevertheless, many of these advancements are driven either by normative assumptions of modellers and their subjective understanding of the reality [16,17] or by a need to improve their standing in the scientific community – for which *impact,* in terms of supporting different energy system actors in decision-making, is increasingly important. For example, policymakers seek support from models primarily for target-setting, exploration of policy instruments and assessment of policy impacts [3,10,14], while also expecting to have complex issues presented in a simple way [18]. Energy industry actors often use models to make important investment decisions [19], and civil society actors may use energy models to advocate for climate and energy targets compatible with the Paris Agreement [20]. Thus, various users use models to address different energy system challenges that influence the development of energy models. These different use cases of energy modelling help us to discuss and explain need differences between users and modellers/developers.

Previous scientific reviews have identified numerous gaps in current and future low-carbon energy systems modelling. These challenges are: modelling of cross-sectoral coverage, flexibility and short-term variability, further electrification, integration of interdependent renewable energy and energy efficiency measures, emergence of new and "disruptive" technologies, technological learning, the role of human behaviour and lock-in effects, incorporating the effect of climate change, modelling of the trade-offs between economic development and environmental protection, modelling a circular economy, and modelling of political goals [11,21–32]. Further gaps have been identified by sustainability transition scholars, who emphasised a need to focus on modelling of socio-technical transitions and better integration of social and political transition factors [33–35]. In the light of the COVID-19 pandemic, researchers have also called for modelling out of their comfort zone, accounting for unforeseen events and changes to produce more radical modelling outcomes [36], with concepts like "resilience" and "adaptability" at the centre of modelling activities [37].

Furthermore, modellers have outlined several challenges underlying the modelling design. First, modellers must become better at defining general and specific modelling purposes to support specific decision- and policymakers [4,10]. This may require greater diversity in models and a combination of different methods, instead of "one-fits-all" models [14,34]. Researchers have also identified the demand for improving temporal and spatial resolution, by, in the best case, applying a flexible approach, allowing to react to specific user needs [14,38,39]. Furthermore, scholars expressed the need to reduce model uncertainties, by applying different approaches available [40,41]. Last, since models are often insufficiently transparent, scholars have stressed the importance of transparent and open-source modelling practices in strengthening the science-policy interface [11,31,42–45].

Strengthening this interaction between science and decision-makers could be partially addressed by applying inter-, multi-, and transdisciplinary modelling that engages external stakeholders in the modelling process [46]. While stakeholder involvement in energy modelling is growing, it is still not common practice [25]. There is a growing understanding that more collaboration may increase both the alignment between research and models and perspectives and needs of policy, the energy industry and society [4, 40]. However, a recent review paper by McGookin *et al.* [47] shows that in particular, the engagement of non-academic

stakeholders in energy system modelling and planning research is insufficient. Nevertheless, to make such transdisciplinary modelling of high value, stakeholders should be engaged in the modelling process in "a deep, meaningful, ethically informed and iterative way" [4]. To enable this, it is important to better understand what the users would seek to achieve by such a process.

This engagement is related to the degree of interaction between model developers and model users, and the first step for engagement is to enable effective and appropriate communication [4,48]. This includes the development of structured and transparent communication channels [36], a common language [15], and that the information provided by modellers is adjusted to the potential target groups [36,49].

While energy models have evolved greatly over the past decade, it is not clear whether this has also made them *better* in the sense that they better reflect the needs of model users. There is contradictory evidence in the literature. For example, Savvidis *et al.* [8] showed that some models can answer a wide range of energy policy questions very well, whereas others are only suitable for a specific area of energy policy. Similarly, Koppelaar *et al.* [10] found that electricity system models are able to provide scenario-based insights for some policy purposes, but not for others, and especially not for the exploration of problem solutions and political or societal paradigm shifts. At the same time, Govorukha *et al.* [50] stress that decision-makers should be better informed about the underlying simplifications applied in modelling: for example, it must be clearly communicated what macro-economic factors are and are not considered in the scenario analysis. All in all, there is plenty of room for modelling improvements to better serve policymaking [11], which requires a better understanding of needs by diverse stakeholder groups.

To the best of our knowledge, there is no systemic review of user needs in the energy systems modelling literature, which considers insights of a large sample of stakeholders on a European-wide level, especially in the context of the EU's ambition to become climate-neutral by 2050.

3 Methods

We investigate the alignment, or lack of alignment, between user needs and how modellers seek to refine their models, investigating the needs of different stakeholder groups in Europe. To do so, we apply a multi-method approach, coupling a literature review, to identify categories of possible user needs in energy systems modelling, with qualitative (interviews) and semi-quantitative (survey) methods to analyse the similarities and the differences in needs for energy system models between modellers and users. **Figure *1*** provides an overview of our approach. The results section is guided by the survey results, while the interviews enrich the findings and provide deeper insights into the different needs.

Figure 1: Overview of the methods applied.

3.1 Literature review

As a first step, we conducted a broad search in energy-related peer-review journal articles found in the scientific databases 'Science Direct' and 'Google Scholar', reviewed textbooks, as well as the SENTINEL project[2] deliverables on modelling trends and challenges [22–24,32]. We identified different needs and categorised them into sub-categories (**Table A *1***). Because there are different structures of 'user needs' regarding energy system models in the scientific literature [e.g., 48,49], we derived from it four analytical categories of user needs (**Figure 2**): Needs can concern **1.** *what* to model ("content"), **2.** *how* to design the model ("design"), **3.** *how* and *with what aim* to engage different stakeholders in the modelling process ("process"), as well as, **4.** *how* to communicate with modellers and model users ("outreach") (see also [53]).

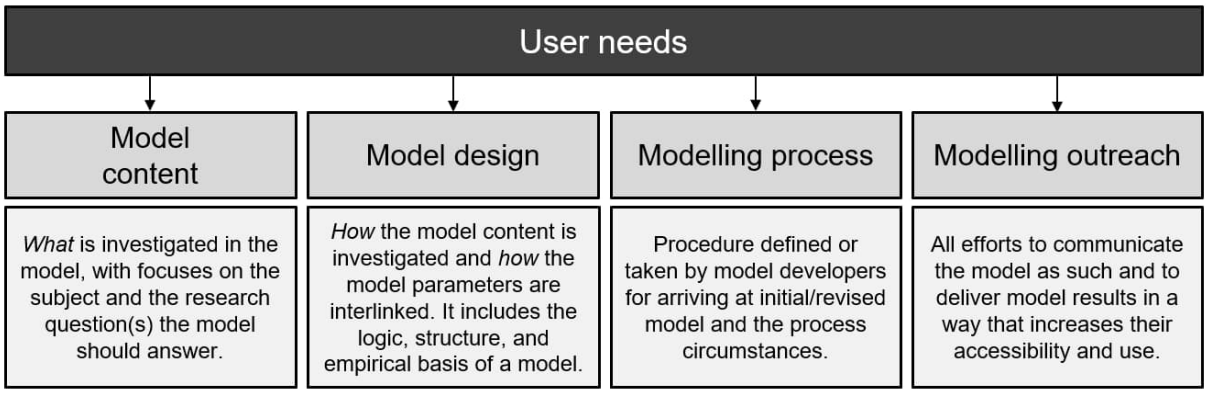

Figure 2: Categorisation of user needs based on insights from scientific literature.

3.2 Online interviews

As a second step, in winter and spring 2020, we conducted 32 qualitative interviews with modellers and model users, who participated in energy policymaking processes with modelling components. The interviewees came from five different European jurisdictions: the EU as a whole, Germany (GER), Greece (GR), Poland (PL), and Sweden (SWE). We selected these cases not only because they represent various geographical, political, and cultural backgrounds, but importantly because different types of energy system models have been used in recent policy processes to support regulatory and legislative reforms, as described by Süsser *et al.* [54] and Stavrakas *et al.* [55]. We selected the interview partners based on their relevance in each case study context and their role, either as a modeller or as a model user, in the policy process under study. All interviewed modellers and users had been involved in energy modelling for several years and were deeply knowledgeable about the epistemology of energy models in general, and particularly the models used in the process they were involved in. Several interviewees had experience both as modellers and as model users from different stages of their careers. As they have all worked in the field of energy systems modelling, either as hands-on developers or as users, they were motivated to participate in the interviews as our work intends to support further model developments and help align modeller and user views on how to improve models. The interviews served us to receive in-depth insights into the different demands and requirements for models by energy modellers, as well as by users from academia and

[2] https://sentinel.energy/

consulting, policy, energy industry, and non-governmental organisations (**Table 1**). To identify a broad range of possible user needs, we asked about the current and future challenges or aspects of the energy transition that should be integrated into energy models, and about the kind of information that energy models should deliver to support decisions related to energy policymaking and other issues. A semi-structured guideline [56] directed us through the interviews, which were conducted in English or the national language of the jurisdiction. We used different semi-structured guidelines for the two interviewee groups, focusing on three central questions for each group. We asked modellers:

- *In your opinion, what kind of information should an energy model deliver, now and in the future, to inform decision-making (processes) in energy policy?*
- *In your opinion, how should the process of model development be designed to increase the chance of the later model use in policymaking?*
- *Which conditions must be given that increase the chance that you would use the models or the results, respectively, in future policymaking / your work?*

We asked model users:

- *What are the current and future challenges or aspects of the energy transition that should be integrated into future energy models?*
- *In your opinion, what kind of information should an energy model deliver to help make good decisions about energy policy/energy issues?*
- *Which conditions must be given that increase the chance that you would use the models or the results, respectively, in future policymaking / your work?*

A full overview of the interview guideline is provided in Süsser *et al.* [57]. We recorded, transcribed, and anonymised the interviews, while the presented quotations below have been translated by the authors in cases where the interview took not place in English. Afterwards, we performed a content analysis by using the four categories identified as coding categories, to guarantee a rigorous style in the interview analysis [58]. We found user needs across the four categories in each interview; however, we found specific sub-categories that were partially dependent on the policy context. **Table A2−TableA5** in the Appendix show the details of the key results and statements from the interviews. The sample size was too small to reach saturation, which is why the interviews are intended to complement the survey.

Table 1
Interviewed stakeholders in the five jurisdictions.

Stakeholder groups interviewed (abbreviation for citation): _____	Scientists and consultants (“research”)	Policymakers (“policy”)	Energy industry (“industry”)	Non-governmental organisations (“NGO”)
Jurisdictions:				
European Union (EU)	1	3	2	2
Germany (GER)	1	2	-	-
Greece (GR)	2	1	1	-
Poland (PL*)	4 (5)	1 (2)	1	3
Sweden (SWE)	4	4	-	-

*Two interviews were conducted with more than one person. Numbers in brackets show the total number of interviewees, which represented the same institution or stakeholder group.

3.3 Online survey

As a third step, in summer 2020, we conducted an online survey among modellers and model result users across Europe to validate our interview findings and receive statistically sound insights on user needs from a larger sample. We designed the survey in LimeSurvey [59] as a semi-quantitative online questionnaire [60], and tested it through an iterative process with modellers from the SENTINEL project and six stakeholders from different target groups. We structured the survey around the four categories identified, plus one further category on general model use and one on general demographic data. The survey questionnaire contained mandatory and optional questions, as well as independent questions and questions that built on previous answers. The questions were formulated to explicitly refer to what is relevant to the respondent – her or his personal needs. We applied different question formats, from single and multiple choice[3] to Likert-like scales[4] and free text boxes, depending on the variables to be addressed. All responses have been anonymised. The survey population was based on a nonprobability sample [56], meaning that it was sent via various channels to clusters of potentially interested stakeholders in energy models. We did not ask participants about specific models but asked them to answer the questions based on their current work and experience with energy system models. In our sample, 88% of the survey participants stated to work with energy models in different contexts, naming well-known energy models such as PRIMES, TIMES, EnergyPlan and GEM-E3, and more than 50% have been working with energy models for more than 6 years. We asked the respondents in what context they "work" with energy models (multi-choices). The answers ranged from developing and applying models, to reading model analysis, to consulting model studies (see answers **Table *2***). Therefore, the respondents are very likely to have a good understanding of energy models, how they work and what their output can and cannot mean. On the other hand, with such long experience, the modellers unsatisfied with the epistemological limitations of models or seeking to work with questions models are not well suited to answer may also have left. In addition, the sample likely has a bias towards the mainstream, arising from the long-term exposure to models, modellers and the type of questions arising in modeller circles. This would align the modeller and user responses, but also giving additional weight to any identified differences in perspectives. The survey was distributed among national, European, and international organisations, and representatives from politics, civil society, business/industry, and research, via private and public online channels. The questionnaire and anonymised aggregated data are openly available at Zenodo [61].

The sample holds 90 completed questionnaires. We analysed the statistical results of the survey in two steps: first, we compiled and compared the quantitative responses; and second, we complemented results based on written replies [60]. To derive and compare differences between responses from modellers and users, we clustered the respondents into two groups. We defined modellers and model users by clustering groups based on an inclusive *OR* of the answers provided in the question "In what context do you work with energy models?" as presented in **Table 2**. The participants included 40 modellers, 20 users, and 30 participants who classify for both groups ("Both") or who have no experience with using models or modelling results at all ("None"). As we investigate the *differences* between stereotypical modellers and users, we excluded for most considerations the overlapping and the inexperienced groups. The actual sample size of the presented results varies, as some questions were optional and we did not receive a full response from every respondent. While many participants also answered the optional questions for modelling content and design, the number of users' responses is very low in the modelling process and outreach categories. For these categories, we present results from all respondents who have replied to the

[3] Survey participants chose between multiple given answers, e.g., select the most relevant or correct statement.
[4] Survey participants had to rank the importance of different aspects, e.g., from not important to highly important.

question, without distinguishing between respondent types. Finally, when referring in the findings to the different stakeholder groups that modellers and users belong to, we used the overall sample and neglected the group "Others".

Table 2
Cluster definition of "modellers" and "users" and sample size.

Answer option	Modeller	User	Both	None
"I develop models technically"	x		x	
"I apply and run models"	x		x	
"I analyse the results of model runs, write model-based studies, or give model-based advice"	x		x	
"I provide model developers with ideas for model improvement, or commission model-based studies"		x	x	
"I read model analysis and model studies"*	x	x	x	
"I have never used models or model results before"				x
Stakeholder group	**Modeller**	**User**	**Both**	**None**
Policymakers	3	4	4	1
Energy industry	4	4	8	0
Non-governmental organisation (NGO)	4	4	3	0
Research, innovation & consultancy	27	5	10	0
Others	2	3	3	1
Total	**40**	**20**	**28**	**2**

*This answer option was no specific selector, as common in both groups. However, if study reading was the only chosen option, we assigned the participant to the "user" group.

4 Results

4.1 Model content

The basic orientation of models is often defined by policy goals − the pathways and the future state of the energy system aimed for. We find that a majority of modellers and users support "typical" energy policy goals as defined by the EU at the beginning of the 21st century [62]: they strive for future energy systems that are resilient, secure, energy-efficient, climate-neutral, cost-efficient, affordable, socially acceptable, and protect humans as well as wildlife (**Table A *6*** in **Appendix**). Among these main energy policy goals, energy security was pointed out as particularly important during the interviews by both modellers and users. For example, one policymaker pointed out that *"energy security […] is a priority for our national actions, and almost always in (creating) energy policy this aspect is taken into account"* (PL_policy#1), while another one raised an important question: *"With which system mix, including networks, storage and flexible options, can we achieve a secure power supply?"* (GER_policy#2). To answer this question, *"energy models should [...] deal with energy security in its broadest sense- including ensuring the supply of energy necessary for the functioning of the country and economy in an optimal way while meeting the climate and environmental objectives"* (PL_research#4; summary of interview results: **Table A 2** in **Appendix**). Although we find a strong agreement between modellers and users for a diversity of policy goals, we observe differences in some energy policy goals, but most of them concern the degree of approval: Modellers place generally higher importance on nature protection, energy efficiency, affordability and free energy trade between countries than users (**Figure 3**).

Figure 3: Policy goals: *How important are the following aspects for the energy transition?*; optional; Modellers: N=34, Users N=14.

Furthermore, we identified different factors that should receive more attention in energy models (**Figure 4**). Both modellers and users expressed a strong need for better consideration of the environmental impacts of the energy transition. Among the users, policymakers found natural resource use most relevant (**Figure A1** in **Appendix**), while one interviewed policymaker emphasised that *"there is also a lack of such a model that would assess the overall costs for the environment"* (PL_policy#1), and another NGO representative stated that *"it is important to look at health impacts and climate impacts"* (EU_NGO#2).

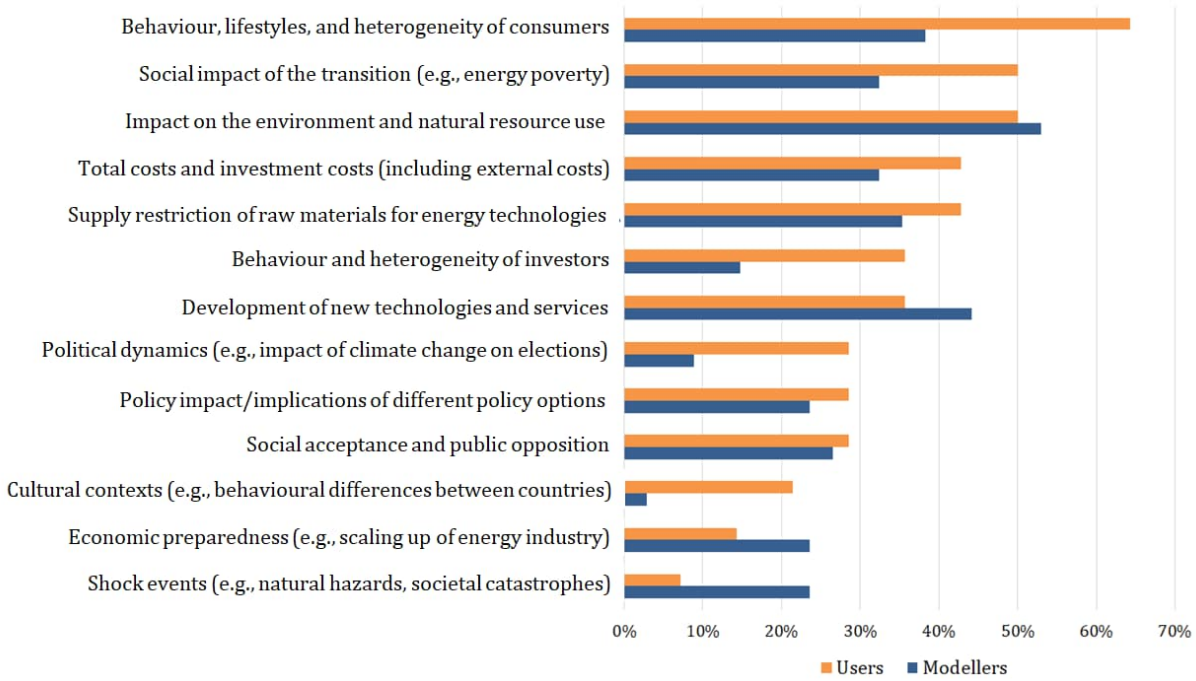

Figure 4: Demanded factors: *Which of the following factors do you think should receive more attention in energy models?*; multiple choice (minimum 1, maximum 5 aspects), optional question; Modellers N=34, Users N=14.

Better integration of behavioural dimensions is also relevant to both groups, although significantly more users than modellers are interested in the topic (**Figure 4**). One industry representative expressed their need by saying *"modelling of social behaviour might be very relevant for modelling potential outcomes"* (EU_industry#1), and a modeller suggested to*"maybe includ[e] energy communities as investors into the models. So just more analysis about the behaviour and acceptance issues that people really have"* (EU_research#1). Comparing the different stakeholder groups, especially surveyed NGO and science representatives found it essential to better deal with consumer behaviour in models (**Figure A1** in **Appendix**). Users perceive the integration of social impacts of the transition in modelling as clearly more important as modellers do. The interviewees confirmed that they are concerned about *"social acceptance, […] job creation, […] socio-economic impacts"* (EU_industry#2), *"social inclusion and justice as well as energy-sufficiency aspects*" (GR_policy#1). Stakeholders connected the social dimension also with the decentralisation of the energy system, as citizens and communities play an increasing role in the energy generation: "*We can supply every house with decentralised electricity. Yes. It is only a question of what kind of effects this will have, precisely on how many wind turbines we need. I think that is a discussion that I believe we still need"* (GER_policy#2).

Furthermore, costs of the energy transition remain one of the main concerns, specifically that *"macro impacts are extremely important, especially the distributional impacts"* are critical, as one policymaker confirmed (EU_policy#1). An NGO representative raised the question of *"how much will it cost the customers and, at the end of the day, the whole economy?"* (PL_NGO#2). Another important issue that models must better address is the question of (local) employment effects: *"It would be very interesting to get some numbers on jobs"*, confirmed an NGO representative (EU_NGO#2). In particular, many representatives from the energy industry found the cost perspective relevant (**Figure A1** in Appendix).

4.2 Model design

When modellers design a model for the first time and apply it, they must make fundamental (and to a certain degree irreversible, e.g. due to hard coding, etc.) decisions in which direction a model may be (further) developed, e.g., whether it should be a simple or a complex model, an optimisation or a simulation model, etc. (see also [16]). As shown in **Figure 5**, we find that the majority of the survey participants prefer existing, well-established and maintained models that are open-source, designed for a specific purpose and explore progressive scenarios with high ambition to protect the climate.

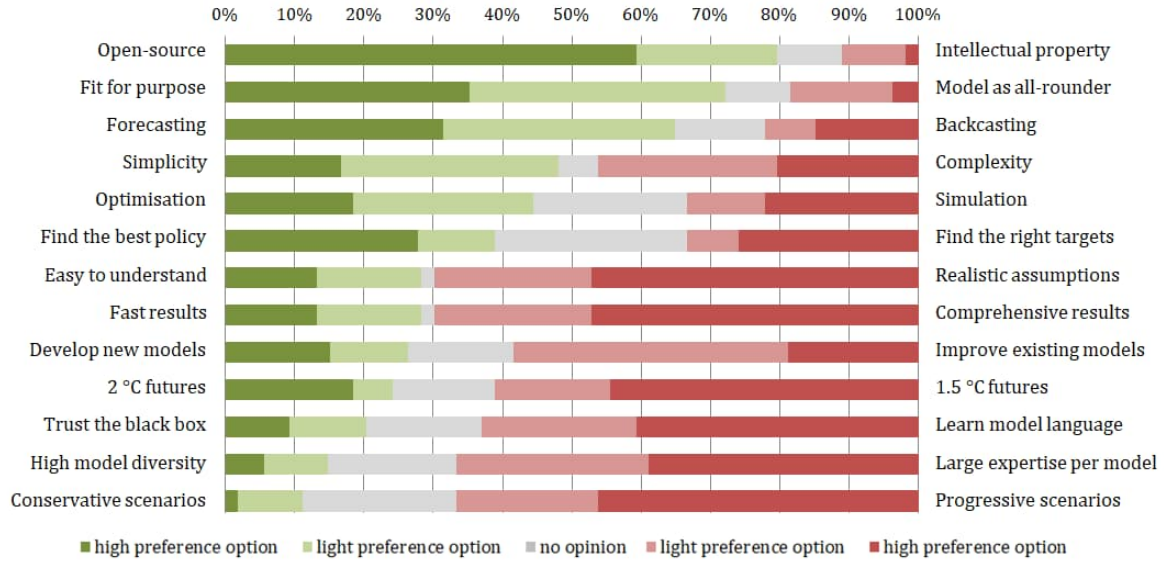

Figure 5: Model design demand: *Which model feature/quality is more important to you? Please choose in each pair the more meaningful to you*; optional question; N=55 respondents (users and modellers); "no answers" excluded from the figure.

For the consideration of similarities and differences between modellers and users, we have only a small sample size of replies, as this question was optional. We find that common needs of modellers and users mirror the overall surveyed sample (**Figure 6**). However, as **Figure 7** shows, we also find differences between the two groups, in particular regarding complexity and detail versus simplicity and understanding: whereas users tend to simply trust the model black box and prefer understandable results from simple models able to quickly provide findings, modellers want to understand the detail and prefer "realistic" assumptions in complex models. Users and modellers alike see the usefulness of models both to identify the right targets and to define measures to reach these targets, though users distinctively emphasise the need for ex-ante assessment of policy measures stronger. Finally, we find opinion deviations between fast vs comprehensive results that modellers vastly prefer complexity, while users in sum show no clear preference for neither direction. However, an important argument supports speeding up models as one interviewee emphasised: *"Now things have to go faster, we need to move faster: policymaking has to be faster; so models also have to follow it"* (SWE_policy#1; summary of interview results: **Table A 3** in **Appendix**).

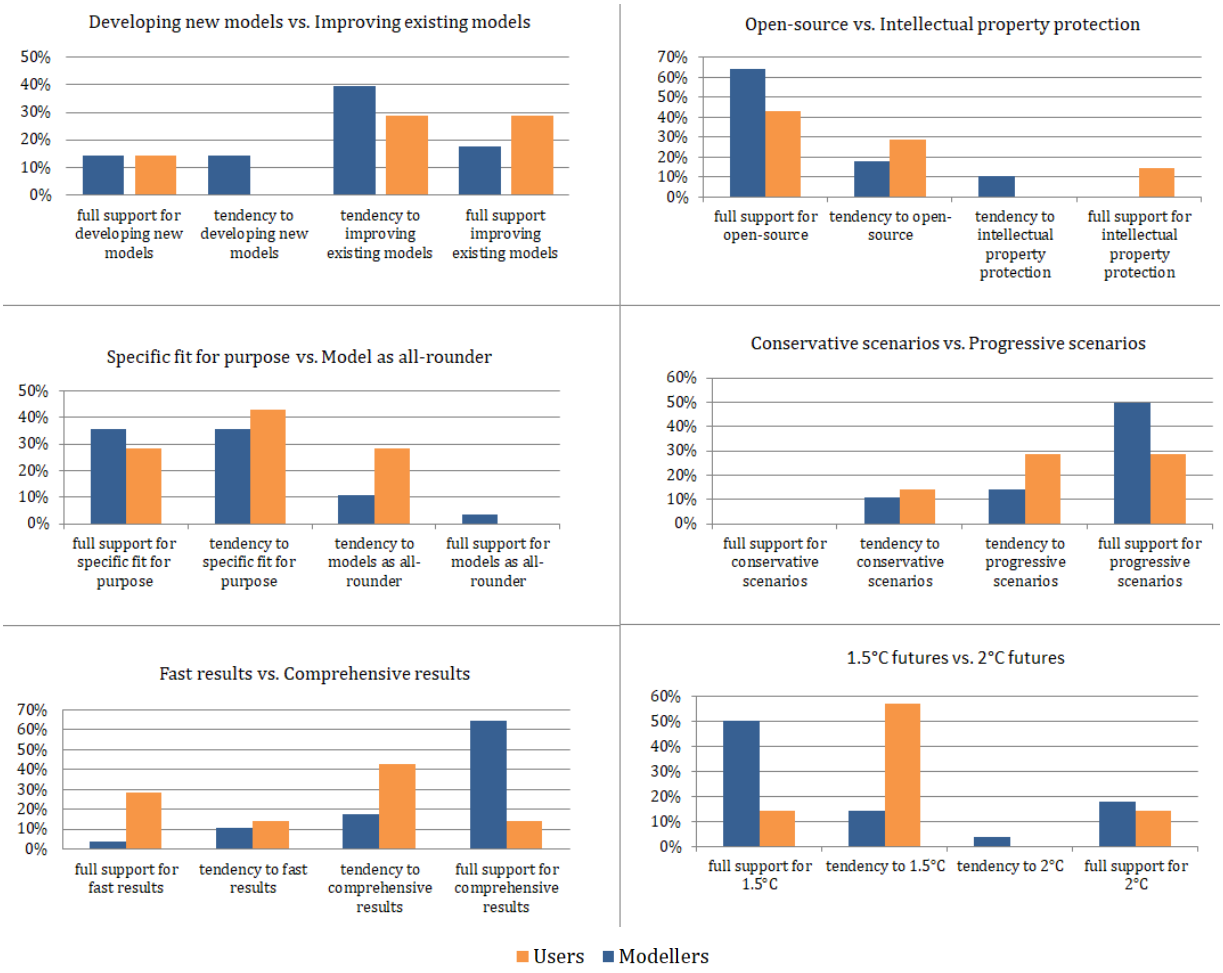

Figure 6: Model design demand similarities: *Which model feature/ quality is more important to you? Please choose in each pair the more meaningful to you*; optional question; "no opinion" and "no answers" excluded from the figure; Modellers N=28, Users N=7.

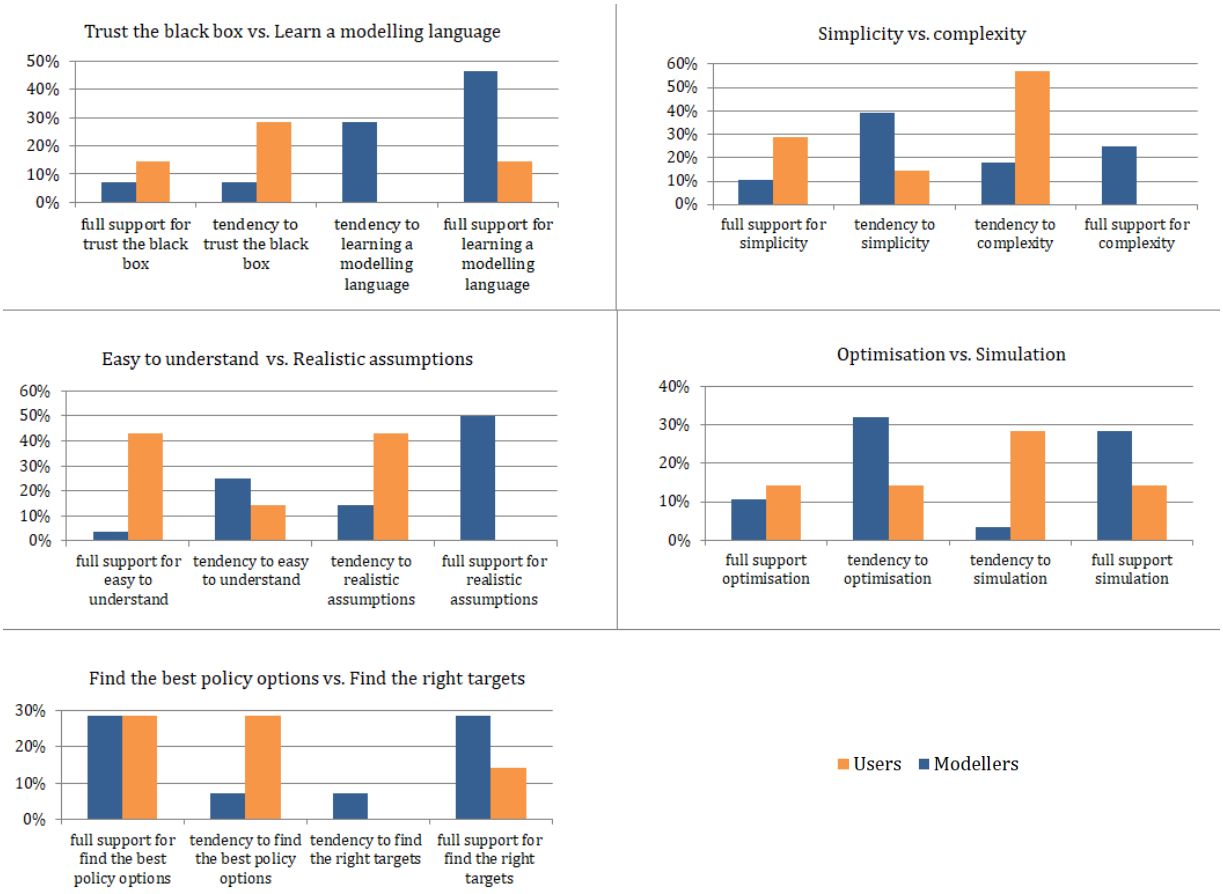

Figure 7: Model design demand differences: *Which model feature/ quality is more important to you? Please choose in each pair the more meaningful to you*; optional question; "no opinion" and "no answers" excluded from the figure; Modellers N=28, Users N=7.

When it comes to the trade-off between simulation and optimisation, we find no clear preference by both groups (**Figure 7**). Our interviews also revealed diverging opinions about the complexity and simplicity of models. On the one hand, simpler models are generally easier to understand, while *"making them more complex and trying to make them more like reality [holds] a risk of decreasing the level of transparency because they are so complicated that nobody really understands them"* (SWE_policy#1). On the other hand, some users call for higher spatial and temporal resolution, like *"more detailed geographical analysis"* (GR_industry#1), and *"a bit more country-specific options"* (PL_research#2), which in turn may demand higher model complexity to allow it to represent different contexts, or even to construct nationally specialised models – which would increase contextualisation and detail, but at the expense of generalisability of results and comparability with other models. A solution can be provided by model structures characterised by the main principles of component- and modular-based system modelling. Such structures reduce simulation complexity owing to the multidisciplinary nature and input data requirements, as recent literature suggests [63].

In addition, the survey shows that modellers and users support open-source models (**Figure 6**), and model transparency was also a critical issue in the interviews. Both modellers and users agreed on the importance of transparency: *"transparency, transparency, transparency. So, everything we put into the model must be publicly available"*, underlined one policymaker (EU_policy#3). Users can only understand what

assumptions models are based on and what underlies the modelling results if the models are sufficiently transparent. We identified different questions by users that modellers must address in this regard: *"which parameters can be changed, and which parameters come out at the back"* (GER_policy#2), *"how this number was calculated"* (SWE_policy#1), and *"what is hidden in the model, we do not know where it comes from"* (PL_NGO#3). Transparency does not necessarily mean open source and data, but modellers and users confirmed that *"policymakers need to base their policy documents on credible data sources, otherwise results can be challenged"* (GR_policy#1).

Although modellers and users agreed in the survey that models need to fit specific purposes, they have partially different opinions about those purposes for model use. Modellers and users commonly see the main purpose of modelling in the strategy development and policy measures formulation (**Figure 8**). In particular, for strategy development, we find high importance across different stakeholder groups from policymakers to NGO representatives (**Figure A2** in **Appendix**). In contrast, large differences between the two groups exist for informing/lobbying in politics, energy system operation, policy implementation, and local energy planning. More than half of the surveyed users apply models especially for informing and lobbying in politics, whereas only a few modellers pursue that goal. One NGO representative explained their use of energy models for lobbying and informing politics: *"(Models) are needed for two main purposes. First of all, we*[/NGO] *need them internally to know which way our message, our campaign, our strategies should go.* […] *The second is to be very specific in such political discussions when it comes down to: 'We here have calculations which show that, for example, the renewable-energy sources-based model is cheaper than the one proposed by the government"* (PL_NGO#1). Moreover, almost half of the modeller respondents use models to investigate energy system operations, whereas almost no user uses results for this purpose (**Figure 8**). This implies that modelling teams, for example in industry, use models to manage and operate existing energy systems. In contrast, users – which tend to be more from policy and NGOs – worry much more about planning a future energy system (**Figure A2** in **Appendix**).

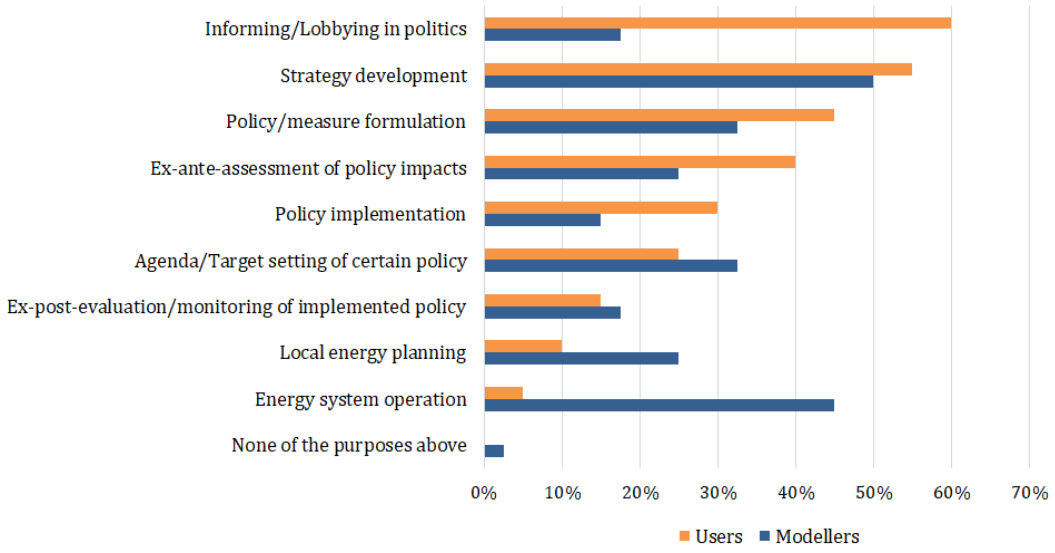

Figure 8: Use and purpose of models: *For what purpose are you using models in your work?*; multiple choice; Modellers N=40, Users N=20.

We find a strong agreement by the two-thirds of modellers and users that models must become better in supporting strategy development, ex-ante assessment of policy impacts, and policy measure formulation –

which are also among the top use cases of models by users (**Figure 9**). This confirms that modellers and users alike seek improved models for their current key model activities. One policymaker underlined the need for models in policy assessment: *"But our most important question is: how can policies impact these developments and what will happen if you do one thing rather than another thing"* (SWE_policy#1). In addition, one Greek policymaker recommended a concrete model type for ex-ante evaluation of competing policy options: *"During policy instrument design, more bottom-up models and tools are required. Multi-criteria as well as financial appraisal tools are most often required for the development of financial support policies to estimate their expected impacts and determine different levels of financing support"* (GR_policy#1). For all factors except ex-ante measure assessment, modellers see a stronger demand for improvements than users, which implies that users are relatively satisfied with what existing models can already deliver – and that modellers are curious about a very broad set of factors.

Nevertheless, there are also fields with substantial differences. While both groups currently use models for agenda- and target-setting, modellers see much stronger demand for improvements. On the other hand, among users, NGOs are especially interested in better models for target-setting (**Figure A*3*** in **Appendix**). Furthermore, big differences in demands remain for energy system operation and local energy planning, which are much more important to modellers than users. Especially, NGO representatives expressed a strong demand for model improvements to support local planning (**Figure A*3*** in **Appendix**).

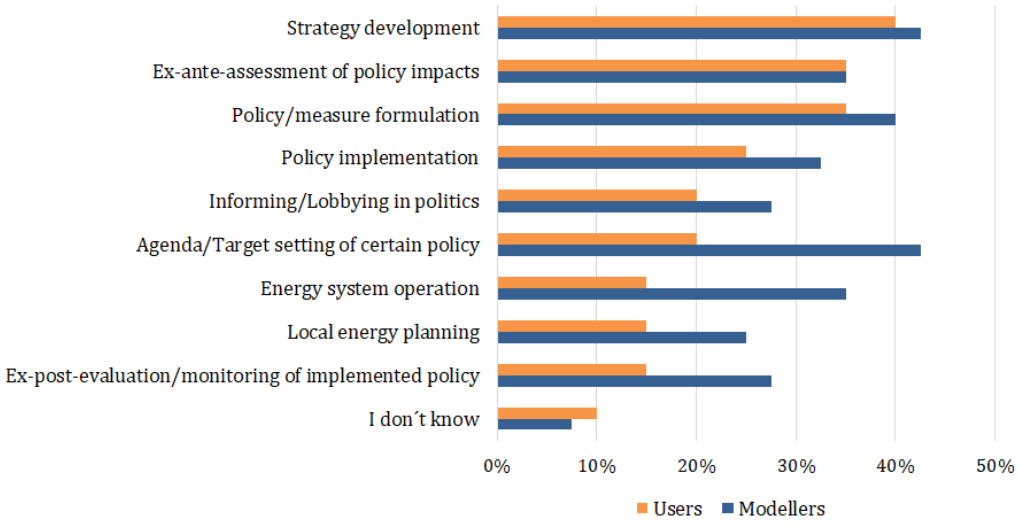

Figure 9: *Where do you see the demand for additional or improved models helping you in your work*?; multiple choice; Modellers N=40, Users N=20.

4.3 Modelling process

We find that different stakeholder groups think that their involvement in the modelling process is important (**Figure 10 a)**). Interestingly, for modellers, it is more important to be involved in the process than for users, as shown in our small sample (**Figure A4**). Furthermore, most modellers think that the participation of different stakeholders in the modelling process is essential, with specific importance dedicated to science, innovation and consulting (**Figure 10 b)**).

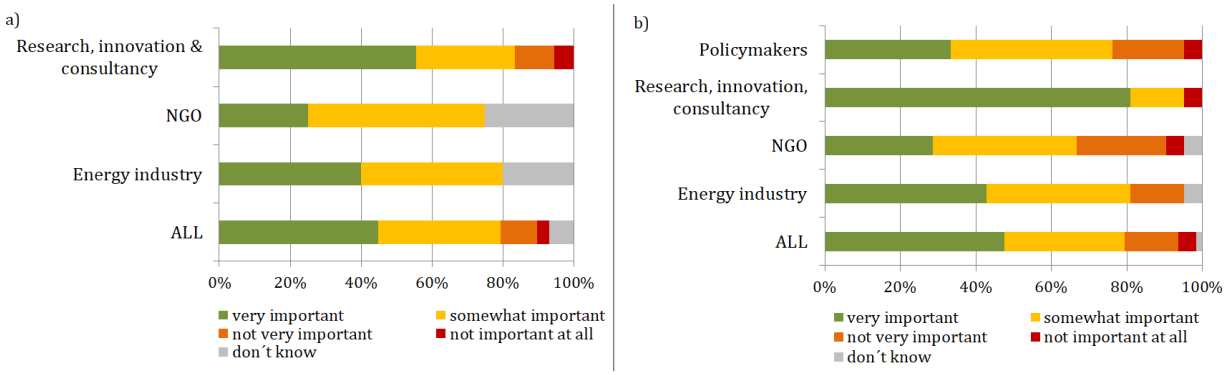

Figure 10: Importance of stakeholder involvement in the modelling process: **a)** Respondents who were involved in modelling or never worked with models (users and modellers): *How important is your involvement in conceptually developing or improving models for you?*, N=29, note: no response from policymakers; **b)** Modellers subgroup (who develop models technically or run and apply them): *How important for you is the involvement of the following groups in your model development and improvement process*?; N=21; optional questions.

The interviews confirmed that modellers value the involvement of stakeholders in the modelling process: *"for us, objectivity is important. And I and my colleagues have the opinion that you can only reach that if you work together with different groups. It doesn't mean that we always agree. But you can talk about complex questions and consider them from different perspectives"*, explained a modeller (SWE_research#4), and added further that it is *"always good to have a kind of jury, which comes from a different world"* (summary of interview results: **Table A 4** in **Appendix**). The high levels of appreciation of the stakeholders' involvement by model developers might also result from their desire to get the legitimacy of the modelling work that they are carrying out.

The interviews also showed that users want to be involved in the modelling process: *"Today, we need to be very much engaged in the modelling process, with modellers to ask questions, understand how these questions change assumptions and primaries in the model and work together to design scenarios"*, confirmed a policymaker (SWE_policy#1). Another user attributed the need for stakeholder involvement in the modelling process to the increasing model complexity: *"Another point is that an effort to increase model complexity should be accompanied with cooperation with relevant institutions. For this, it is necessary to engage institutions and not only consultants and personalities"* (GRE_industry#1). Furthermore, a user from the industry stated that stakeholder-involved modelling is important for understanding the modelling process: *"Well, it's very clear, I think, that stakeholder involvement from very early stages and openness and transparency about what is happening, as well as openness to conflicting views [are important]. I think that everybody learns from different views, so there is neither '100% right' nor '100% wrong"* (EU_ industry #1).

The collaboration between modellers and stakeholders is important to *"agree on a common language, and […] to get the same picture of the system"* (SWE_research#4) and to create a *"system understanding"* (SWE_ research #1). When it comes to the themes to be discussed, most respondents found it very important to exchange about defining assumptions and developing scenarios, as well as to collectively discuss and interpret results (**Figure 11**). We find no substantial differences between modellers and users in the respective small sample (**Figure A5** in **Appendix**). One EU policymaker confirmed the importance of having *"time to consult with stakeholders about assumptions; the Member States about what is happening in their countries, and for example, so far we have not had such a situation that the percentage is already*

completed, and some country would say: 'this is rubbish, it doesn't fit my country at all, and our national projections are not at all consistent with this'" (EU_ policy#3). Decisions about the data basis and model communication were also seen as important, but to a lower degree than the other factors. Overall, this result supports the increasing use of more participatory methods in modelling as an important approach to increase the relevance of models.

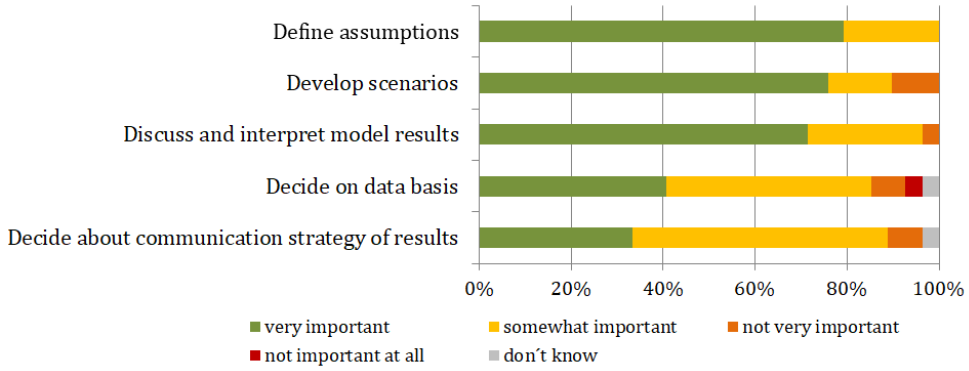

Figure 11: Importance of topic-specific exchange: *In the process of the model development or improvement, how important is the exchange about the following aspects between model developer and external stakeholders for you*?, optional; N=20 (modellers and users).

4.4 Model outreach

We find that when it comes to the model outreach, modellers and users prefer different communication formats (**Figure 12**). In particular, modellers value more detailed information about the model input and output data, and they look for model documentations, but also direct contact to fellow modellers. In contrast, users require easy-to-understand visualisations such as graphs and figures, model presentations or factsheets. One policymaker confirmed that they look for a visual, meaningful representation of modelling results: *"In a simple and in a visually appealing way, illustrate possible futures you know and the effect of policies on those futures"* (SWE_policy#1). In addition, users suggested "informative education packages" and "FAQs" as communication ways (EU_industry#2, SWE_policy#1), or even to allow users to *"play with the numbers […] so that they understand that the result is not something carved in stone, but you can have different results depending on the different options, parameters and assumptions that you have*" (EU_policy#2). This underlines the common sense of the modelling community that the purpose of models is to generate insights but not to produce facts or generate numbers. Both modellers and users demand that models are *"explained in very easy and understandable way, even though it's a very complex issue"* (EU_research#1). Furthermore, both equally require transparency about how modelling results are produced, *"but one cannot understand exactly how the results XY came about in every case"* (GER_research#1). One industry representative confirmed this need by saying: *"[O]ne important thing is the open modelling environment that would allow learning from each other, rather than one closed, black box, knowing everything and just doing everything in the best way"* (EU_industry#1) (summary of interview results: **Table A 5** in **Appendix**). Overall, modellers prefer to work with more technical documents and do technical documentations, but this is not seen to be very important to users. Model users seek for visual communication formats that provide easy access to the model functionalities and results. Thus, if the main aim of the modelling studies is impact, modelling teams and supporting communication teams in institutions must develop such communication formats for specific user groups.

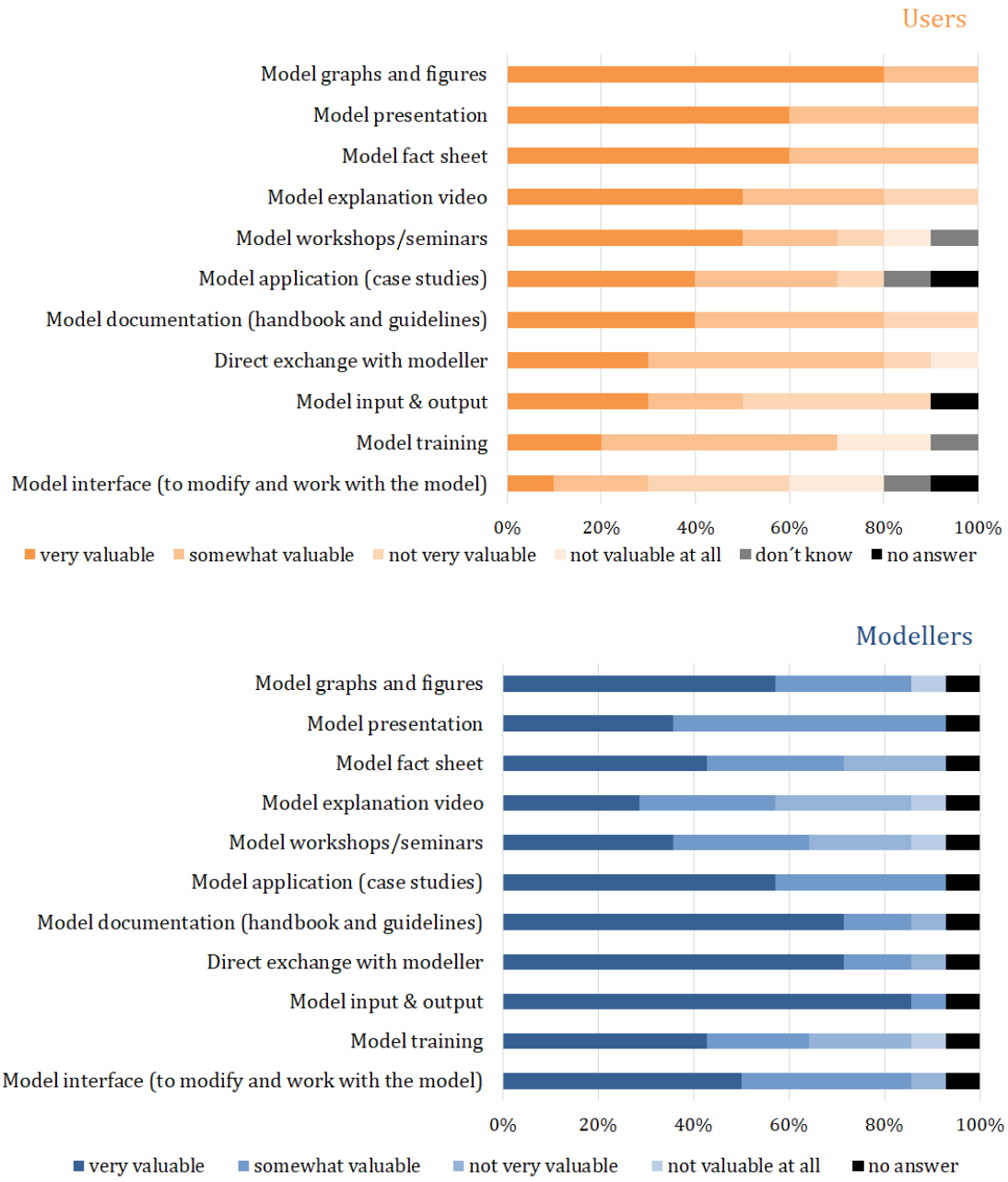

Figure 12: Model outreach: *How valuable are the following forms of model communication for you?;* optional question; Modellers N=14; Users N=10.

5 Discussion

Our results show that user needs and the ongoing refinement of energy system models align to a large degree (**Table 3**). Because perceptions of what models should do are similar in many respects, future energy models are likely to be *better* than current models, in terms of meeting the needs of users and being more relevant to different stakeholder groups. However, we also find important mismatches between needs of modellers and users, indicating that there is a need for closer collaboration between the two groups to ensure that model improvements make the models more useful for their intended audience.

Table 3 Synthesis of the similarities and differences between modeller and user needs.

Common needs of modellers and users	
Use of and need to advance models for strategy development, especially policy formulation and ex-ante policy assessment	
Develop models with a specific fit for purpose	
Deeper consideration of environmental (beyond climate) impacts of the energy transition	
Increase spatial and temporal resolution of models	
Increase transparency in the modelling process	
Make models openly available	
Enhance collaboration between modellers and users in modelling, especially for defining assumptions, developing scenarios and discussing results	
Differences in needs	
Modeller needs	**User needs**
Higher importance of integrating new technologies and services (44% modellers vs. 36% users), and shock events (24% modellers vs. 7% users)	Higher importance to integrate behavioural and lifestyle aspects in modelling (64% users vs. 38% modellers), and social impacts (50% users vs. 32% modellers)
Importance of more details in models (complexity) (25% full support) and “realistic assumptions” (50% full support)	More emphasis on understandability (43% full support) and simplicity (29% full support) of models and results
Detailed documentation of modelling details, including inputs and outputs (86% very valuable), handbooks and guidelines (71% very valuable)	Visual and intuitive presentation of model results, such as graphs, figures (80% very valuable) and presentations (60% very valuable)

Our findings have four important implications for future model development and use. First, both modellers and users perceive that energy system models should be improved towards providing ex-ante policy support and become better aligned to assessing the impacts of both policy targets and measures. As previous research found, models have gained increasing relevance and are used to support policymaking along the policy cycle at the European, national [54], and municipal levels [64]. Hence, although modellers and users do not focus on the same specific details, they agree on the overall use of models as thought experiments and as instruments to explore the effects of different actions. Whereas there is broad agreement on this in general, our findings also reveal a big gap: to allow for meaningful ex-ante assessment of (policy) options, models must be able to accurately depict the effects of multiple instruments, and they must consider different social and institutional contexts. Users are much more interested in such aspects than modellers, reflecting how these issues are closer to their realities, and here is a large and important gap for model improvement. For example, many models include a carbon price, often labelled as “climate policy”, as the only explicit policy instrument. This convention, based on economic theory and its cleanness in an

optimisation model, makes such models useless for analysis of policy options because they only have one explicit option: they can only recommend different carbon price levels, but not compare or combine different instruments.

Second, whereas ongoing model developments will increase the detail, resolution, and technical precision of energy models, it will be particularly important for modellers to also pay attention to social, political, and environmental aspects, at least if policy impact and societal relevance are important factors for their projects and models. These issues are not all new, but our findings empirically support previous calls to adapt modelling to make models more relevant for advising and finding solutions to actual energy and climate policy challenges [10,14,28]. Our findings suggest that modellers focus mainly on improving the aspects of models that are (more or less) easily quantifiable so that the areas of user/modeller needs align mainly in these fields. In contrast, we find fundamental mismatches whenever issues are difficult to quantify or the underlying mechanisms are less deterministic. For example, we note that modellers recognise social factors as very important drivers or barriers of the energy transition, but they often have no implementation strategy and exclude them from their models not out of disinterest but because they are hard to quantify in a robust way – one of the main reasons modellers cite why their models do not include social factors [14,34,65]. Most modellers have a technical background and thus develop models based on their understanding of technical systems because they are not trained to analyse non-technical factors. The large and growing social scientific energy research insights are often too context-specific or too vague – it depends! – to be directly implementable in the rigid mathematical language of models. Important conceptual contributions have been made to integrate social aspects into energy models ([66,67]*;* see Krumm *et al.*, this issue). However, continued efforts to integrate techno-economic modelling and social science and make modelling studies truly interdisciplinary, or even transdisciplinary, are necessary. This would include efforts to educate engineers in basic social science – and vice versa – at universities. It is essential for modellers to both accept and find ways to integrate social science insights in their models, but it is equally important for social scientists to accept technology-centred energy modelling as a valid method and a source of insight also for social and political problems. Integration of perspectives requires both sides to develop, leave their comfort zone and actively engage the other side. A specific role is for funders not only to enable an open search for solutions but also to allow for experimentation and model development beyond the modellers' and policymakers' comfort zone, particularly into the social and political realm. Because of the growing awareness in the importance of social and political issues for energy modelling in policy, industry, and NGOs – and, hence, in the organisations commissioning most modelling studies – there is instrumental gain in being first mover: the modelling teams that first step into the societal, political and advanced environmental realms of energy modelling will have a head start also in terms of future third-party funding.

Third, an explicit and broad agreement between modellers and users that "modelling" is a process is needed, recognising that stakeholder involvement is important for both modellers if *impact* and policy-relevance are important for their projects, and users. The "modelling" starts long before the coding and data preparation with the identification of research questions and extends beyond the generation of result figures and tables. Both the research design and the result evaluation processes can be co-creative, involving users and stakeholders, as ways to improve the relevance and usefulness of the modelling. However, although stakeholder involvement in the modelling process has been increased over the past few years [54], citizens and consumers are still rarely engaged in any deeper way [25], as the survey among participants of the Energy Modelling Platform for Europe (EMP-E) confirmed [69]. Transdisciplinary, co-creative

collaboration between modellers and model users is very challenging and there is very little practical experience with actually doing it. To change this, researchers can draw on various participatory methods in energy modelling, including multi-criteria decision analysis, cognitive mapping and storyline building, which have been tested in research projects [21,47,68]. It is important for modelling teams to improve the involvement of stakeholders in the model development and application process, not only to ensure that models answer the questions that stakeholders need to have answered but also to increase legitimacy and trust in the modelling process and "using" process. We agree with Gardumi *et al.* [45], that the creation of communities of practice for stakeholder-informed modelling could advance the collaboration and trust between modellers and users, and allow also to include underrepresented groups and audiences in the process.

Fourth, and related to the previous point, open-source and transparent energy model developments can allow modellers and users to discuss different needs and to create a common understanding of modelling, as has been highlighted by previous research [64,71]. We find that users and modellers both value open modelling processes and want to exchange about different modelling aspects to build confidence and trust in models. A two-way approach may be a solution: modellers could also develop "toy" versions of their model, allowing users to get an understanding of the simulation runs, while simultaneously maintaining and continuously developing more comprehensive, sophisticated versions for more advanced model runs. Critically, complexity and understandability must be carefully balanced. On the one hand, a model that is incomprehensible to its users is not helpful as a decision-making support tool, and risks becoming the black box [72] that policymakers can refer to when supporting their existing agenda – and become the instrument for policy-based evidence-making, as found by Ellenbeck and Lilliestam [16]. This can seriously damage the trust of modellers in users' motives and make them feel that their work does not have a meaningful and realistic impact, reducing their willingness to engage users to make their models more comprehensive and comprehensible. On the other hand, energy systems and energy transitions are extraordinarily complex processes. "Dumbing down" models will not do this justice, but instead risks giving misleading results if important factors are ignored. There is value in simplicity and "models as thought experiments" and there is value in details and complexity, but it is critical to keep complexity as low as needed and not add details for their own sake, or mathematical beauty, but limit the analysis to factors that affect the conclusions and implications of findings. It is important to keep the main purpose of modelling in mind: to generate new insight about mechanisms and options, and not only (or mainly) to produce numbers in support of some development.

The findings presented here are robust, but we also acknowledge that our study has limited generalisability, in the sense that it does not necessarily reflect the needs of decision- and policymakers in all European countries, or outside Europe. We find it reassuring that many of our findings empirically verify statements from previous studies that have addressed different issues where models should advance (**Section 2**), adding to that literature the empirical insights about differences in perspective between modellers and model users. We call for further research to investigate user needs in specific country contexts, to support modellers to adapt their models to the needs in specific geographical and political challenges and scales. Because problem constellations, histories and geographies are different across countries, decarbonisation pathways and policy requirements are different too, and hence modelling needs may be substantially different in different places and contexts. Interviews could be a suitable method here to generate deeper insights into user needs. Furthermore, our survey sample was rather small for some questions, especially for the users' group. While our survey results are supported by our interviews, as both survey and interview findings are

strongly aligned, further survey research would be needed to strengthen our quantitative findings. In addition, we were not able to survey all stakeholder groups equally, which led to user needs of policymakers remaining under-represented compared to the other groups', as reaching out to decision- and policymakers during the ongoing COVID-19 crisis was challenging. Besides, as most model users report long experience with models, it is likely that they have aligned their views somewhat to the views of modellers, if nothing else due to the long "exposure" to modellers and the epistemic world of modelling. This could partially explain the alignment of user and modeller perspectives but also emphasises the salience of identified differences. Moreover, because researchers and stakeholders, just as everybody, were affected by the pandemic during the period that this research was conducted, the crisis may have led to changes in the perceptions and priorities of user needs [73] and may have contributed to the strong need to model energy security, lifestyle changes, as well as environmental impacts. Therefore, we encourage further research to see if our identified needs can be confirmed in the post-pandemic world. Finally, our work predominantly focused on identifying and reporting the mismatches between further model improvements and adjustments as perceived by modellers with the actual needs of model users. Further research is required to explore in more detail the reasons behind these discrepancies (why), and possible ways to bridge the existing gaps (how).

6 Conclusions

As models are refined, our results indicate that they are not only becoming more complex and detailed but are indeed getting *better* in the sense that they are becoming more aligned with the needs of users and thus being more relevant to address the problems for which different stakeholder groups seek and develop solutions. There is broad agreement among modellers and users about what models are supposed to do and that environmental impacts of the energy transition and spatial and temporal resolutions need to be better depicted in future models and model versions. However, modeller and user needs are not always well aligned: Modellers want to improve existing models and users also want that, but users also need new modelling approaches, including more understandable modelling frameworks and models putting societal and political factors at their core. Hence, our findings suggest that models can improve and should improve even further if modellers want to have an impact and constructively contribute to the transition to sustainable energy systems. A useful way to increase the usefulness of models is to let modellers and users engage more in inter- and transdisciplinary modelling work, tailoring models and model runs to the specific needs of specific cases and contexts. These approaches could unlock the vast potential of models to support and guide the transition to a climate-neutral Europe by 2050.

Appendix

Table A 1

Categories and examples of potential user needs of energy models.

Category	Sub-category	Need (target/subject)	Literature[5]
Model content	General needs (energy system)	Reflect political goals (security of supply, economic performance and affordability, environmental friendliness, social acceptance, compatibility with democracy and law…)	[21,27]
	General needs (energy transition)	Reflect transition types: techno-economic, socio-technical, political, ecological, cultural…	[14,34]
		Include topics: Climate change mitigation, climate change adaptation, technology portfolio, market reaction and financing/investment, science, demographics, governance, politics, policy, sustainability strategies, life cycle assessment, resource conflicts, weather/climate dependency, sector-coupling, flexibility, digitalisation, circular economy, social acceptance, human behaviour, sufficiency, resilience, risks, opportunities and drivers.	[14,25–27,74]
		Develop a systemic perspective/vision (include all aspects)	[74]
	General needs (sector-specific)	electricity, heat, mobility, industry, land use, …	Common across literature
	Specific needs (model type)	Models for the electricity market, strategic energy system planning, technology diffusion, life cycle assessment, integrated assessment, investment behaviour, macroeconomic equilibrium, simulation models, optimisation models…	Common across literature
	Specific needs (model)	SENTINEL model (QTDIAN, ENVIRO, ATOM, DESTINEE, BEVPO, HEB, DREEM, EnergyPLAN, Calliope, IMAGE, EMMA, BSAM, WEGDYN), or other models, e. g. in openENTRANCE or EMP-E	[22,23,29,75–77]
Model design and data	General and specific purposes	Model structure: internal and external assumptions	[14,27,78]
		Role of model: models as an eye-opener, models as arguments in dissent, models as vehicles in creating consensus, models for management	[79]
	Complexity	Modularity	[14,15,78]
		Degree of integration of different models	
	Uncertainty	Types of uncertainty: epistemic, aleatory, linguistic, decision, planning	[14,15,78]
	Resolving time and space	Geographical coverage	[14,15,27,78,80]
		Sectoral coverage	
		Technological coverage/richness	
		Time horizon: short, medium, and long term (2050, 2100…)	
	Underlying methodology	Analytical approach (top-down vs. bottom-up)	[14,27,78]
		Mathematical approach: linear or non-linear	
		Model type: simulation, optimisation, or hybrid model	
	Data requirements	General availability, public availability, open-access, preparation and validity (empirical basis), type of data, format, license/credibility, time resolution, thematic data of input data	[15,27,78]

[5] These sources focused on criteria of good practice of model development and current challenges.

Category	Sub-category	Need (target/subject)	Literature
Modelling process	Inter- and transdisciplinary modelling	Strategies for collaboration: Bridging strategy, iterating strategy, merging strategy	[32,37,72,73,37]
		Content: inclusion of human dimension, energy-water-food nexus, empirical research on quantifiable patterns	[15,34]
		Stakeholder participation, agility	[70]
	Scientific standards / Quality	Transparency, repeatability, reproducibility, scrutiny, scientific progress, accessibility/licensing (open-source vs. protection of intellectual property)	[14,15,27,70]
	Scenario development	Qualitative and mixed-methods scenarios, Transformation path analysis	[14,27]
Model outreach	Model communication	communication of model design and results, tractability (easy to understand), visualisation	[14,15,70]
	Model utilisation	Usability, applicability, re-usability, efficiency (low run-time of the model), flexibility (effort for model adjustments to new research questions)	
	Supporting infrastructure	Reputation of the model developers, compatibility (familiarity of the model user with a software platform and programing language), consistency (with previous results)	[27,70]
	Organisational factors	Organisational conditions (responsibility for unsuccessful implementation), model advocates and their trustworthiness	[70]

Table A 2
User needs related to content to be modelled; interview results.

Sub-category	Need focus	Country	Quotations from the interviewees
System-specific needs	Sector coupling / integration	EU, PL, SWE	"First of all, the aspect of **sector integration** is extremely important." (EU_POL#1) "[…] so, the **energy system becomes more and more connected** and this is the main focus of models, I think, to try to capture these things as much as possible. I think, from my experience you have extremely detailed power sector models, but then very aggregated on other sectors." (EU_POL#1) "I think that important thing now is **how different sectors interact we have each other**, so it's about integrating decentralised energy into models, which I haven't seen many models that achieved that yet. Understanding how to combine the best large scale with small scale, for example." (EU_NGO#2) "But this also strongly points out that you cannot look at the whole forecasting part of the PEP [Energy Policy of Poland by 2040] only in terms of electricity. This is the whole system of interconnected vessels, so it is very important for us that this forecasting is done in terms of all three energy sectors, and not only in terms of electricity." (PL_POL#1) "And we are still working on the **coupling of different sectors** of the energy system – between industry, electricity market, heat market, transport and so on. That's still topical." (SWE_SCI#4)
	Flexibility	EU, SWE	"But I think that within the energy system modelling, I think that there are two main aspects somehow missing or not taken up in total yet. And I think that the first one is the **links between different sectors** due to **sector coupling** and **flexibility requirements**." (636-639) (EU_SCI#1) "**Flexibility** and consumer side were a big issue in Sweden." (SWE_SCI#4)
	Energy security	EU, GER, PL, SWE	"I think that there should be an issue of **security of supply**." (958) (EU_IND#2) "Today, all instruments have the ability [...] to map the dynamics and availability of a completely renewable energy system in the case of **darkness and calm weather** [...] and the like. You don't even have to start if you don't have such a model." (GER_SCI#1) "With which system mix, including networks, storage and flexible options, can we achieve a **secure power supply**?" (GER_POL#2) "The accepted assumptions concerning safety. What is the **level of reserves**, […]" (PL_NGO#3) "Energy models should, in the first place, deal with **energy security** in its broadest sense - including ensuring the supply of energy necessary for the functioning of the country and economy in an optimal way, while meeting the climate and environmental objectives. Apart from the volume of energy, an important role in this type of task is played by the analysis of available and required power reserve, especially in conditions of dynamic development of renewable sources of unstable character. The overall economic results in such an analysis should also take into account the role of local consumers and generators." (PL_SCI#4) "And there is still the question, what do we do in those days and hours where is no wind and sun, and where hydropower is not sufficient? […] what you have to think of now, what you have to discuss now, is to think about the **reserve capacity**. [….] I think the security of supply will be the next big thing." (SWE_SCI#4)
	Levels and implications of energy import and exports	GER, PL	"So pure energy models are no longer enough. You have to map the **macroeconomic interactions**, although it is problematic and more difficult. Because then you also get all the foreign trade relations and the like, keyword CO2 price [...]. That's something we've been getting hit with lately. Did you take that into account? And when you then say it's our turn, but haven't finished it yet, then, of course, it's difficult." (GER_SCI#1) "At the level of power systems, analysis taking into account neighbouring systems is needed, in order to account for flexibility and adequacy sharing resources via international interconnections." (GRE_IND#1) "It always puzzles me as a layman in the context of models, for example, how we have those models that show: "Well, we'll have, let's give it 70% RES and we'll have 10% imports in this mix." So **how does he count these imports**? For example, let's say that the sun does not blow or shine, so it is easiest to model, if we make a model limited to the borders of Poland, then we will import the rest if necessary. And the question is, if we also have such a mix in Germany, in the Czech Republic and Slovakia, etc., then there will be no real import, because then there will be no blowing anywhere, or there will be too little blowing." (PL_NGO#1) "What is the level of **interconnection exchange** - Why does the Polish government stubbornly accept zero and claim that there will be no exports or imports." (PL_NGO#3)
System-specific needs	Decarbonization options	EU, GER	"[…] **how to decarbonise** the total energy system." (EU_IND#1) "[…] but it would be very important to have that [**detailed data sets**] in order to really assess the best combination of all **possible decarbonisation solutions** and flexibility options in the system."(EU_SCI#1)

			"It should be possible to show how all sectors of the energy industry can be converted to **zero emissions**. That is why all technologies that are emission-free must be described. The interactions between the sectors must be described, which is what I just mentioned. In any case, you have to show that such an energy system works in principle." (GER_SCI#1)
	Decentralization	EU, GER	"Here I can burn out of the bridge right away because that was something that we **missed a lot with our long-term strategy - the whole aspect of decentralisation.**" (EU_POL#3) "And this is actually something great about **decentralised energy on our roofs**. (…) So, this is one of the things that we really missed in models." (EU_NGO#2) "So, this whole aspect and the renewable's potential, maybe that, you know, maybe that's not what is going to happen, but the **potential of citizen's energy** has never been included in
			these models." (EU_NGO#2) "That massive share of renewables must be included in models. It will show that we can actually achieve higher renewable shares much quicker. And also looking at how **distributed renewables** can have an impact on prices because you are reducing transmission costs, you are reducing lots of factors. The costs of distributed renewables are seen by utilities as a really big cost, but if you look at it from a different angle, you can show how distributed renewables can reduce the costs of the overall energy transition. And it's not tackled by any of these models." (EU_NGO#2) "We can supply every house with **decentralised electricity**. Yes. It is only a question of what kind of effects this will have, precisely on how many wind turbines we need. I think that is a discussion that I believe we still need." (GER_POL#2)
	(Socio-) Technological potential and impact	EU, GER, PL	"So, in order to reduce the fleets, we should have a lot of share mobility and transition to different types of mobility, including public transport etc., and that also has an impact on electricity grids, of course." (EU_NGO#2) "There was the stipulation that we would like to know (A) how **renewable energies** can be expanded, and (B) how their **costs develop**, how they can **replace other energies**. But it has always been demanded that we naturally incorporate this into **a realistic development** of the entire energy system." (GER_SCI#1) "And of course the wind conditions, so that we could know more or less what the **capacity factor** of those particular turbines could be. Such things would be interesting, especially in Poland, where this spatial layout leaves a lot to be desired, or in Germany, where there is now a big problem as far as **NIMBY** and windmills are concerned, which is some kind of extreme situation." (PL_NGO#1) "I don't know PRIMES so well, etc., but I assume that it is the models that take into account that this system is to balance every hour of the year. But I also don't know how much they take into account**, how many windmills could be built in Poland** without some mega violations of some **protection zones**, at the same time as some... well, because it is known that these are issues of compromise, but with some preservation of local community interests." (PL_NGO#1)
	Macro-economic costs and distributional impacts	EU, GER, PL	"The **macro impacts** are extremely important, especially the **distributional impacts**, this is critical." (EU_POL#1) "But at the end, you **don't really want the least costs energy system**, you want something that is the **best system for the whole society**, for distributional effects and stuff like that." (EU_SCI#1) "[…] at the moment most modelling exercises try to minimise energy system costs, at least the most important ones, I think, and they do not include the **macroeconomic impacts and effects that are outside of energy system**. So, there is also a missing link, there are many soft links between these models, but as I mentioned before, macroeconomic modelling is very difficult and very sensitive, so I think it's also very difficult to integrate that." (EU_SCI#1) "There was the stipulation that we would like to know (A) how **renewable energies** can be expanded, and (B) how their **costs develop**, how they can **replace other energies**." (GER_SCI#1) "I would like this to be the case in such analyses, I know it is much more complicated, but we take it into account... because if we look at the energy bill of the end-user, it is about half of it here in Poland. The price of electricity and the cost of delivery, right? And just to have a full picture, these analyses should also take into account how much it will cost us not only to rebuild the generation capacity but also to rebuild the whole system because this only gives a full picture **of how much it will cost the customers and at the end of the day the whole economy.**" (PL_NGO#2) "Because the costs seen from the investor's point of view, i.e. investment outlays, operating expenses, yes, costs related to capital... But there is no such model that would calculate the **total cost for the whole economy**, for the whole country." (PL_POL#1)
	Economic costs for consumers	PL	"[…] but in fact, at the end of the day, the energy consumer is not interested in how much energy company A or B has invested in this transformation, but in **how much it has on its bill**, or how much it produces and does not pay the bill because it has a PV or a gas installation." (PL_NGO#1)
System-specific needs	External costs and environmental impacts	EU, PL, SWE	"All the other things that we've been thinking about is this whole concept of cost-efficiency. Like cost efficiency means… cost efficiency doesn't take into account **climate impacts**. Cost efficiency is simply a model looking at… I mean, the whole concept is wrong." (EU_NGO#2) "There is one issue there that I think should be more widely taken into account when assessing the impact of external policies, and in general I consider it absolutely necessary, because these costs, these are the costs that we all pay. And the state, indirectly with our money and the citizens in the form of, for example, treatment of diseases caused by air pollution. The state, due to sickness absence, etc., these costs are quite enough. And if you take into account different costs, including **external costs**, when assessing the policy options, the hierarchy of profitability of investing in different energy sources is completely different." (PL_SCI#3)

			"There is also a lack of such a model that would assess the **overall costs for the environment**, such ecological costs. So many, many actors have different tools at their disposal, but I don't think there is one available to the public, I don't know if there is one at the European level that would take all these components into account." (2261-2265) (PL_POL#1) "It is a question of resource efficiency. The resources to reduce climate gases, but also what we need **to use the resources we are having as efficient as possible** – also if its waste we are using." (SWE_SCI#4) "**What are the (environmental) consequences of a large scale use of renewables?**" (SWE_SCI#4) "I think it's important to look at **health impacts and climate impacts**, to kind of juxtapose costs of acting with costs of inaction. And if you are able to do that, you can clearly show, even if the 65% reduction costs each of us individually and we need to pay 100 euro a month to be able to do that, that's much more less than thousands of euros that we all lose because we will be flooded or our houses will get into the fire." (EU_NGO#2) "Also, the whole environmental, like the **biodiversity aspect** of the wind. It's very interesting, I mean, we can't achieve 100% renewables without having hundreds of gigawatts of offshore wind. That is going to be crucial, but you also have to do it in a sustainable way." (EU_NGO#2)
	Social and socio-economic impacts	EU, PL	"And then, I think, we have connections to **social acceptability**, because if we go into a more decentralised approach, we can create more value in the regions or in all European places, where you have your own creation of energy and you have your own value chains. You have local jobs, local economy and then, local acceptance." (EU_NGO#1) "It can be in terms of social acceptance, it can be in terms of **job creation**, it can be in terms of socio-economic impacts that are not all factored in the model that is being run." (EU_IND#2) "It would be very interesting to **get some numbers on jobs** and those kinds of aspects. I mean, how many jobs there are in the renewable sector and how many jobs there are in the fossil fuels sector. I mean, in the US you have some great numbers on it, showing how exactly many jobs you have in the renewable sector and how much in fossil fuels. If the government wants to choose, it should choose more jobs. In Europe, I haven't seen so many numbers around that. That would be interesting. I think jobs is good." (EU_NGO#2) "The grid extension is fundamental […] but **grid extension is dependent on social acceptance**. You really need to know, if you need more grids to make it cheaper between North and South of Germany, and you can have fantastic plants of grid extension, and that's good, that says your model. And then you realise that because of socio-economic elements, the TSOs cannot develop the overhead cables, but they need to bury cables underground and that is multiplying by factor 10 the costs of the HDVC, between the North and South of Germany. That is a fundamental thing, but how can you integrate that into the model? I don't know, so what I'm answering to you it's not a scientific answer." (EU_POL#2) "Maybe something like for the actors, I think could be, **how they really value an autarky**, so whether people really invest in batteries and PVs, for example. Also, regarding the financing aspect and **how far it's important for the people in the financing the energy system**: **if they do so, which technologies and which geographical areas they** prefer." (EU_SCI#1) "Because if you do in an optimised model, you get, I mean, if you have wind, it gets first to the locations with the highest wind speeds, but maybe they don't get so easily the financing for these locations, because people don't live there. Or people live there, but they don't want to have so many wind turbines. I think that might be the aspect of importance." (EU_SCI#1) "[…] is primarily a model that assesses the overall costs, i.e. includes the overall costs, also assessing the costs related to the development of energy infrastructure, the macroeconomic costs, the **social costs related to change**, especially in different segments burdened by the costs of energy policy change, such as mining." (PL_POL#1) "Social aspects, especially in this crisis, which is beginning to develop, are certainly employment. Well, it is also a question of what we often discuss, as if the **level of employment in a given technology**." (PL_NGO#3) **"Social topics** are indeed one big hole, a great neglect in most energy and economic analyses in Poland." (PL_SCI#1)
System-specific needs	Impacts of social and actors behavior	EU, GRE, PL	"I would say that **modelling of social behaviour** might be very relevant for modelling potential outcomes." (EU_IND#1) "[…] maybe including **energy communities** as investors into the models. So just more analysis about the behaviour and acceptance issues that people really have." (EU_SCI#1) "It can be in terms of **social acceptance**, it can be in terms **of job creation**, it can be in terms of **socio-economic impacts**, that are not all factored in the model that is being run." (EU_IND#2) "I also think that there could be an endless story about **how different models deal with the fact that the actors are not entirely predictable in their decisions**, which is the famous discussion about discount rates, not only those for calculating costs but those for making decisions." (EU_POL#3) "I think that the second point is the **behaviour of actors** that is not included yet, at least in the optimising models. And you have, of course, the electricity market models, there are some models that have agent-based behaviour in them, but somehow it is not very linked at the moment." (EU_SCI#1) "It would be desirable to conceptualise and explore alternative (not only technological) pathways that are less bounded by cost-effectiveness considerations and which embody aspects of **social inclusion and justice** as well **as energy-sufficiency aspects**." (GRE_POL#1) "The improved simulation of **'real-world' decision-making and behavioural aspects** are always welcome and offer robust results in the quantitative analysis." (GRE_POL#1) "Plus, one related topic as if from the social side, as if from the other side, but also socially related, that is **acceptance** for, for example, RES development." (PL_SCI#1)

	Unforeseen events	GRE	"The role of **uncertainties and unforeseen events** should be integrated into energy models." (GRE_POL#1)
Sector-specific needs	Industry	SWE	"The remaining issues we have from an energy perspective and climate perspective are the transport sector and the **industry sector**." (SWE_SCI#4) "So this year we have also been improving the model very much in respect to the **industry sector**, and fuel options for the transportation sector." (SWE_SCI#1)
	Transport and mobility	EU, GER, SWE	"[…] one of the most important issues is to have more clarity about the transport sector. So, how is the **transport sector evolving** until 2025, 2030, 2040, 2050. So, what kind of **technology innovation** can be foreseen." (EU_IND#1) "I think it's also important to look at the mobility sector. So, we can't have so many cars on the roads, we can't have so many planes in the sky, we need **more rail**, we need **more public transport**, we need **more bikes**, we need **more bike lanes** and this whole element is also very interesting. By 2028 we should phase out the whole combine engine if you want to be 1.5. So, what does it mean in practice for electric mobility? Can we have so many cars by then, which electric mobility shouldn't have because it would be extremely resource intensive and it would carry its own challenges? So, in order to reduce the fleets, we should have a lot of share mobility and transition to different types of mobility, including public transport etc., and that also has an impact on electricity grids, of course." (EU_NGO#2) "I also don't see any **socially accepted understanding** about which **energy sources** we will actually use or which form we will actually use, for example in mobility in the car sector. At least in the media public, I see the topic of **electric mobility**. On the other hand, I have noticed an interest in **hydrogen or synthetic fuels** in political committees that I have noticed." (GER_POL#1) "Another question is the transport system because it will likely **demand more and more electricity**." (SWE_SCI#4)
	Heating and cooling	EU	"[…] that we will focus more and more on **heating and cooling**, that this is a bit of a neglected plot." (EU_POL#3) "In contrast, heating and cooling have been quite neglected so far, and yet this is a large part of the power system. Also better management of this plot, I think it will be something very **popular in the next years**, especially since here come all these issues, that you could use decarbonised gases, you could use biomass, but the question is what biomass, that you can earn sector coupling, that is electricity and heating. Also, these topics are already very fashionable, but I do not have the impression that they are very, very elaborate in models, with those I work with." (EU_POL#3)
	Agriculture	EU	"And then you have **agriculture**, this will be processing in the industry of the non-CO_2, and then you have to see how you can deal with carbon removal. So, carbon removal is also a very important aspect. And land-use change, to compensate for this. So, all of them are very important." (EU_POL#1)
Technology-specific needs	Diversity and differences of tech	EU, PL	"And also**, future technology developments** and costs developments are also a problem. I think for renewables it's clear now, but for these new technologies, like electrolysers and the heat pumps, they still have a lot of uncertainties, maybe that could be included to improve model outcomes." (EU_SCI#1) "That is to say, **involving many different technologies**, that is, not just one, two, three basic technologies, such as water electrolysis of one technology and good-bye, just as many connections between the sectors as possible, so that it is simply possible to take account of this greater number of possible paths." (PL_SCI#2) "[…] is the possibility of **quite easy integration of additional technologies**. I mean, governments have different priorities, or they want to understand how different technologies will behave." (PL_SCI#2)
	Hydrogen	GER, PL	"An example would be these **synthetic fuels**. An intermediate product here is **hydrogen**, which I can use directly in mobility or in other areas. Or it can be further processed, for example by means of hydrogen synthesis to liquid or gaseous synthetic fuels, the so-called e-fuels. I would find that a socially exciting topic on which I still don't see any consensus in society." (GER_POL#1) "That is to say, involving many different technologies, that is, not just one, two, three basic technologies, such as **water electrolysis** of one technology and good-bye, just as many connections between the sectors as possible, so that it is simply possible to take account of this greater number of possible paths. In the case of hydrogen, for example, we have electrolysis, we also have hydrogen production from CCS gas, electrolysis can also be linked either to RES or to an atom. There are even technologies that can produce hydrogen from coal with CCS. Well, it is probably not the best technology, but also some stakeholders are asking about it and there is a problem that it is difficult to put it into models because models are often made in such a way that there is only electrolysis with RES. There are various flowers that limit the choices a little." (PL_SCI#2)
	Power-to-X	EU, PL	"[…] one of the most important issues is to identify 'power-to-x', so the 'X', what are the real, let's say, different energy carriers – **are we talking about H_2, are we talking about CH_4, are we looking on climate-responsiveness**, so these kinds of things." (EU_IND#1) "And basically, then these issues of dynamic price, how do customers, consumers react to this, like every hour, if we have cheap RES, do we make power-to-x out of it or do we make something out of it? But for this, we probably need a bigger granularity, as we say beautifully, who would catch it better and we still have a lot to learn from it." (EU_POL#3) "I would very much like to see in these decarbonisation models a little more of just such a mix of different technologies and those at the end, i.e. all **those 'power-to-x' from different sources, biomass, biofuels, CCS** where, as if the firing of these selected technologies at the very end is somehow modelled." (PL_SCI#2)
	Storage	PL	"The second thing, you know, is **storage**, although it's now taken into account there in some way, nevertheless, this aspect is still underestimated." (PL_SCI#1)

	Grid infrastructure	EU, GER, PL	"It will become more and more important in the future, I think, for example, **the heating grids and also the gas grids**. Also, if you think about **hydrogen grids** it might come up not properly included yet into the normal energy system models that mostly look at the electricity sector. Or you have separate models for gas, of course, and separate models for heating and cooling. I think, that the main thing is to integrate everything, and also the data for the other sectors, apart from electricity and gas, it's not that good yet." (EU_SCI#1) "And what I would like to see, is the **focus on grid aspects**, because as I need to emphasise, I am quite convinced that renewables are, as I said, cost-competitive and best solution in regard to climate policy in the energy sector. So, the question is not whether we go 100% in renewables, but how. And there is a dichotomy, I would say, two aspects: the decentralisation and big grids." (EU_NGO#1) "So, the **interplay between different grids**. This has to be investigated, I guess, it has not been investigated enough so far." (EU_NGO#1) "[…] that it has not yet been sufficiently clarified is what our **power grid** should look like if we really say very clearly that it is designed for 100 percent renewables. [...] If we had reliable statements about **which network** we need for 100% renewable energies, in 2030 if you like, then we would have a much better argument that we really need these networks. And if anyone can say that we only need this power line to be able to operate coal-fired power plants somewhere, then the **support for it** will disappear very quickly. Yes, then I would also say that I don't want this power line." (GER_POL#2) "One thing from me, it is also the **network** in Poland that is underestimated. As if a network barrier, especially distribution in all models. It means that it is assumed that you can connect some gigawatts of photovoltaic, and then when you're an investor, it turns out that one megawatt cannot be connected because there is simply no network. I don't know how to model it, but in any case, it's a problem that is completely overlooked." (PL_SCI#1)
Technology-specific needs	Biomass and biofuel content	PL, SWE	"Also, when it comes to the issue of biomass - in my opinion, this is a threat in the understanding of pan-European models, which shows that "oh yes, here we will put a lot of wind and PVs and we will replenish ourselves with gas for a while and at the end of the day we will replenish the rest of the biomass there". And every model you see for the future shows that you will use 2-3 times more biomass. And the question is, **where will we take this biomass from** now on, in Germany, palm oil from Indonesia is being used in transport, and this is already some total, total stupidity. And now the question, because we know that we also can't use that much biomass, so in this expertise, nearly 100% of the RES depends also **on creating a scenario that will have little biomass**, because it is easy to show because here even this can be thrown into the furnace and everything is cool, but we can't do it in a sustainable way. And it seems to me that these are cool issues as if the models are taking more into account." (PL_NGO#1) "[…] one big policy we are discussing at the moment is to have a **quote for how much biofuels should be implemented** based on the carbon content. (SWE_POL#3)
	Carbon Capture, Storage, and Utilisation	EU	"[…] that the **carbon capturing** and its **further use** […]" (EU_IND#1)
	Circular economy	EU, SWE	"And then, as a final aspect, where I think there is very little development and very room for development is **circular economy**, this type of aspects. I think this is very relevant for energy system models." (EU_POL#1) "I think something that is really tricky to model is topics like **circular economy**. It is a big topic." (SWE_SCI#1)
Country-specific needs	Application to the member state level	PL	"From the point of view of..., referring to the analyses coming from the European Commission or analyses related to European regulations, it is indeed the case that what we see from the point of view of the recipient is the Impact Assessment at the European Union level. On the other hand, we repeatedly, basically to every new document that comes from the European Commission, request that the costs be shown at the level of the Member States because this is really very important for us. To assess how much we, as Poles, would have to bear the costs, what changes had to be introduced to achieve the objectives proposed by the European Commission." (PL_POL #1)
Policy-specific needs	Policy instrument options and impacts	GER, GRE, SWE	"What is perhaps becoming important now is how to model the design of **CO2 pricing** in ever more detailed form and **how that affects the energy system** as a whole. And if you now increasingly include social components in the pricing, you can model it. There has been a lot of heated discussion in the last few weeks about **who will be charged what costs**." (GER_SCI#1) "During policy instrument design more bottom-up models and tools are required. Multi-criteria tools, as well as financial appraisal tools, are most often required for the development of financial support policies to estimate their expected impacts and determine different levels of financing support (ex-ante policy evaluation)." (GRE_POL#1) "But our most important question is: **how can policies impact these developments** and what will happen if you do one thing rather than another thing." (SWE_POL#1) "And in the area of policy instrument, how you can move faster with the climate action; **what instruments do we need?**" (SWE_SCI#4) "The two main things are policy measures and effect." (SWE_POL#3) "**What are the most important choices that we got to do in the future.** And I think that is the most policy-relevant insight that policymakers need. Not exactly the exact level but what are the most important choices." (SWE_POL#3)
	Regulatory measures	EU	"If you establish a one-stop-shop for licensing and critically reduce the 'red taping' and the **licensing procedure** for renewables deployment in Europe, in the Member States, let's say, then, of course, you decrease investments cost, because you need lower, I mean, you can access cheaper capital, because the procedure from the moment you run the project and the moment you implement it, is much shorter. And it reinforces the investment considerably. But how can you put that into a model? I don't know…" (EU_POL#2)

			"**How EU regulations are taken into account,** especially those, because they have the strongest impact, so here they influence the level of carbon dioxide prices." (PL_NGO#3)
	Policy impact assessment	PL	"[…] impact assessment, the **impact of policies**, but I don't know how to relate it to modelling..." (PL_SCI#3)

Table A 3
User needs related to model design and data; interview results.

Sub-category	Need focus	Country	Quotations from the interviewees
Systemic/holistic approach		GRE, PL	"There is a growing need to consider a **systemic approach** in energy modelling regarding the decarbonisation of the energy system. **New opportunities and alternative options** will evolve drawing from the increased synergies between sectors of the energy system." (GRE_IND#1) "And from the RES point of view, we do not think only from the point of view of **investment outlays**, for example on particular technologies, but we also think about how to implement solutions to the national power system. How much investment outlays would really have to be incurred on infrastructure development, on development of storage technologies, on development of balance and reserve sources. In fact, what costs had to be the costs associated with reduced production from conventional sources already existing in the system, because these are in fact the **costs for the whole system, costs for the economy**, which have to be incurred and associated with the development of renewable energy sources. This is probably not very much discussed on the European forum, there is only talk of the expenditures related to renewable energy sources, the benefits from the point of view of environmental protection, reduction of greenhouse gas emissions, possible benefits related to the development of innovation. On the other hand, this area related to balancing the whole system, adjusting its flexibility to the variable work of RES, apart from slogans, is not really counted. And this is missing in energy analyses." (PL_POL#1)
Scientific standards	Transparency	EU, GER, GRE, PL, SWE	"And so that there is no such easy criticism as to avoid it, it is **transparency**, transparency, transparency. So everything we put into the model must be **publicly available**." (EU_POL#3) "Well, what I find sometimes difficult is the fact that I am often missing what are the clear assumptions behind this model. I think it would be great to be a bit more transparent on that, on the assumptions. And… because the model itself, of course, it can be released, but the assumptions – yes." (EU_IND#2) "In any case, [**transparency**] is a basic requirement. Otherwise, you have to expose yourself to the accusation that you actually want to manipulate or that you deliver incomprehensible results. But then your colleagues pay attention to that (laughs). You actually do that among each other. You also exchange ideas, both for good and in competitive behaviour." (GER_SCI#1) "Model **transparency** is important." (GRE_SCI#1) "Well, I think that such **transparency**, but also such inclusiveness, that is, it's really important that if someone has his or her favourite technology because he or she is an engineer working in a given technology for 30 years, it's really important for that person to see how the technology behaves in this model and for what reason. And such inclusivity, openness of modelling frames to additional technology, simply described by the user, is very important in my opinion." (PL_SCI #2) "It's better to make them simpler and **more transparent**, and user-friendly, that is my personal opinion." (SWE_POL#1) "With the data, we put into the model, we try to be **as transparent as possible**, allowing everyone to say and think if he believes in the results or not. So data might be also secret because we work in some areas with specific industries or societies. […] But otherwise, we **try to be open**, and we also expect that everyone engaged and says "yes this is okay" or "that's not okay"." (SWE_SCI#4). "It must also be **transparent** because if we do not know what is **hidden in the model**, we do not know where it comes from. It seems to me that these are basic things." (PL_NGO#3)
	Assumptions	EU, GER, PL, SWE	"And I think it's true. And that's one of the problems, I think that all models that we have seen, they don't put science first. They assume business as usual, kind of business as usual thinking is the **main assumption** and that's for us a problem. That's what criticise, but then you are someone in a fossil fuel industry […]. But I think that it's really fundamental if we don't start where we need to go." (EU_NGO#2) "So, it's **not just taking the historical time series and extrapolating** them to the future, but trying to find out what climate change really is, what is happening. This is basic – the fast changes." (EU_IND #1) "Or you go, and this is done often, you go to the literature, look what are the results of the literature in regard to the costs, then you make estimates about average literature publication of costs, and then you will end up with very, very **conservative assumptions** that are scientifically based, but are far away, from where we currently are." (EU_NGO#1) "What the [employees in the ministry] should still know is **which parameters can be changed and which parameters come out at the back**." (GER_POL#2)

			"Well, because it is probably important with RES variables, **why such a load factor is assumed**, not another." (PL_NGO#3) "I would say that the **best source data**, i.e. even data on raw materials, assumed prices, weather data, everything you need to count." (PL_SCI#1)
Scientific standards	Assumptions	EU, GER, PL, SWE	"It is very important in the construction of energy models to properly define the **limitations of the parameters** in the model so that the solution is both optimal and achievable." (PL_SCI#4) (written replies) "In fact, if the **assumptions** are not generated objectively, where, for example, there is no computer that draws what it is supposed to assume. You know, even IPCC modelling, which is considered to be the main reference point, there are a lot of **uncertainties in these models**. I do not know if this is a good question when it comes to trusting energy models, but it would be worth asking about the conditions that have contributed to greater objectivity of the results of energy modelling. Which could give them more of an experimental character than a purely argumentative one." (PL_IND#1) "You always have to ask yourself, is it something useful that I found out or is it just a result of the **way how I constructed the model**." (SWE_SCI#4). "There is **very little debate about how this number was calculated**. Now, I think the discussion is much more major, much more nuanced." (SWE_POL#1)
Characteristics	Higher spatial and temporal resolution	GER, SWE	"[Simple Excel sheets] are of course no longer appropriate in their form today [...] when it comes to the **spatial or temporal resolution** of the availability of renewable energies and the like. Or the cost development on the electricity market that results from it." (GER_SCI#1) "In the last years, it became more and more important over the last years is that you have a model in the electricity economy that can describe variabilities. For 10-15 years, the time resolution of MARKAL and TIMES was rough. Now, if you want to perform an electricity economic analysis, you need hourly descriptions. And in some years, no need **even smaller time frames**." (SWE_SCI#4).
	Geographical details	GRE, POL	"More **detailed geographical analysis** is needed to be performed and published." (GRE_IND#1) "I think it's definitely worthwhile still at the stage of preparing the model, let's let the technology consult so extensively to take into account its framework, just to take into account such a bit more exotic, a bit **more country-specific options**." (PL_SCI#2) "You know that you probably have to work with many decentralised elements that **municipalities** have to function, that they have to do it, keyword thermal management plans in districts. Such things could be modelled **more precisely**. How can a municipality use its instruments to ensure that all actors convert their buildings in line with a thermal management plan [...]." (GER_SCI#1)
	Flexibility of models	EU, PL	"To me, a model is a **living thing**, it cannot be as a one-shot." (EU_POL #2) "And unfortunately, we are also a little bit at the point where we will be able to **update** one part, and the situation shows that maybe this forecast is already outdated. And so we could probably show these projects endlessly. It's very **difficult to balance out where exactly to say stop** when we need to have some official document." (PL_POL#1)
	Complexity vs. simplicity	EU, GER, PL, SWE	"Very complex, very hard to compute, it's very hard computational effort. In my view today, it's not justified, I would suggest having **simple, linear models** for the overview (EU_NGO #1) To be honest, I don't see so many problems to get into assumptions, but it's so many technical details, technical complications, that for **non-modeller to understand** what is in the models, it's a very hard task." (EU_NGO #1) "So, these kinds of questions are, I think, are important nowadays. It's **more complicated now** when we have so many different inputs and outputs." (EU_NGO#2) "[…] making them **more complex** and trying to make them more like reality, it also...so there is a risk of decreasing the level of transparency because they are **so complicated that nobody really understands them**." (SWE_POL#1) "And the second thing is that this model has to be useful for the policy later, for such a campaigning purpose. So it simply has to be reliable... it has to be recognised, yes... and simply, if such a model is not recognised, because it will be treated, for example, as lay people use it later and it is **too simplistic**, so I think that the **value** of this model will later be somehow **limited**." (PL_NGO#1) "They should be more transparent, perhaps **simpler instead of more complicated**." (SWE_POL#1) "If you want to solve a complex that you **need often very complex models** and other models are also in a lot of resources to use them, to understand them, and to use them correctly in a way." (SWE_SCI#2) "There is a **risk of decreasing the level of transparency** because they are so complicated that nobody really understands them and not even the people that use them are able to understand them all the time." (SWE_POL#1)
Data requirements	Update technological and economic data	EU, PL, SWE	"[…] but it's like the assumption related to economic growth, for example. Assumptions related to the oil price. OK, you put oil price, the expected oil price in the coming years, but actually, you don't have any idea seeing that actually, oil prices have collapsed. And does it mean that all models now are totally meaningless? No, not necessarily, but you **should be able to recalculate, or at least constantly update**, in light of these different parameters, like oil prices are lower than expected, it's influencing our model this way or that way. Economic growth, OK, imagine there is the financial crisis and then the economic growth is lower than expected, saying that it affects the level of cost-effectiveness of different scenarios. And all that." (EU_POL#2) "So, all of that are parameters that you cannot consider as carved in stone, that you need to be transparent about and that you need to **regularly update**. Because there is also a lag between the moment you run your model and the moment you take the decision." (EU_POL#2)

			"Of course, the **predictions** about fuel prices, about the level of prices to be emitted and what the CO2 price will be." (PL_NGO#3) "Well, yes, it seems to me that it is just such functionality and openness, and okay, predefined data sets, technology sets, but at the same time **easy to edit and update**." (PL_SCI#2) "And the question is more technical, **how far this flexibility can go and how quickly the new parameters will be generated**. This is also a challenge." (PL_SCI#2) "[…] to estimate future costs of different technologies." (SWE_POL#1)
	Ensure reliable, high data quality	EU, GER, GRE, PL, SWE	"[…] of course, in theory, if you open up the model and you have many valuable inputs from everyone added, it can improve potentially. Then, if you also have a very decentralised development of the model, it makes it more problematic to make sure that the quality is there, that there is **quality insurance**." (725-728) (EU_SCI#1) "[...] instead the question was asked **whether the results are reliable and useful**." (GER_SCI#1) "This means that with the input data and the suspected developments in the data, you quickly reach limits. That's why you do **scenarios** and the like to **narrow it down**." (GER_SCI#1) "Policy makers need to base their policy documents on **credible data sources**, otherwise the results can be challenged." (GRE_POL#1) "I'd say that there is excessive optimism about the quality of the data that is available. The data is more or less approximate. For example, when it comes to the energy demand of end-users, in general, the **quality of this data** depends directly on the specific technologies implemented in a given EU Member State, e.g. countries where smart metering is still being implemented." (PL_IND #1) "It needs **democratic trust** that the results are validated and not politicised." (SWE_POL#3)
	Make data open-source	EU	"And of course, I look at a model and I look at the data basis, so I would ask how they built that database and what is really included in different categories because **finding information is sometimes not easy**." (EU_IND #2) "For example, in Germany, we don't have a **good dataset** on cooling and heating grids. That might be different in Denmark, but it would be **very important** to have that […]" (EU_SCI#1) "Because it is, of course, the models used somewhere to support KPEiKu, PEP, or the latter analysis of the centre in KOBIKA, concerning how the prices of CO2 emission allowances will rise if the EU's emission reduction target is raised to 50% or 55% by 2030, well, I think that here such an obligation would certainly help, with all the data, as far as analyses **financed with public money** are concerned, to make it **publicly available**, and not only some dry results of this are described." (PL_NGO #2) "[…] that is, opening up to the maximum, **sharing all the data** that are behind these results, formulas, generally good documentation of results. Well, this is one of the ways that stimulates comments from decision-makers, but also from other researchers and other institutions. So it's like building trust in these results." (PL_SCI#2)
Harmonization and comparability of models		GER, SWE	"It was then decided to **harmonise the input data**. It has been discussed where the differences in the assessments come from. [...] that was extremely important because you learned from it where you can simplify and relativize. And where one can make the model results absolute so that they are no longer questioned. [...] During such discussions it quickly became clear where the deficits [of the models and results] lay." (GER_SCI#1) "We work now more with different models, which we try to do together, **compare or complement**, that we have a super big that can do all best (SWE_SCI#4) and how we can compare models with each other." (SWE_POL#3) "And it can be that we have a model with a different system boundary, or it can be also that we have different models, which are quite similar, and then you can **compare the results**." (SWE_SCI#4)
Comparability of cases		PL	"It's also important that if you **compare between different countries**, then you have to use the same models because taking into account the characteristics of these models, you can get different results. So that would be the boundary conditions. And the correct output, because how do you verify that?!?" (PL_SCI #3)
Linking of models	Linking (generally)	GER, SWE	"We always made models that were for themselves. And actually, you **didn't automatically transfer the results from one model to the other** and then continue calculating. Instead, the results were disclosed, discussed and then empirically decided which results would be used in other models. We have other models such as ReMix or the like that model such structures or model networks. You can totally tie them together so that the models do it automatically. But from my experience, you **lose the overview** and can no longer understand it. We always built on positions and interpreted the results by hand and then said that we would continue to work with certain results and not with others." (GER_SCI#1) "[…] we talked about soft linking and so on. But I'm **not sure about linking at all**, because I think what is needed is a diversity of models that try to answer to some specific questions and at the end, it is often a choice that we face." (SWE_POL#1)
	Linking energy models with	PL	"Energy models should **work in combination with economic and other sectoral models**. Future energy policy must take maximum account of the interconnection between specific economic sectors and the climate and environment. An optimal solution for one sector does not have to be optimal for the whole economy or the environment and climate." (PL_SCI#4) (written replies)

	economic models		
	Energy models combined with climate and weather models	EU, PL	"I think that one of the important additional points **to add to the model is climate change**. So, most of the climate models so far, a little bit historical (…?) getting better grid of climate change (?). Not just a continuation of the history, a climate modelling type of environment could be very significant, keeping in mind that most of our energy transition is driven by wind and solar, so by climate." (EU_SCI#1) "Yes, of course, I mean, weather aspects, climate zones, on how many wind zones, do you think, are in the Northern Sea, five to ten, or one hundred, is correlation between wind very high and very low, this kind of **modelling of climate and environment**." (EU_IND#1) "[…] bringing this one [weather and climate impacts] in an open modelling environment in order to look at the potential impact on energy infrastructure – I find it more than relevant." (EU_IND#1) "[…] the connection to the climate in some more intelligent way. In the sense that historically they are climatologists, there are some economists/energy specialists and they don't get along so well. What they were able to do was make those models for Integrated Assessment that were used in the IPCC, but now everyone agrees that they are little... I mean, they're neither climate good nor energy tragic at all. So, as if this **connection with climate models**, with weather details and temperature forecasts and so on, there is practically nothing at all in energy modelling at the moment." (PL_SCI#1)

Table A 4
Model needs related to the modelling process; interview results.

Sub-category	Need focus	Country	Quotations from the interviewees
Modelling purpose	Define purpose (generally)	PL	"When designing energy models, it is necessary to **define the specific applications** for which they will be used in the future so that the models can respond to the questions raised to the fullest extent possible. It is very important in the construction of energy models to properly define the limitations of the parameters in the model so that the solution is both optimal and achievable." (PL_SCI#4) (written replies)
	System understanding	SWE	"[…] you agree on a common language, and then you try to **get the same picture** of the system. And then you moved an important part forwards." (SWE_SCI#4) "[…] what those energy system models teach us is **system understanding**." (SWE_SCI#1)
	Basis for decision-making	EU, SWE	"Policymakers need **clear basis for making the decisions**, in order to provide this objective basis for decision-making." (EU_IND#1) "And the analyses we do are often **consequence analyses**: what would it mean for the energy system in Sweden and the Nordic countries if suddenly part of bio energy is not anymore compliant with the climate policy goals." (SWE_SCI#4) "And again make sure what you produce is really **relevant to those people**." (SWE_POL#1) "[…] they should be used to ask questions to **highlight different strategies** rather than trying to come up with some kind of truth or very very detailed answer to different questions that are there." (SWE_POL#1)
	Exploration tool	EU	"But something catchy, easy to use, even if it's not 100% scientifically accurate. Because you cannot replicate it with a simple model, but at least you would allow people to **play with numbers** a little bit, so that they understand that the result is not something carved in stone, but you can have different results depending on the different options, parameters and assumptions that you have. And to me, that would help policymakers to understand the role of modelling, the importance of modelling and also the thing, they have to work on in order to be held accountable of the decision." (EU_POL#2)
Inter- and transdisciplinary modelling	Continued stakeholder involvement	EU, SWE	"Well, it's very clear – I think that **stakeholder involvement** from very early stages and openness and transparency about what is happening as well as openness to conflicting views. I think that everybody learns from different views, so there is neither "100% right" nor "100% wrong". For me is the key to have the engagement from the very **early stages** to allow for multiple modelling views in an open environment." (EU_ IND #1) "I think doing **workshops at different steps engaging different stakeholders** that would be helpful. […] And then towards the end, we also had workshops on how to interpret these results." (SWE_POL#1) "Today, we need to be very much **engaged in the modelling process**, with the modellers to ask questions, understand how these questions change assumptions and primaries in the model and work together to design scenarios." (SWE_POL#1)
	Engage different groups to increase objectivity	EU, GRE, SWE	"I think it's very important to engage as **many stakeholders** as possible. I don't know if you know about the TYNDP… I think it's a good example because it has been done for the first time this year by ENTSO-E and ENTSO-G and the **results were very surprising**, especially when you look at the gas supply, if I remember well, even in comparison to the Commission's scenario for the long term strategy…" (EU_IND#2) "Another point is that an effort to increase **model complexity should** be accompanied with cooperation with relevant institutions. For this, it is necessary to **engage institutions** (i.e. structures with continuity) and not only consultants/personalities." (GRE_IND#1) "[…] for us, **objectivity** is important. And I and my colleagues have the opinion that you can only reach that if you **work together with different groups**. It doesn't mean that we always agree. But you can talk about complex questions and consider them from different directions and with different perspectives." (SWE_SCI#4) "It's always good to have **a kind of jury, which comes from a different world** – which doesn't come from the energy area, and which may have no modelling understanding. I think that is very important." (SWE_SCI#4)
	Make time for consultations	EU	"Also, this process before the European Commission's proposal, it must be a long one, so that we have **time to consult the stakeholders** about the assumptions, the Member States about what is happening in their countries, and for example, so far we have not had such a situation that the percentage is already completed, and some country would say: "this is rubbish, it doesn't fit my country at all, and our national projections are not at all consistent with this." (EU_ POL#3)
	Work with social scientists	GER	"I just noticed that as a technician, who we are still trained to do, of course, you are first entering a lot of new territory. You definitely have to work together with **multidisciplinary and include social scientists**." (GER_SCI#1)

Open modelling among the modelling community	**Information exchange and collective learning**	**EU**	**"My point of view, anyway, one of important thing is the open modelling environment that would allow learning from each other, rather than one closed, black box, knowing everything and just doing everything in the best way." (EU_IND#1)** **"And** the **peer-to-peer type of learning in the modelling community." (EU_IND#2)**
	Modeling network/platform	EU	"Just to be clear – we are not talking about one huge system, with a couple of modellers around explaining what it is, but I think a network of systems and modellers working open and transparent, exchanging information – this is what we should go for." (EU_IND#1)
Pace of modelling	Adapt speed to policymaking	GER, SWE	"[...] Interplay between the quickest possible and direct results that one wanted because suddenly the current pressure to act was great [...]" (GER_SCI#1) "Now things have to go faster, we need to move faster: policymaking has to be faster, so models also have to follow it." (SWE_POL#1)
	Pragmatic approach	GER	"[…] and that was always a situation that the pragmatic model builders handled well. Anyone who started with models too theoretically at the beginning has not gained a foothold. But if you have pragmatically pushed your way from the simple model based on the situation and systematically developed it, then you could stay in the discussion and have not lost contact with experts."(GER_SCI#1)
	Integrate different methods	GRE, PL	"So all those methods where, for example, [anonymised person] knows very well how well you know. These foresights, or **other types of research methods**, like experts, or like society, like non-experts, how they imagine energy and so on. These are very useful tools, and if they are to be implemented in modeling, then it's cool that a couple of teams do it." (PL_SCI#1) "**Multi-criteria tools** as well as **financial appraisal tools** are most often required for the development of financial support policies." (GRE_POL#1)

Table A 5
Model needs related to the outreach of models and results, interview results.

Sub-category	Need focus	Country	Quotes
Communi-cation	Provide details about the model: assumptions, uncertainties (generally)	PL, SWE	"It seems to me that **information about who makes the model, for what purposes and what are the assumptions**. What it refers to, what it uses, why it is different in some aspects from what." (PL_NGO#3) "And they did not take into account this resource constrain in the latitude of the model, which mapped the free space, put in as much as it takes, which is unrealistic. The results were very much communicated, because they showed the operation of this photovoltaic, production and so on, that it will generate so many jobs that the Lubelskie or Śląskie Voivodeship will be basically 'whole' during the transformation and everything will be tip-top, it will come together. It will not because they used **very unrealistic assumptions**. It is known that this is their contribution to the discussion, but this is still a very underdeveloped element, especially in Poland." (PL_SCI#1) "It is **not always clear in models, what they can, what they cannot say, what they are based on**, roles they are using, everything that makes model comparable and not comparable when we should use them and when not." (SWE_POL#3) "I think the Swedish Energy Agency is doing a pretty good work, **explaining** in a 100 pages report how the agency model is working and what the assumptions are." (SWE_POL#3) "[…] and being really clear about the **uncertainties**." (SWE_POL#1)
	Explain model functionality	PL, SWE	"[…] people are *using* these models are becoming **better at explaining** what they actually do and so." (SWE_POL#1) "you need to educate people working of model, doing the analysis or people like me: **what can the models do** and not trying to convince people that you can do everything because they can't." (SWE_POL#1)
Communi-cation	Model´s abilities and limitations	PL, SWE	"In my opinion, the use of energy models and their results is determined by the **knowledge of both the limitations and possibilities** of given tools by the administration/recipients. Many times we are confronted with unrealistic expectations about the details of long-term models. The possibility to determine, for example, weather conditions - and thus the momentary generation from RES - in the long run, is burdened with a big mistake and at the same time significantly increases the size of the model without improving the quality of results. It is important to make consumers aware that the optimal solution from the point of view of short-term models is not the same as the optimal solution from the point of view of long-term models for developing national strategies." (PL_SCI #4)

			"We have to **admit** that there is a **weakness with some output data**, for example in the field of RES. And I would like to point out one more thing, that in our country when it comes to RES development, it is completely thrown to the market at the moment. Of course, with a few supporting instruments, disrupting this market, right?" (PL_SCI#3) "[…] there is still a limit, what the models can do and should do." (SWE_POL#1) "It is not always clear in models, **what they can, what they cannot say, what they are based on,** roles they are using, everything that makes model comparable and not comparable when we should use them and when not." (SWE_POL#3) "So to questions the analysis and to do **sensitivity analysis** is one of the main results the model can do." (SWE_POL#3) "So, we should have a good understanding what is technical and what is **stand-point** of those models." (SWE_POL#3)
	Understandable documentation	GER, PL, SWE	"But not in all cases, one can **understand why exactly the result XY came about**. You may have to rework the documentation or the presentation. Studies often have a chapter on model descriptions. There are a lot of things in there and a lot of flow charts. But I never know if anyone will ever read it very carefully and discover that something may be wrong." (GER_SCI#1) "[…] that is, opening up to the maximum, sharing all the data that are behind these results, formulas, **generally good documentation of results**. Well, this is one of the ways that stimulates comments from decision-makers, but also from other researchers and other institutions. So it's like building trust in these results." (PL_SCI#1)
	Appealing visualization	SWE	"[…] they have a very **nice visualisation tool** they use to visualise different scenarios going forward." (SWE_POL#1) "In a **simple and in a visually appealing way**, illustrate possible futures you know and the effect of policies on those futures." (SWE_POL#1)
	Training materials	SWE	"[…] to work with simple but **informative education packages** for policymakers how modelling works." (SWE_POL#1)
	FAQ	EU	"Well, I think that you can easily start with **FAQ** to provide that people will always get answered the same question, of course." (EU_IND#2)
	Simple wording / "translation" of modelling language	EU, PL	"[…] secondly, that it is explained in **very easy and understandable** way, even though it's a very complex issue." (EU_SCI#1) "Now I think so because what we do is that we invite journalists more and more often, that we **translate and show how something is done**, we prepare shortcuts from it. Even if this modelling is done well, you have to get to someone with it later. And it's not that this is missing from what you asked about, absolutely not, but here I see a big chasm between somewhere closed to me modeller who does great things and speaks a difficult language, but does it well, to go to see someone: "Okay, that produces the result I need for something." That's quite a challenge." (PL_NGO#3) "Just like [anonymised person] and I are recipients of the results, we are somehow involved in the work, while we do not work as people in such current work, we do not work on models, so we can talk about model assumptions in general, but the difficulty is to speak in a very **expert way** about specific forecasting platforms. And this may cause some kind of **barrier** in reception." (PL_POL#1)
	Model advertisement	EU	"So, maybe it's a mixture between modelling quality and publication and **advertisement**." (EU_SCI#1)
	Raise awareness for model benefits	GER, PL	"[…] I think it is essential that the results of science, especially those of energy modelling, are **taken really seriously** and that politicians try to make more progress in their implementation." (GER_SCI#1) "However, it is more necessary to build in Poland the **awareness** that it is necessary, necessary, and that it serves something." (PL_NGO#1)
Engagement and exchange between modellers and users	Discuss models and results	PL, SWE	"[…] plus openness to talks, discussions, showing assumptions, showing the model itself, what its structure is, how it is built, whether it is economic optimisation or some other kind of optimisation. It seems to me that **openness, transparency of discussions** is what can **guarantee greater credibility** of analyses." (PL_POL#1) "That you don't distribute model results, but that you **discuss them**. Because you also know, in a model you have to exclude things, what you are not able to include, but what is still important. So, then you discuss afterwards and you agree on what this should mean. What do the results mean? And what does it imply for things that are not included in the model." (SWE_SCI#4)
	Ability to use and explore models	EU, GER, PL	"And then maybe there should be a different layers' complexity so that you can enter the code, but you don't have to. And you can **change everything** that you want to, but if you don't change anything, then it still runs. And then you get a nice graphic representation." (EU_SCI#1) "That would be very interesting, especially if you can **play around with it**, you can change the variables slightly, and then you can save it and send it to your colleagues." (EU_NGO#2) "For me, it should be a very, very, very simplified tool because you cannot put, you cannot replicate the whole model online, but a very simple tool, **where you can choose**, I don't know, a reasonable number of parameters, like 10 different parameters. Very simplified, like growth rate, the price, carbon price, technology costs, capacity factor and social acceptance – let's say it is, or maybe few others. Like a very limited number of parameters, which you can as a policymaker yourself pretty with and that would give you a different outcome." (EU_POL#2)

			"But something catchy, easy to use, even if it's not 100% scientifically accurate. Because you cannot replicate it with a simple model, but at least you would allow people to **play with numbers** a little bit, so that they understand that the result is not something carved in stone, but you can have different results depending on the different options, parameters and assumptions that you have. And to me, that would help policymakers to understand the role of modelling, the importance of modelling and also the thing, they have to work on in order to be held accountable of the decision." (EU_POL#2) "[...] but maybe just a gimmick. I thought if you could **'play' with simple parameters** - in quotation marks - yourself, build your own energy system, then it could be that some people sit down and find out, aha, if I do this and that, then maybe I can save more CO2 or something else. But how many people would really do that and how many then abuse the system by simply writing in a lot of nuclear power [...], that's not what I would want to build it for (laughs). So, I don't know if that really helps." (GER_POL#2) "The first thing is that a person who simply knows about these energy topics at the level of observing what is happening on the electricity market and politically, let's say a person like me, to **be able to use such a model**, in the sense that he or she generally knows somehow how the energy model works, how the energy market works in general, but he or she doesn't know about modelling that he or she can just **click there himself or herself**, that would be the first thing." (PL_NGO#1) "This is, I don't think it's important, because I don't think anyone really understands how the models from A to Z work, I mean, it's necessarily very complex, so we can't track them intuitively, we just look at the selected pieces, then we integrate them, but the **new user, necessarily, is able to verify how the model works only by experimenting**, that is adjusting the inputs." (PL_SCI#2)
	User-friendly interface	EU	"[…] it's an **easy user interface** for things that standard assumptions and everything bit, that you can use just by **clicking and getting results**." (EU_SCI#1)
	Allow for personal contact between modellers and decision-makers	EU, PL	"Maybe first the email to understand better what is the question of the person and then the answer could vary from **email**, if it's enough or maybe directly a short **phone call** if it needs to go into more details. That is something that I could imagine." (EU_IND#2) "In my opinion, **personal contact with recipients** of forecasts is important. What we are trying to achieve with the help of the Steering Committee is to identify the real, present and future needs of the administration, adjust the directions of development of analytical models to them, make the awareness of what solution from the point of view of a particular analytical problem should be applied in a given situation and facilitate understanding and interpretation of the results obtained. The latter is crucial, given that the model tools we use are very complex and generate a very large number of results covering different aspects of the energy sector. The **interpretation of the results** is not always easy and unambiguous - especially when comparing very different scenarios of the sector development." (PL_SCI#4) "I mean, I think that if you could just have a **person in such a project who would let us sit down with me**, that's the example... we want to model this 100% RES in Poland, so we're already sitting down, dating somehow remotely, or meeting and being able to click something like that, that would be great. And if you have dedicated resources in the project to do something like that, that even if it would be too much for me, that even with your guide, with such professional programming and modelling, we would be able to do it. That's okay too, right? You just date a session there for a couple of hours or we meet, you come back to me next week, yeah, and you show me, we still have some challenges there, we discuss them and then you come back after some time. Then you can increase the entry barrier as well, it can somehow be easier than making a mega friendly interface that will make a lot of things go down and just leave it on your shoulders, but just **giving a service**, a service that would let just, I would say, **'make your dreams come true'** for people who would like to have this model." (PL_NGO #1)
Engagement and exchange between modellers and users	Create trust	GER, PL	"It is not a question of the credibility of the models themselves, but the belief that one can believe some fact-based opinions. Anyway, in Poland, there is a **problem with listening to experts and think-tanks** and so on. This is nothing new and I guess the same trap is just being trapped by models. But it has to be built, it has to be systematically built and shown, defended by data and so on." (PL_NGO#3) "You can then see how the study develops around your own question. Then I can take a closer look at it. You can compare and then perhaps have **more confidence in the study you commissioned than in what anyone else has done**." (GER_POL#2)
Usability of results	Reliable results	GER	"[…] The question was asked whether the **results are reliable and useful**. (GER_SCI#1) "So especially the ministry employees, they need reasonable statements. And I think the system is too complex for me to trust the ministry employees or even myself to come up with really **reliable arguments** with easy-to-use models. I think it would be better if the scientists were asked." (GER_POL#2)
	Contextualized results	EU	"And when you have the social aspect, which you cannot really appropriately model, you should put model results into a **context of social acceptability**, the things that are on the ground. I really, really would like to emphasise this. You shouldn't look into the numbers, if you are not on the ground, but in your University building." (EU_NGO#1)
	Action corridors	GER	"It's no longer about big things, but about working in an implementation-oriented manner. And also if one makes studies to show how one can implement this, **which mechanisms of implementation [are needed]**. That is actually more of a task for social scientists." (GER_SCI#1) "And for me, it's about putting the stress on the **big choices** that the society should take, and not so much saying it's this much Euros and stuff. It's about messages and choices. Big messages and big choices." (SWE_POL#3) "How can you show what is the **likely outcome in the scenario** but then we could also end up here and what would happen then." (SWE_POL#1)
Model availability	Ensure diversity	SWE	"Sweden has a lack of **diversity in the models** that are present at the moment." (SWE_POL#3)

	Make models open-source	EU, GRE, PL	"I mean, if the model would be **open-source**, it just let's say, look, we will put carbon footprint prices in and what would that mean? I'm kind of interested in that kind of quick output on things like that." (EU_NGO#2) "**Open access** to such models as well as their databases and their high-resolution results are often not available to policy-decision makers in Greece. This has caused policymakers to become less familiar with the processes and requirements for using such models." (GRE_POL#1) "In general, a very **big problem** with this is that a lot of models are **non-public**. There have not even been published results, or anyone bragged about their results, or about the fact that they have done some modelling for the Ministry or another institution. This doesn't mean that modelling wasn't done, but it wasn't strictly policy, but, let's just say, someone was optimising the use of low voltage lines, which is also absolutely important." (PL_SCI#1)
Model platform	Provide an intuitive and user-friendly interface	PL	"And this **interface**, it has to be **friendly**, I mean it has to be **intuitive**, it can't be a model in Excel or in some documents that nobody understands in a few minutes. then it'll work." (PL_NGO#3) "This is the main challenge, I think because it is supposed to be user-friendly, not to lose the professionalism of the model." (PL_NGO#1)
	One model language	EU	"And if probably you include several models, it would be much easier, if you have the **same language for all models**." (EU_SCI#1)
	Providing different formats between different users	EU	"I think that the trick when it comes to models and data in general, we need to make sure that they are easily understandable to people, who are not familiar to the topic or also not familiar with data or modelling. But also, they deliver enough information for people, who are really looking for this data. So, I think it is important to **distinguish**, also maybe in case of interfaces on the website **between readers** that would go there only to learn about key messages and results and someone, who is looking for more granularity and data." (EU_IND#2)
Model platform	Different levels/ layers of complexity depending on the user category and his technical capabilities	PL	"In a perfect world it would be possible to do it in such a way that somewhere in the world you have this **mega model**, mega-precision, hidden somewhere in the back, and as a layman, literally, I'm not saying that I'll do it in a minute, but let's say one afternoon or another time, I'm able to do what we'd like with a team of two people and he [this model] will show us some kind of super modelling, comparable to what people there simply commission and three months or six months are waiting for what this model will do. This is, of course, an ideal world, the question of whether this is at all achievable and whether the final product for such a layman will be of sufficient quality so that these results will mean something at all and the ministry will actually say: "Well, well, well, well, that's really good modelling, and here we'd have to **go deeper** into what you've shown". That would be very important to me." (PL_NGO#1) "Maybe one by one: The possibility of **modifying these assumptions** and doing the sensitivity analysis yourself. They have to be quite simple models, if they are to show some dependencies, it's more like the **second stage**, that is, they have to be such that everyone can go in and check it, and if someone wants more, they can click and see somewhere: "Okay. It works like this and yes, it matters to me, and that's because of it"." (PL_NGO#3)
	Transparency on model updates, timelines and publications	PL	"We know that not every model ends up with, for example, a large presentation or a large report, but it would be nice if someone from those modellers on the **Sentinel platform** would add an **update**, what we did with the **next version**, where it is visible whether the view is public or private, whether the view is made for whom it is made, whether someone made a publication based on it. There is a **track record, a timeline**." (PL_SCI#1)
	Communicate unique selling-points	PL	"Since **several such platforms have already been created**, you are probably aware of that, it would be nice to **do things that are not in these other platforms**, even if they are very simple." (PL_SCI#1)
	Explain model differences /compare models	PL	"Maybe what would be also useful in this online tool, is to **explain different types of models** and to give a very concrete example, like POTEnCIA, PRIMES, Cambridge analytics or energy economics and so on, and explain, like very clearly, in few sentences, but also in few numbers, how they work, are they, like, based on… which type of predictions they use and which type of practical reasoning they use. That would be also very useful. And also, you could compare different models and see, for example, by using PRIMES on the one hand, and Cambridge analytics, on the other hand, I put exactly the same parameters, but still, the result was a bit different. And why?" (EU_POL#2) "I would be very interested in knowing how other countries organise themselves and how we can **compare models** with each other, so that what they can do and so." (SWE_POL#3)

	Ensure sustainability	PL	"And if there are any platforms or Horizontal tools at all, the big problem is to keep them. In the sense that they are created, everyone starts picking something up, then the project ends, and you can see that these platforms are a little underdeveloped... Just in the sense that they are not maintained, not everything works, is not described and so on, the documentation, all that. For example, I would aim at a **simpler platform**, but easy to manage and well described and **which will actually work when the project ends**." (PL_SCI#1)

Table A 6

How important are the following aspects for the energy transition?; optional; N=68 (modellers and users).

Goal	Answer option	Modellers	Users	Policymakers	Energy industry	Non-governmental organisation (NGO)	Research, Innovation & Consultancy
Resilience & security of supply	not important at all	0%	0%	0%	0%	0%	0%
	not very important	0%	0%	0%	0%	0%	0%
	somewhat important	9%	14%	17%	8%	14%	9%
	very important	82%	86%	50%	92%	86%	89%
	don´t know	3%	0%	0%	0%	0%	3%
	No answer	6%	0%	33%	0%	0%	0%
Low-hazard technologies	not important at all	0%	0%	0%	8%	0%	3%
	not very important	3%	7%	17%	8%	0%	6%
	somewhat important	56%	43%	17%	31%	57%	60%
	very important	21%	36%	33%	38%	43%	17%
	don´t know	12%	7%	0%	0%	0%	11%
	No answer	9%	7%	33%	15%	0%	3%
Nature protection	not important at all	3%	0%	0%	15%	0%	0%
	not very important	0%	0%	0%	8%	0%	9%
	somewhat important	21%	43%	17%	31%	43%	26%
	very important	68%	57%	67%	38%	57%	63%
	don´t know	3%	0%	0%	0%	0%	3%
	No answer	6%	0%	17%	8%	0%	0%
Human health	not important at all	3%	0%	0%	8%	0%	0%
	not very important	6%	0%	0%	15%	14%	14%
	somewhat important	29%	43%	33%	31%	43%	26%
	very important	53%	57%	50%	46%	43%	54%
	don´t know	6%	0%	0%	0%	0%	6%
	No answer	3%	0%	17%	0%	0%	0%
Energy efficiency	not important at all	0%	0%	0%	0%	0%	0%
	not very important	6%	14%	0%	15%	0%	14%
	somewhat important	18%	36%	33%	15%	14%	29%
	very important	65%	50%	33%	62%	86%	54%
	don´t know	3%	0%	0%	0%	0%	3%
	No answer	9%	0%	33%	8%	0%	0%
Climate-neutrality	not important at all	0%	0%	0%	0%	0%	0%
	not very important	0%	7%	0%	0%	0%	3%
	somewhat important	12%	7%	0%	38%	0%	11%
	very important	79%	86%	67%	62%	100%	83%
	don´t know	3%	0%	0%	0%	0%	3%
	No answer	6%	0%	33%	0%	0%	0%
Social acceptability	not important at all	0%	0%	0%	0%	0%	0%
	not very important	6%	14%	33%	23%	0%	6%
	somewhat important	41%	36%	17%	23%	57%	37%
	very important	44%	50%	33%	46%	43%	54%
	don´t know	3%	0%	0%	0%	0%	3%
	No answer	6%	0%	17%	8%	0%	0%

Affordability	not important at all	0%	0%	0%	0%	0%	0%
	not very important	6%	7%	0%	15%	0%	11%
	somewhat important	35%	57%	33%	23%	57%	43%
	very important	50%	36%	33%	62%	43%	43%
	don´t know	3%	0%	0%	0%	0%	3%
	No answer	6%	0%	33%	0%	0%	0%
Cost-efficiency	not important at all	0%	0%	0%	0%	0%	3%
	not very important	6%	21%	0%	0%	0%	11%
	somewhat important	41%	36%	33%	31%	43%	51%
	very important	41%	43%	33%	62%	57%	31%
	don´t know	3%	0%	0%	0%	0%	3%
	No answer	9%	0%	33%	8%	0%	0%
Free energy trade between countries	not important at all	12%	0%	0%	0%	29%	6%
	not very important	12%	36%	17%	23%	0%	23%
	somewhat important	41%	43%	0%	15%	29%	54%
	very important	24%	14%	33%	54%	43%	14%
	don´t know	3%	7%	17%	0%	0%	3%
	No answer	9%	0%	33%	8%	0%	0%

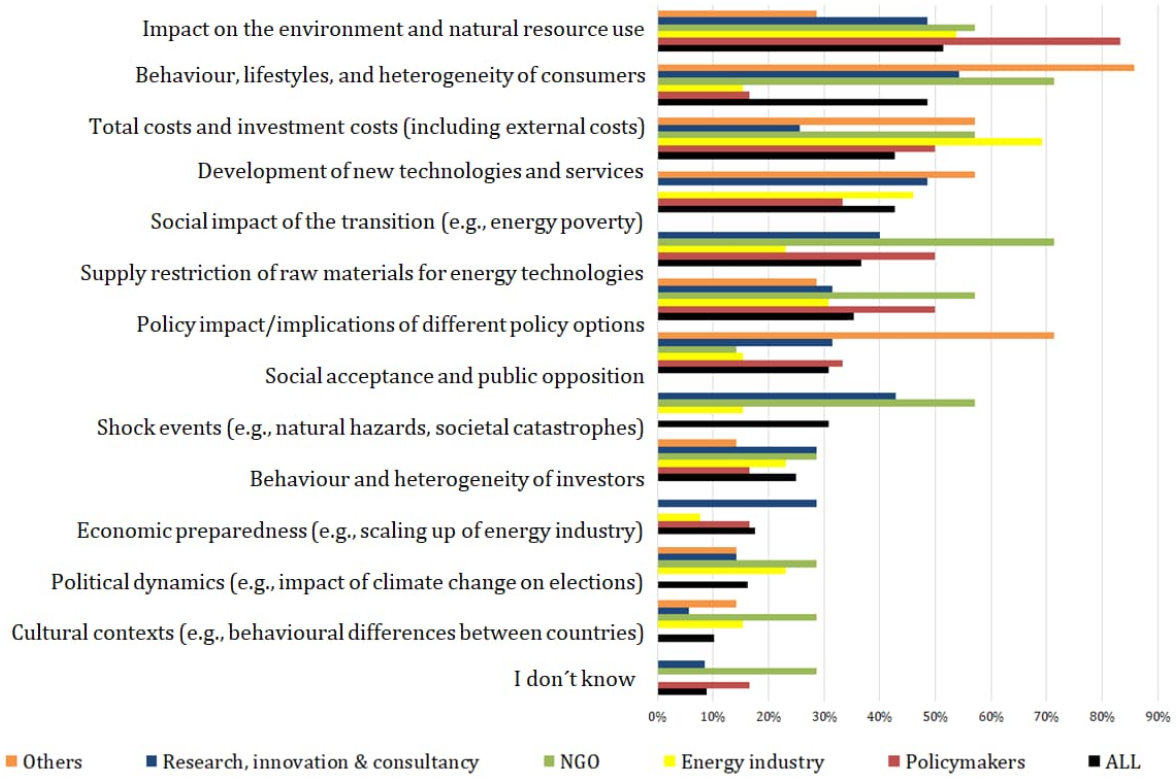

Figure A1: Factors that should receive more attention in energy models: *Which of the following factors do you think should receive more attention in energy models?;* mandatory, multiple choices, between 1 and 5 answers; N=68; figure sorted by sample. Note: across different stakeholder groups, we find modellers and users.

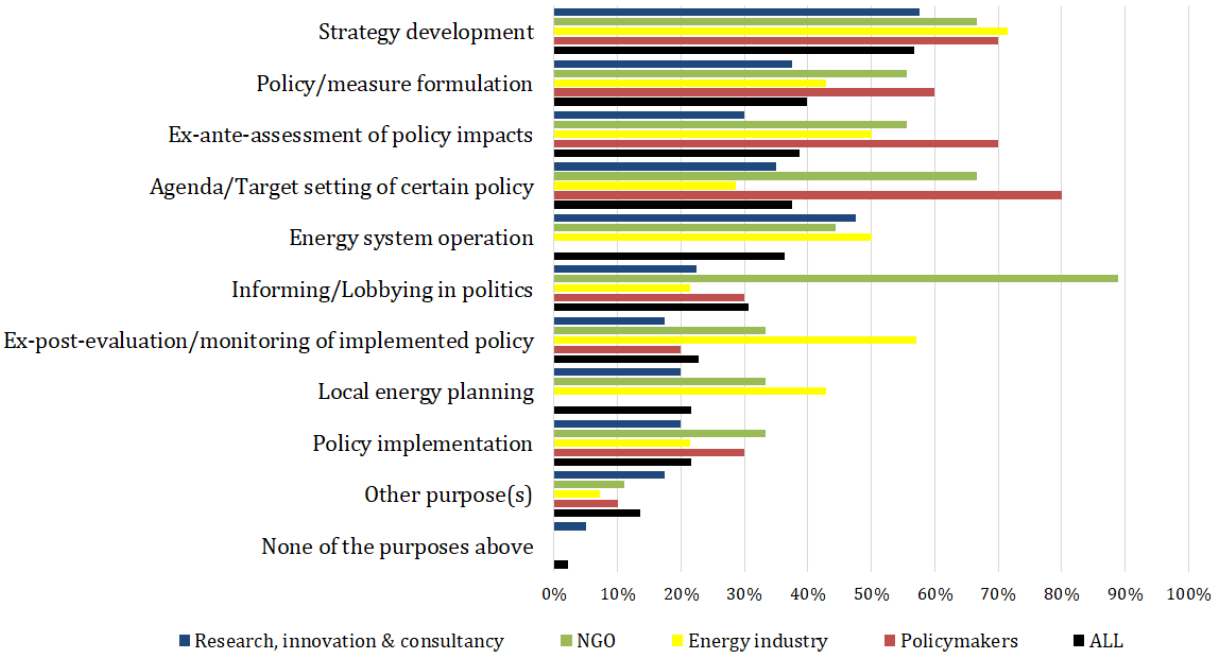

Figure A2: Purpose of model use: *For what purpose are you using models in your work?;* optional, multiple choice; N=88. Note: across different stakeholder groups, we find modellers and users.

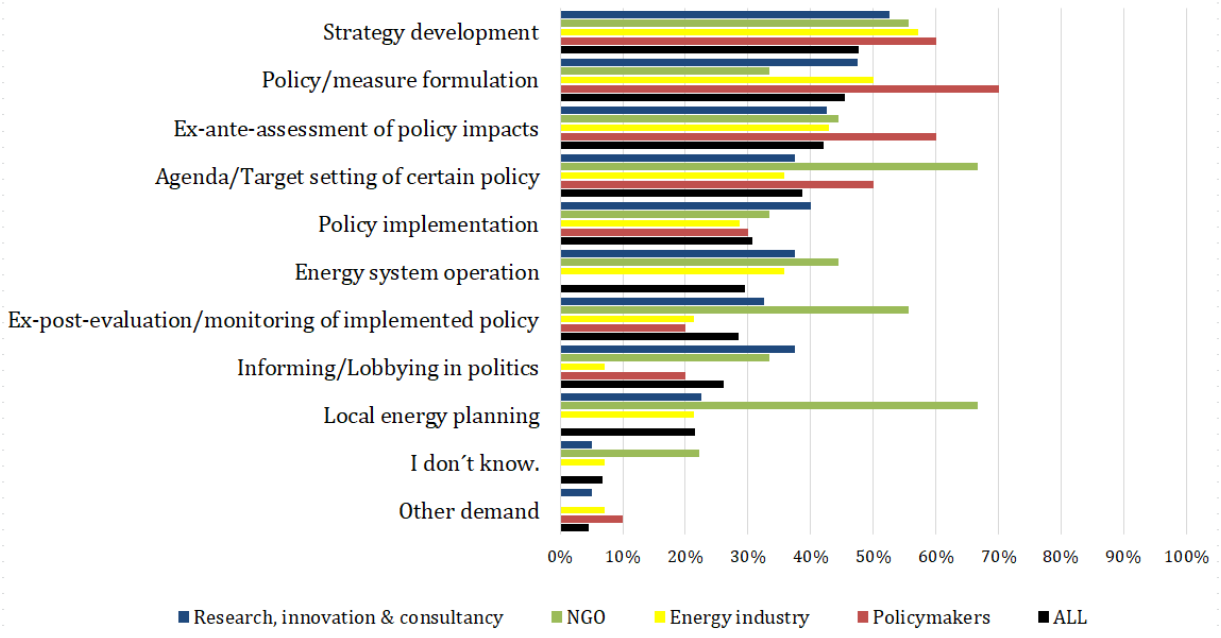

Figure A3: Need for model improvements: *Where do you see the demand for additional or improved models helping you in your work?* (multiple choice, optional); N=88. Note: across different stakeholder groups, we find modellers and users.

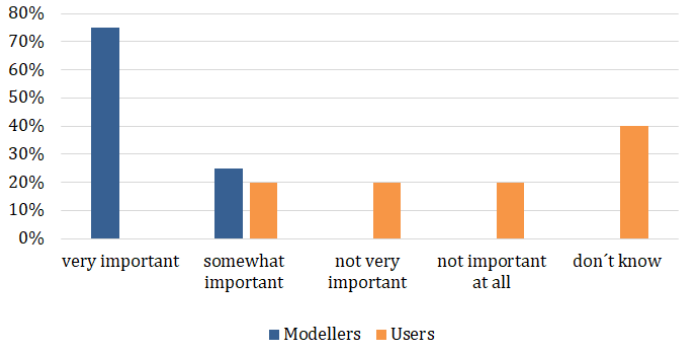

Figure A4: Importance of involvement in the modelling process: *How important is your involvement in conceptually developing or improving models for you?*; optional; Modellers N=12, Users N=5.

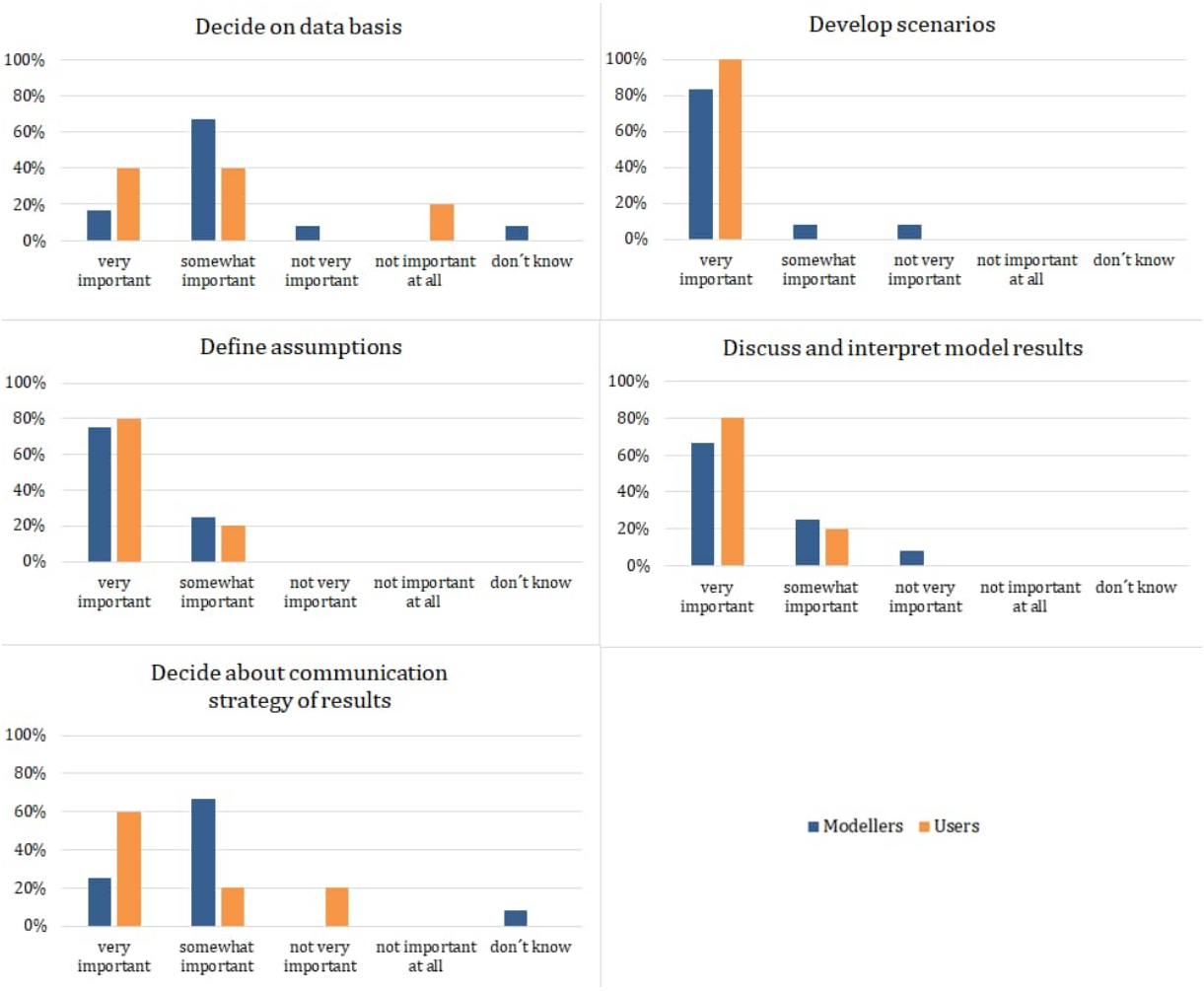

Figure A5: Importance of topic-specific exchange: *In the process of the model development or improvement, how important is the exchange about the following aspects between model developer and external stakeholders for you*?; optional; Modellers N=12, Users N=5.

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