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BUILDING A LOW-CARBON, CLIMATE RESILIENT FUTURE: SECURE, CLEAN AND EFFICIENT ENERGY

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EU-RES	Classified Information: RESTREINT UE (Commission Decision 2005/444/EC)	
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EU-SEC	Classified Information: SECRET UE (Commission Decision 2005/444/EC)	

User needs for an energy system modeling platform for the European energy transition

November 2020

SENTINEL

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

Acronyms

Calliope	A multi-scale energy systems modeling framework
CORDIS	Community Research and Development Information Service
EnergyPLAN	Advanced energy system analysis computer model
ENVIRO	Environmental and Bio-economic Impacts and Constraints model
GEM-E3	General Equilibrium Model for Economy, Energy system and the Environment (energy model)
GER	Germany
GHG	Greenhouse gas emissions
GIS	Geographical information system
GRE	Greece
GUI	Graphical User Interface
HDF5	Hierarchical Data Format
HOMER	Hybrid Optimization of Multiple Energy Resources (energy model)
IDE	Integrated development environment
IND	Energy industry
IPCC	Intergovernmental Panel on Climate Change
LEAP	Long-range Energy Alternatives Planning system (energy model)
METIS	Modeling the European Energy System (energy model)
MIRO	Online visual collaboration platform for teamwork
MoSCoW	MoSCoW-prioritization method (with the categories Must have, Should have, Could have and Won´t have)
NetCDF	Network Common Data Form
NGO	Non-governmental organization
OECD	Organization for Economic Co-operation and Development
openENTRANCE	open ENergy TRansition ANalyses for a low-Carbon Economy (Horizon2020 project)
PL	Poland
POL	Policymaker
PRIMES	Price-Induced Market Equilibrium System (energy model)
P2X	Power-to-X (other energy type/storage)
PyPSA	Energy model
QGIS	open geographical information system software
QTDIAN	Energy model for technology diffusion
SCI	Scientific community
SENTINEL	The Sustainable Energy Transition Laboratory (Horizon2020 project)
SPINE	Open-source software tools for energy system modeling (Horizon2020 project)
STET	Socio-technical energy transition
SWE	Sweden
TIMES	The Integrated MARKAL-EFOM System (energy model)
USP	Unique Selling Point
WEGDYN	Wegener Dynamics Computable General Equilibrium (CGE) Model

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Executive Summary

Energy models support decision- and policymakers who have to decide on decarbonization strategies and energy policy options. However, energy models are often not geared to the needs of the users. Hence, despite increasing methodological sophistication and rapidly growing detail, the usefulness of models as advice and policy support tools may be limited because they do not take into account all user issues.

In this report, we **identify the needs of the energy model users and the users of energy model results** in policy, industry, civil society, and science, both in the present and future. Based on a comprehensive literature review, qualitative interviews in five European jurisdictions, a survey, and a workshop, we identify what different user groups need from energy models: *What types of questions, input, and results are useful to them?* We also identify user needs regarding the modeling platform of SENTINEL: *How do we need to define such a platform to make it worthwhile for potential users?*

Although decision-makers use energy models as support tools, existing models do not always provide the necessary information. We find several unmet user needs regarding **(i) model content, (ii) model design and data, (iii) modeling process,** and **(iv) model outreach**.

We find that decision- and policymakers need models that inform them and help them to make decisions, for example on targets and various measures. To do this, models must capture the most important variables for each type of user, and they must be able to identify trade-offs between options of decision-making.

It is therefore necessary to further improve the models by including all energy-related sectors, which is essential to support national energy planning and to assess the social and environmental impacts of different energy options in a holistic way. To date, most models lack social factors and human behavior. However, such factors are key drivers (e.g., desire for ownership) and key barriers (e.g., project opposition) to the decarbonization of the energy system.

Similarly, environmental impacts beyond climate are rarely included in models, but are increasingly important as renewables grow and become a mainstay of the energy system. In contrast to conventional energy, the effects of renewables are often more limited in time and space. Hence, models must have a high spatial and temporal resolution and should have flexible resolution scales so that model users can adapt the analysis to the appropriate scale for each problem analyzed.

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Moreover, existing models are often closed and non-transparent. In many cases, it is not only difficult but impossible to fully understand what a model does. Hence, open code and open data as well as transparency of the entire modeling process are crucial to increase the legitimacy of models as policy advice tools. The involvement of stakeholders in the modeling process would help improve the context-specificity and legitimacy of the analysis and to improve the societal understanding for modeling approaches, the derivation of model results, and the meaning of model results. Thus, modelers need to communicate model purposes proactively to ensure that their users apply the most appropriate models in specific contexts and to guarantee that the best policy implications are drawn.

Finally, the high interest in the SENTINEL modeling platform among all user groups implies that developers should meet several needs: The platform must contain information for modelers, such as model and data catalogs, and details for non-modelers, including ways to interact with the models and what the results of each model mean (and what they do not mean).

We conclude that model users and users of model results have specific and defined requirements for energy models and play an essential supporting role in the European energy transition. The improvement of participation and transparency as well as the adaptation of models to the needs of users are critical aspects for models to increase their usefulness as advice instruments. Modelers and platform developers can benefit from following the **ten critical implications and recommendations** of this report (see next page).

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TEN KEY RECOMMENDATIONS TO IMPROVE YOUR MODEL

1

Strive for a holistic and systemic perspective

Modelers should consider all goals, dimensions, sectors, and technologies of the energy system, its transition, and the interlinkages between elements.

Integrate environmental sustainability beyond GHGs

2

Think beyond the reduction of greenhouse gas emissions in your model. Environmental sustainability is more than climate change. And climate change goes beyond CO_2.

3

Put social factors and human behavior at the center

Systems do not change, but *humans* change systems – by altering lifestyles, investment decisions, and political action. Shift your focus to socio-technical change!

Design models to support policy decisions

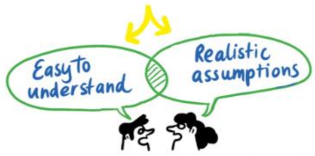
4

Policymakers need models that support decisions about policy options and can assess policy impacts, including trade-offs between options.

5

Specify your target group to deal with design trade-offs

User groups have different preferences. Listen closely to your target group's needs to make the best choices. There's no one-size-fits-all.



Manage and communicate uncertainties proactively

6

Be open about limitations and uncertainties. Stay one step ahead of criticism with uncertainty analysis of scenarios and input, but also about what your model does and does not do.

7

Use the power of transparency to build trust

"Transparency, transparency, transparency." Trust in models cannot be built without it. And most stakeholders favor transparency over intellectual property.

Involve stakeholders as often as possible

8

Leave your 'ivory tower' to interact with and learn about your target groups. It´s easy: Many stakeholders *want* to be involved in the model development, improvement, and application.

9

Communicate your results thinking about your audience

In the information age, attention is a rare resource. What does the user – the target audience – of your model need to know, and how can you communicate that answer?

Tailor your model platform for your user groups

10

Next to using common standards, focus on 'Unique Selling Points' like an easy-to-use, front-end oriented modular platform design to grow the users´ network.

1 Introduction

Energy models are important support tools for decision- and policymakers who have to decide on decarbonization strategies and energy policy options. However, energy models are often not geared to the needs of the users they are meant to advise. Models that are tailored to users and their needs are more appropriate for the purpose and more likely to be used (e.g., Gilbert *et al.*, 2018; McIntosh *et al.*, 2007; Van Daalen *et al.*, 2002). Thus, an iterative approach with reconcilement between model developers and model users is essential, as *"[…] it can result in a better correspondence between model analyses and user needs, making the results more relevant to potential users"* (Stalpers *et al.*, 2009:966).

In this report, we identify current and future user needs that energy models should address. We define user needs as all the demands, requirements, and standards mentioned by potential users of an energy model or users of energy modeling results. We involve two different types of stakeholders: model users and users of the model results, coming from research, policymaking, the energy industry, and civil society. Our primary research question is: **What are specific demands of certain stakeholders for future energy models?** In particular, we **(i)** identify differences between different user groups, **(ii)** identify and prioritize the user needs for aspects that have so far been largely neglected within energy models, and **(iii)** identify and prioritize specific needs regarding modeling platforms. The prioritization is necessary to support modelers in defining the demands on which they have to focus when improving their models. As the term 'user needs' emphasizes the importance of the individual stakeholders, we will continue to use this term in the following.

We investigate the needs for energy models in general, but with a special focus on the SENTINEL models. We are also placing a special emphasis on the original SENTINEL products, which have to be developed from scratch. These innovative elements are the open-source model platform and two new models that address the social drivers and constraints of innovation diffusion (QTDIAN) and the environmental impacts of the scaling up of particular energy technologies and systems (ENVIRO). We apply a multi-method approach based on a literature review, interviews, an online survey, and an online workshop. This multi-faceted approach allows us to gain rich qualitative and quantitative insights into the user needs of energy models. The critical user needs presented in this deliverable are relevant for informing the development and improvement of the SENTINEL models and for models that want to better respond to the problems and questions of their users. Finally, we discuss user needs' implications to maximize model impact for supporting a low-carbon, climate-resilient, and just future – assisted by secure, clean, efficient, affordable, and socially accepted energy.

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2 Multi-method approach

To theoretically and empirically study and reveal the user needs of different stakeholder groups for energy models for the European energy transition, we applied a multi-method approach (Creswell and Creswell, 2018). The multi-faceted approach was based on a systematic literature review, qualitative interviews in five different European contexts, an online survey, and a stakeholder workshop. We combined various methods to get an comprehensive overview of user needs, and to arrive at a robust 'checklist' to improve models. **Figure 1** shows the methodological procedure in more detail.

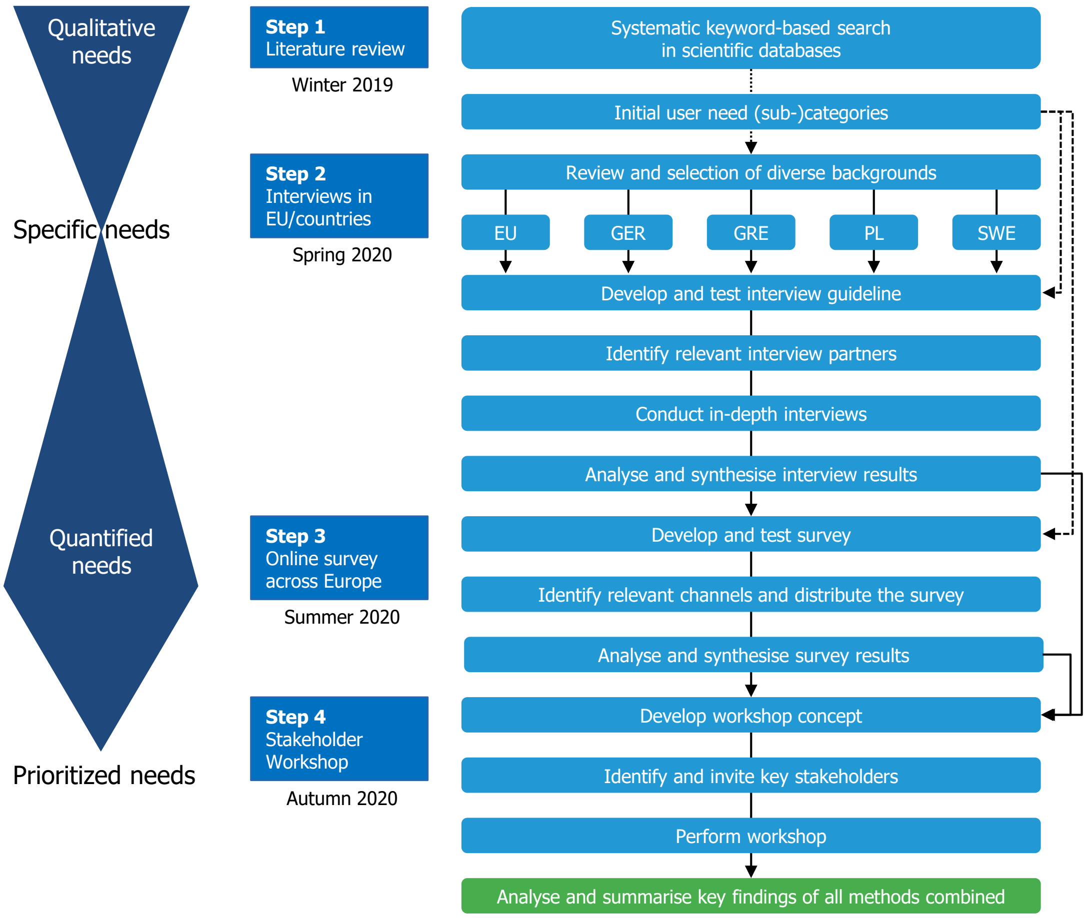

Figure 1: *Methodological approach to identify user needs*

2.1 Literature review

We reviewed relevant literature to gain a comprehensive and systematic overview of general requirements and user need categories. These categories and sub-categories informed the further steps in the multi-method approach. They helped structure the guidelines of the interviews, the questionnaire of the online survey, and the stakeholder workshop program. Moreover, the literature review served us as a basis for discussing and comparing our findings in the interviews, the survey, and the workshop.

The literature review was based on a broad search in energy-related peer-review journal articles found in the scientific databases 'Science Direct' and 'Google Scholar' and textbooks that deal with modeling. Besides, we reviewed four SENTINEL deliverables that investigated the challenges and trends of energy models (D2.1, D3.1, D4.1, and D5.1). According to our broad definition of need, trends and challenges are unique forms of need expression and, we, thus, included them in our search.

The structure of 'user needs' regarding energy models and model platforms varies in the literature due to different study focuses and individual clustering methods. Energy system models, like those applied in SENTINEL, are a unique form of software. For example, in software engineering, specific requirements arise at different stages of the software development lifecycle (see, e.g., Balzert, 2011). Besides, further modeling process descriptions exist, like, e.g., the framework described by Refsgaard *et al.* (2007), which includes the five steps of (1) model study plan, (2) design and data, (3) model set-up, (4) calibration and validation, and (5) simulation and evaluation.

As we did not find a satisfactory framework of model user needs, we developed a comprehensive need structure that constitutes our analytical framework. Based on the above-mentioned common findings from software development and more accurate findings in the literature of science-driven energy modeling, we clustered the needs into four categories: needs concerning the model content, the model design and data, the modeling process, and the model outreach. These categories reflect the steps of model development, application, and use. We defined the categories as follows:

i. The **model content** represents the central aspects of a model. It focuses on the subject and the research question(s) that should be answered by the model. It deals with 'what' is investigated, for example, whether sector-coupling can improve energy efficiency and lower the energy transition's overall economic costs. Usually, the subject is intricately connected to the model´s input and output data.
ii. The **model design and data** refer to the logic, structure, and empirical basis of a model. It focuses on 'how' we investigate the model content and 'how' the model parameters are interlinked (the model throughput). The design focuses on the

assumptions behind a modeling approach, meaning how the real-world is translated into a model. For example, how it deals with the complexity of the energy system in time and space, or how it reacts to the uncertainty of human societies' reactions to future challenges. As a 'how' must always be translated into the 'what,' design and content are intricately linked.

iii. The **modeling process** is equivalent to the procedure defined or taken by the model developers for arriving at an initial and a revised model and the process circumstances. For example, who is part of the modeling team, what stakeholders should be involved in the model development, and at what stage, or which scientific standards are applied in what way? Therefore, it stands at the beginning and middle of the modeling process.

iv. The **model outreach** summarizes all efforts to deliver model results in a way that increases their accessibility and use. For a new model, it stands conceptually at the end of the modeling process. For models being revised, the outreach overlaps with the start of a subsequent run of the modeling cycle and, thus, with the modeling process. An overlap occurs, e.g., when results attract interested but critical stakeholders that support further model improvements. In contrast, the model outreach focuses on how models and their results are presented and communicated to the target audience. For example, it concerns forms of model reports, model visualizations, interactions between modelers and model (result) users, and so forth.

As 'user needs in energy models' is not a technical expression, the search in the scientific databases has involved several synonyms, related terms, and additions for making it even more specific, e.g., demand regarding single steps in modeling or the European context. The term 'needs', for example, overlaps with 'challenges', 'trends', and 'scenarios.' Challenges can be understood as 'barriers for improvement,' and improvement always means that there is a need for making things better. Furthermore, trends can refer to 'trends in modeling' or 'real-world trends.' We see trends in modeling as reactions to identified gaps of models by modelers for which they try to find or already have found some solutions. If there were no need for improvement and implementation, modelers, users, and stakeholders would probably not seek such opportunities. Scenarios are not necessarily real-world developments but possible futures and are being created in many interdisciplinary and transdisciplinary projects. Scenario ideas are communicated within and exceeding the project, indicating a driving force behind them. From an economic point of view, needs, challenges, trends, scenarios, and other similar terms identified by modelers and model result users are, therefore, representatives of 'demand' in general (compared to 'supply' by modelers) and were all included in the literature review (Stalpers *et al.*, 2009).

2.2 Interviews

Second, we conducted qualitative interviews to receive in-depth insights into arguments and reasons for different stakeholders' modeling demands.[1] We conducted 32 interviews from all relevant stakeholder groups in five jurisdictions within Europe: the EU as a whole, Germany, Greece, Poland, and Sweden, representing various geographical, political, and cultural backgrounds (**Table 1**). We defined and used four stakeholder groups with a high impact on energy policy and also, in general, relatively high potential interest in energy models: policymakers, working in the governments/European Commission or governmental organizations (abbr. 'POL'); energy industry representatives, including transmission and distribution system operators (abbr. 'IND'); representatives of non-governmental organizations (abbr. 'NGO'); and scientists, researchers, and analysts, working in academia or consulting (abbr. 'SCI').

Table 1: *Stakeholder groups interviewed in the different case studies*

Country \ Group	POL	IND	NGO	SCI
EU	3	2	2	1
GER	2	-	-	1
GRE	1	1	-	2
POL[2]	1 (2)	1	3	4 (5)
SWE[3]	4	-	-	4

The interviews followed a semi-structured guideline, which has been pre-tested and revised project-internally. It addressed questions, such as: *What are the current and future challenges or aspects of the energy transition that should be integrated into future energy planning models? In your opinion, what kind of information should an energy model deliver to inform decision-making processes? And how should the process of model development be designed to increase the chance of the later model use in policymaking?*

The interviews were recorded, transcribed, and anonymously analyzed. We performed a content analysis of the interviews (Creswell and Creswell, 2018), applying four need categories, which we derived from the literature review: **(i)** model content, **(ii)** model design and data, **(iii)** process of model development, and **(iv)** model outreach. We identified different sub-categories for each case study and compared them. We partially conducted the interviews in the case study country's official language, and thus, we translated the presented quotations.

[1] We conducted joined interviews for user needs (D1.2) and the interaction between energy modeling and policymaking (D1.1). The combination was reasonable due to a large overlap of both tasks, as the actual interaction of energy modeling and policymaking can strongly be influenced by the needs of modelers and policymakers.

[2] Since in two cases the interview was conducted with more than one person, numbers in brackets show a total number of interviewees, which represented the same institution or stakeholder group.

[3] One interviewed scientist was based in Norway, while being interviewed because of its expertise in the context of the Nordic electricity market.

2.3 Online survey

Third, we conducted an online survey to gain data for statistical analysis. Its essential characteristics in the design, concept, and distribution of the online survey followed the methodological questions raised in Creswell (2014:200 ff.).

The online questionnaire's objective was to study the urgency of possible current user needs of energy models by different stakeholder groups. On the one hand, these groups are affected by European energy policy and, on the other hand, want to influence decisions taken by political institutions, in particular the European Parliament and the European Commission. A co-creative survey development ensured maximum practical usefulness to the modelers and congruency with the SENTINEL goals of user-need-driven model development and improvement. The survey addressed the same four stakeholder groups as the interviews.[4]

We created the survey in an iterative process with all SENTINEL partners and collaboration with the openENTRANCE[5] project, the 'sister project' of SENTINEL financed by the Horizon2020 program. For the survey´s development, we used findings from the literature review and interviews to structure it, in particular, to incorporate the four identified user need categories (content, design, process, and outreach), and to define the questions. The survey's central part was structured in six sections and included 58 items/questions (**Table 2**). While sections B, C, and D focused on the needs for models in general and individual SENTINEL models, section E included questions regarding the model platform. Sections A and F were needed for nesting of depending queries and support in inferential statistics (e.g., to identify need differences of the stakeholder groups, or differences by model experience). The full questionnaire is included in **Appendix D**, all detailed descriptive survey results as **Appendix C**. The questions are numbered consecutively per section for easy assignment (A1, A2, A3… B1, B2, B3…).

As we were interested mostly in the participants' most critical needs, we set many questions as obligatory and included conditional clauses for more specific questions. Such dependent questions were only asked when a survey participant fulfilled one or several conditions by answering former independent questions in a particular way, e.g., being interested in a topic in the first place. About 60% of all items (35 of 58 questions) were dependent ('nested') with at least one condition. For the survey questions, we used categorical scales (single choice, multiple choices, and open field) and continuous scales (Likert scale and ranking). Many single and multiple-choice questions also had a free text slot to minimize systemic biases and to allow participants to add further needs.

[4] We use identical abbreviations for the stakeholder groups in the interviews and survey. In the questionnaire, we included the group 'Research, Innovation & Consultancy'. As it largely overlaps with science, we refer to it as scientific community, scientists, and SCI in the report.

[5] https://openentrance.eu/

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Table 2: *Structure, purpose, and items of the user need survey*

Section	Title	Purpose	Items
A	Personal background, model use, and general demand (13 questions)	Personal background: better understand the target groups' context and characteristics and adapt to their background	Working on geographical scales (A2), model experience (A4), model importance for energy transition and policymaking (A9) [sector focus (B4)]
		Model use: learn about use characteristics	Usual ways of working with models (A3), preferred model types (A5) regularly used specific models (A6), use frequency (A7), barriers of model use (A8), the purpose of model use (A10), and the usual time horizons of decision support (A12)
		General demand: quantify needs likely to have cross-model impact	Purposes for which improved models are necessary (A11) and need categories to which respondents wanted to contribute (A13)
B	Model content (17 questions)	Understand and prioritize thematic themes models should be dealing with (more)	Critical general aspects in the energy transition (B1-2), priorities regarding factors of all system dimensions (B3), demand regarding specific social factors and status quo in models (B4a and B4a2), demand regarding specific environmental factors and status quo in models (B4b and B4b2), essential practical questions as well as research questions that need to be answered for the different energy-related sectors soon (B6-12), demand regarding further technological innovations (B13-14)
C	Model design (4 questions)[6]	Understand and prioritize the demands regarding the model performance each modeler must think about	Beneficial model conditions (C1), valuable model features (C2), preferred solutions regarding uncertainty management in modeling (C3-4)
D	Modeling process (7 questions)	Identify and prioritize demand for its general improvement to increase stakeholder satisfaction	Respondents´ wish to participate in modeling processes (D1), her/his past involvement (D2) and the perceived satisfaction with the process (D3), routines and general and specific usefulness of the involvement of external stakeholders in own participation processes (D4-6), topics which should be discussed in these processes (D7)
E	Model outreach (10 questions)	Understand how stakeholders want to have models and their results to be communicated	Beneficial forms of model communication (E1), support-based assets to maximize platform use (E2)
		Receive user preferences in the technical design of the model platform	Likely platform users (E3), preferences regarding software products (E4), graphical interfaces (E5), programming languages (E6), integrated development environments/editors (E7), command-line use (E8), and operation systems (E9), recommendations of other modeling platforms (E10)
F	Others and demographic data (7 questions)	Understand the target groups´ context and characteristics and adapt to their background	Country of residence (F1), gender (F2), working experience in the energy field (F3), interest in user need workshop (F4-5), option to comment on the survey (F6), opportunity to receive survey result (F7)

[6] The term 'and data' was added in the need category 'model design and data' after the literature review and interviews had already been finished due to the perceived high relevance of data for models. The modification was made after the survey went public.

We designed the questionnaire as an online survey to minimize costs and to maximize the probability of peer-to-peer forwarding of the survey to increase the sample size. The questionnaire was implemented with the tool 'LimeSurvey'. Six stakeholders from different target groups tested the pre-final online version. Based on these tests, we adapted the survey by a further nesting for the main categories (**question A13**) to reduce the time for the survey needed (see **Appendix B; Figure 2**).

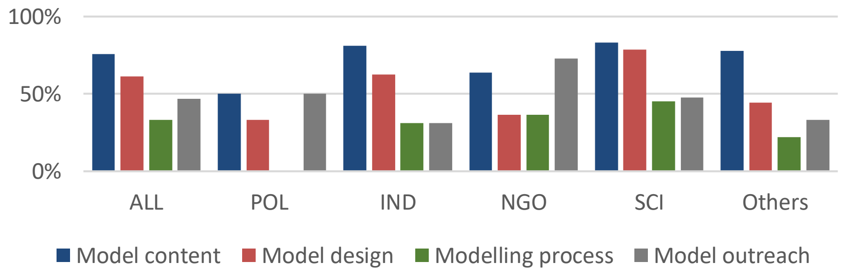

Figure 2: *In which field(s) do you want to contribute to the model improvement in particular (mandatory, multiple choices)? N: 90*

The survey population was based on a nonprobability sample, respectively convenience sample (Creswell, 2014:204), meaning that it was sent via various channels to identified clusters of potentially interested stakeholders in energy models.[7] In total, the survey was distributed among national, European, and international organizations and representatives of politics, civil society, economy/industry, and science. We used a diverse set of private and public distribution channels, including:

- Mailings to established stakeholder contacts and networks of the SENTINEL partners (minimal estimate of 3,300 contacts, also including stakeholders organized in the OECD).
- Mailings to the partners´ and stakeholders´ networks from other European energy- and model-related projects found in the 'Community Research and Development Information Service' (CORDIS), a database offered by the European Commission (20 contacted projects of which six responded to our request on distributing it further).
- Mailings to organizations that are listed in the European transparency register and are interested in the fields 'Energy, Climate Action, Environment, Transport, Agriculture and Rural Development, Business and Industry, Consumers, Employment and Social Affairs, Research and Innovation' (250 contacts).[8]
- Mailings to the National Contact Points of the European Research Council with a request to distribute it among their research institutes (more than 40 registered national organizations).
- Sharing on SENTINEL partner websites, scientific mailing lists, the 'openmod' forum, and social media (e.g., Twitter, LinkedIn, and ResearchGate).

[7] A random sample would have been ideal for the best approximation to representativeness. However, such a randomization was not possible among European stakeholders due to different practical challenges.
[8] These categories are filter options in the official European transparency register.

The survey was publicly and unrestricted online from the 13th of July to the 5th of September 2020. After finishing the data collection, we performed a descriptive analysis, in which we aggregated the individual data to group-specific and cross-group results. Here, we primarily made stakeholders' urgent needs visible by ordering results based on the priorities and rankings.[9]

Ninety participants completed the questionnaire, and ninety-five participants started but did not finish the survey. All addressed stakeholder groups have responded to the invitation; however, with a disproportionate interest of the scientific community, making about 47% of participants (**Figure 3**).

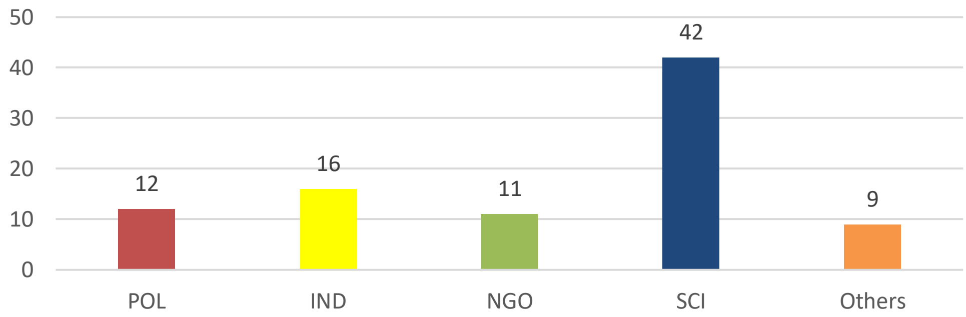

Figure 3: *Which stakeholder group would you count yourself among? (single choice, mandatory), N: 90; completed questionnaires only*[10,11]

The respondents who completed the survey can be characterized as energy experts with model experience from across Europe interested in the European energy transition and using models for decision-making in various sectors. Many survey participants have a lengthy background in the energy field, 67% longer than six years. Many stakeholders are active at the national and the European levels; much fewer respondents focus on the subnational or regional level. Stakeholders from 14 European countries have participated in the survey, with most of them having a residence in Germany (42%), followed by Greece (14%), and Belgium (9%).

[9] Further work based on inferential statistics, including analysis of biases, reliability, and corresponding interpretation and implications, will be done on own demand and requests by the SENTINEL partners. The original, anonymized disaggregated and aggregated survey data will be made available on the SENTINEL modeling platform.

[10] Many participants who did not complete the survey dropped out before finishing section A 'Personal background, model use, and general demand'. Only 27 of the 95 dropouts indicated their stakeholder status which was mandatory before proceeding to section B. Thus, the actual group-specific dropout rate can hardly be estimated. Amongst those who answered the question, the dropout rate was lowest for other/undefined groups (10%), followed by NGOs, (15%), the SCI (18%), the IND (27%), and highest for POL (43%).

[11] Others included policy energy-related business companies exceeding the (classical) energy industry like a start-up for 100% renewable energy, the energy intensive sector, manufacturing industry for energy technologies.

2.4 Online workshop

Finally, we organized an expert workshop on the 1st of October 2020 to discuss energy modeling expectations for the European energy transition. Due to the COVID-19 situation, the workshop was – in contrast to the original plan – implemented as an online workshop. Compared to the physical event, the advantage of the online workshop was that stakeholders did not need to travel and could likely participate more easily (Süsser *et al.*, in preparation).

The workshop's first objective was to discuss, verify, and prioritize findings in face-to-face interaction between different stakeholder groups, e.g., about conflicting needs (trade-offs), extracted from data collected within previous methods. The secondary objectives were to receive specific requirements for the development of SENTINEL models and their thematic focus.

The workshop took place as a four-hour online interactive event. Around 30 invitees from the primary stakeholder groups of SENTINEL with a background in modeling participated in the workshop:

- 2 policymakers,
- 11 energy industry and business representatives,
- 6 civil society representatives, and
- 7 scientists

The workshop was structured in two plenary sessions (one opening and one closing) and two rounds of five parallel sessions (see **Appendix E** for the workshop schedule). In the plenaries, we let the stakeholders rank key user needs and summarized the key findings. The parallel sessions were structured around the SENTINEL work packages – **Session 1** on social and political aspects of the transition (Work Package 2), **Session 2** on environmental aspects in energy models (Work Package 2), **Session 3** on energy demand and supply (Work packages 3 and 4), **Session 4** on economic impacts (Work Package 5), and **Session 5** on the energy modeling platform (Work Package 7). The sessions were organized, hosted, and facilitated by the SENTINEL modelers. We repeated the sessions with a second set of participants. Thus, we reduced the group size for more in-depth discussions. Given the different status of SENTINEL model development and improvement, we did allow for two different designs of the session:

- Explorative design with a focus on identification of (new) needs and their prioritization, and
- Reflective design with a focus on feedback on planned improvements, and their comparison with needs

The workshop design was interactive, using different tools, such as live polls, annotation (drawing), and virtual sticky notes.

The workshops´ results have been voice recorded and virtually recorded in the form of sketchnotes by the company 'Ellery Studio' (see **Figure 27-Figure 32** in **Appendix F**). The visualizations provide appealing summaries of critical findings and will be further used for project communication. Thus, the sketchnotes work as eye-catchers on the project website, partner websites, and the projects´ Twitter account to build the models and modeling platform's social network.

Furthermore, written notes were taken for each session, and figures from the live polls´ and other online tools´ results were saved. Key findings of the workshop have been analyzed, summarized, and disseminated to the workshop participants in a workshop summary. The SENTINEL session hosts have drawn conclusions for the development of the new models, the improvement of the existing models, and the development of the SENTINEL platform that will allow a wide range of decision-makers to address the critical energy system design challenges they confront.

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3 Results

On the basis of the literature review, interviews in five jurisdictions, the online survey, and the online workshop, we have identified many needs for energy models. In four sections, we present the key needs of stakeholders – both model users and model results users – regarding model content, model design, modeling process, and model outreach from the four methods used (cf. **Figure 4**).

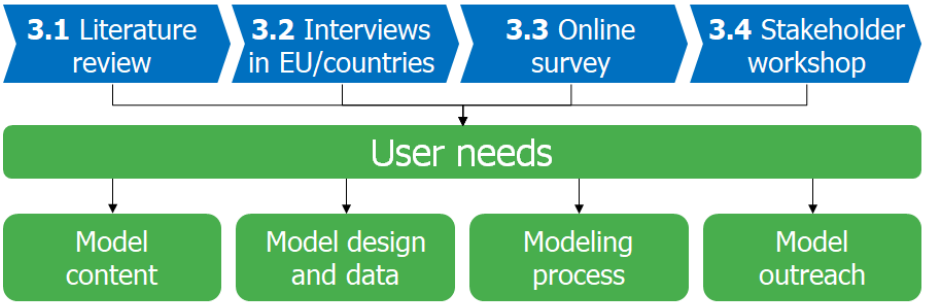

***Figure 4**: Navigation through the results section*

First, we identify different needs for model content, looking at 'what' should be modeled to support users answer their questions. We summarize the critical specific and prioritized findings in **Box 1** below.

***Box 1:** Summary of identified user needs for the model content*

- Stakeholders demand a systemic and holistic perspective of energy system transformation in modeling. For this, models should integrate all energy-related sectors. In addition, the models should include economic, societal, environmental, and political factors in order to show a broader set of societal impacts.
- Models should take greater account of environmental impacts and the use of natural resources. Stakeholders gave priority to the demand of raw materials, impacts on nature and biodiversity, as well as life cycle impacts of energy infrastructure.
- Models should better integrate social and behavioral aspects into modeling. Stakeholders gave priority to drivers and constraints of innovation diffusion, benefits of community energy, as well as social acceptance, attitudes, and impacts of social issues on politics.
- Modeling must support the development of strategies, policies, and measures, and the ex-ante-assessment of policy impacts.

Second, we reveal user needs regarding the 'how' the models should be designed. In **Box 2**, we summarize the key specific and prioritized findings.

***Box 2:** Summary of identified user needs for the model design*

- Models should be transparent, including the data basis, as this is the key for managing uncertainty and creating model trust.
- Models should use reliable open-source data of high empirical quality, which are continuously harmonized and updated.
- Models should be able to provide higher temporal and spatial/geographical resolution to account for local and distributional effects of the energy transition.
- Stakeholders gave priority to the modeling of progressive scenarios and scenarios with high environmental ambitions (1.5°C futures). However, there are diverging needs of the different stakeholder groups for the design of the models, e.g., in terms of model complexity, and whether the models should find right targets or policies.

Third, we find user needs for how the modeling process should be organized. We summarize the key specific findings below in **Box 3**.

***Box 3:** Summary of identified user needs for the modeling process*

- Model teams should pursue interdisciplinary and transdisciplinary modeling approaches. Different stakeholders want to be involved in the modeling process, especially in the phases of conceptual development and model improvement.
- The modeling community should strengthen their collaboration. Scientific standards (like transparency) and scientific quality of the modeling work are essential for this.

Last, we identify user needs for how the models and the modeling platform should be communicated and designed. In **Box 4**, we summarize the critical specific and prioritized findings.

***Box 4:** Summary of identified user needs for the model and platform outreach*

- Models should be communicated in a simple, understandable, visually appealing and actionable way. Priority requirements were model presentations, graphs and figures and model applications in case studies. Transparent communication is essential, including model assumptions, uncertainties and what model results can say (and what not).
- The modeling platform should provide relevant information for different user groups. Stakeholders gave priority to the modeling platform containing information on specific models (incl. use cases), model overviews and catalogues, downloads of models and sources as well as training material and interlinkages between models.

3.1 Literature review

Based on our four categories of user needs, we could identify diverse corresponding needs. We have grouped them into sub-categories (**Table 4** in **Appendix A**). In general, scientific studies with and without stakeholder participation on a possible and desirable energy system and transition in all its facets are numerous and stand for a need to investigate the future (**Table 5** in **Appendix A**). Furthermore, the SENTINEL researchers have identified current trends, modeling paradigms, and challenges (see **Box 5** in **Appendix A**). Overall, these comprehensive findings are in line with the defined need-categories. The essential user needs in the four categories identified across the literature are:

Model content: Needs for model content comprise the modeling of diverse political goals (Ernst *et al.*, 2018; Lopion *et al.*, 2018), various transition types (Pfenninger *et al.*, 2014; Trutnevyte *et al.*, 2019), all energy-related sectors, and specific topics within the energy transition (Martin *et al.*, 2014; Pfenninger *et al.*, 2014; Lopion *et al.*, 2018; Samadi *et al.*, 2017; Hache and Palle, 2019) to arrive at a systemic and holistic perspective of the system´s transformation (Hache and Palle, 2019). Modelers need to check and discuss which of these topics are relevant for their models, resulting in model-specific, model-type-specific, and general needs applicable to all energy models.[12]

Model design and data: Important needs in model design and data concern the significant role of clear model purpose (Van Daalen *et al.*, 2002; Pfenninger *et al.*, 2014; Lopion *et al.*, 2018; Müller *et al.*, 2018), dealing with complexity and uncertainty (Pfenninger *et al.*, 2014; Hilpert *et al.*, 2017; Müller *et al.*, 2018), resolving of time and space (Pfenninger *et al.*, 2014; Hilpert *et al.*, 2017; Lopion *et al.*, 2018; Müller *et al.*, 2018; Lacroix *et al.*, 2019), choosing consciously the analytical and mathematical approach as well as the model type (Pfenninger *et al.*, 2014; Lopion *et al.*, 2018; Müller *et al.*, 2018), and requirements for high quality and open data (Hilpert *et al.*, 2017; Lopion *et al.*, 2018; Müller *et al.*, 2018). The design of models is overly complicated and interdependent, meaning that it includes many trade-offs. Thus, improving one aspect can result in new challenges at another end.[13]

Modeling process: Due to the growing need for more complex and realistic models as well as the need for higher acceptance and legitimacy of models, inter- and transdisciplinary modeling is a crucial issue in general (Kolkman *et al.*, 2016; Hilpert *et al.*, 2017; Trutnevyte *et al.*, 2019), as well as for, more specifically, scenario development (Pfenninger *et al.*, 2014; Lopion *et al.*, 2018). Moreover, scientific standards and scientific quality become even more relevant. Demanded

[12] We define model types by their content focus and investigation approach. Common types are, e.g., models for electricity market, strategic energy system planning, technology diffusion, life cycle assessment, integrated assessment, investment behavior, macroeconomic equilibrium, simulation models, optimization models and so on.

[13] For example, more detailed assumptions for more realism demand more detailed empirical data, which are often not available in the requested quality and resolution, increasing uncertainty of model results. Moreover, higher complexity comes with time-intense model runs, and reduced user-friendliness.

standards include aspects like transparency, repeatability, reproducibility, scrutiny, accessibility, and licensing (Pfenninger *et al.*, 2014; Kolkman *et al.*, 2016; Hilpert *et al.*, 2017; Lopion *et al.*, 2018).

Model outreach: For the model outreach, the primary user needs concern the model communication and utilization (Pfenninger *et al.*, 2014; Kolkman *et al.*, 2016; Hilpert *et al.*, 2017), supporting infrastructure (Kolkman *et al.*, 2016; Lopion *et al.*, 2018), and organizational factors (Kolkman *et al.*, 2016). Thus, needs like tractability, visualization, usability, applicability, re-usability, efficiency, flexibility, compatibility, and consistency play a key role in model impact and must be discussed with the decision- and policymakers. However, some aspects like modelers' reputation and organizational factors can only indirectly be influenced by modelers, especially by building the 'best' models possible.

The sub-categories and needs are interlinked with each other, like, e.g., complexity, uncertainty, risk, resilience, scenarios, transdisciplinarity, and communication of assumptions and results. Yet, they are far from being identical. Besides, the content sub-categories are alternative ways of in-depth structuring as they almost completely overlap. In contrast, the sub-categories of model design, process, and outreach are complementary.

3.2 Interviews

To get more in-depth insights into specific user needs, we conducted interviews with different stakeholders in five jurisdictions. The case studies revealed user needs of models for each category – model content, model design, the process of model development, and model outreach. For each category, we could find further sub-categories. The tables in **Appendix B** summarize the identified user needs, including outstanding quotes of our interviewees.

3.2.1 Model content

We find different user needs regarding the model content (**Table 6** in **Appendix B**). We identified energy system-specific, sector-specific, technology-specific, country-specific, and policy-specific demands of energy models to be considered to develop and improve energy models.

Interviewees expressed the need for a systemic perspective in modeling, including external costs and costs on individual and macroeconomic levels in all societal areas, such as the overall costs for the environment, resources, biodiversity, health impacts, and welfare/jobs. One researcher dealing with EU policies stated: *"[b]ut 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). This goes in line with the demand for a better assessment of the consequences of political, technical, and social interventions and improved modeling of human behavior, including the role of attitudes, preferences, and acceptance. A further suggestion was to *"[…] maybe includ[e] energy communities as investors into the models. So just more analysis about the behavior and acceptance issues that people really have"* (EU_SCI#1).

Moreover, interviewees demanded the consideration of all energy-related sectors (electricity, heating and cooling, mobility, industry, and agriculture) and their specifics. Sector coupling, all zero-emission technologies, and flexible demand and supply (as options that a model can pick) should be integrated as default case in energy models because 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*", as stated by an EU policymaker (EU_POL#1).

Furthermore, interviewees highlighted the consideration of grids within and between sectors in modeling as an often-neglected factor. One EU policymaker underlined the demand by saying that *"[t]he grid extension is fundamental […] but grid extension is dependent on social acceptance"* (EU_POL#2).

Energy security was also an essential issue for many of the interviewees. They expressed the demand for enhanced modeling of security of supply in its various dimensions (amongst others, energy and capacity reserves, all forms of storage and grid technologies, and import/export) and unexpected and unforeseen events (resilience). For example, one German policymaker raised the question: *"With which system mix, including networks, storage and flexible options, can we achieve a secure power supply?"* (GER_POL#2).

Last, policymakers demanded quantitative support in making decisions. *"How can policies impact these developments, and what will happen if you do one thing rather than another thing?"* asked one Swedish policymaker (SWE_POL#1). One Greek policymaker expressed the need for models for ex-ante policy evaluation: *"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*" (GRE_POL#1). Thus, we identified the need for more real-world policy impact consideration and assessment of competing policy options.

3.2.2 Model design and data

We reveal user needs about the model design, especially regarding scientific standards, model characteristics, data requirements, and model compatibility and linkage (**Table 7** in **Appendix B**).

In general, models should be maximally transparent. *"Transparency, transparency, transparency. So everything we put into the model must be publicly available,"* emphasized an EU policymaker (EU_POL#3). Due to the critical role of assumptions for model results, interviewees demanded that modelers communicate their logic, unique selling points, limitations, and uncertainties actively and as open as possible. One Polish NGO representative underlined the importance by saying: *"Well, because it is probably important with renewable energy variables, why such a load factor is assumed, not another"* (PL_NGO#3).

Model transparency has also been linked to the issue of model complexity. For example, a Swedish policymaker said that *"[…] 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). Nevertheless, increased collaboration may encounter challenges of model complexity, as a Greek stakeholder stated: *"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). The level of complexity is an ambiguous topic, for which we did not find a clear tendency. While some interviewees preferred simple models, others preferred more complex ones.

Nevertheless, interviewees stated that models should increase their temporal and spatial/geographical resolution, which is necessary to investigate the decentralized and localized renewable energy potential. We find the need for *"more detailed geographical analysis"* (GRE_IND#1) and *"a bit more country-specific options"* (PL_SCI#2).

Furthermore, interviewees expressed different requirements on data. Interview partners highlighted that modelers should clarify which of their numbers are assumed and have an empirical basis. One Greek policymaker underlined the demand for useful data by saying: *"Policymakers need to base their policy documents on credible data sources. Otherwise, the results can be challenged"* (GRE_POL#1). Data used should be of high empirical quality, reliable, open-source, harmonized, and updated continuously. One EU policymaker underlined the latter by saying: *"[…] but it's like the assumption related to economic growth, for example. Assumptions related to 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 this different parameters, like oil prices are lower than expected, it's influencing our model this way or that way"* (EU_POL#2).

Interviewees also highlighted that models with similar purposes and their results should be compared to identify model differences. One Swedish researcher stated: *"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). Furthermore, the interviewees also did not show a clear tendency for no-, soft- or hard-linking. While some demanded *"energy models [that] work in combination with economic and other sectoral models"* (PL_SCI#4), others stated that they are *"not sure about linking at all"* (SWE_POL#1).

3.2.3 Modeling process

We see different user demands for the modeling process, especially regarding model purpose, continuous and diverse involvement of various stakeholders, and inter- and transdisciplinary and open modeling (**Table 8** in **Appendix B**).

We find the demand for clear purposes of model development, from the beginning. One Swedish policymaker stressed that a modeler needs to ensure that *"[…] what [she/he] produce[s] is really relevant to those people [policymakers]"* (SWE_POL#1).

Interviewees preferred a continuous involvement in the modeling process, to gain a mutual understanding of the model and the energy system in general, and higher objectivity of results. One EU industry representative described his need by saying: *"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 not '100% right' or '100% wrong'. For me, the key is to have the engagement from the very early stages to allow for multiple modeling views in an open environment"* (EU_IND#1).

Furthermore, interviewees stated the value of more interdisciplinary modeling approaches, e.g., by integrating social scientists and using various supportive methods − e.g., multi-criteria decision analysis has been declared. *"I think it's very important to engage as many stakeholders as possible",* stated one EU industry representative (EU_IND#2). One Swedish scientist emphasized the importance to have an independent party: *"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 modeling understanding."* (SWE_SCI#4).

Last, the interviewees also valued the recent open modeling approaches, which allow for a *"peer-to-peer type of learning in the modeling community"* (EU_IND#2).

3.2.4 Modeling outreach

We find user needs regarding the modeling outreach, including aspects of model communication, engagement with modeling tools, the modeling platform, and modelers directly (**Table 9** in **Appendix B**).

Interviewees demanded a transparent, simple, understandable, detailed, target-group oriented, appealing, and actionable representation of model explanations and documentation and visualization of purposes, assumptions, and results. Regarding the latter, one Swedish policymaker expressed: *"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).

We also find that the interfaces should be intuitive and user-friendly. Some interviewees would like to use the models directly without pre-knowledge as an easy-to-use online tool to experiment with assumptions. *"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",* stated one NGO representative (EU_NGO#2).

Regarding modeling platforms, interviewees demanded that they be executable (without producing errors), adapted to different user groups, and maintained after the related projects´ expiration date. Here, one EU policymaker confirmed: *"I think that the trick when it comes to models and data in general, we need to make sure that they are easy understandable to people, who are not familiar to the topic or also not familiar with data or modeling. 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_POL#2).

Last, options to contact modelers directly − via e-mail, telephone, and meetings − are essential for some stakeholders. *"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*", stated one EU industry representative (EU_IND#2).

3.3 Online survey

3.3.1 Model use and general demand

We asked the participants in what context they work with energy models. We find that all stakeholder groups work with models starting from their development to using modeling results (**Figure 5**). Only 2% of the participants stated that they do not use models at all. The technical development, application of models, analysis of results, writing of reports, and giving advice is most common among the scientific community (in all three context categories above 70%), energy industry (44-75%), and NGOs (36-64%). Model studies are mainly commissioned to external entities by the energy industry (56%) and policymakers (50%). Finally, 63% of the participants stated that they read model-based studies.

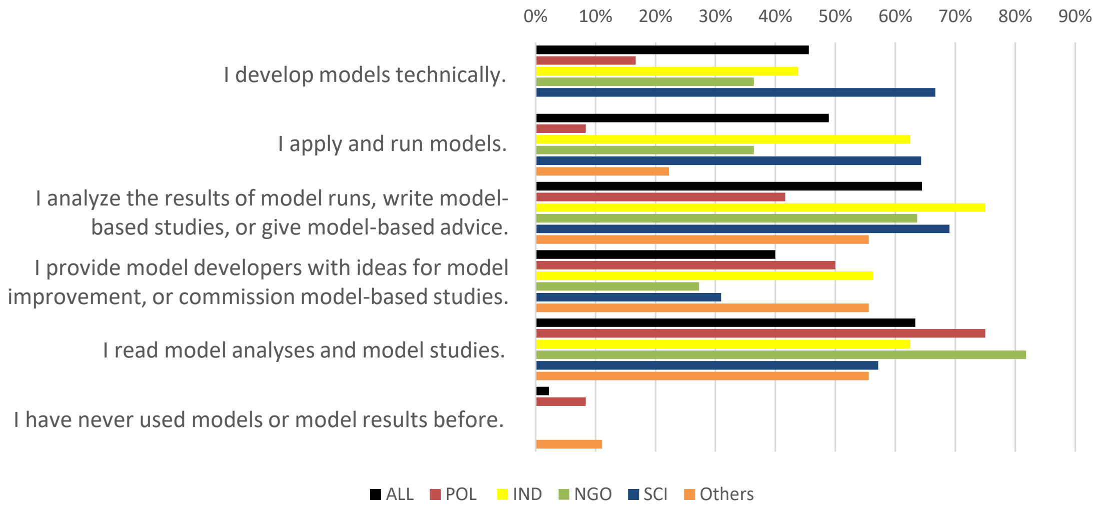

Figure 5: *In what context do you work with energy models? (mandatory, multiple choices, at least one answer), N: 90*

Next, we asked the participants about how important models are in the energy transition and policymaking. An overwhelming majority of the respondents across all stakeholder groups think that models are important for both contexts (98% and 94%), which underlines the interest of using models for decision-making. In addition, four out of five participants focus on the electricity sector, two out of five also on sector-coupling, digitalization, and system flexibilization. Few participants work in or with the mobility, heating, industry, or agricultural sector, but still enough to receive an overview of current demands in these sectors (**Figure 6**).

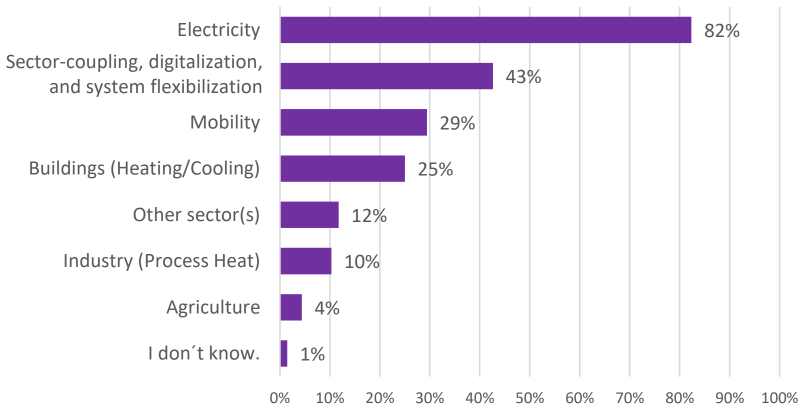

Figure 6: *Which sector(s) is/are currently of main focus in your working context? (voluntary; multiple choices, maximum of 3 answers), N: 68*

We also asked the participants what type of models they are working with. The most common model types are electricity market models (61%), followed by strategic energy system planning models (60%), and electricity grid models (43%). The top three model frameworks used are optimization (60%), simulation (52%), and geographical information systems (GIS; 24%). We find that among participants who worked with at least one model, they use a variety of specific models, most commonly: PRIMES (11), TIMES (9), GEM-E3 (4), EnergyPLAN (3), HOMER (3), LEAP

(3), METIS (3), PyPSA (3), and QGIS (3). PRIMES and GEM-E3 are most popular among policymakers (4 and 3 mentions), and TIMES among scientists (4 mentions).

On average, we find that models and model results are used quite frequently. 33% of all survey participants use them weekly, and 26% even daily, while daily use is highest in the energy industry (38%) and weekly highest among NGO representatives (45%). About 40% of the survey participants use them only monthly and occasionally. Every third respondent never or only infrequently used models (as indicated in **questions A3 and A7**; see **Appendix C**) stated that other methods and tools are used if models are not appropriate to answer a stakeholder´s question (30%). However, we also find other reasons for not using the models, such as time restrictions (22%), general skepticism regarding model assumptions (19%), and lacking model availability (16%). Besides, respondents mentioned budget limitations, the frequency of model updates, and the primary use as an auxiliary method in decision-making as "other" reasons.

Furthermore, we asked respondents for what purposes they use models. We find that the top five reasons for using models are the development of strategies (57%), the formulation of policies and measures (40%), the ex-ante-assessment of policy impacts (39%), the agenda and target setting of policies (38%), and the operation of energy systems (36%). Strategy development is relatively similar significant for all stakeholder groups (58-71%), but we find more diversity in other purposes. For example, policymakers have the highest use rates for agenda/target setting (80%) and ex-ante-assessment of policy impacts (70%). These purposes of model use correspond with the, on average, longer time horizons that are most relevant for the respondents in their working contexts. Stakeholders deal mostly with the medium-term perspectives of the next decades (2030, 2040) (72%), followed by long-term time horizons beyond 2050 (57%), and short-term perspectives up to 2025 (54%). The monthly and shorter time horizons are, in general, less relevant in their energy-related working context (<31%).

Moreover, we also asked those respondents who stated their purposes of model use (in **question A10**; see **Appendix C**) about the purposes for which they would need enhanced models. The highest demands were: development of strategies (48% of the respondents), the formulation of policies and measures (45%), the ex-ante-assessment of policy impacts (42%), the agenda and target setting of specific policies (39%), and their implementation (31%). These demands are in line with the current model use. Policymakers and NGOs have the highest group-specific deviation from the average. For example, policymakers demand the most vital for improved models helping in policy/measure formulation (70%), and NGOs are especially interested in better models for target setting of policies (67%).

3.3.2 Model content

We asked the participants about important aspects of the energy system and its transition and find that the three central aspects/goals are the security of supply/resilience (96%), climate-neutrality (94%), and cost-efficiency (85%). Other aspects supported by many of the participants (>65%) include nature protection, low-hazard technologies, affordability, energy efficiency, social acceptability, human health, and free trade of energy. We find only small differences between stakeholder groups. Moreover, about one-third of respondents stated further new or more detailed aspects that should have been included in our list. Mentioned aspects are the fair distribution of burden and profits, the connection to the existing legal framework, political feasibility, and others (see **question B2** in **Appendix C**).

We also asked the participants about more concrete factors that should receive more attention in energy models (**Figure 7**). About every second question´s respondent stated that "impact on the environment and natural resource use" (51%) and "behavior, lifestyle, and heterogeneity of consumers" (49%) should be considered more, followed by "total costs and investment costs (including external costs), and the "development of new technologies and services" (each with 43%). These aspects were ranked high almost among all user groups, while the ranking order differed (see **question B3** in **Appendix C**). The participating policymakers found the impact on the environment and natural resource use most relevant (83%), energy industry representatives the total costs and investment costs (69%), and NGO representatives as well as the scientific community behavior, lifestyles, and heterogeneity of consumers (71% / 54%). Importantly to note, the NGO representatives were not convinced by new technologies in energy models (0%). The policymakers and energy industry did not think that behavior should receive more attention (15% / 17%).

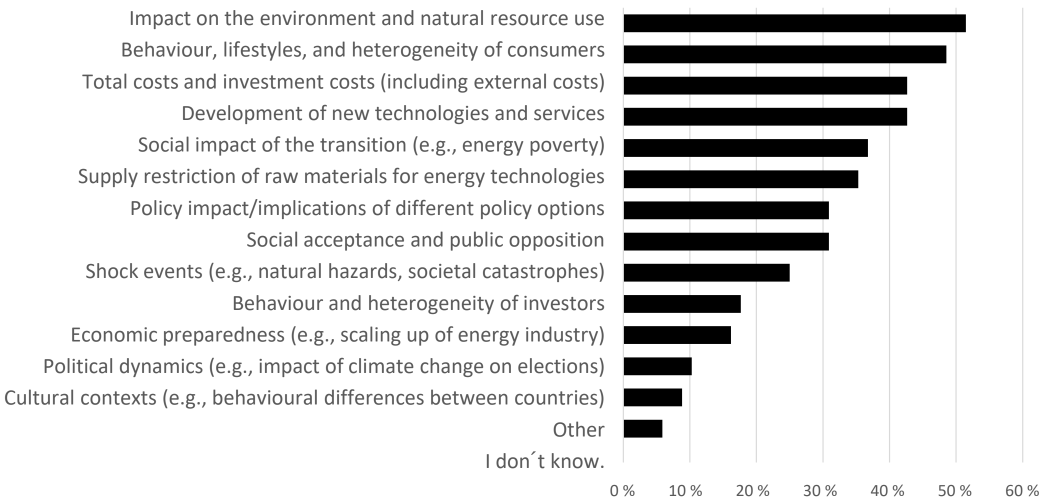

Figure 7: *Which of the following factors do you think should receive more attention in energy models? (mandatory, multiple choices, between 1 and 5 answers), N: 68; figure sorted by total share*

Respondents who expressed their demand in social aspects in the previous question were confronted with even more detailed social modeling options (**Figure 8**). We find that the top three social aspects that should be included in energy models are "Co-benefits of prosumerism and community energy" (43% of question´s respondents), the "Social drivers and barriers of innovation diffusion" (43%), and the "Dynamics of social acceptance and individual attitudes" (39%). These aspects were ranked high across the user groups, with some noteworthy exceptions (see **question B4a** in **Appendix C**): For example, co-benefits of prosumerism and community energy were most important for energy industry representatives (60%), social drivers and barriers for the scientific community and policymakers (52% / 50%), and especially NGO representatives would like modelers to focus on acceptance dynamics, e.g., the habituation to new technologies (90%). On the contrary, none of the participating policymakers were convinced by prosumerism and community energy, and energy industry representatives were least interested in social barriers and drivers of innovation diffusion and acceptance dynamics (each with 20%). Some respondents also added "other" aspects, including the techno-economic limitations of the incumbent paradigm, the costs for low-income groups, the impact on energy poverty (distributional analysis), unemployment, and wages, as well as co-prosumerism in a commons´ logic.

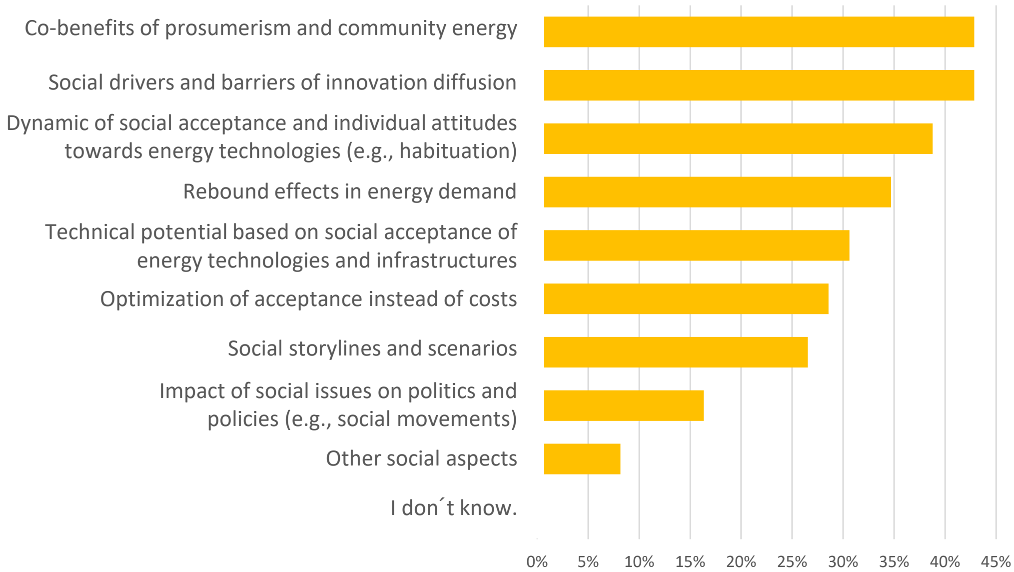

Figure 8: *You stated that social aspects should receive more attention in models. What social aspects would you like to see integrated into energy models? (voluntary, multiple choices, up to 3 answers), N: 49; figure sorted by total share*

Survey participants, who indicated their demand for ecological factors, were also asked a follow-up-question given more detailed options (**Figure 9**). Respondents stated that raw material demand (57%), greenhouse gas emissions (49%), air pollution (40%), water usage (40%), and loss of diversity (32%) should especially receive more attention, again with some noteworthy differences between the stakeholder groups (see **question B4b** in **Appendix C**). For example, while raw material demand and greenhouse gas emissions were ranked relatively high by all groups, none of the energy industry representatives saw the loss of biodiversity as an essential modeling topic. One respondent added in the free text "other" field that raw materials demand should also consider required transmission grids.

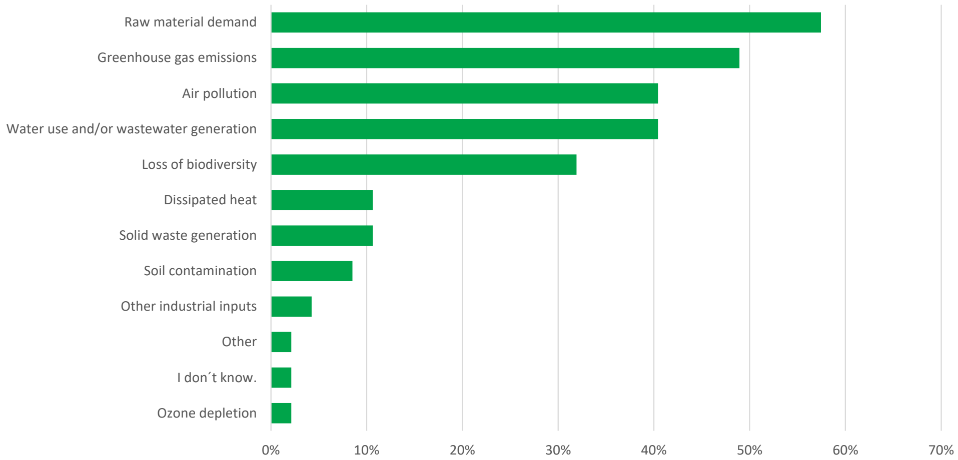

Figure 9: *You stated that environmental or resource issues should receive more attention in energy models. What environmental factors would you like to see integrated into energy models more in the future? (voluntary, multiple choices, up to 3 answers), N: 47; figure sorted by total share*

Survey participants who indicated their demand for new technologies were also asked about their preferences regarding different innovative technology options (**Figure 10**). We find that CO_2-reduced and CO2-neutral energy carriers (like solar fuel, green hydrogen, Carbon Capture and Storage, and Utilization from coal and gas) are perceived as the most pressing modeling topic (71%). Moreover, every second respondent wants to see new solar applications like PV-integration into buildings and streets or combination with agriculture (50%). These options were followed by new wind power technologies, including, e.g., Air Borne, Far-Off-Shore, and Micro-Wind (42%) and new hydropower possibilities like, e.g., wave energy (29%). New biomass resources and innovative nuclear power, e.g., atomic fusion, received the least attention (21% and 13%). Overall, the technology preferences were strongly influenced by the scientific community (14 out of 24 respondents). As one policymaker, four energy industry representatives, and no NGO representative participated, we cannot analyze group-differences on a sound basis and, therefore, only include the aggregated figure.

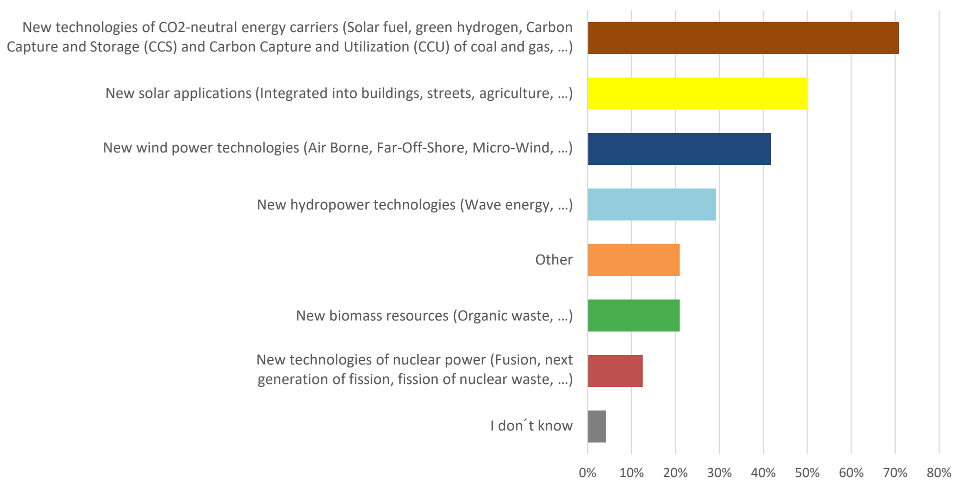

Figure 10: *Which innovations in the electricity production sector should be included in energy models? (voluntary, multiple choices, up to 3 answers), N: 24; figure sorted by total share*

Participants got also the chance to add "other" innovative technologies. One participant named here *"gas engines (e.g., for cogeneration) running on natural gas, biogas, bio-methane or hydrogen"* as production option in energy models. Other responses included (amongst others): concentrating solar power, energy storage (e.g., batteries) and P2X-technologies, system integration technologies like micro flexibilization and demand management, new energy transmission options like superconductors, and direct CO_2 air capture and storage.

3.3.3 Model design and data

To identify different demands regarding the model design, we asked respondents about the importance of model conditions. We find significance across all model conditions and characteristics (**Figure 11**). Considering only the aspects to be "very important", the respondents ranked transparency (75%), fit for purpose (67%), the availability of reliable data (65%), and trust in models (60%) highest among the options.

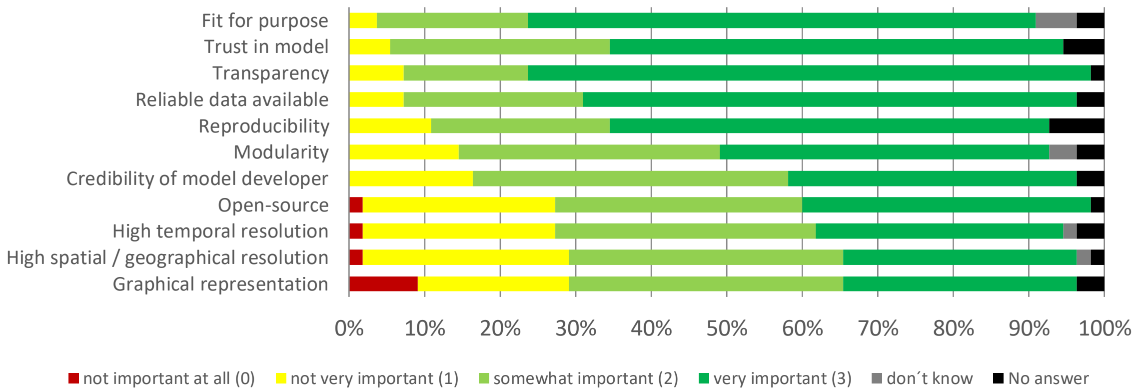

Figure 11: *How important are the following model conditions for the use of models or their results in your work? (voluntary, Likert scale), N: 55; figure sorted by total share of "not important at all" and "not very important"*

Respondents had the chance to indicate their preferences regarding different design trade-offs that modelers usually deal with and decide about during the model development and application (**Figure 12**). Most respondents expressed the demand for models that already exist, fit-their-purpose, and are realistic and open-source. Additionally, they want modelers to focus on comprehensive, progressive, and 1.5°C scenarios. For some model features, the preferences seemed less clear on the aggregated level, e.g., for simplicity versus complexity (47% versus 45%), finding the best policy options versus finding the right targets (38% versus 33%), and optimization versus simulation (44% versus 33%). However, differences were significant on the group-specific level. Policymakers, for example, preferred simple models; NGO representatives liked complex models more. Policymakers unambiguously preferred the search for good policy options, while NGO representatives found the right targets much more critical. And energy industry representatives strongly favored optimization models over simulation models (**question C2** in **Appendix C**).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

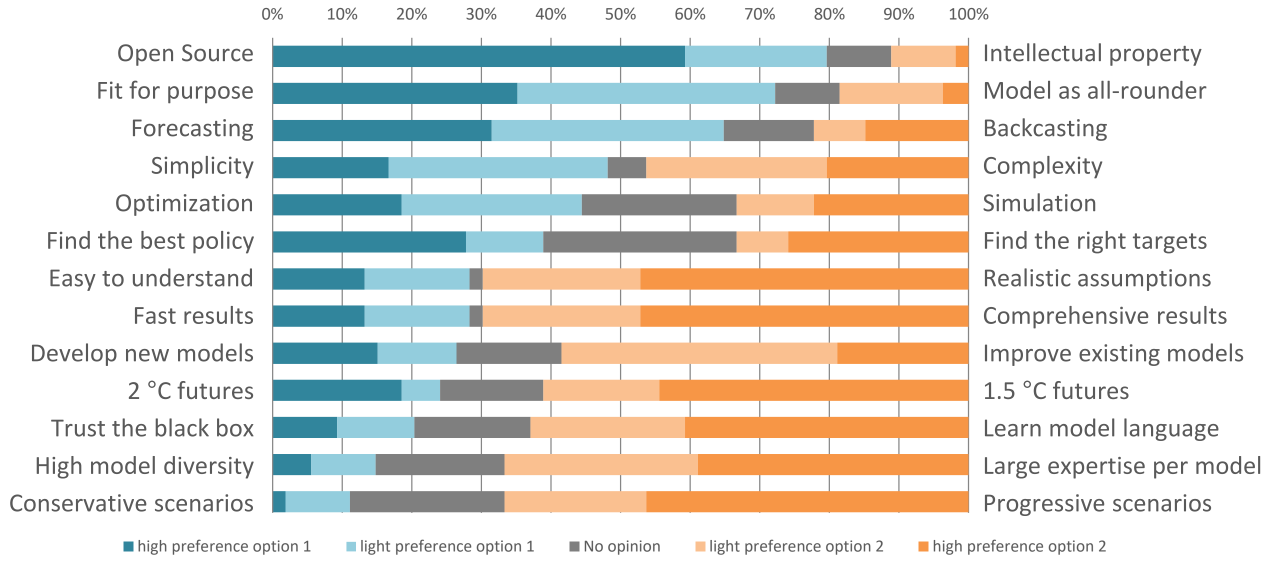

Figure 12: *Which model feature/quality is more important? (voluntary, Likert scale), N: 55; figure sorted by total share of "light" and "high preference" of the left option; "no answers" excluded from the figure (2-4% for all trade-offs); remaining answers normalized to 100%*

Furthermore, participants were asked to rank the importance of four widespread solutions to uncertainty management in modeling (**Figure 13**). We find that transparency is most important (51%), followed by realistic model assumptions (24%), scenario analysis (14%), and sensitivity analysis (12%). The well-represented fraction of the scientific community (32 out of 55 respondents) overall determined in no small extent the cross-group result. However, differences between the groups exist: for example, none of the policymakers ranked realistic model assumption highest, while NGO representatives did the same for scenario and sensitivity analysis.

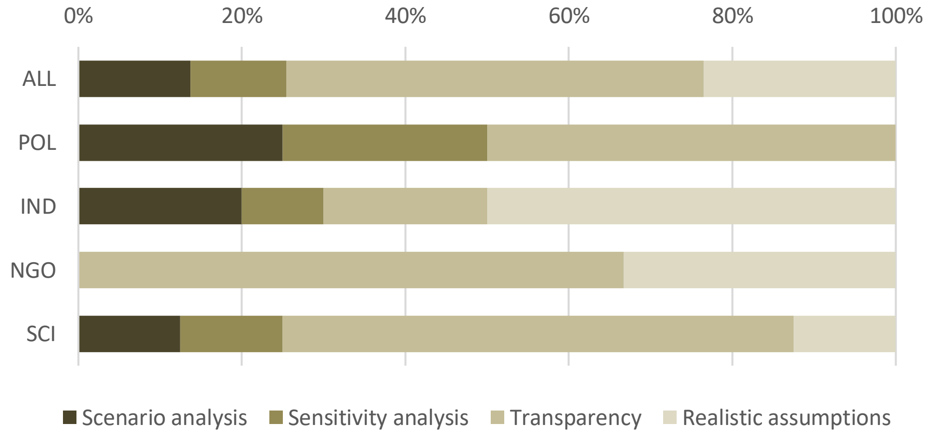

Figure 13: *How important are the following measures to reduce model uncertainty? (voluntary, ranking), N: 51; the figure shows the distribution of uncertainty solutions ranked to the 1st place*

We also provided the participants with the opportunity to clarify their rankings. One of the respondents stated, *"[…] that uncertainty comes in many flavors, and each has its own appropriate set of remedial actions."* Another respondent wrote that transparency should be operationalized as open-source models, code, and data on public platforms (e.g., GitLab), as it assures quality.

Respondents suggested as further solutions for uncertainty management the explicit modeling and presentation of uncertainty (as a model output), and the use of stochastic models. However, stochasticity was seen quite critical by another respondent: *"In general, the way people deal with stochasticity is overly simplistic; either brute force scenarios or cherry-picked scenarios. Sampling techniques like genetic algorithms, and Latin hypercube (and the combination of both), should be widespread because those sample more evenly, more representative (likely) scenarios."*

3.3.4 Modeling process

Participants, who neither had worked with models nor were indirectly involved in modeling so far, were asked to report their need of own involvement (cf. **question D1** in **Appendix C**). Overall, we find that a high share of respondents likes to be involved in the conceptual development or improvement of models (79%). Almost half of the respondents even stated that their involvement is "very important" (45%). In group comparison, the energy industry and NGO representatives signaled stronger interest than the scientific community.[14]

Furthermore, a large share of 89% of all modeling process respondents in the questionnaire had already contributed to the development or improvement of models, 72% even frequently (cf. **question D2** in **Appendix C**). Scientists were most experienced (83% frequently), followed by the energy industry (80%) and NGO representatives (50%). A large majority of these experienced stakeholders were satisfied with their involvement (**Figure 14**). About every second respondent found it very beneficial and would like to contribute again (54%), and nearly every fourth respondent found it "mostly beneficial" (27%). Although no respondents were mostly or very disappointed about the modeling process, some assessed their involvement as "ambivalently" (15%).

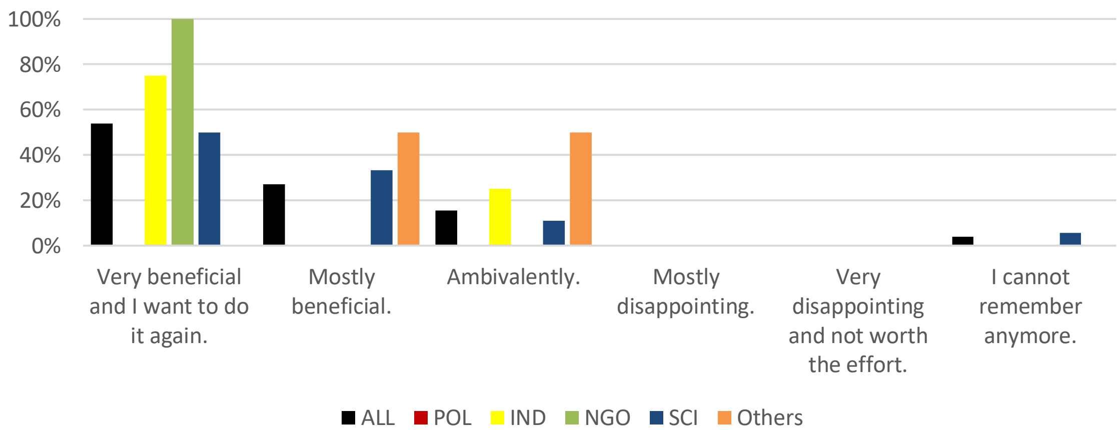

Figure 14: *When looking back, how useful was the involvement in this process for you? (mandatory, single choice), N: 26*

[14] As policymakers were not interested in the contribution to the modeling process (as indicated in A13), no group-specific data is available for the whole question section.

Participants who develop models technically or run and apply them were, on the contrary, asked about the involvement of external stakeholders in their model development or improvement (cf. **question D4** in **Appendix C**). About every third question´s respondent has not involved stakeholders so far (33%), involved them once (29%), or frequently (38%). Many of those modelers who had involved externals once or several times found the involvement very and mostly beneficial (64%). Two respondents were mainly disappointed (14%), and one arrived at an ambivalent judgment (7%). We also asked them about their satisfaction with the involvement of different external stakeholder groups. Overall, we find that many modelers highlighted the involvement of each group as positive (range of a sum of "somewhat important" and "very important" between 67% and 95%). Importantly to note, four out of five respondents assess the involvement of the scientific community as "very important" (81%), while these shares are significantly lower for the other stakeholder groups (29-43%; **Figure 15**).

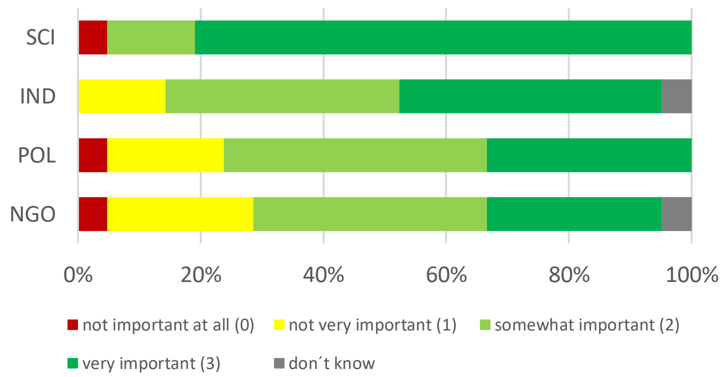

Figure 15: *How important for you is involvement of the following groups in your model development and improvement process? (mandatory, Likert scale), N: 21; figure sorted by total share of "not important at all" and "not very important"*

We also asked about when the exchange between modelers and stakeholders is essential (**Figure 16**). We found that it is "very important" most often for defining assumptions (77%), developing scenarios (73%), and discussing and interpreting model results (67%).

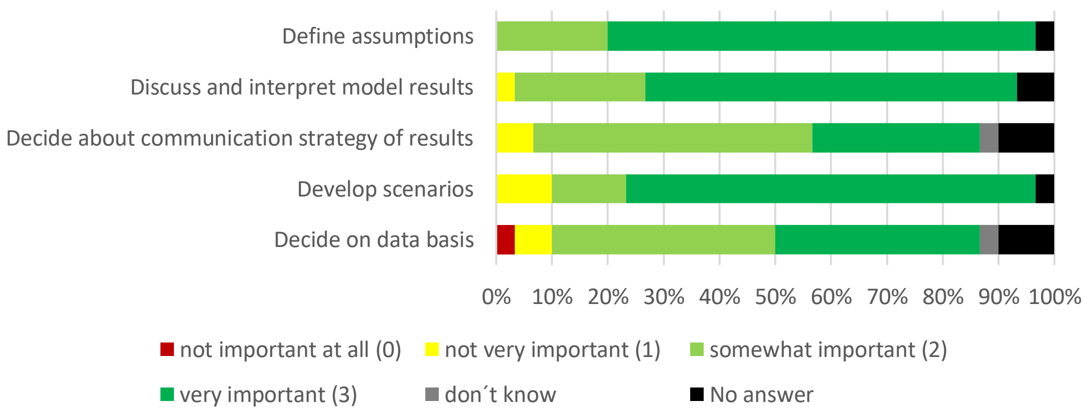

Figure 16: *How important is the exchange about the following aspects between model developer and external stakeholders for you? (voluntary, Likert scale), N: 30; figure sorted by total share of "not important at all" and "not very important"*

Group-specific differences are relatively small, while the overall result is strongly influenced by the large share of scientific contributors (19 out of the 30 respondents). However, it is "very important" for all energy industry representatives to exchange between model developers and external stakeholders about defining assumptions and deciding about the data basis.

3.3.5 Model outreach

To derive important information for our model and platform communication, we asked the respondents about their preferences regarding different model communication types. Here, we found that all predefined communication options seem to be valuable (**Figure 17**): the sum of "somewhat valuable" and "very valuable" replies ranged from 62% to 90%, with model graphs and figures being most favored (90%), followed by case studies of model application, model presentation, and the direct exchange with modelers on the second place (each with 86%). However, we found model graphs and figures (64%), model databases with input and output (62%), and case studies (52%) are the most desired communication types ("very valuable"). Differences between the groups are relatively small for each communication form and do not oppose its overall result. However, the group-specific ranking can differ from the joint perspective.

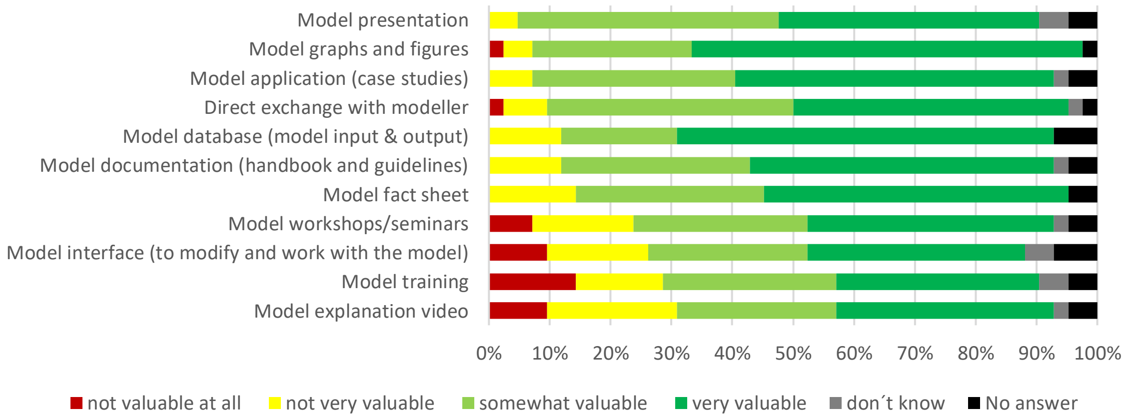

Figure 17: *How valuable are the following forms of model communication for you? (voluntary, Likert scale), N: 42; figure sorted by total share of "not valuable at all" and "not very valuable"*

We, furthermore, found that respondents mostly need information about the functionality and use cases of specific models (67%), model overview and catalog (64%), training material for the model application, and description of the relation and linkage of different models on the platforms (55%; **Figure 18**). Besides these predefined aspects, respondents saw a need for "other" platform assets. One respondent would also like to see a *"description (and perhaps metrics) of the communities associated with each model and the options for engagement"*, and another participant emphasized the importance of the possibility to download model results data.

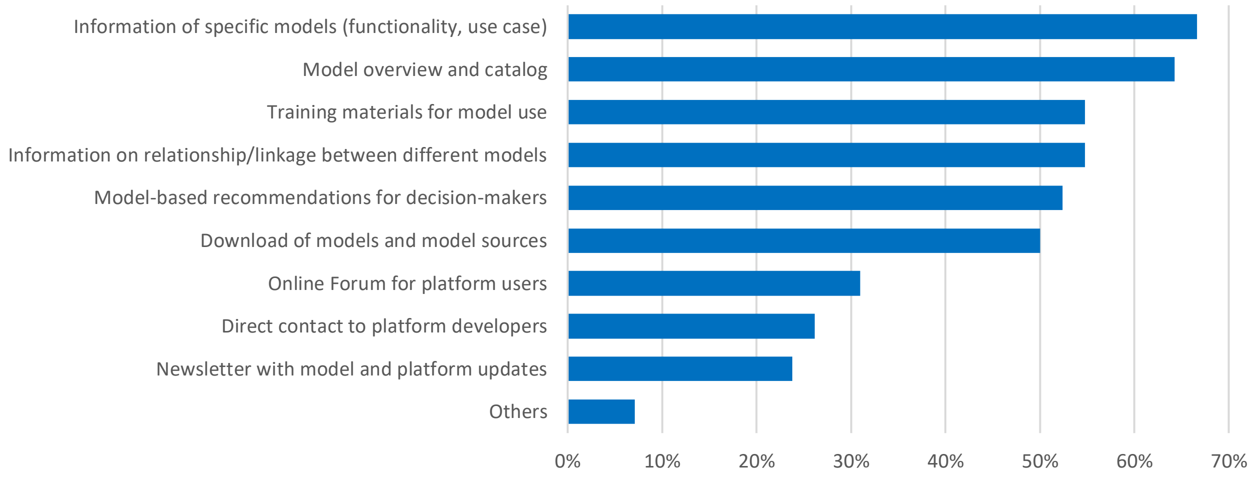

***Figure 18:** What is essential for you to use the model platform?*
(voluntary, multiple choices, minimum 1), N: 42; figure sorted by total share

About 40% of the participants indicated that they would like to use the model platform directly, while about 30% were still not sure yet (**Figure 19**). Most of the potential users come from the scientific community. Modelers in NGOs were less interested in using the platform, followed by the energy industry representatives, while all policymakers were unsure about using the platform.

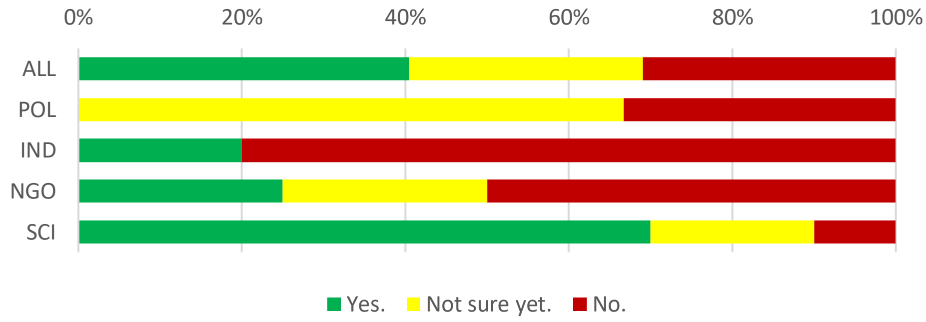

***Figure 19:** Would you be interested in using that platform directly as a modeler? (mandatory, single choice), N: 42*

Participants, who were already sure to use the model platform, were asked about technical preferences of different technical decisions in the platform design connected to the communication and interaction with users. A large majority wants to use a programming language as a basis of interaction (71%), less prefer a web application (18%) or a graphical user interface on their desktop (6%). Those participants who prefer a programming language use Python most often in their analysis (83%). Every third modeler also uses C/C++ and R (both with 33%). These participants also favored dedicated graphical environments and general-purpose graphical editors (both with 42%) as preferred integrated development environments (IDE). Every fourth user prefers the command line (25%), and two respondents admitted that they do not know which IDE they use (17%). Those two respondents who prefer a graphical user interface (GUI) to interact with the platform voted for Excel and Libre office. Besides, every second modeler uses Windows (53%), followed by Linux (23%) and macOS (18%) as their preferred operating systems.

Last, we asked about recommended modeling platforms. Six modelers, five from the scientific community and one from NGOs, recommended additional platforms: GitHub, GitLab, the 'Open Energy Modeling Initiative' and its free energy mod list/wiki, the 'Strategic Energy Roadmap Scenario Explorer', and the project 'Integrating Integrated Assessment Models' (for corresponding URLs see **Appendix C**).

3.4 Online workshop

We conducted an online stakeholder workshop to prioritize previously identified user needs and derive specific user needs for the SENTINEL models and the modeling platform. The workshop focused on the demands for the model content, while model design and outreach were mainly addressed in the workshop's main session.

3.4.1 General demands for energy models

To identify the most critical aspects of the modeling content, we, first, asked the stakeholders which factors should receive more attention in energy models. We find that the top four ranked thematic aspects to be integrated into energy models are: (1) the impact on the environment and natural resources, (2) policy impact/implication of different policy options, (3) total costs and investment costs, and finally, (4) social impacts of the transition (**Figure 20**).

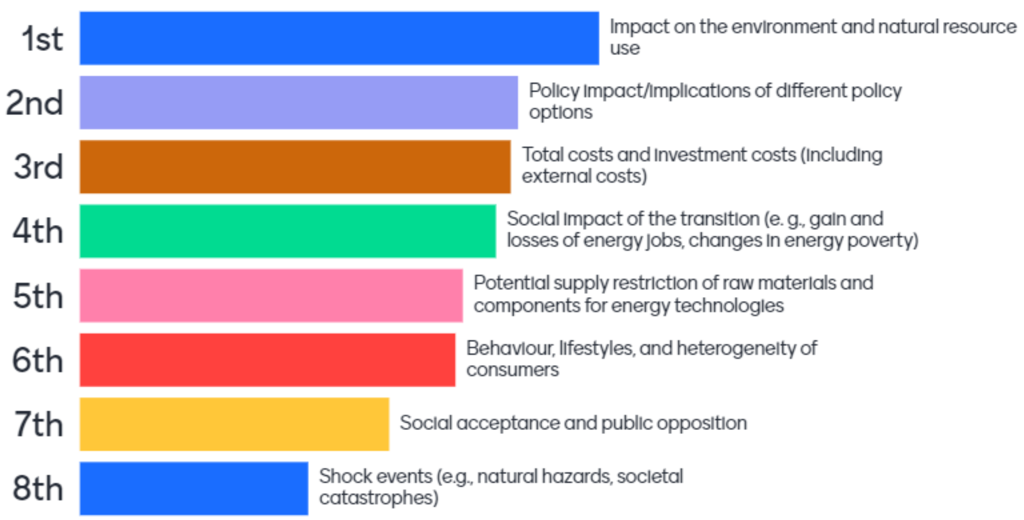

Figure 20: *Ranking to the question: Which of the following factors do you think should receive more attention in energy models? (N: 28, live poll)*

The second live voting addressed the model design question of which model feature/quality is more important to the participants. Voting results highlighted a clear consensus on models' ability to analyze progressive scenarios and scenarios with high environmental ambitions (1.5°C futures; **Figure 21**). However, we find no clear answer if models must rather be easy to understand or have realistic assumptions and if they should support finding the best policy options or rather the right targets.

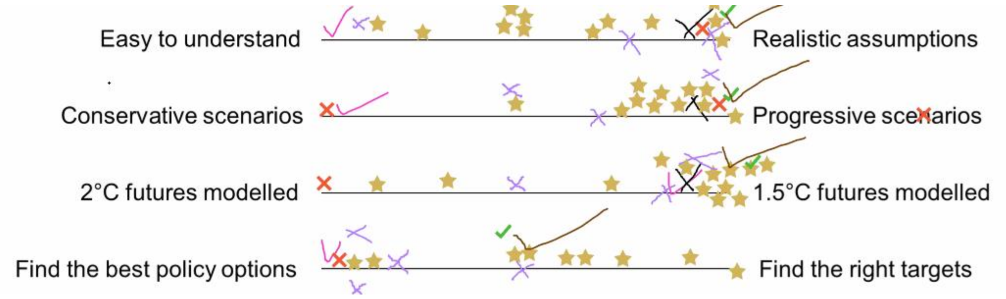

Figure 21: *Prioritization to the question: Which model feature/quality is more important to you? (N: n/a; live annotation with stars, crosses, and tick-marks optionally)*

The last live polling was dedicated to the modeling platform, and thus the outreach demand. We asked the participants what is essential for them to use the modeling platform. We find a high need for model overviews and catalogs (general model documentation), specific information on models (application in case studies), as well as information on linkages between models, and the ability to download models and sources on the SENTINEL platform (**Figure 22**).

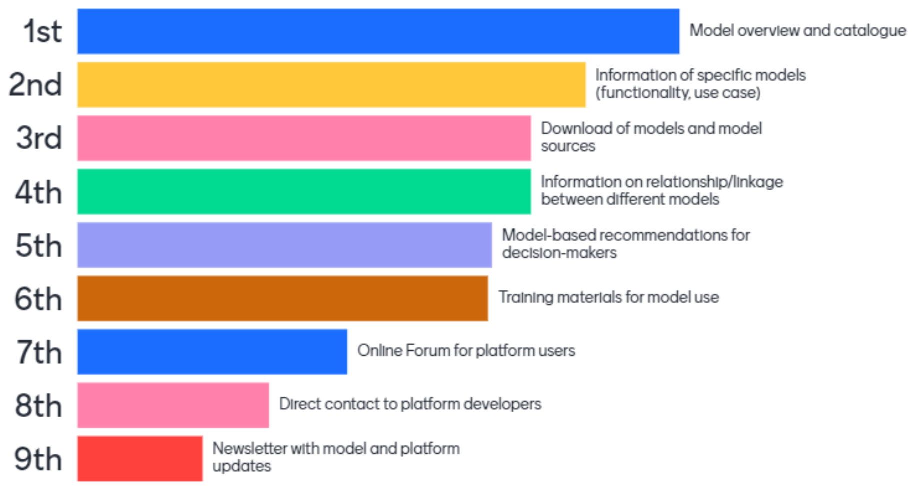

Figure 22: *Ranking to the question: SENTINEL will build a model platform that documents different models. What is essential for you to use it? (N: 22, live poll)*

A discussion followed the prioritization of user needs. One issue brought up concerned the models' ability to take various regulatory framework conditions into account – to model different incentives and mechanisms. One participant emphasized the differentiation between policies and regulations and how both affect each other. Furthermore, one stakeholder raised the importance of presenting modeling results at the modeling platform so that stakeholders can dive into more details and build up their future work. The presentation would lead to an increased understanding of models and more transparency of modeling results. Last, one participant expressed the need for energy models that include agricultural activities.

3.4.2 Specific model content demands for energy models

Beyond the plenary session, we identified further demands for specific modeling themes. The virtual recordings of the sessions can be found in **Appendix F** (**Figure 27-Figure 32**).

In session 1 – social and policy aspects in energy models – we asked the stakeholders what non-technical aspects are currently missing in energy models. Using the word clouds function of 'Mentimeter', we find that different aspects regarding citizens/consumer behavior, social choices and impacts, environmental impacts, and policy and policy frameworks are essential for the stakeholders (**Figure 23**). As a next step, different needs for the integration of these aspects had been discussed. These include: (i) the need to understand the science and to compare it with ongoing policy processes, (ii) to understand the social implications of different energy scenarios, (iii) to understand how policy changes can trigger behavioral changes, and (iv) to measure distributional impacts, like for example local (co-)benefits, but also actual and perceived costs on less wealthy parts of the society.

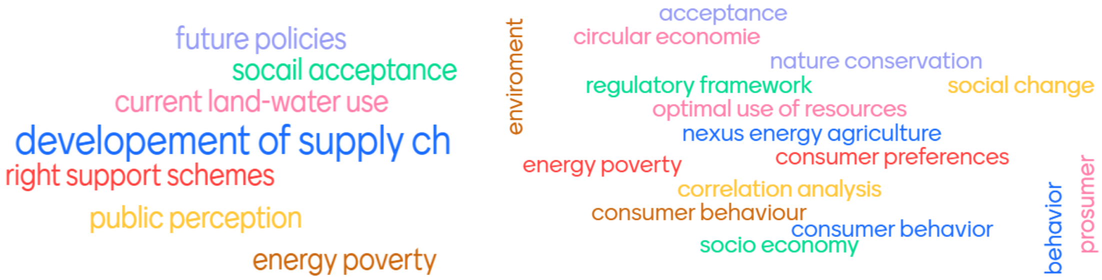

Figure 23: *Answer to the question: What non-technical aspects are, from your perspective, missing in the models or model results that you use? (N: 9, live word clouds, from 2 rounds)*[15]

Next, we conducted a live poll to address the most important social aspects to be integrated into energy models. We find that the workshop participants demanded the improved integration of the impacts of social issues on energy politics (e.g., forced by social movements), the social acceptance of energy technologies and infrastructure, and consumer behavior in energy models. Nevertheless, all aspects have been ranked relatively high, and no element appeared to be irrelevant (**Figure 24**).

[15] Color and size have no meaning in the figure.

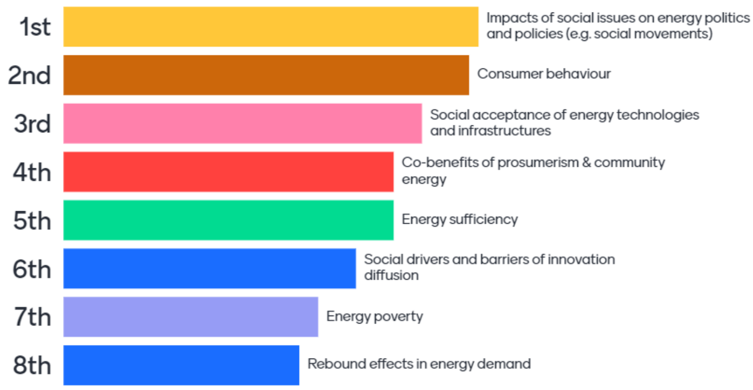

Figure 24: *Answer to the question: What's most important to be (more) integrated? (N: 7, live poll, first round)*

In session 2 – integrating environmental aspects – we began by asking participants to list environmental aspects or impacts that they think are important to include in energy modeling. After using the '*Mentimeter*' word cloud board to identify needs, we have processed the frequency of responses by our own environmental (and social) categories as follows:

1. Nature and biodiversity: 5
2. Full life cycle impacts: 4
3. Electromagnetic & noise pollution: 2
4. GHG and other emissions: 2
5. Raw materials/circularity: 2
6. Human health: 1
7. Water pollution: 1
8. Land use: 0

We next asked participants to repeat the above process using a matrix in the 'MIRO' application to prioritize these categories. Participants were asked to write text within 'sticky notes' and then place these blocks of text onto a matrix that included four priority scores – *must, should, could,* and *won't* – according to the 'MoSCoW' method (IIBA, 2009). The blocks could also be grouped by user type – science, policy, industry, and NGO – regardless of the group, they fall into themselves (**Figure 25**). Importantly to note, no opinions were posted for the 'won't' score.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

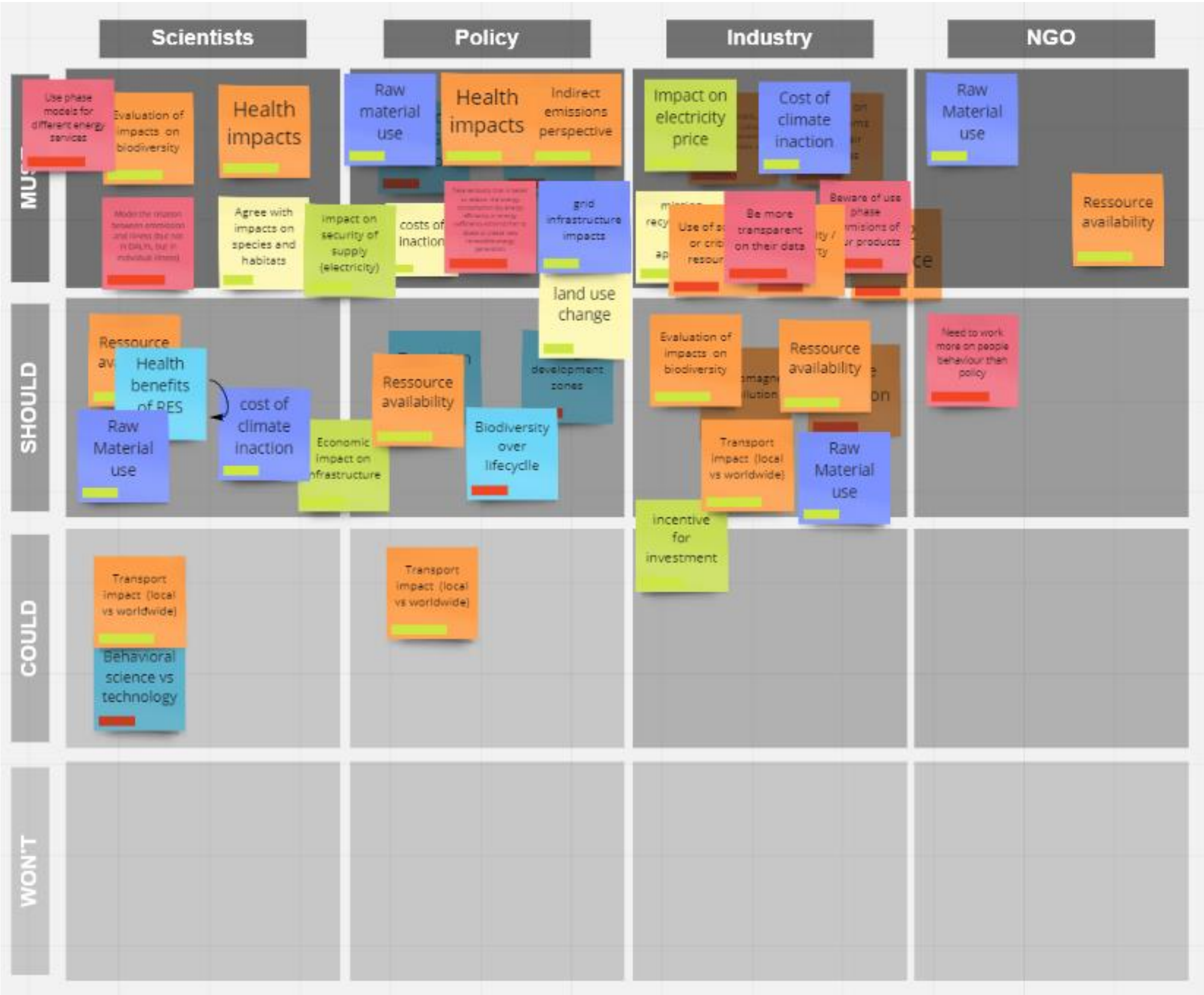

Figure 25: *Responses to the question: What environmental aspects are needed? (N: 7)*

By weighting the 'must', 'should' and 'could' scores with four, three, and two points, respectively, a final score for each category of environmental issues/impacts were derived as follows:

1. Raw materials/circularity: 39
2. Nature and biodiversity: 22
3. Full life cycle impacts: 21
4. GHG and other emissions: 12
5. Human health: 12
6. Electromagnetic & noise pollution: 6
7. Land use: 6
8. Water pollution: 0

Lastly, to assess why these categories were deemed essential and how they will be used, we undertook an interactive exercise by allowing participants to write their thoughts within a *'MIRO'* mind mapping sheet and launched a discussion to clarify the added points. We find three key categories:

1. To aid decision-making processes
2. To enable links to other models, policies, and strategies
3. To facilitate citizen empowerment and stakeholder engagement

Session 3 – energy demand and supply – started with a presentation about the importance of modeling energy demand and supply, and the introduction to the four energy demand models (DESTINEE, BEVPO, HEB, and DREEM) as well as the three energy supply models within the SENTINEL modeling framework (EnergyPLAN, Calliope, IMAGE). Both the demand and supply models play a vital role in supporting policymaking and decision-making. A discussion of key questions followed the presentation: What do you think a demand model should assess and till what time (2030/2050, 2100)? What kind of supply modeling is crucial to you?

Based on the discussion, we find that demand and supply models should be used to model demand and supply of energy for 2030 and 2050 (decarbonization targets of the European Union). Modeling for 2050 to 2100 involves too much uncertainty, and it has been perceived to be like *"modeling the unknown"*.

Moreover, we find a high demand for modeling behavioral aspects, such as prosumer and consumer profiles, demand-side management, and demand responses. These aspects are important because they could provide flexibility and balancing services to the grid. Furthermore, we discussed that renewable energy production, including building-integrated renewable energy generation, varies geographically, and this is an aspect that should be incorporated in the demand and supply models.

In addition to modeling demand and supply, we also identify that it is vital to understand and acknowledge the essential role of strategic investments in technological innovations, such as hydrogen, battery storage, and system integration, to achieve 100% renewable energy production. This aspect of assets demands much more emphasis on the coordination of demand and supply modeling. Although some of the key effects of energy efficiency measures, such as digitalization, are already considered in demand models, we identified further needs. Smart features (e.g., smart appliances) should be incorporated in energy demand models, and energy efficiency should also be modeled in supply models.

In summary, we identify four key gaps in demand modeling that should be tackled:

1. Modeling of lock-in effects
2. Integration of renewable and energy-efficient measures
3. Modeling of the 'human factor'
4. Data scarcity in energy demand modeling

Session 4 – economic impacts of the energy transition – started with a presentation about the relevance of modeling and an introduction to the three economic-focused models within the SENTINEL modeling framework: EMMA, BSAM, and WEGDYN. We presented the critical model improvements planned and discussed the models' relevance, model improvements, and model linkages with the participants. We received a high ranking for all three aspects in 'Mentimeter', with different weights in the two rounds (**Figure 26**).

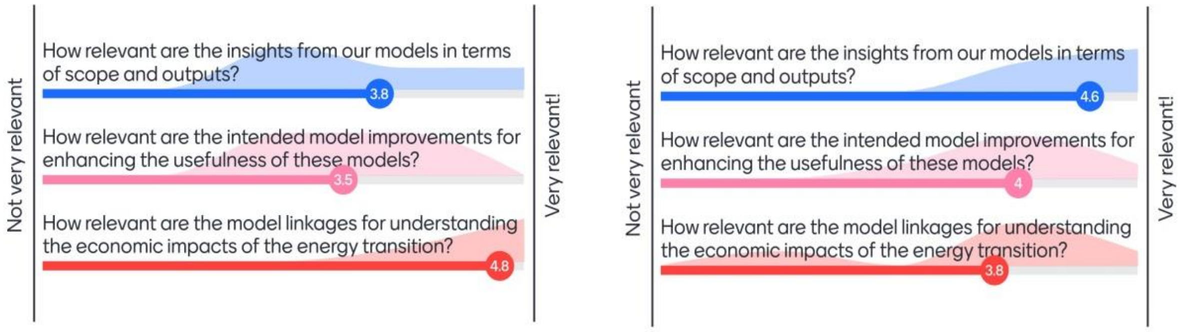

Figure 26: *Responses to the questions of the relevance of the models, model improvements, and model linkages (round 1 with N: 4, round 2 with N: 6, live poll)*

A discussion followed the live ranking. The debate revealed the significance of temporal and geographical resolution of models to be considered when inter-linking models. The participants emphasized the importance of harmonized model inputs and outputs during modeling exercises. Furthermore, we find the demand to model pathways towards a point in time instead of simulating specific moments because it would make modeling analyses much more dynamic. A steady perspective allows highlighting concrete steps and milestones along the way necessary to achieve societal targets such as the 'well below 2°C' objective of the Paris Agreement.

Additionally, an important point discussed was the topic of uncertainty. Participants expressed the demand to communicate model uncertainties transparently. This can be done by comparing the outputs of different models with similar scope and conducting sensitivity analyses both in a standalone and in a soft-linked manner to find the most important factors related to the models' outputs.

Moreover, we identify the need for a better consideration of issues such as energy poverty at the micro-level in models and accounting for achieving emission reduction targets at the macro level. In looking at such trade-offs, the stakeholders consider it necessary to analyze how to manage or overcome them. This could be done by using multiple criteria for measuring societal well-being when comparing different energy system designs.

We also find specific needs linked to session 1 and session 2. Participants stated that models should capture the social aspects (e.g., social acceptance of new technologies or citizen lifestyles) of the energy transition. Policymakers specifically demanded that insights regarding the environment and society should be provided through modeling exercises.

Another key takeaway is that revenue streams of the centrally organized energy system (i.e., few large utility companies) will shift from wholesale markets to ancillary service markets because of the increasing share of generating variable renewable electricity de-centrally. Towards this direction, the session participants have seen demand-side management to provide significant additional value.

Last, we find that policy implications based on the model results should consider the timing of decommissioning and policies for renewables to derive business models and strategies for the coming years.

Session 5 – the modeling platform – was about the technical aspects of developing the SENTINEL energy modeling platform. Modelers from the SPINE and the openENTRANCE projects participated in this session and shared their opinions on needed development and synergies between the projects.

One participant remarked that a primarily text-based data format is challenging to scale to large datasets. Thus, there is a need to extend the frictionless data package to existing binary data formats like HDF5 and NetCDF.

The participants of this session compared the workflow managed in the SPINE project and SENTINEL. The SPINE project provides an integrated workflow solution based on the Python library dagster. In comparison, the SENTINEL modeling platform does not propose any solution to manage workflows; it is solely focused on the frictionless data format. This choice is motivated by the desire to accommodate diverse working environments. That said, providing workflows for frequent repetitive tasks like dataset creation has been identified to be useful potentially.

Another point of discussion was data validation. We find potential overlap with the SPINE project, and there is potential for collaboration on this topic. A common requirement for both projects is validating against foreign keys, meaning that a condition should validate a part of the dataset on a different part of the dataset, e.g., when a model has definitions of entities, forming an allowed set. The next step will encompass checking in another part of the dataset if an entity is present in the allowed set.

Furthermore, we find there is a common requirement to reconcile different temporal and spatial resolutions. Often the basis of segmenting data may be incompatible, e.g., a spatial dataset can be segmented by administrative regions or structurally, say, a power company might segment demand data based on their installed capacity. This issue does not have a clear solution. However, the issue of scale is partially addressed by the SPINE toolbox by defining 'moldable regions'. It retains the data in their most granular units and aggregates them to create the larger units as needed.

Last, the topic under discussion was the Application Programming Interface (API) design. One possibility that emerged from the debate was to follow match the API used by the SPINE project to read/write datasets. This approach will improve the compatibility between the SENTINEL platform and the SPINE project.

4 Discussion

We find a variety of needs in the four categories of model content, model design and data, modeling process, and model outreach. The differences between the stakeholder groups were mostly small but significant for some identified needs.

Decision- and policymakers demand models that can help them to define policy goals and strategies, assist in policy formulation, and assess policy impacts. Furthermore, we show a demand for a broader consideration of the impacts of the energy transition. Stakeholders have given priority to take into account the overall environmental impact, policy implications, macro-economic and investment costs, and social impact to identify the effects of different decision options for society.

This request for a more systemic approach in modeling is also reflected in the user need to integrate all energy-related sectors into the models and the need for improved temporal and spatial resolution to take account of the local impacts of the transition. Although we note some differences between user groups in terms of model design, all users strive for model transparency, reliable and open-source data, and realistic assumptions. Furthermore, modeling of progressive scenarios and a 1.5°C future were prioritized user needs.

Users demand simple, understandable, visually appealing, and actionable model communication and want to be involved in the modeling process. Last, we find great interest in the SENTINEL modeling platform with high priority requirements. In particular, the platform should provide information for different users, an overview of the contained models, and descriptions of their application in specific case studies.

4.1 Synthesis of findings

4.1.1 Need for a holistic and systemic perspective of the energy system

Our literature review, the interviews, and the online survey confirmed that models should provide a holistic and systemic perspective that includes all goals, dimensions, sectors, and technologies of the energy system, its transition, and the interlinkages between the system elements.[16]

Potential users of models and model results consider different targets for energy change and related energy, climate and other policies to be important. These include security of supply/resilience, climate-neutrality, cost-efficiency, nature protection, low-hazard technologies, affordability, energy efficiency, social acceptability, human health, and free trade of energy. Thus, modelers should consider a broad spectrum of political goals in their models, as successful

[16] We use the term 'holistic' in the sense of a comprehensive scope. As addition, the term 'systemic' emphasizes the interlinkages within the scope.

transition pathways from a systemic perspective should avoid negative and promote positive side-effects of energy policy in adjacent policy fields (like, e.g., healthcare). Democratic systems react to side-effects in various ways, like significant media awareness for negative side-effects of energy policy, changing acceptance of political leadership in society, amending policy packages by the ruling governments, or changing voting behavior in coming elections. Therefore, models that want to successfully and foresighted advise politicians and other decision-makers should take a multi-goal or multi-criteria approach for increasing the chance of being heard.[17]

Potential users perceive a variety of aspects of all system dimensions essential for the energy transition. Stakeholders named environmental, cultural, social, participatory, political, administrative, legal, economic, technological, and other aspects in the interviews, survey, and workshop. We find that some of these topics, especially for the modeling of transition, currently seem to be more in the spotlight than others. Two prominent examples are modeling social aspects (cf. **Section 4.1.3**) and policy (cf. **Section 4.1.4**), which is also in line with the literature (compare, e.g., Pfenninger et al., 2014; Trutnevyte *et al.*, 2019).

In the interviews, many stakeholders expressed a need for a stronger interconnectedness of different sectors. In the survey, we also collected questions that were of specific relevance to the respondents (see **questions B 6-12** in **Appendix C**). Although much emphasis has been put on the electricity sector in the past, more attention is currently paid to heating and transportation. This attention has primarily shifted in countries that progressed much in the renewable electricity transition. Still, many strategic energy system models neglect the role of grids in a sector-coupled future, not least because the size of the models and their running times grow exponentially if it is considered. Compromises must be made between different system borders and resolution levels, at least as long as the next generations of high-performance computers are out of reach. Thus, an ongoing discussion with the potential users about the model's purpose and required resolution is essential (cf. **Section 4.1.5 and 4.1.8**).

In term of specific technologies, we also find the demand to integrate a diversity of technologies, including CO_2-neutral energy carriers and storage technologies (e.g., power-to-X, hydrogen, Carbon Capture, Storage, and Utilization), new solar applications (e.g., integrated PV), and innovative wind technologies (e.g., Far-Off-Shore) into models. These are the most pressing technology topics. However, there are also other options with less modeling demand, which could, however, still be promising to be included, for exploring ambitious pathways compatible with the Paris Agreement: when innovative technologies, e.g., the next generation of nuclear power plants (fusion reactors, or fission of nuclear waste), are excluded from modeling for whatever reason, science could miss opportunities of surprising outcomes that can support the achievement of a climate-neutral and just energy future. Also, modelers could be confronted with the argument of

[17] An overview of multi-criteria assessment approaches towards sustainable renewable energy development can be found, e.g., in Kumar *et al.* (2017). An explicit multi-goal framework to assess energy policy for the energy transition is provided and discussed, e.g., in Gaschnig and Göllinger (2019).

unscientific prejudice, which could limit the trust in and legitimacy of models. Our results do not support technologies' exclusion; they can only show technology integration order into models.

4.1.2 Need to integrate environmental sustainability broader

We find that users define environmental sustainability much broader than climate change mitigation. Many stakeholders demanded to include the impact on the environment and the use of natural resources of the energy system into models, with its pure physical consequences and monetarized as external costs (see **Figure 7, Figure 9, Figure 20,** and **Figure 25**).

Raw material demand and circularity, (further) greenhouse gas emissions, air pollution, and biodiversity loss were of paramount importance for users. We observed slight differences between the different methods (e.g., water usage/pollution was ranked high in the survey but low in the workshop) and stakeholder groups (e.g., overall, IND scores lower for environmental factors than NGO). The demand to progress on environmental topics is in line with Lopion *et al.* (2018), who analyzed eco-technical challenges and modeling trends. These researchers emphasized that models should be able to deal with Paris Agreement Scenarios and must include all sources of the various greenhouse gas emissions and their process chains.

High material and area intensity of renewable energies and the increased demand for rare earth metals by innovative energy technologies are crucial risks for the success and acceptance of the energy transition pathway due to limited land and resources availability. Moreover, the different impacts of climate change and its adaptation are still underrepresented in many energy models, leading to unfavorable decisions. One solution, which could address a drawback stemming from this finding, is to start working on modeling tools that combine existing energy models with climate and other environmental models. While it would undoubtedly increase the complexity of modeling tools (cf. **Section 4.1.5**), it could also show a broader range of potential effects or action pathways.

4.1.3 Need to integrate factors and human behavior better

Behavior determines path dependency and path change like nothing else. If there is still a chance to reach the Paris Agreement and the 1.5°C climate target (or even the 2°C target), we need social acceptance and must overcome societal barriers. Humans define and change natural and social systems – especially by altering lifestyles, investment decisions, and political inaction into action. The demand to put social factors and human behavior in the center of attention is the core message we received when looking into user and stakeholder needs. Different social and political aspects of the energy transition were mentioned with emphasis by interviewees and ranked high in the survey and the workshop (see **Figure 7, Figure 8, Figure 20,** and **Figure 23**). Much attention received behavior, lifestyle, and heterogeneity of consumers, the co-benefits of prosumerism and community energy, the social drivers and barriers of innovation diffusion, the dynamics of social acceptance and individual attitudes, and societal impacts on energy politics (e.g., forced by social movements).

As confirmed by our literature review, many research and modeling teams have started to emphasize the importance of the human dimension in the socio-technical transition (see, e.g., Pfenninger *et al.,* 2014; Koppelaar *et al.*, 2016; Bolwig *et al.,* 2019; Gambhir, 2019; Trutnevyte *et al.*, 2019; Martin *et al.*, 2020). However, a research gap still exists between socio-technical transition and social theory and their representation in energy-related computer models. The critical voices emerge from the models´ limited representation of *"societal actors and socio-political dynamics, poor representation of the co-evolving nature of society and technology, and hence an inability to analyze socio-technical change"* (Li et al., 2015:290).

The model criticism comes from unrealistic assumptions and substantial abstractions, which modelers need to overcome. According to Trutnevyte *et al.* (2019:425) only a few mapping attempts regarding conjectures on societal transformations in models have been made. The existing overviews include assumptions like *"aggregate social planners with or without perfect foresight, rational decision-makers for investment and dispatch, households of various income, and so on."* These authors have mapped challenges for the following three fields within the social dimension: (1) behavior of all types of actors in transformations, (2) transformation dynamics in time, and (3) heterogeneity across and within society. Although the identified high-ranked challenges are 'soft' aspects (meaning hard-to-grasp and challenging to operationalize), socio-technical transition modeling can be described as a 'rising star' for modelers and model result users. Stakeholders expressed an urgent need for empirical data that reliably describe causal social relations. Thus, interdisciplinary work that directly integrates social science data or social scientists is a fundamental requirement for well-designed and often-used socio-technical transition models (cf. **Section 4.1.7**).

4.1.4 Need for policy models for supporting policymakers

We find that policymakers demand models that can support decisions about policy instruments and help assess policy impacts. Stakeholders especially urged improved models for developing strategies, formulating policies and measures, assessing policy impacts ex-ante, and setting and implementing agendas and targets of specific policies (in descending order). Thus, four out of the 'Top 5' demanded modeling purposes deal with concrete policy interventions. And when explicitly looking at the modeling trade-off between "Finding the best policy options" and "Finding the right targets", we find a clear preference of policymakers for the analysis of policy options (see **question C2** in **Appendix C**). Furthermore, the interviews showed that exact numbers are not highly relevant, but rather the identification of action corridors. Interviewees emphasized the relevance of aligning modeling and decision-making speed to increase the use and significance of modeling results.

Policy modeling attracted increasing attention by modelers in the past, and some have already reacted to this need (e.g., Stalpers *et al.,* 2009; Halbe *et al.,* 2015; Holtz *et al.,* 2015; Koppelaar *et al.,* 2016; Metcalf and Stock, 2017; Ernst *et al.,* 2018; Pye *et al.*, 2020). These authors have understood that change in a path-dependent system must be driven by policy, as exogenous change is dominant in such systems. However, further efforts are necessary to build better policy (option) assessment models, which consider, e.g., also the existing legal framework (statement of a workshop participant) and the interplay between different system elements (Trutnevyte *et al.*, 2019a). Until behavioral aspects and reliable empirical data become an integral part of such models (cf. **Section 4.1.3**), realistic results will stay a matter of 'luck'. Thus, modelers should add further efforts to include these aspects and, in turn, to arrive at more reliable policy models.

Additionally, modelers should speed up model improvement and application. As political debates are changing fast, modelers face the challenge of finding ways to integrate new policy suggestions and arguments much quicker into their models. High modeling pace might help to be relevant for actual decision-making, e.g., by anticipating future discussions more precisely and following present debates more closely if modelers can only slowly accelerate the modeling process, which is a goal by itself. Perhaps, having a simplified but faster version of a model would support some decisions during the policymaking process. In contrast, a more complex version of the same model could provide more detailed information at the later stage of this process (cf. **Section 4.1.5**).

4.1.5 Need for target-group specific model designs

When modelers design a model for the first time and apply it, they need to make many fundamental decisions. These decisions can be challenging as a modeler has to decide (to a certain degree irreversibly) in which direction a model should develop, e.g., whether it should be a simple or a complex model, an optimization or simulation model, and so on (see also Ellenbeck and Lilliestam, 2019).[18] These challenges can originate from real goal conflicts or are caused by resource limitations. For example, there are many possibilities for producing results (like 2°C or 1.5°C scenarios, conservative or progressive scenarios), but limited human resources in the modeling team and little public attention for a topic hinder such efforts (cf. **Section 4.1.9**). As we find no clear tendency in the interviews, we included various trade-offs in our survey and talked about them in the online workshop.

For three fundamental trade-offs, we find 'draws' on the aggregated cross-group level. Stakeholders did not show a clear tendency for model 'simplicity versus complexity', 'find the best policy options or the right energy and climate targets', and 'optimization versus simulation'. However, differences in the stakeholder-group-specific levels were significant.[19] Policymakers, for example, preferred simple models; NGOs liked complex models more. Policymakers clearly

[18] The recommendation to strive for a holistic and systemic perspective (cf. **Section 4.1.1**) contributes to the challenging trade-off 'complexity versus simplicity'.

[19] These results were significantly different from the average. However, the representativeness is uncertain due to the low numbers of group-specific participants.

preferred "Find the best policy options" over "Find the right targets", and energy industry representatives strongly favored optimization models over simulation models (cf. **question C2** in **Appendix C**). Thus, modelers should consider specific demands of their target group when they decide about these trade-offs. However, further measures are necessary because of the increase of actual complexity by some real-world developments, like, e.g., liberalization, flexibilization, and internationalization of energy and electricity markets (as listed in Pfenninger *et al.,* 2014). Options are using a diversity of specific and nimble models rather than a one-fits-all model and the combination of different methods like model modularity, flexibility, and degree of integration (see ibid). Additionally, now more than ever, modelers should include insights and practices from other disciplines and complexity science to deal with real-world complexity (see Trutnevyte *et al.*, 2019).

Most participants of the survey (and the workshop) have prioritized existing, fit-for-purpose, realistic, and open-source models. Besides, they want modelers to focus on comprehensive, progressive, and 1.5°C scenarios. Differences between the groups were relatively small. Reasons for the strong support of progressive scenarios are probably the high public and scientific acceptance of the Paris Agreement and the growing risk of a dangerous climate change. Given raised ambitions for climate and energy targets, it seems likely that these trends will continue.

The integration of weather and place dependency of fluctuating renewable energy production in the energy system was a significant driver of higher temporal and spatial resolution, since initial energy system models were supposed to deal with baseload and dispatchable plants (Pfenninger *et al.*, 2014). In general, newly-developed models are more flexible in spatial and temporal resolution, making it easier to adopt such models for changing research purposes (Lopion *et al.*, 2018). Our findings support the efforts to increase resolution, at least to a certain degree. The interviewees expressed the demand for higher temporal and spatial resolutions, also in specific geographical locations. However, high temporal resolution and high spatial/graphical resolution were among the design aspects with the weakest support among the survey participants. Therefore, we assume that stakeholders see resolution in the light of 'fit for purpose', meaning that its level needs to be chosen on a case by case basis. The stakeholders' operational level (EU, national, subnational, regional) might be one important influence factor for the question of whether the resolution fits the purpose.

4.1.6 Need for proactive management and communication of uncertainties

The interviews showed that modelers should communicate their logics, unique selling points, limitations, and uncertainties proactively and as open as possible due to the critical role of assumptions for the model results.[20] Overall, transparency was ranked highest in the survey among central solutions addressing the uncertainty challenge, followed by (in descending order) realistic model assumptions, scenario analysis, and sensitivity analysis. Thus, users see

[20] For a collection of uncertainty types and ways to deal with it, also see, e.g., some papers from our literature review: Pfenninger *et al.*, 2014; Mirakyan and De Guio, 2015; Ilmola and Rovenskaya, 2016; Koppelaar *et al.*, 2016; Hilpert *et al.*, 2017; Köhler et al., 2018; Stavrakas et al., 2019.

transparency also as a key duty of good scientific practice for uncertainty management (cf. also **Section 4.1.7**).

In addition, one breakout session of the workshop revealed that a focus on shorter time horizons could reduce uncertainty. Demand and supply models should be used to model demand and supply of energy for 2030 and 2050 (including the European Union's decarbonization targets). Modeling for 2050 to 2100 – often done by Integrated Assessment Models – involves too much uncertainty, and it has been perceived to be like *"modeling the unknown"*.

In contrast, other options to deal with uncertainty are not welcome. Unrealistic model assumptions like *"central planners with perfect information, excluding market competition and knowledge limitation effects"* (Koppelaar *et al.* 2016:1542) may reduce uncertainty for modelers. However, it can produce unrealistic model results, increasing tension for results users at the same time. The need for a holistic perspective (cf. **Section 4.1.1**) contributes to the tradeoff between complexity and understandability (cf. **Section 4.1.5**) and makes the trade-off challenging to solve. In that case, only a clear orientation towards the need for transparent assumptions can advance the trust in models and their modelers. Being open about what models can and cannot do (currently) defines good communication (cf. **Section 4.1.9**) through 'expectation management'.

4.1.7 Needs for maximal model transparency

According to the interviewed stakeholders and our survey results, model transparency is essential. In comparing features in the model design, transparency received significant support from stakeholders. Furthermore, other important model features depend on openness. Even experts cannot answer whether a model fits for purpose when assumptions about model input, throughput, and output are only visible to the developers. Third parties cannot reproduce and, thus, evaluate models if they are black boxes. The reliability of data depends on the possibility of looking into it. Trust in models cannot be built without transparency. Therefore, transparency is the basis of all sound scientific practice and must be a fundamental duty to the modeling world to ensure scientific progress (see, e.g., Pfenninger *et al.*, 2014; Kolkman *et al.*, 2016; Hilpert *et al.,* 2017; Lopion *et al.*, 2018). These findings are also underlined by the IPCC's Fifth Assessment Report, highlighting the lack of transparency to its Integrated Assessment Models as a risk to model results' credibility (Robertson, 2020).

So why are so many models still not fully transparent? One crucial factor might be that transparency can contradict the protection of intellectual property. In our survey, where we included this trade-off, a large majority of stakeholders still favored transparency over intellectual property. Therefore, funding parties should consider making transparency the default case of their research and development tenders. Besides, the missing availability of open data sometimes originates from data protection requirements. Data subjects, data stakeholders, and regulators must find common ground about data use ethics because our findings show that high quality, reliable, open-source data are a crucial demand.

Although high transparency is a fundamental goal of good scientific practice, its realization comes with subsequent practical problems. On the one hand, information costs about a model, measured by employees' invested time, are extraordinarily high (prohibitive) when data is not available. On the other hand, the rising quantitative availability of information also comes with growing information costs. Thus, the quality of availability (meaning well-structured, concise, and understandable information) becomes vital to reduce information costs to a reasonable level. Quantity and quality of transparency of models, code, and data are equally important for good scientific practice.

Unfortunately, the trend is in the opposite direction. According to Lopion *et al.* (2018), the number of open models has stagnated after strong growth in the 2000s, while the number of proprietary energy system models had a revival. Pfenninger *et al.* (2017a), for instance, recommend that public funding should incentivize open access to overcome the lack of transparency in model data and model code. To support and accelerate the trend, modelers who organize in the Open Energy Modeling Initiative have shared their experience in a practical how-to-guide for broader openness (Pfenninger *et al.*, 2017b).

4.1.8 Need for frequent involvement of diverse stakeholder

Stakeholder-informed modeling is an essential requirement for the inclusion of potential user needs and is the key to creating models relevant to policy decisions. Inter- and transdisciplinary modeling becomes even more crucial with the growing demand for more complex and realistic models that cannot be generated by disciplinary perspectives alone and is, therefore, necessary for acceptance and legitimacy. The interviewees confirmed these findings. Stakeholders want to be involved in the modeling process to increase model objectivity and build trust in models.

In general, studies with and without stakeholder participation on a possible and desirable energy system and transition in all its facets are numerous and represent the need to examine possible futures (**Table 5** in **Appendix A**). Here, we find that consecutive meetings between modelers and the same stakeholders have been best practices for iterative improvement (Stalpers *et al.*, 2009). Participation has the highest value when user engagement in the modeling process happens in *"a deep, meaningful, ethically informed and iterative way"* (Gilbert *et al.*, 2018). Thus, modelers can only build stakeholders´ ownership and trust in scenario planning if (a) project governance seeks to ensure that stakeholders make vital decisions on project directions, processes, and outputs, and (b) engagement is based on collaboration and partnership (Soste *et al.*, 2015).

The survey showed that modelers, who have experience in the modeling process, appreciate these collaborations and exchanges with external partners. They perceived all stakeholder groups as important discussion partners, but with a surprisingly high interest in the scientific community, compared to the other groups.[21] Defining assumptions, developing scenarios, and discussing and interpreting model results are the most exciting stakeholder engagement topics. Possible reasons for scientists' strong interest could be that (1) the modeling scientists with similar questions can support each other best, and (2) they do not stand for partial interests and overemphasize single aspects. However, too many unrealistic assumptions, abstract modeling results, vague model-based policy recommendations, and the strong influence of lobby interests often cause discrepancies between scientific findings and real policy decisions (see Süsser *et al.*, 2020). Thus, modelers must (1) understand and learn more about the stakeholders they want to advise, and (2) should actively seek every occasion to get in touch with their target audience.

As we identified, in particular, the need for high-performance policymaking support tools (cf. **Section 4.1.4**), it is essential to embed policymakers in custom-made participation processes focusing on current and probable political debates. Such model interaction opportunities are best designed to answer the policymakers´ urgent questions about target setting and existing and planned policy suggestions for the next steps in the energy transition. Since models do not fully reflect social and political realities, energy modelers (and policymakers) should also consider including experts and specialists dealing with the energy transition's social and political aspects. They can support interpreting modeling results in specific socio-political contexts. Combining specific models with various foresight methods could be useful in that manner (cf. **Section 4.1.6**).

4.1.9 Need for an understandable, appealing, and target-group oriented model communication

Model results, which aim at informing decision- and policymakers, must reach the target audience. In a world with almost limitless information but limited interest in single topics, competition about attention is ubiquitous. Therefore, intelligent model communication is essential, at least to create a scientific-based impact.

The most desired communication forms were model graphs and figures, model databases with input and output, and case studies in the survey. Information was mostly demanded about the functionality and use cases of specific models, model overview and catalog, training material for the model application, and description of the relation and linkage of different models on the platforms. Interviewees stated that explanation, documentation, visualization of purpose, assumptions, and results should be transparent, simple, understandable, detailed, target-group oriented, appealing, and actionable. Interfaces should be intuitive and user-friendly – in the best case to apply the models directly without pre-knowledge as an easy-to-use online tool to experiment with assumptions (cf. **Section 4.1.10**).

[21] However, we did not investigate the reasons for these differences yet, which would be necessary for the modification of involvement strategies.

These findings are supported by the literature where we find corresponding needs: contextualization, tractability, familiarity, visualization, usability, applicability, re-usability, efficiency, flexibility, compatibility, and consistency as essential requirements of good model communication (Mai *et al.*, 2013; Pfenninger *et al.*, 2014; Kolkman *et al.*, 2016; Hilpert *et al.*, 2017; Gilbert *et al.*, 2018; Skelton *et al.*, 2019; Sultan *et al.*, 2020).

Further aspects are necessary that apply to disseminating results, in general, to receive attention with sufficient probability. For example, Klebs (2008) discusses news factors for sustainability communication and lists classical and new success factors. Many of them can be applied to energy models: (1) novelty/curiosity/surprises/rarity can, e.g., be reached by the pioneering integration of new dimensions, goals, sectors, or technologies into models, (2) geographical and psychological proximity to the reader is provided by region- or country-based case studies, (3) bearing/consequences/personal concern of readers can be addressed, e.g., by results of the social impacts of the energy transition, (4) progress can be shown by, e.g., the comparative analysis of alternative, innovative and currently debated policy options for Paris Agreement compatible and progressive scenarios. The timing of the presented results is often critical in short-lived, demand-oriented public media work.

Furthermore, to generate an impact on the political level, other requirements need to be fulfilled. For instance, modelers' high reputation can help build enough trust into models to convince policymakers. Or, as revealed in Deliverable 1.1 of SENTINEL (Süsser *et al.*, 2020), commissioned model studies by state institutions, like ministries, have a higher chance of being considered in policymaking processes, respectively policy cycles, than external studies.

4.1.10 Need for a modeling platform providing information for diverse user groups

Any platform's benefit increases with the size of the social network it uses (the so-called network effect). To grow a motivated network of modelers working with the platform, the platform developers should focus on the majority's needs. A smart model platform design considers all steps in the modeling cycle, for which users have needs: the development, use, and maintenance of the platform. For the development, the platform should orient towards one common, widespread programming language (probably Python) and be programmed for Windows as the default case – which most users use according to the survey. For the platform use, potential users in the interviews and survey stated that they especially need (1) information about the functionality and use cases of specific models (what they can do and what they cannot do) and should be offered a (2) model overview and catalog, (3) training materials for model application, (4) descriptions of the relation and linkage of different compatible models on the platforms, (5) download options of models as well as input and output data, and (6) a contact point to reach out to in case of technical difficulties. Stakeholders also raised the matter to ensure the platform's maintenance beyond the project duration as a selling point for potential users.

When designing the platform, the target group that will form the majority of users should be defined. The survey showed that especially the scientific community is interested in the direct use of the platform. However, some interviewees from the other stakeholder groups stated that they would also like to use the platform and its models to test different scenarios by themselves if it has an easy-to-use interface.[22] Important is here – again (cf. **Section 4.1.7**) – the information costs, and more specifically, the learning costs. Other stakeholder groups will only use the platform if it has direct use for them, e.g., in country-specific case studies. Communication of the multi-performance and multi-purpose platform needs to be managed for the different groups to maximize direct use (cf. **Section 4.1.9**). Furthermore, consecutive meetings and exchanges in diversified participative formats can reduce the need to learn everything immediately and generate synergies (cf. **Section 4.1.8**).

As far as all potential users' information and learning costs are concerned, the biggest challenge for any platform is the sheer volume of offers, including the different models, data, and supporting infrastructure. As modelers already use certain models (via their websites) or platforms, they would need to be persuaded to bear the learning costs for a new platform, which could act as a barrier to change or additional use. When modeling platforms are imagined as a market with supply and demand, it can be characterized as a competitive and collaborative environment at the same time. Here, we assume that competitive thinking can help identify 'Unique Selling Points' (USPs) of the platform not provided by others. The ease of access, consistency, and compatibility of the elements and models on each platform is probably its most sensitive drawback. Therefore, we suggest an easy-to-use, front-end oriented modular platform design to fit various purposes and research questions of different stakeholder groups.

4.2 Reflection and recommendations

From the perspective of an experienced modeler with a broad, transdisciplinary background, many of the identified user needs were probably expected. On the contrary, they may be unexpected, surprising, and valuable for modelers with a strong disciplinary focus who want to reflect on their past work to date and scientists who just have started their modeling career. Given the increasing complexity of the energy system and the need to support future energy policies, models, and modeling platforms, if designed based on identified robust user needs, it could nevertheless directly benefit potential users or decision-makers and policymakers. Based on our findings, we derive **ten key implications and recommendations** for model and platform developers (**Table 3**). These recommendations are relevant for certain types of models.

[22] Examples of such direct stakeholder-model-interactions are the Decision Theater of the Global Climate Forum or ENERGETIKA, a strategic energy system game conceptualized by DIALOGIK.

Table 3: *Ten key implications and recommendations for modelers and platform developers*

Need category	Recommendation
Model content	1. Strive for a holistic and systemic perspective 2. Integrate environmental sustainability beyond GHGs 3. Put social factors and human behavior at the center
Model design and data	4. Design models to support policy decisions 5. Specify your target group to deal with design trade-offs 6. Manage and communicate uncertainties proactively
Modeling process	7. Use the power of transparency to build trust 8. Involve stakeholders as often as possible
Model outreach	9. Communicate your results thinking about your audience 10. Tailor your model platform for your user groups

(1) Modelers should aim at a **holistic and systemic perspective**, taking into account different energy-related sectors where possible. They should also consider factors influencing energy transitions, from technological and economic aspects to political, social, and environmental impacts. In particular, energy demand and supply models and economic impact assessment models could deal with energy security and resilience issues.

(2) Modelers should consider the **environmental impacts of the energy transition by going beyond greenhouse gas emissions**. Models that specifically address environmental transition constraints should play an essential role by considering the use of raw materials, assessing energy technologies along their life cycle, and measuring the impact on biodiversity.

(3) Modelers need to take better **account of the social aspects of the energy transition and human behavior**. Many social factors have been largely neglected in energy modeling. Energy demand and supply modelers should consider how far they can better integrate such aspects to achieve results that reflect social realities.

(4) Modelers who seek to be relevant for influential policymakers for the European energy transition (such as the European Commission, the European Parliament, and national governments) should **design their models and case studies to support policy decisions** by assessing policy options and impacts. As the representation of policy impacts in the real world is still underdeveloped in many models, modelers should discuss how best to adapt their models to these needs as soon as possible.

(5) As the different stakeholders have different model design preferences, the **modelers have to specify their target groups**. Assuming that all stakeholder groups should be addressed equally, the best way to deal with compromises is modularity, i.e., that modelers can easily switch between different options to answer specific questions flexibly, serve various purposes, change the resolution, and the data basis.

(6) Modelers should **adequately deal with uncertainty in their models**, e.g., by using methods that deal with input-related data variation (e.g., scenario and sensitivity analysis) and by plans for output-related research (e.g., risk assessment). The choice of uncertainty management can be made according to the needs of the targeted user groups, and in all respects, **uncertainties and limitations should be openly communicated**.

(7) Modelers should **strive for maximum transparency in order to build confidence and trust in models**. Modelers can operationalize transparency in the form of open source and open data models and by building on the best practice of transparency. Modeling platforms should be open and free of charge in order to make them accessible to different users.

(8) Modelers should **involve stakeholders in their model development and application process**. Consequently, model results could better meet the needs of specific users, thus creating a win-win situation for collaboration between modelers and users of results. Interdisciplinary and transdisciplinary modeling approaches should be the norm.

(9) Modelers should **communicate their results by thinking clearly about the audience**. In the information age, attention is a rare resource. Therefore, modelers need to think about what the target audience needs to know and how their messages can best be communicated. Particular emphasis should be placed on model graphics and figures, model databases with input and output, and case studies of model application.

(10) Platform developers should design a **platform that provides added value for different user groups**. The modeling platform should be an open-source and open-data modeling platform containing information on specific models (including use cases), model overviews and documentation/manuals, downloads of models and sources, training material, and exemplary links between models. Also, we recommend that platform developers act collaboratively and think competitively – not to get rid of competitors, but to provide the maximum benefit to users. Therefore, they should overview other initiatives and analyze the other platforms in terms of best practices and blind spots to identify the potential for their own 'unique selling points' such as a user-friendly, front-end-oriented modular platform design.

4.3 Outlook

We have provided a structured analysis of the diversity of user needs for energy models. Our research ranged from the conditions for the content that should be modeled, over how models should be designed and how stakeholders want to be engaged, to how they want to learn about energy models and their results. Adapting models to these user needs could increase the chances that different user groups will use the energy models and have more influence on decision-making and policy-making.

One limitation of this research concerns the question of generalizability. Although we were able to engage over 150 stakeholders (30 interviewees, 90 survey participants, 30 workshop participants; not counting scientific authors of the literature examined), the number of European policy and decision-makers affected by European and national energy transitions is significantly higher. Furthermore, we were not able to involve all stakeholder groups equally, so that the user needs of policymakers remain under-represented. We also conducted our research during the COVID 19 pandemic. The current crisis has affected all of us, and therefore alike the stakeholders involved. This may have led to changes in the perception and priorities of needs, which may change again after the pandemic. These may include increased relevance of energy security and the importance of lifestyle changes in addressing the climate challenge. Therefore, we encourage further research to see if our identified needs can be confirmed in a post-COVID world. To this end, future work on user needs for energy models can build on the research methodology presented.

A possible change to the survey and the approach could concern sustainability, which is based on three pillars: environmental, social, and economic sustainability. We could not investigate the economic dimension with the same intensity as the other two pillars and encourage future empirical work to examine under-represented economic aspects in energy models that could significantly impact the model results. Moreover, we focused our research on general user needs without going into specific details of the individual modeling tools or the geographical context to be studied. The general needs identified could serve as a basis to guide us towards such specifications.

Finally, future modeling must assess the role of cross-project collaboration more critically and, to put it plainly, critically evaluate whether and how the modeling community can be consolidated. Stakeholders want few, specific, and existing models with large inter- and transdisciplinary networks of experts. Therefore, the modeling community would probably be wise to look for opportunities for consolidation and cooperation. Future research should directly address the question of ideal collaboration and tendering, as the grown structures in the modeling community are interlinked with them.

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Appendix

Appendix A: Literature review

***Table 4:** Categories and examples of potential user needs of energy models*

Category	Sub-category	Need (target/subject)	Literature[23]
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…)	Ernst *et al.*, 2018 Lopion *et al.*, 2018
	General needs (energy transition)	Reflect transition types: techno-economic, socio-technical, political, ecological, cultural…	Pfenninger *et al.*, 2014 Trutnevyte *et al.*, 2019
		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, digitalization, circular economy, social acceptance, human behavior, sufficiency, resilience, risks, opportunities and drivers.	Hache and Palle, 2019 Lopion *et al.*, 2018 Martin *et al.*, 2014 Pfenninger *et al.*, 2014 Samadi *et al.*, 2017
		Develop a systemic perspective/vision (include all aspects)	Hache and Palle, 2019
	General needs (sector specific)	electricity, heat, mobility, industry, land use, …	Common; see **Table 5**
	Specific needs (SENTINEL modules)	System design, energy demand, economic impact, social and environmental transition constraints	SENTINEL Grant Agreement
	Specific needs (model type)	Models for the electricity market, strategic energy system planning, technology diffusion, life cycle assessment, integrated assessment, investment behavior, macroeconomic equilibrium, simulation models, optimization models…	Common
	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	Müller *et al.*, 2018 openENTRANCE, 2019 SENTINEL Grant Agreement

[23] These sources focused on criteria of good practise of model development and current challenges.

*Continued (**Table 4**)*

Category	Sub-category	Need (target/subject)	Literature
Model design and data	General and specific purposes	Model structure: internal and external assumptions	Lopion *et al.*, 2018 Müller *et al.*, 2018 Pfenninger *et al.*, 2014
		Role of model: models as an eye-opener, models as arguments in dissent, models as vehicles in creating consensus, models for management	Van Daalen *et al.*, 2002
	Complexity	Modularity Degree of integration of different models	Hilpert *et al.*, 2017 Müller *et al.*, 2018 Pfenninger *et al.*, 2014
	Uncertainty	Types of uncertainty: epistemic, aleatory, linguistic, decision, planning	Hilpert *et al.*, 2017 Müller *et al.*, 2018 Pfenninger *et al.*, 2014
	Resolving time and space	Geographical coverage Sectoral coverage Technological coverage/richness Time horizon: short, medium, and long term (2050, 2100…)	Hilpert *et al.*, 2017 Lacroix *et al.*, 2019 Lopion *et al.*, 2018 Müller *et al.*, 2018 Pfenninger *et al.*, 2014
	Underlying methodology	Analytical approach (top-down vs. bottom-up) Mathematical approach: linear or non-linear Model type: simulation, optimization, or hybrid model	Müller *et al.*, 2018 Lopion *et al.*, 2018 Pfenninger *et al.*, 2014
	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	Hilpert *et al.*, 2017 Lopion *et al.*, 2018 Müller *et al.*, 2018
Modeling process	Inter- and transdisciplinary modeling	Strategies for collaboration: Bridging strategy, iterating strategy, merging strategy	Trutnevyte *et al.*, 2019
		Content: inclusion of human dimension, energy-water-food nexus, empirical research on quantifiable patterns	Hilpert *et al.*, 2017 Trutnevyte *et al.*, 2019
		Stakeholder participation, agility	Kolkman *et al.*, 2016
	Scientific standards / Quality	Transparency, repeatability, reproducibility, scrutiny, scientific progress, accessibility/licensing (open-source vs. protection of intellectual property)	Hilpert *et al.*, 2017 Kolkman *et al.*, 2016 Lopion *et al.*, 2018 Pfenninger *et al.*, 2014
	Scenario development	Qualitative and mixed-methods scenarios, Transformation path analysis	Lopion *et al.*, 2018 Pfenninger *et al.*, 2014
Model outreach	Model communication	communication of model design and results, tractability (easy to understand), visualization	Hilpert *et al.*, 2017
	Model utilization	Usability, applicability, re-usability, efficiency (low run-time of the model), flexibility (effort for model adjustments to new research questions)	Kolkman *et al.*, 2016 Pfenninger *et al.*, 2014
	Supporting infrastructure	Reputation of the model developers, compatibility (familiarity of the model user with a software platform and programing language), consistency (with previous results)	Kolkman *et al.*, 2016 Lopion *et al.*, 2018
	Organizational factors	Organizational conditions (responsibility for unsuccessful implementation), model advocates and their trustworthiness	Kolkman *et al.*, 2016

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Table 5: *Overview of exemplary identification processes of content-related user needs*

Model specific	Year	Authors	Demand / Purpose	Quanti-fication	Sector					Method					Stakeholders					Others / Comment	Country
					E	H	M	I	L	O	R	I	S	W	SC	PM	EI	ENO	CS		
y	2020	Van Sluisveld *et al.*	Integration of socio-technical transition insights into integrated assessment modeling	(y)	x	x	x	-	-	x	x	-	-	-	x	-	-	-	-	Development of own framework	EU (4 c.)
y	2019	Trutnevyte *et al.*	Integrate socio-technical transition in models (like behavior, social risks and opportunities, transition dynamics, heterogeneity across and within societies)	(y)	x	-	x	-	(x)	x	x	-	-	-	x	-	-	-	-	Modelers´ perspectives	EU (7 c.)
y	2019	Hache and Palle	Research trends and policy implication for renewable energy integration into power networks	Y	x	-	-	-	-	-	x	-	x	-	x(!)	x	x	x	x	-	EU, inter-national
y	2019	Goodess *et al.*	Advancing climate services for the European renewable energy sector	(y)	x	-	-	-	-	x	-	-	x	x	x	x	x	x	-	-	EU
y	2018	Bachner *et al.*	Development of climate-neutral transition pathways for the steel and electricity sectors, focus: risks to and of implementation and possible measures for risk minimization	Y	x	-	-	x	-	-	x	x	x	x	x	x	x	-	-	+ steel industry	Austria
y	2017	Samadi *et al.*	Implementation of behavioral change towards sufficiency-oriented lifestyles and corresponding sufficiency policy into energy scenarios and models	N	-	-	-	-	-	x	x	-	-	-	x	-	-	-	-	-	-
y	2015	Li *et al.*	A review of socio-technical energy transition (STET) models	N	x	x	x	-	-	-	x	-	-	-	x	-	-	-	-	Overview and analysis of models	-
y	2015	Fortes *et al.*	Storylines highlighting different visions about a country´s development, including the energy system	(y)	x	x	x	x	x	-	x	-	-	x	x	x	-	-	x	-	Portugal
y	2014	Pfenninger *et al.*	Identification and discussion of energy modeling challenges in the twenty-first century; including the "human dimension and social risks and opportunities"	N	x	-	-	-	-	x	x	-	-	-	x	-	-	-	-	Modelers´ perspective	-
y	2009	Stalpers *et al.*	Develop and test different climate policy proposals	(y)	-	-	-	-	-	-	-	x	-	x	x	x	-	-	-	Iterative model improvement	Inter-national
(y)	2020	Cradock-Henry *et al.*	Climate adaptation pathways for agriculture	N	-	-	-	-	x	-	x	x	-	x	x	x	-	-	x	+ agricultural stakeholders	New Zealand
(y)	2019	Skoczkowski *et al.*	Climate-change induced uncertainties, risks, and opportunities for the coal-based region	Y	x	(x)	-	x	(x)	-	x	x	-	-	x	x	x	-	x	-	Poland
(y)	2017	Vercelli *et al.*	Full range of topics and concerns related to the potential impacts of CO_2 geological storage; focus: impacts and long term safety of storage sites	Y	-	-	-	-	-	-	-	-	x	(x)	x	x	x	-	-	-	EU, inter-national

*Continued (**Table 5**)*

Model specific	Year	Authors	Demand / Purpose	Quanti-fication	Sector					Method					Stakeholder					Others / Comment	Country
					E	H	M	I	L	O	R	I	S	W	SCI	POL	IND	ENO	NGO		
(y)	2017	Ernst *et al.*	Qualitative scenario development for the national energy transformation; focus: targets of energy and climate policy	Y	x	-	-	-	-	-	x	-	x	x	X	x	x	-	x	-	Germany
(y)	2011	Tight *et al.*	Visions for a walking and cycling focused urban transport system	N	-	-	x	-	-	x	x	-	-	x	X	-	-	-	-	Included stakeholders not clarified	UK
(y)	2008	Connor *et al.*	Risks and uncertainties regarding smart grid development	N	x	(x)	(x)	x	-	-	-	x	x	-	X	x	x	x	-	-	UK
(y)	2008 / 2007	Seymour *et al.* / Hugh *et al.*	Strategic planning / road mapping for the successful introduction of hydrogen into the European energy infrastructure; focus: acceptance / perception of hydrogen production feedstocks, production and distribution technologies	Y	-	-	-	-	-	-	-	-	-	x	X	x	x	x	-	+ vehicle manu-facturing, SME representa-tives	Europe (10 c.)
n	2019	Salim *et al.*	drivers, barriers, and enablers to end-of-life management of photovoltaic panels and battery energy storage systems	Y	x	-	-	-	-	-	x	x	x	-	X	x	-	-	-	-	Australia
n	2019	Lacroix *et al.*	Multiple visions of the future and major environmental scenarios	(y)	-	-	-	-	(x)	-	x	-	-	-	(x)	(x)	(x)	(x)	(x)	Literature analysis of scenario studies	(France)
n	2017	Toivanen *et al.*	Visions for the development of the national strategy to reach its EU 2030 decarbonization targets	N	x	x	x	(x)	(x)	-	x	x	-	-	(x)	-	x	x	x	Applied Q methodology	Finland
n	2017	Kishita *et al.*	Designing backcasting scenarios for resilient energy futures	N	x	x	x	x	-	x	x	-	-	x	X	-	-	-	-	Applied backcasting	Japan
n	2014	Virtanen *et al.*	Identify market needs, market barriers, and existing and new business models in area of district level energy services	Y	x	x	-	-	-	-	x	x	x	-	X	x	x	x	x	-	Europe (6 c.)
n	2014	Spickermann *et al.*	Scenarios for urban mobility and multimodal cities	Y	x	-	x	-	-	-	x	x	x	x	-	x	-	-	x	+ automotive industry and customers	Germany
n	2014	Martin *et al.*	Low-carbon transition of cities	Y	x	x	x	-	-	-	-	-	x	x	X	x	x	x	x	-	UK
n	2014	Breukers *et al.*	Analyzing the past and exploring the future of sustainable biomass	Y	x	x	x	-	x	-	x	x	-	x	X	x	-	-	x	Applied Q methodology	Nether-lands
n	2013	Michalena and Frantzeskaki	Impediments of the sustainable energy transition	N	x	-	-	-	-	-	-	x	-	-	X	x	-	-	(x)	Applied PEST analysis	Greece
n	2011	Svenfelt *et al.*	Backcasting for decreasing energy use in buildings by 50% by 2050; focus: political and other measures	N	x	x	-	-	-	-	x	x	-	x	-	x	-	-	x	+ building residents and owners	Sweden
n	2008	Truffer *et al.*	Expectations about system transformations; focus: development of four scenarios in utility sector	N	x	x	-	-	-	-	-	-	-	x	X	x	x	-	x	+ private companies, component suppliers, media	Germany

Legend: Model-specific: y: yes, n: no | Quantification: n: only overview, y: prioritization included | Sector: E: Electricity, H: Heat, M: Mobility: I: Industry, L: Land use; if no sector-category is marked the energy-related topic is discussion in general across all sectors. | Method: O: Opinion of article´s authors, R: Review of literature, I: Interview, S: Survey, W: Workshop | Stakeholders: SCI: Scientific community, POL: Policymaker, IND: Energy Industry, ENO: Energy network operators, NGO: non-gov. organization | (n/x/y): Brackets indicate that the aspect is not at the core of the approach or only partly included | Country: c.: country

Box 5: *Trends and challenges in energy modeling from different angles (summary of SENTINEL deliverables)*

Energy demand (Chatterjee and Ürge-Vorsatz, 2020): Key trends are the (1) increase of global energy demand, (2) the addition and switch from fossil and nuclear energy to renewable energy, and (3) efforts for increasing energy efficiency. Modeling paradigms are identified for models of the building and transport sector and focus on used methodologies: models can be simulation, optimization, and equilibrium models. All of these models face diverse challenges. Building models struggle with the modeling of common technical, political and social measures for a transition towards renewable and energy efficiency. Critical issues and challenges are the (1) modeling of lock-ins, the (2) integration of interdependent renewable energy and energy efficiency, and (3) the modeling of the human factor. A key challenge of transport models is the modeling of transport-related emission mitigation policies that follows the Avoid-Shift-Improve (A-S-I) framework. The institution lock-in (like unsustainable land–use) that may cause behavioral lock-ins is identified as a crucial inhibitor of modal split change. And scarcity concerning spatial, temporal, technological, socio-economic, demographic, behavioral and stock data is a major topic for both, building and transport models.

System design (Chang *et al.*, 2020): Overview of system energy models dealing with the energy supply including energy production, storage and transmission / distribution and energy demand. Important assessment criteria and challenges of models are the (1) modeling methodology with (again) simulation, optimization and equilibrium models (2) modeling of resolution and scope, (3) the giving of policy advice, (4) the degree of cross-sector coverage (needed for the assessment of the whole picture and sector-coupling measures), (5) accessibility and transparency and (6) cross-platform integration. Modeling challenges for energy demand exist concerning its elasticity and dynamics, its sectoral disaggregation, its projecting forwards and backwards in time and the general data availability.

Economic impacts (Mayer *et al.*, 2020): Major socio-economic trends are the global population, income, and energy demand growth. A critical challenge is the trade-off between economic development and environmental protection as consumption has negative side-effects (social costs of carbon), risks (planetary boundaries) and opportunities (green innovations and possible post- and degrowth). Paradigms in economic energy-related modeling and modeling challenges are analyzed for bottom-up-approaches and top-down-approaches. Bottom-up models deal with optimization of dispatch and investment and centralized and decentralized supply alternatives. Critical challenges are the modeling of (1) dispatch and investment as endogenous parameters to reflect interdependent change and (2) the amount and market behavior of decentral technology options, and (3) further features like combined production units, heat networks, and imperfect foresight. Top-down models as macroeconomic perspectives deal with additional challenges regarding the modeling of (1) real economic flows, (2) financial flows, (3) market-based mechanisms as well as (4) the model evaluation and (5) linking of different models. In addition, both model types face the challenge of endogenous modeling of a coupling of the electricity and heat sector in particular. Moreover, model linking, complexity and uncertainty, inter- and transdisciplinary embedding, transparency, and data availability play an important role for model improvement.

Social and behavioral aspects (Martin *et al.*, 2020): Seven key modeling issues are identified for scenario development, model input/output and "optimization". These are (1) Modeling energy transition dynamics; (2) Modeling social technology preferences and acceptance: Do different RES sources and their impacts (e.g., on landscapes) influence the attitudes in the population and affect the degree of opposition? Can different deployment strategies (e.g., maximum tolerable RES density, maximum local deployment pace) reduce opposition and support local energy transitions? (3) Modeling attitudes regarding social justice: Who profits from and who is burdened by the energy transition? How do local job gain and losses impact the energy transition? How does energy/fuel poverty impact the acceptance and overall pace of the energy transition? What impact would specific social policy strategies (e.g., maximum tolerable electricity price) have on the transition? (4) Modeling the preparedness of the economy: How does the acceptance of or resistance against the energy transition in the economy effect the diffusion? How are (local) economies prepared for the needs of the energy transition? (5) Responsibilities/ownership: Do prosumers and community energy groups accelerate the energy transition? Should we think nationally or at a continental level? How do these options influence the common energy targets? (6) Consumption behavior: How do individual consumption patterns influence each other and what impact does that have on energy savings? Would energy sufficiency be a viable option? (7) Policy support: What are best practice policies for the expansion of RES grids and storages? What are policies supporting a just transition?

Appendix B: Interview results

Table 6: *User needs related to content to be modeled*

Sub-category	Need focus	Country	Quotes
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 decentralized 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 modeling, 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 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 neighboring 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)

*Continued (**Table 6**)*

Sub-category	Need focus	Country	Quotes
System-specific needs	Decarbonization options	EU, GER	"[…] **how to decarbonize** 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 decarbonization 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 decentralization.**" (EU_POL#3) "And this is actually something great about **decentralized 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 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 overall energy transition. And it's not tackled by any of these models." (EU_NGO#2) "We can supply every house with **decentralized 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 modeling exercises try to minimize 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 modeling 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)

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*Continued (**Table 6**)*

Sub-category	Need focus	Country	Quotes
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 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 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 more decentralized 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 renewable sector and how much in fossil fuels. If the government wants to choose, it should choose the 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 realize 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 to 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 optimized 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)

*Continued (**Table 6**)*

Sub-category	Need focus	Country	Quotes
System-specific needs	Impacts of social and actors behavior	EU, GRE, PL	"I would say that **modeling of social behavior** might be very relevant for modeling potential outcomes." (EU_IND#1) "[…] maybe including **energy communities** as investors into the models. So just more analysis about the behavior 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 **behavior of actors** that is not included yet, at least in the optimizing models. And you have, of course, the electricity market models, there are some models that have agent-based behavior in them, but somehow it is not very linked at the moment." (EU_SCI#1) "It would be desirable to conceptualize 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 behavioral 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 in 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 **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 has 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 comes all these issues, that you could use decarbonized 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 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)

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*Continued (**Table 6**)*

Sub-category	Need focus	Country	Quotes
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 electrolyzers 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 ca se 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 decarbonization 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 modeled." (PL_SCI#2)
	Storage	PL	"The second thing, you know, is **storage**, although it's now taken into account there in some way, but 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 emphasize, 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 decentralization 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)

*Continued (**Table 6**)*

Sub-category	Need focus	Country	Quotes
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 Utilization	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 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 is the most important choices that we got to do in the future.** And I think that is the most policy relevant insights 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, **impact of policies**, but I don't know how to relate it to modeling..." (PL_SCI#3)

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Table 7: *User needs related to model design and data*

Sub-category	Need focus	Country	Quotes
Systemic / holistic approach		GRE, PL	"There is a growing need to consider a **systemic approach** in energy modeling regarding the decarbonization 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 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 behavior." (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 favorite 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 modeling 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) "Well, I think that such **transparency**, but also such inclusiveness, that is, it's really important that if someone has his or her favorite 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 modeling frames to additional technology, simply described by the user, is very important in my opinion." (PL_SCI#2)
	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 criticize, 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)

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*Continued (**Table 7**)*

Sub-category	Need focus	Country	Quotes
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 modeling, 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 modeling. 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)
Characteris-tics	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 electricity economic analysis, you need hourly descriptions. And in some year, 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 decentralized elements that **municipalities** have to function, that they have to do it, keyword thermal management plans in districts. Such things could be modeled **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 much technical details, technical complications, that for **non-modeler 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 recognized, yes... and simply, if such a model is not recognized, 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 correct 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)

*Continued (**Table 7**)*

Sub-category	Need focus	Country	Quotes
Data require-ments	Update technological and economic data	EU, PL, SWE	"[…] but it's like the assumption related to economic growth, for example. Assumptions related to oil price. OK, you put oil price, the expected oil price in the coming years, but actually you don't have no 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 this different parameters, like oil prices are lower than expected, it's influencing our model this way or that way. Economic grow, 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 decentralized development of the model, it makes it more problematic to make sure that the quality is there, that there is a **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 politicized." (SWE_POL#3)
	Make data open-source	EU	"And of course, I look at model and I look at 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 **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 center 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)
Harmoni-zation and compara-bility of models		GER, SWE	"It was then decided to **harmonize 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)
Compara-bility 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)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

*Continued (**Table 7**)*

Sub-category	Need focus	Country	Quotes
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 in 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 economic models	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)
	Energy models combined with climate and weather models	EU, PL	"I think that one of 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 history, a climate modeling 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 **modeling of climate and environment**." (EU_IND#1) "[…] bringing this one [weather and climate impacts] in an open modeling environment in order to look at 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 modeling at the moment." (PL_SCI#1)

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Table 8: *Model needs related to the modeling process*

Sub-category	Need focus	Country	Quotes
Modeling 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 are 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 modeling, the importance of modeling and also the thing, they have to work on in order to be held accountable of the decision." (EU_POL#2)
Inter- and transdisciplinary modeling	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 not "100% right" or "100% wrong". For me is the key to have the engagement from the very **early stages** to allow for multiple modeling 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 modeling process**, with the modelers 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 on 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, the **objectivity** is important. And me and my colleagues have the opinion that you can only reach that if you **work together 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 modeling 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 **multidisciplinary and include social scientists**." (GER_SCI#1)
	Integrate different methods	GRE, PL	"So all those methods where, for example, [anonymized 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)

*Continued (**Table 8**)*

Sub-category	Need focus	Country	Quotes
Open modeling among the modeling community	Information exchange and collective learning	EU	"My point of view, anyway, one of important thing is the open modeling 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 **peer-to-peer type of learning** in the modeling community." (EU_IND#2)
	Modeling network / platform	EU	"Just to be clear – we are not talking about one huge system, with a couple of modelers around explaining what it is, but I think a **network of systems and modelers working open and transparent, exchanging information** – this is what we should go for." (EU_IND#1)
Pace of modeling	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)

Table 9: *Model needs related to the outreach of models and 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 model, 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)

*Continued (**Table 9**)*

Sub-category	Need focus	Country	Quotes
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 model, **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 visualization tool** they use to visualize 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 modeling 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 modeling language	EU, PL	"[…] secondly, that it is explained in **very easily 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 modeling 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 modeler 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 [anonymized 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 modeling 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 modeling, 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)

*Continued (**Table 9**)*

Sub-category	Need focus	Country	Quotes
Engagement and exchange between modelers 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 optimization or some other kind of optimization. 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 after wards and you agree what this should means. 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 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 modeling, the importance of modeling 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 modeling 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 **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 modelers 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 modeling, 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)

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*Continued (**Table 9**)*

Sub-category	Need focus	Country	Quotes
Engagement and exchange between modelers 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 emphasize 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 modeling for the Ministry or another institution. This doesn't mean that modeling wasn't done, but it wasn't strictly policy, but, let's just say, someone was optimizing the use of low voltage lines, which is also absolutely important." (PL_SCI#1)
Model platform	Provide 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 easy understandable to people, who are not familiar to the topic or also not familiar with data or modeling. 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)

*Continued (**Table 9**)*

Sub-category	Need focus	Country	Quotes
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 modeling, 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 modeling, 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 modelers 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 organize 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)

Appendix C: Online survey – detailed results

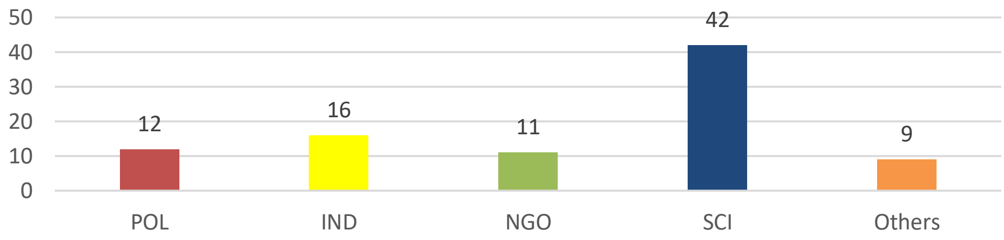
The detailed presentation of the results follows the original structure of the questionnaire.

A Personal background, model use, and general demand

A1 | Which stakeholder group would you count yourself among?

N: 90 (mandatory, single choice)[24]

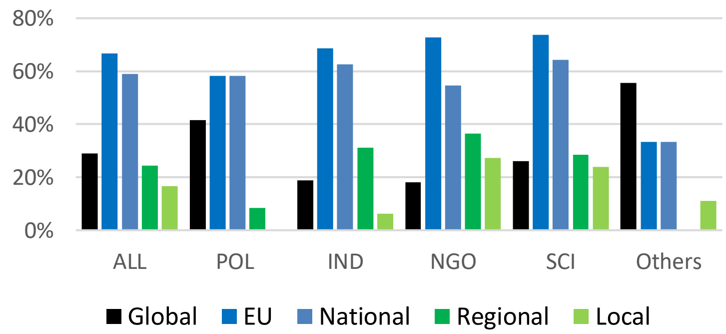
In total, ninety participants completed the questionnaire, and ninety-five participants started but did not finish the survey during the nine weeks that the survey was publicly available and unrestricted. All addressed stakeholder groups have responded to the invitation, however, with a disproportionate interest of the scientific community, making about 47% of participants that completed the questionnaire.



Nine stakeholders who did not find themselves captured by the four groups did also respond. These participants work in a statutory advisory council to a government (1), a start-up with solutions for 100% renewable energy (1), in the energy-intensive sector (1), in the manufacturing industry for energy technologies (1), in banks in the financial sector (2), and unidentified sectors (3). As SENTINEL focuses on the first four stakeholder groups, "others" are only included in central figures.

A2 | What levels are you working at?

N: 90 (mandatory, multiple choices)



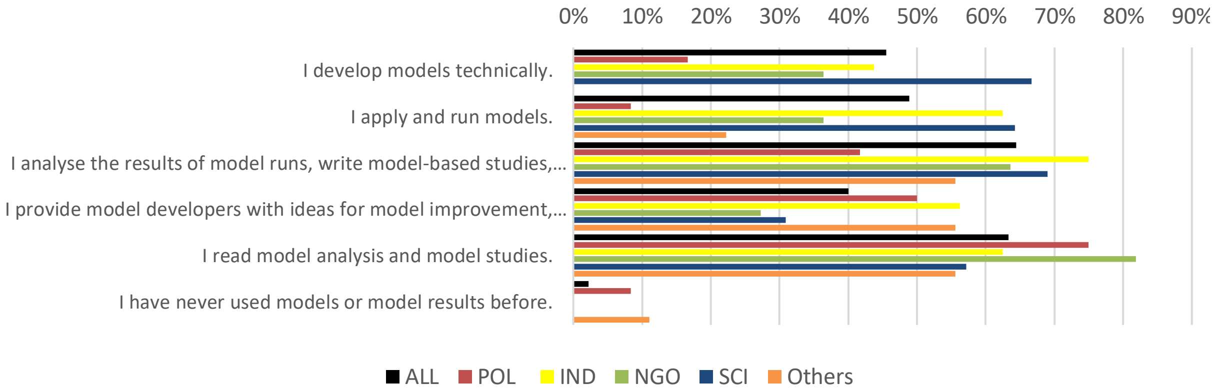
The majority of participants work on the European (67% of all participants) and the national level (58%). These levels were also the primary target groups of the survey. Group-specific differences are relatively small.

[24] For all questions, the number of respondents is displayed in the following order: (1) total number, (2) policymakers, (3) energy industry, (4) non-governmental organizations (NGOs), (5) research, innovation & consultancy, and (6) other stakeholders.

A3 | In what context do you work with energy models?

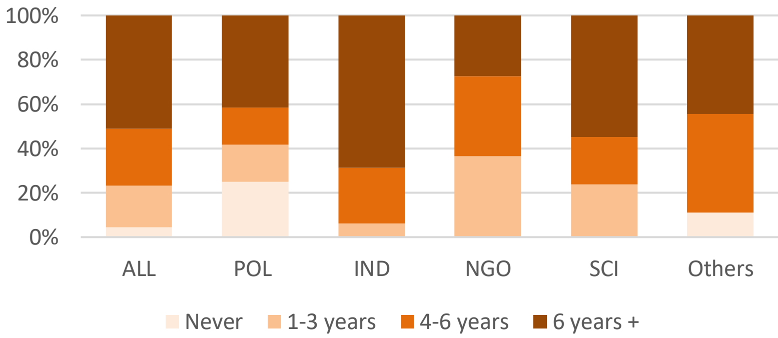
N: 90 (mandatory, multiple choices, at least one answer)

All predefined groups of modelers (developers, contributors, appliers, and users) are quite present among the survey participants, while differences between them were observable. The technical development, application of models, analysis of results, writing of reports, and giving advice is most common among the scientific community (in all three categories above 70%), energy industry (>44%), and NGOs (>36%). Model studies are specially commissioned by the energy industry (56%) and policymakers (50%). More than every second group member in the survey is reading model studies (63%), while the highest among NGOs (82%) and policymakers (75%). Non-model-affine participants are negligible among the survey participants (2%).



A4 | How long have you been working with models (as you indicated in the previous question)?

N: 90 (voluntary, single choice)

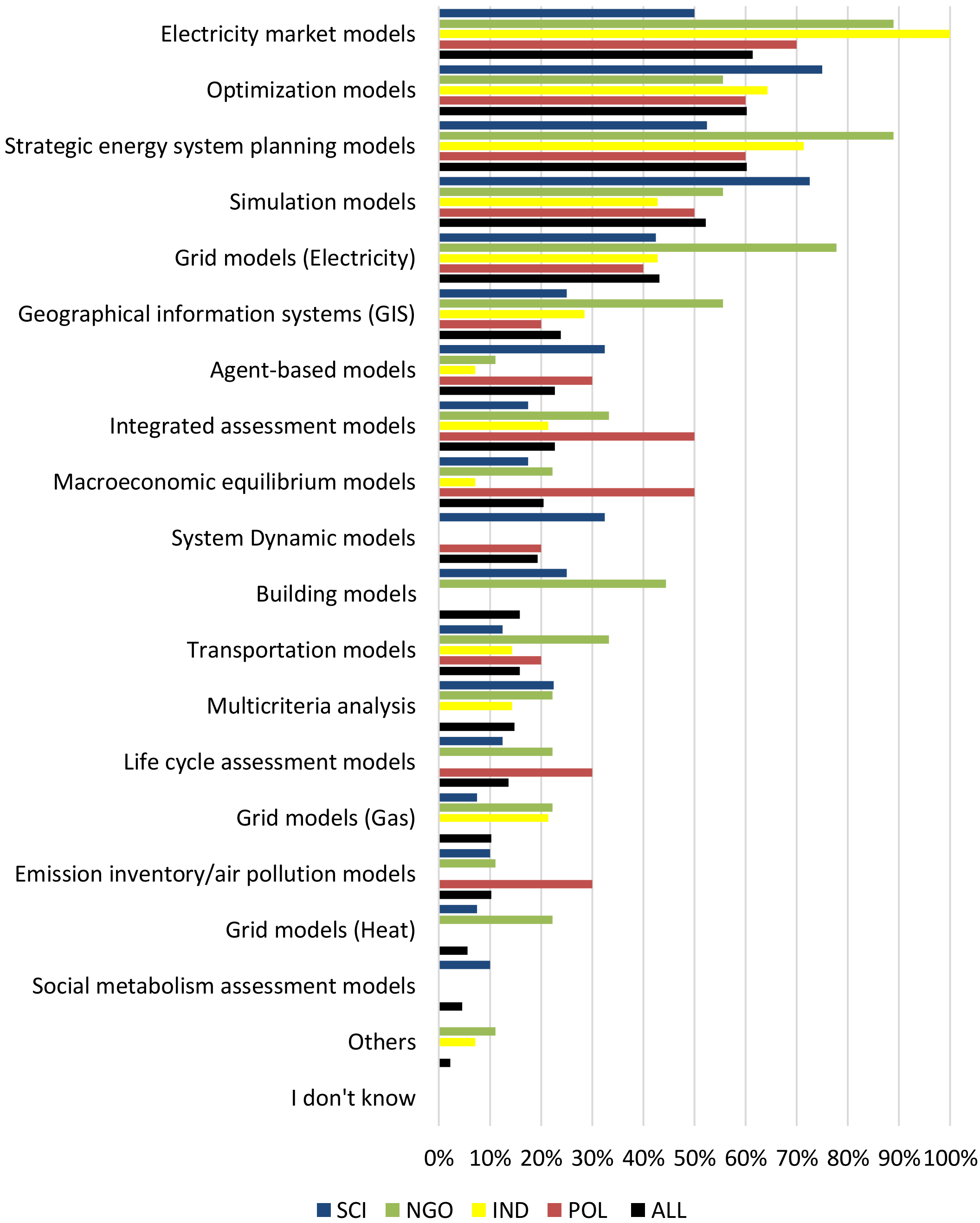


The questionnaire was answered primarily by stakeholders with model and modeling experience. The majority in each group, ranging from about 60 to more than 90 percent, had at least four years of experience in the fields that they indicated as their working context with models. Only a few participants had no background with models, highest among policymakers.

A5 | You stated above that you work with energy models in one way or another. With which kind of models in terms of model topics and model type have you worked so far?

N: 88 (voluntary, multiple choices; figure sorted by total share)

In terms of model topics, participants have worked – as Top 3 – most often with electricity market models (61%), followed by strategic energy system planning models (60%), and electricity grid models (43%). In terms of model type, optimization models are common among survey participants (60%), followed by simulation models (52%) and geographical information systems (GIS; 24%). Group differences are observable but are not discussed in detail.

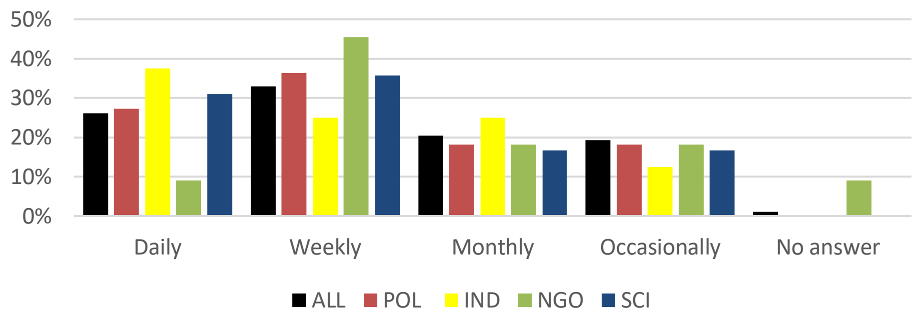


A6 | You stated above that you use specific models or model results in your work. Which models or of which models exactly? Please type in the model abbreviation(s).
N: 64 (voluntary, free text)

A follow-up-question displayed to those who worked with at least one model (in A5) respondents could voluntarily indicate the specific models. In total, 64 participants listed 105 different models. Those with the highest mentions were: PRIMES (11), TIMES (9), GEM-E3 (4), EnergyPLAN (3), HOMER (3), LEAP (3), METIS (3), PyPSA (3), and QGIS (3). All other specific models were mentioned two times or less. Besides, some participants referred to self-made and so far unnamed models. PRIMES and GEM-E3 is most popular among policymakers (4 and 3 mentions), and TIMES among scientists (4 mentions).

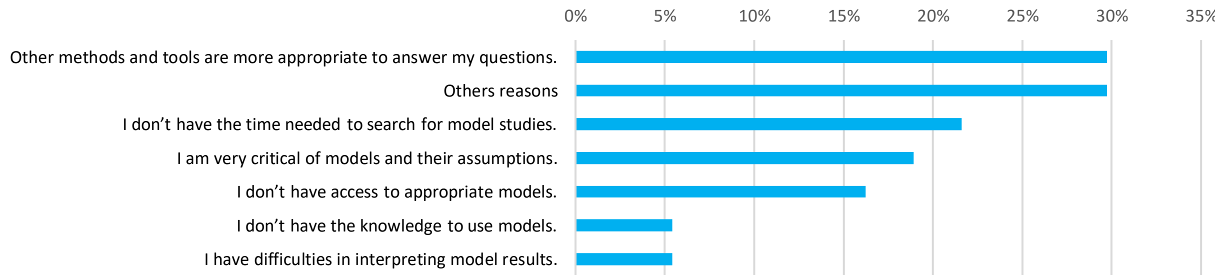
A7 | Related to that, how often do you use models or modeling results?
N: 88 (voluntary, single choice)

On average, models and model results are used quite frequently. 33% of all survey participants use them weekly, and 26% even daily. Monthly and occasionally account for about 40%. Differences in stakeholder groups seem small in general, while the energy industry and NGO representatives deviate most in the daily and weekly sample.



A8 | What are the reasons that you do not or not often use model results?
N: 37 (voluntary, multiple choices; figure sorted by total share)

This question only appeared for survey participants who never used models before (as indicated in A3) or used them only monthly or occasionally (A7). In particular, other methods and tools are used if models are not appropriate to answer a stakeholder´s question (11 clicks) and account for about 30% of all reasons. Time restrictions (22%), criticism, respective lacking trust, in model assumptions (19%), and lacking model availability (16%) were also mentioned more often. Besides, also about 30% of question participants used the free text field to explain their causes not available as a predefined option. Answers included, e.g., budget limitations, the frequency of model updates, or primary use as an auxiliary method in decision-making.

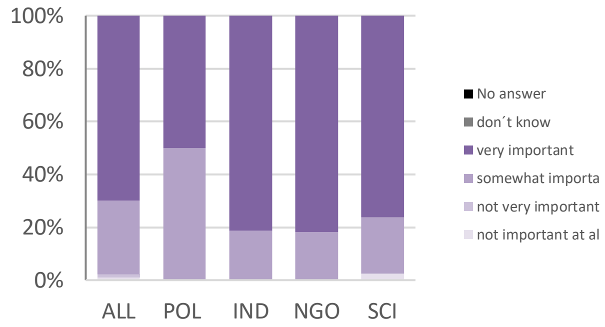


A9 | In your opinion, how important are models for…?
N: 90 (mandatory, Likert scale)

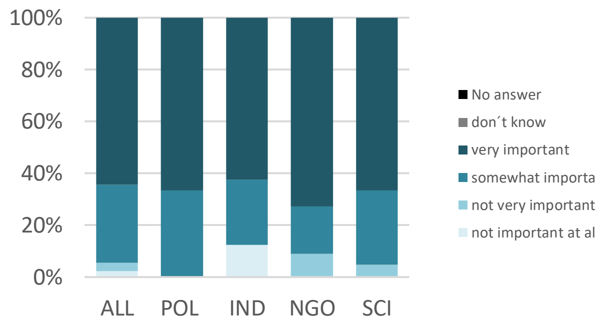
On average, the overwhelming majority of survey participants perceived models as somewhat important (28%) to very important (70%) for the energy transition as a whole and its associated policymaking (27% / 58%). Overall, group differences were small, while primarily for policymakers, the share with only "somewhat important" mentions was highest, with 50% for the energy transition and 33% for policymaking.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

… the energy transition as a whole

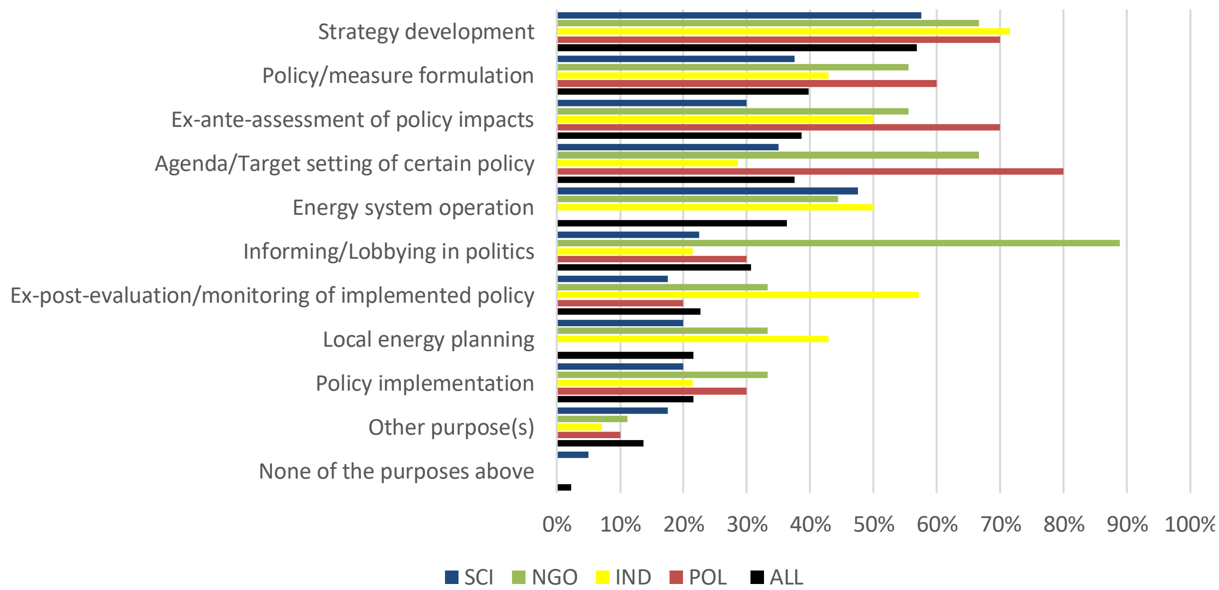


… policymaking in the energy transition



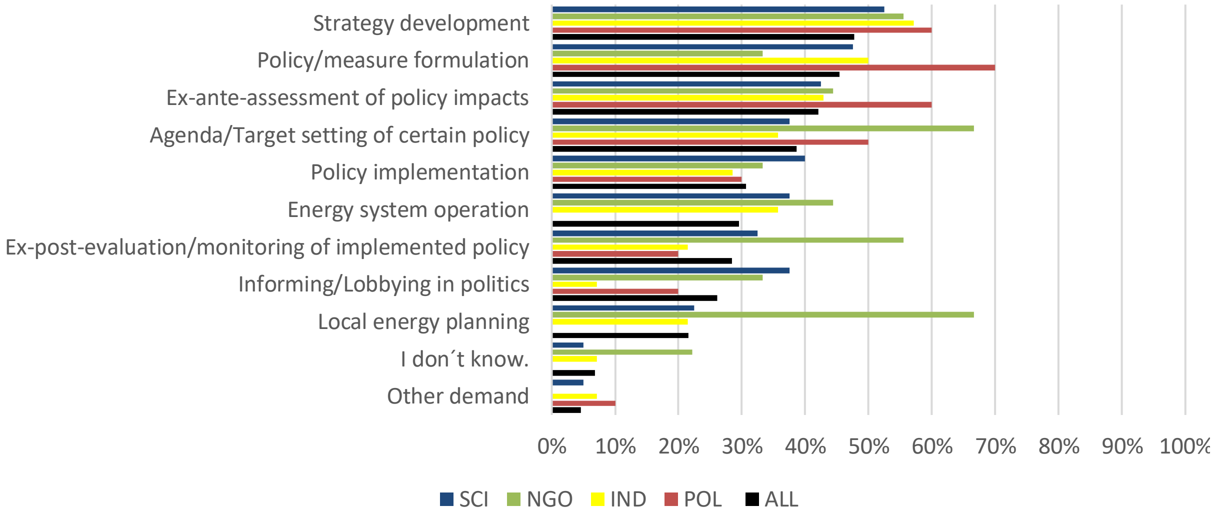
A10 | For what purpose are you using models in your work?
N: 88 (voluntary, multiple choices; figure sorted by total share)

This question appeared for all participants with model experience (as indicated in A3). These participants use models in particular – as the Top 5 – for strategy development (57%), policy/measure formulation (40%), ex-ante-assessment of policy impacts (39%), agenda/target setting of certain policy (38%), and energy system operation (36%). While strategy development is relatively similar significant for all groups (range between 58% and 71%, excluding others), group-specific deviations, especially for NGOs and policymakers from the average, are more common for the other four purposes. For example, policymakers do not use the model for energy system operations (0%) but have the highest use rates for agenda/target setting (80%) and ex-ante-assessment of policy impacts (70%).



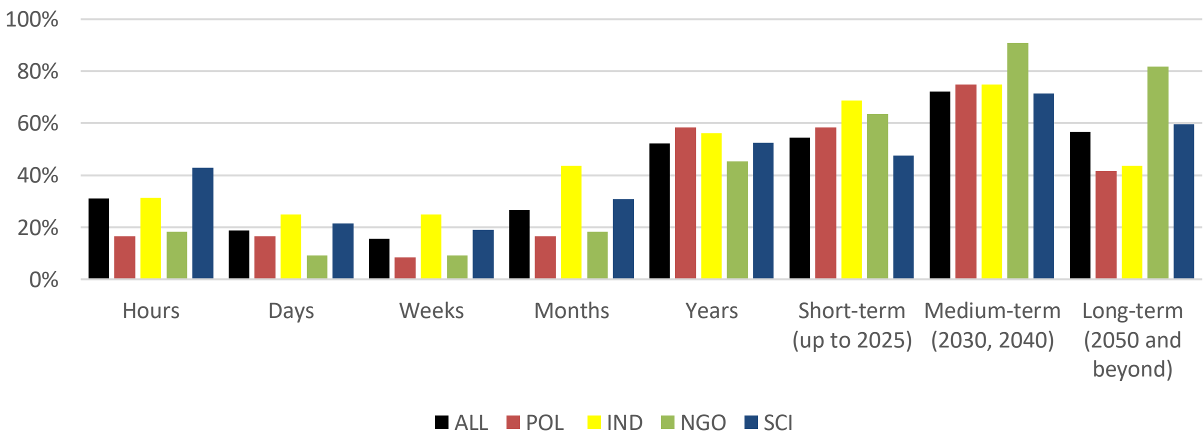
A11 | Where do you see the demand for additional or improved models helping you in your work?
N: 88 (voluntary, multiple choices; figure sorted by total share)

This question appeared for all participants with model experience (as indicated in A3). In general, participants demanded improved models for the purposes of – as the Top 5 – strategy development (48%), policy measure formulation (45%), ex-ante-assessment of policy impacts (42%), agenda/target setting of certain policy (39%), and policy implementation (31%). Policymakers and NGOs have the highest group-specific deviation from the average. For example, policymakers demand the strongest for improved models helping in policy/measure formulation (70%), and NGOs are especially interested in better models for agenda/target setting of policy (67%).



A12 | What time horizon(s) are you dealing with in your energy-related work?
N: 90 (voluntary, multiple choices)

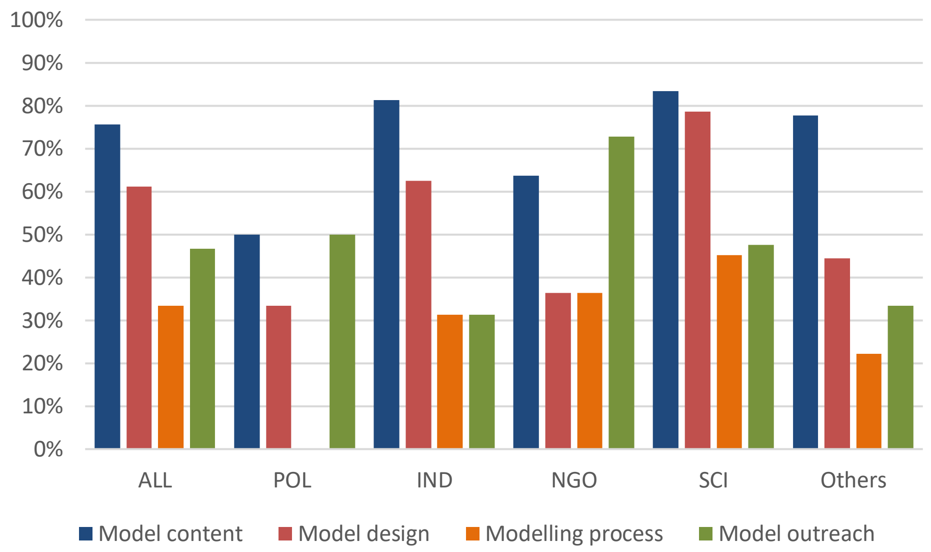
In sum, survey participants are especially interested in longer time horizons. They deal with medium-term perspectives of the next decades (2030, 2040) (72%), followed by long-term time horizons beyond 2050 (57%), short-term (54%), and yearly focuses (52%). All of the time horizons on the level of months and shorter are, in general, less relevant in their energy-related working contexts (<31%). Group differences are relatively small, although observable. For example, NGOs have a strong focus on future decades (91% for medium-term, and 82% for long-term horizons).



A13 | In our projects, we want to improve models in all possible directions. In which field(s) do you want to contribute to the model improvement in particular?
N: 90 (mandatory, multiple choice)

In sum, survey participants wanted to improve models, especially regarding their content (76%), followed by model design (61%), model outreach (47%), and modeling process (33%). Policymakers focused most on model content and outreach (each with 50%), but showed no interest in the process (zero times clicked). The energy industry representatives were especially interested in model content (81%) and model design (63%), and less in process and outreach (each with 31%). NGO representatives wanted to contribute to outreach in particular

(73%), followed closely by model content (64%). The preference order of the scientific community corresponded with the aggregated view. Besides, the groups were not equally interested in contributing to the categories. On average, participants clicked on 2.2 categories, while scientists were most interested (2.5), followed by the energy industry and NGOs (2.1), and policymakers (1.3).



The answers given to the question about the contribution determined which need categories the survey participants received further questions. This nesting of the questionnaire and some "voluntary" questions explain the reduced number of participants in the following sections.

B Model content

Survey participants interested in the model content (as indicated in A13) received the following question section.

B1 | How important are the following aspects for the energy transition?
N: 68 (voluntary, Likert scale; figure sorted by total share of "not important at all" and "not very important")

The respondents showed a clear tendency towards the overall importance for all predefined answer options of the question. Although free energy trade received the highest rejection rate, a majority of 65% still perceived it as necessary. In total, the three central goals of energy and climate policy of security of supply/resilience (96% importance), climate-neutrality (94%), and cost-efficiency (85%) were ranked highest. Group-specific differences were observable but were relatively small and did not contradict the overall resume.

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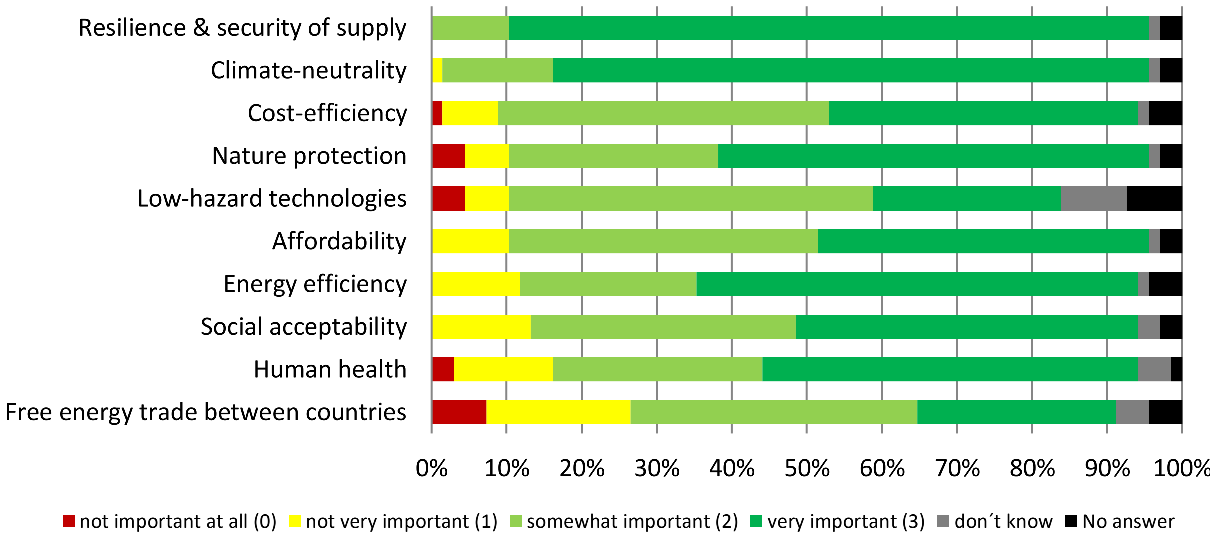

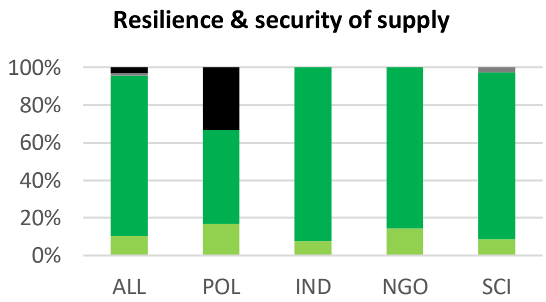

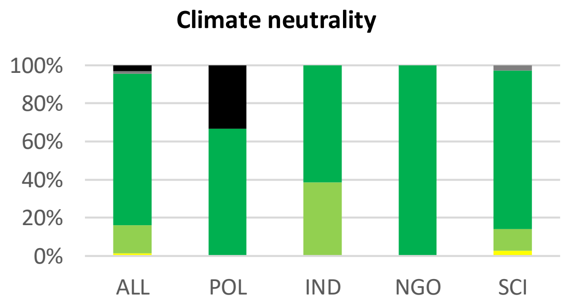

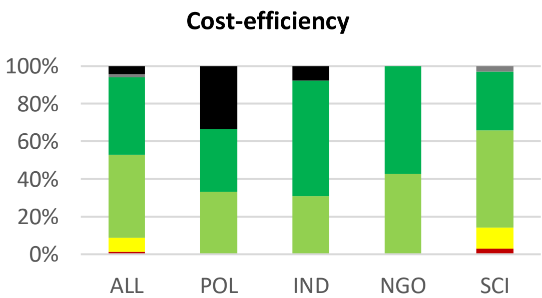

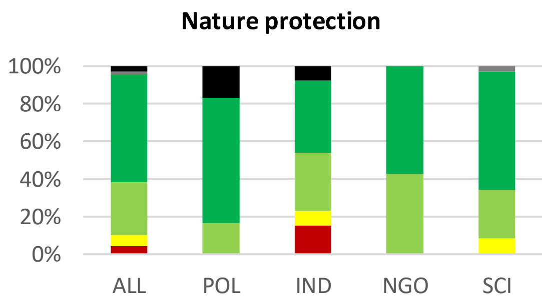

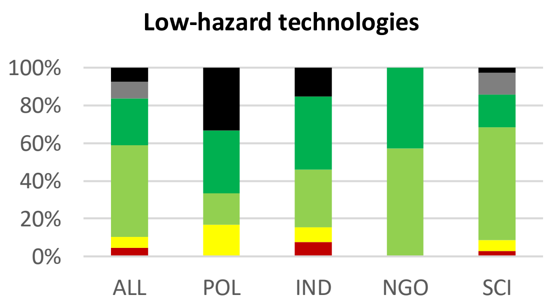

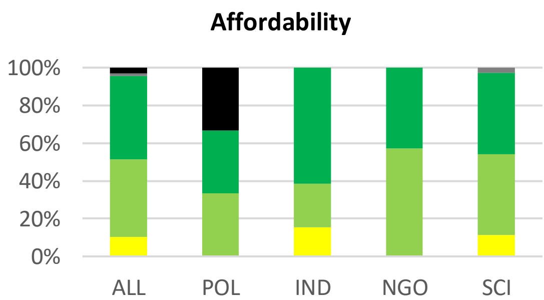

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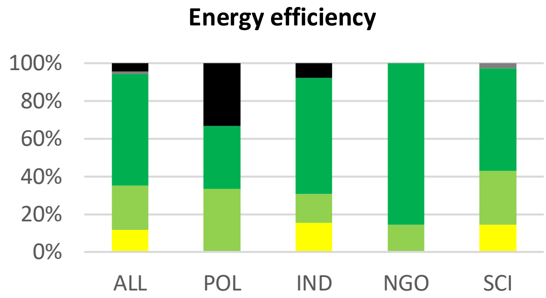
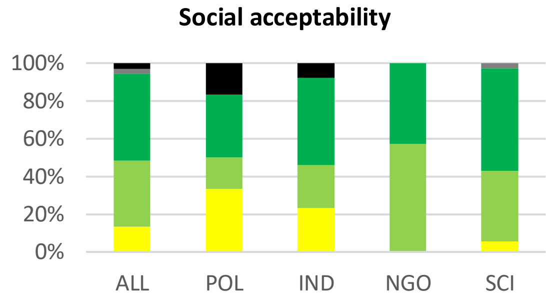
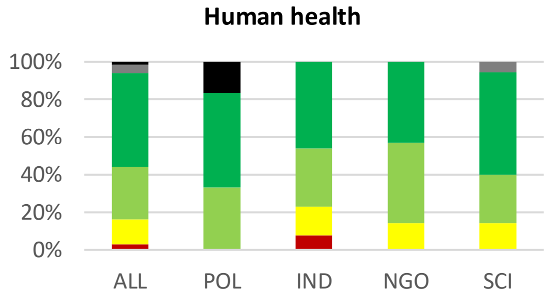
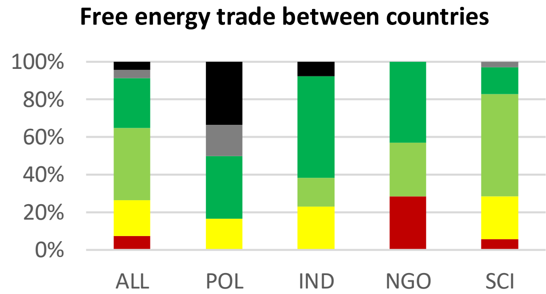








B2 | Regarding the previous question, did we miss to include aspects that are important to you?
N: 20 (voluntary, free text)

About one-third of participants, which answered the previous question about important aspects of the energy transition, mentioned further aspects that should have been included in our list. Participants highlighted details of the broad aspects from the list as well as added new aspects. The full list included (clustering by the study authors in bold[25]):

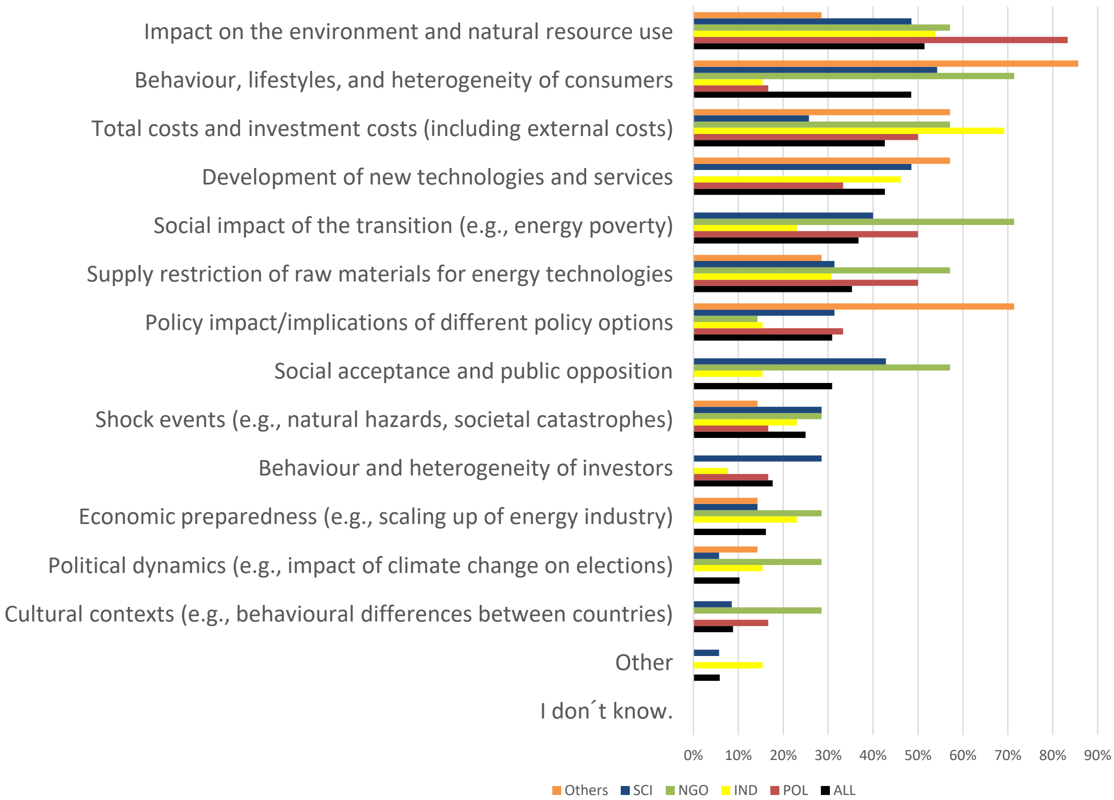
- **Environmental aspects:** Complete decarbonization, resource efficiency, supply restriction of raw materials, resource shortages, afforestation
- **Social aspects:** Just transition, fair distribution of burden and profits, distributed generation, storage, and curtailment, energy jobs
- **Participatory aspects:** Participation, stakeholder involvement, model-mediated public engagement, consultative processes like citizens assemblies, collective/horizontal and vertical cooperation and empowerment
- **Political and administrative aspects:** Political feasibility, connection to the existing legal framework, administrative bureaucracy, legislative complexity
- **Economic aspects:** Market feasibility, maintaining optionality, competitive market, RES business models, learning curves, total LCOE of alternative power systems at the end-user level
- **Technological aspects:** New technologies/products, clean energy technologies, sector coupling, electrification, hydrogen, supply flexibility, customer flexibility, demand-response, digitalization
- **Other aspects:** Path dependency and interdependencies

[25] The original answers included not only bullet points. Single expressions needed to be slightly edited to be understandable from an outside perspective. The original data are included in the excel-based data set.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

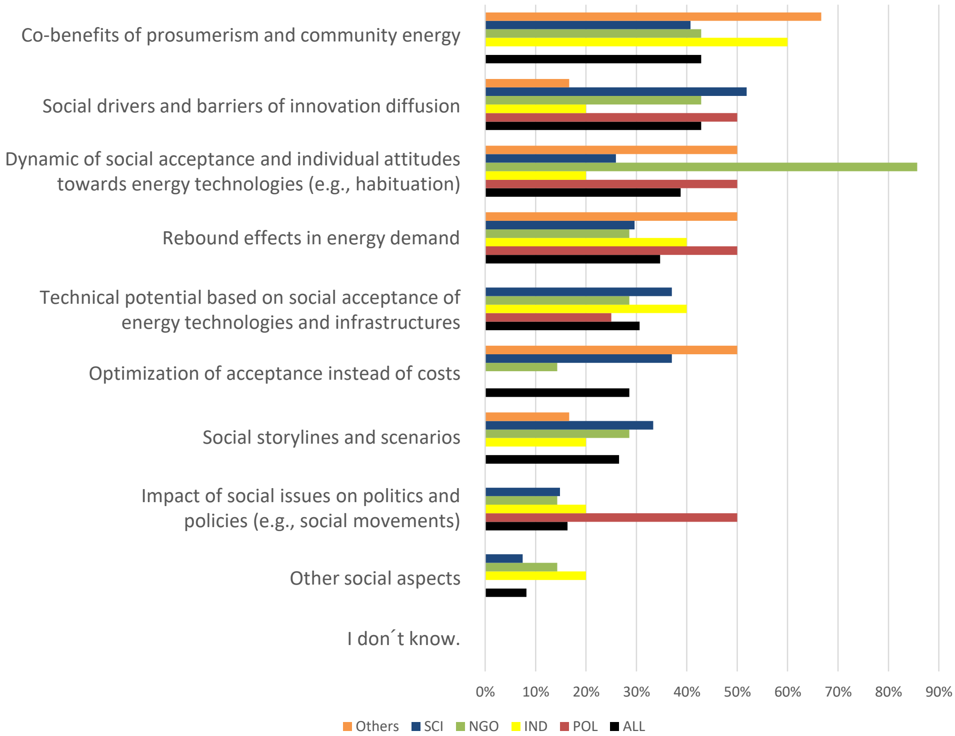
B3 | Which of the following factors do you think should receive more attention in energy models?
N: 68 (mandatory, multiple choices, between 1 and 5 answers); figure sorted by total share)

About every second respondent stated that "Impact on the environment and natural resource use" (51%) and "Behavior lifestyle, and heterogeneity of consumers" (49%) should receive more attention in energy models. Also, "Total costs and investment costs (including external costs), and the "Development of new technologies and services" were viewed as a priority (each with 43%). These aspects were ranked high almost in all groups, while the order of the ranking differed. The participating policymakers found the impact on the environment and natural resource use most relevant (83%), energy industry representatives the total costs and investment costs (69%), and NGO representatives as well as the scientific community behavior, lifestyles, and heterogeneity of consumers (71% / 54%). Importantly to note, the NGO representatives were not convinced by new technologies in energy models (0%). The policymakers and energy industry did not think that behavior should receive more attention (15% / 17%).



B4a | You stated that social aspects should receive more attention in models. What social aspects would you like to see integrated into energy models?
N: 49 (voluntary, multiple choices, up to 3 answers, figure sorted by total share)

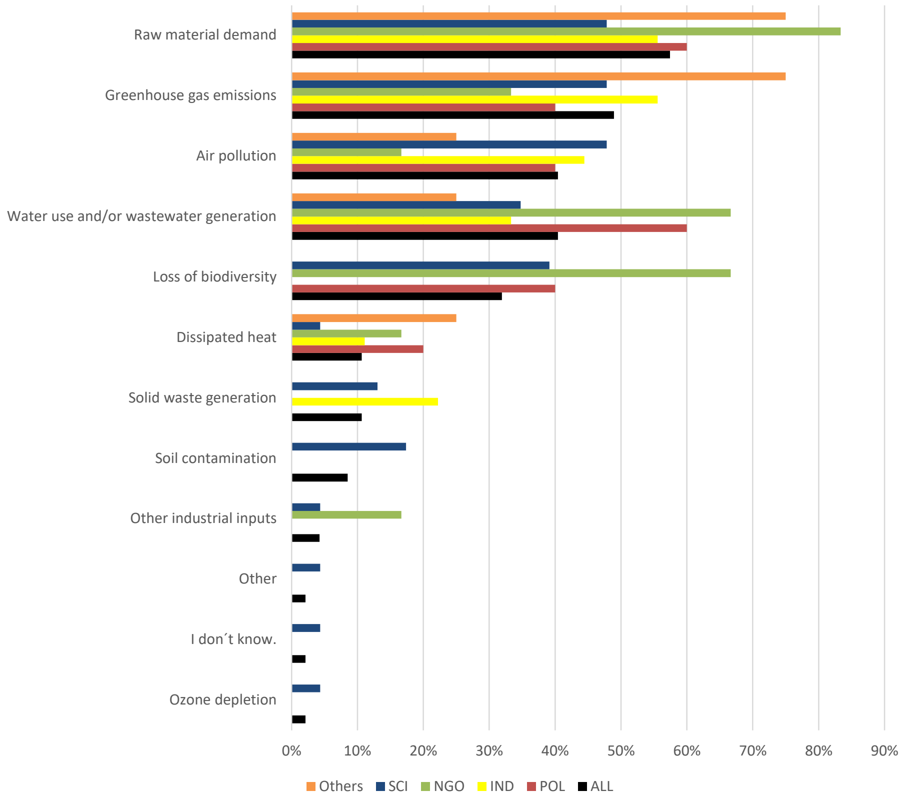
Respondents who stated in the previous question that social aspects should receive more attention received this follow-up-question with further and more detailed options. The ranking is led – as Top 3 – by the "Co-benefits of prosumerism and community energy" (43%), the "Social drivers and barriers of innovation diffusion" (43%), and the "Dynamics of social acceptance and individual attitudes" (39%). These aspects were ranked high across the user groups, with some noteworthy exceptions: For example, co-benefits of prosumerism and community energy were most important for energy industry representatives (60%), social drivers and barriers for the scientific community and policymakers (52% / 50%), and especially NGO representatives would like modelers to focus on acceptance dynamics, e.g., the habituation to new technologies (90%). On the contrary, none of the participating policymakers were convinced by prosumerism and community energy, and energy industry representatives were least interested in social barriers and drivers of innovation diffusion and acceptance dynamics (each with 20%).



Some respondents added new aspects in the free text field of "Other social aspects", including (1) the techno-economic limitations of the incumbent paradigm, (2) the costs for low-income groups, (3) the impact on poverty (distributional analysis), unemployment, wages, and (2) co-prosumerism in a commons´ logic.

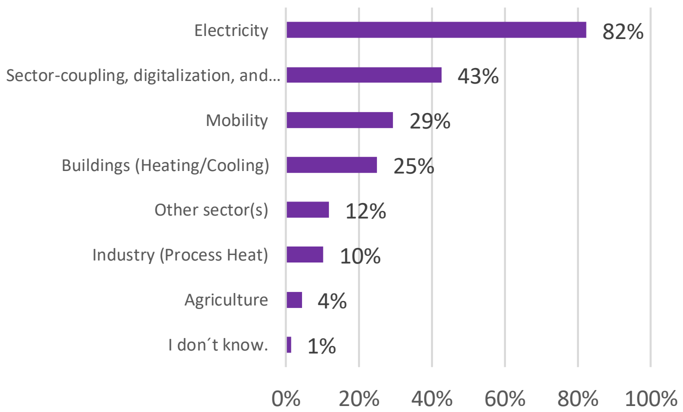
B4b | You stated that environmental or resource issues should receive more attention in energy models. What environmental factors would you like to see integrated into energy models more in the future?
N: 47 (voluntary, multiple choices, up to 3 answers, figure sorted by total share)

Survey participants who indicated their interest in ecological factors in question B3 were asked a follow-up-question given more detailed options. Respondents stated that raw material demand (57%), greenhouse gas emissions (49%), air pollution (40%), water usage (40%), and loss of diversity (32%) should receive more attention. All other options received significantly less attention (<11%). We found noteworthy differences between the stakeholder groups. For example, while raw material demand and greenhouse gas emissions were ranked relatively high by all groups, none of the energy industry representatives saw the loss of biodiversity as an essential modeling topic.



One respondent who used the free text "other" field mentioned that raw materials demand should also consider raw material demand for required transmission.

B5 | Which sector(s) is/are currently of main focus in your working context?[26]
N: 68 (voluntary; multiple choices, maximum of 3 answers)



Those participants who were interested in the improvement of model content were asked their specific sector focus. Most work on electricity (82%). Fewer respondents work in the field of sector-coupling, digitalization, and system flexibilization (43%), mobility (29%), the heating and cooling of buildings (25%), on process heat in the industry (10%), and agriculture (4%). Every tenth mentioned other sectors.

[26] This question was part of the section 'model content', although it questions the personal background. For the analysis, we placed it here.

B6-12 | You stated above that electricity / buildings (heating/cooling) / industry (process heat) / mobility / agriculture / Sector-coupling, digitalization, and system flexibilization / other sector(s) is currently the main focus. Please list up to three questions (your 'Top 3') regarding this sector that should be answered by energy models.

N: 38 (voluntary, free text)

Respondents provided 'Top 3' questions interesting for the stakeholders in their daily sector-specific working contexts. In sum, we received 110 answers for electricity, 41 for sector-coupling, digitalization, and system flexibilization, 41 for mobility, 30 for buildings (heating/cooling), 14 for industry (process heat), 6 for agriculture, and 8 for other sectors. Some topics recurred in the answers quite often, especially questions primarily regarding the potential and pace of innovative technology diffusion and secondly regarding social, economic, and political feasibility. The list below presents original and refined questions.[27]

Electricity

Policymakers

1. What is the best phase-out trajectory for fossil fuels and nuclear?
2. What is the energy demand in the future, up until 2050, in the EU/Sweden? There is a need for further scenarios and updates, such as when the transition is sometimes fast in society.
3. What is technically and economically (factoring in externalities) feasible in terms of speed and scale of expansion of renewables?
4. How to safeguard RES deployment in Europe with European and member states policy measures and instruments?
5. Can we rely on renewable electricity to meet the demand in the EU until 2050?
6. What are the tipping points accelerating the phase-out of fossil fuels?
7. What are robust strategies for energy transition with the aim of climate neutrality based on fluctuating RES?
8. What is the cost of building renewables to the extent that it meets future demand in the EU (to avoid coal, natural gas, oil, and potentially also nuclear power)?

Energy industry

1. Is 100% renewable even possible?
2. What is the cost versus transition efficiency (i.e., reduction of CO_2) in time if different green technologies are widely used?
3. How are costs correlated to the different storage technologies?
4. How to deal with exhausted energy efficiency and raised up targets?
5. *What is the role of electrification in the clean energy transition?*
6. How can we have cheaper electricity (AKA be more energy-competitive)?
7. How can we model the risk, the frequency, and the consequences of extraordinary events happening in the energy transition process relating to the loss of security of supply?
8. How can we avoid higher energy prices?
9. *What are the advantages of accelerated electrification in the other sectors of the economy?*
10. *How to achieve 100% RES and cheaper electricity with equivalent security of supply?*
11. What is the relationship between the level of policy support and the wide penetration of clean technology to small consumers?
12. How to deal with hydrogen regarding cooking appliances?
13. How high are the overall costs of electrification to the society, including costs of distribution and transmission infrastructure?

Non-governmental organizations (NGOs)

1. Is it technically, socially, politically possible to decarbonize the electricity sector?

[27] Several of the answers were bullet points or statements. Those who were easily and unequivocally translatable into questions are included in *italic* in the overview.

2. *What is the optimal distribution of renewable energy plants across Europe with the objectives of balancing renewable energy feed-in, reducing the annual peak load and the need for back-up power plants?*
3. How much will it cost to decarbonize the electricity sector?
4. *How can I map the temporal, economic, and social dimensions of flexibility?*
5. *What will be the role of prosumers in a future energy system?*
6. What are the external costs - raw material usage, water, emissions related to decarbonization?
7. *What are optimal socio-economic futures between electricity, gas, and heat infrastructure?*

Research, Innovation & Consultancy

1. *Which options like, e.g., green gas and other e-fuels have higher lock-in potential?*
2. What are possible architectures of future net-zero emission electricity systems?
3. How much is thermal capacity needed during the time of long-term transition pathways towards a decarbonized energy system with high RES shares?
4. How can we model the system operation properly under high variable RES penetration?
5. Is DC an alternative in LV grids?
6. Where does our future electricity come from?
7. How should grid stability (inertia) be modeled?
8. How do decentralized concepts / high level of autarky influence the need for transmission grid extension, overall system cost, and social acceptance?
9. How to cope with different dynamics for the supply of clean energy and the use of clean energy?
10. How can a renewable but cost-efficient system (grid and market) be designed?
11. What is the impact of legal frameworks on technology development?
12. What is the optimal allocation of renewable energy technologies?
13. In which and where to invest in new energy infrastructure?
14. *Policy trade-offs: What are the impacts (cost, landscape, jobs...) of policy option 1 compared to policy option 2?*
15. Are factors in the distribution of costs and benefits in electric grid operation externalized?
16. What is the most efficient grid design to facilitate a higher share of electrification (70% + share of electricity in energy demand)?
17. How to achieve a cost-efficient, resilient, emission-free electricity system?
18. *How can an electricity system with a high share of renewables be resilient?*
19. *What are the trade-offs between grid reinforcement and less controversial options like storage and demand-side flexibility?*
20. What are the expected economic benefits and power injection risks of RES business models for each producer category (small-scale, large-scale, aggregators)?
21. What is the most appropriate calculation methodology for storage needs to minimize curtailment and ensure stable operation?
22. Will electricity be affordable?
23. How will demand profiles change?
24. How would a stronger European integration of the electricity impact on overall system cost, acceptance, and environmental impacts?
25. What is the potential value of different potential energy system innovations?
26. How to cope with the new allocation of decentralized and centralized systems?
27. How resilient are our systems to climate change?
28. What is the impact of policy frameworks on technology development?
29. What role will storages play in the future energy system?
30. How to balance sustainability, affordability, and security while ensuring meeting climate goals?
31. Policy trade-offs: Does public opposition AS OBSERVED IN REALITY really constitute a barrier (i.e., are outlooks with high opposition fundamentally different than such with low opposition, again in terms of cost, physical design, landscape, jobs, but also decarbonization speed)?
32. How does the implementation of models assist across different cultures/contexts/climates and needs?
33. What new technologies and regulation changes are required to facilitate the above grid design?
34. How optimally integrate smart technologies?

35. *What is the role of distributed energy sources on the distribution side?*
36. How much RES capacity and storage is needed to reach a 100% renewable energy electricity mix without excessive curtailment? How does RES capacity relate to RES generation and storage needs? What is the cost of each additional percent of RES generation injected into the system?
37. How can the security of supply issues be integrated into power system planning with high RES?
38. Will we be dependent on other countries?
39. How will energy storage be modeled (environmental impacts)?
40. What is the optimal ratio between wind power and PV for a carbon-neutral system, taking into account aspects of social acceptance, biodiversity, and technological development in both technologies to be more environmentally benign (e.g., agro-photovoltaics, building-integrated PV, bird, and bat monitoring and protection systems for wind turbines)?
41. How do most cost-effective energy systems vary with technical and cost characteristics of component devices?
42. How to cope with investment decision-making?
43. Is sector coupling cost-efficient?
44. How much will additional electricity demand occur through sector coupling/ Power-to-X?
45. How to implement infrastructure measures?
46. How can demand-side management be less sensitive to the behavior of the consumer, and instead focus on how a logic / alternative rules can be structured to shape a logic based on electricity infrastructure as commons, such that the co-prosumer has incentives to be/exist and act accordingly?
47. What is the most efficient method of meeting electricity demand using a European approach to the distribution of generation rather than on a national basis?
48. How to structure the system to reduce risks and the impact of uncertainty?

Other stakeholders

1. Is it possible to reach 100% self-sufficient 'local' power grids (without connection to the overlay grid) using only renewable sources + battery storage?
2. How can local real-time markets reduce CAPEX and LCOE?
3. *How high is the total cost of the different electricity production means, including all economic impacts for each of them?*
4. How to manage a 100% renewable electricity supply?
5. Hydrogen vs. Electricity: coexist or compete?
6. What is the flexibility potential that can be harvested in an optimal energy system (from sector coupling and process flexibility)?
7. *How do different forms of energy interact (gas, electricity, hydrogen)?*
8. *What are interesting incentives to prosumers for adopting storage technologies?*
9. *What is a reasonable storage mix?*
10. *What will be the cost of goods (panels, batteries) in the coming years?*
11. *How high are the costs associated with a zero-carbon electricity supply?*
12. *Have applications for hydrogen/electricity the highest efficiency and/or lowest cost today, 2030, and 2050?*
13. *How can we deliver negative emissions in the electricity sector, and when can it be achieved?*

<u>Sector-coupling, digitalization, and system flexibilization</u>

Policymakers

1. What regulatory adjustments need to happen in order to manage the energy transition?
2. *How big are the footprint and rebound effects of digitalization?*
3. What adjustments need to take place with respect to energy taxes, carbon pricing, net fees, financing RES deployment - without comprising flexibility options and sector coupling?
4. Are low-tech options sometimes better, particularly when factoring in resource/material demand, etc.?

Energy industry

1. *What role can demand-side response (incl. batteries, P2X) play in achieving system flexibility?*
2. *What is the role of digital technologies, including pros and cons, in the energy transition?*

3. What is the effect of P2P trading in enabling sector coupling and system flexibility?

Non-governmental organizations (NGOs)

1. Digital infrastructure and digitalized processes are currently thought of as purely centralized since the energy providers are allowed to set specifications in this regard. To save costs and achieve a high level of resilience, systemic aspects should be given greater consideration. In addition, the wishes of the users should be considered to a greater extent. *How can models be used to optimize these aspects?*
2. *Multi business cases could significantly increase the returns of flexible consumers and minimize investment risks with respect to own power consumption, balancing group balancing, frequency maintenance, congestion management, string optimization (low voltage), pooling.* How can flexibility be used to generate income in all areas?

Research, Innovation & Consultancy

1. To what extent could demand-response technologies limit the need for costly storage installations and increase the system's flexibility?
2. How can the 'old' industry be useful in the green deal?
3. How can smart systems and local electricity markets facilitate decentral concepts to become more beneficial to the overall system?
4. Which level of sector coupling is adequate?
5. What is the impact of policy frameworks on technology development?
6. What is the impact of increasing sector-coupling on system security?
7. How to mainstream nexus assessments to find synergies of the energy, waste, and water sector?
8. *How high is and will be the impact of Power2Heat on energy demand and system stability?*
9. *How can the capture of information-rich smart system technologies be improved?*
10. What are the benefits of combining electricity storage with demand-response technologies and how are these benefits distributed between actors in the electricity supply chain? What financial incentives should be applied to attract consumer participation?
11. What are the opportunities for digitalization in the 'old' industry (e.g., refineries)?
12. How do different concepts to supply hydrogen (local/regional, national/EU, global trade) impact system cost, public acceptance, and the environment?
13. How to find a balance between solidarization and solidarization of grid-connected and off-grid systems - how to make the best of both worlds and find an appropriate infrastructure for different contexts and scales?
14. *How high is the impact of electro-mobility on energy demand and system stability when you consider charging behavior?*
15. *How can autonomous decision making better be included and characterized (in models)?*
16. How do different RES/storage business models (i.e., P2P, P2G, OPG) perform in terms of profit for different actors? What are the respective governmental costs, if any?
17. How can we make linear processes more flexible (aiming circularity)?
18. How centralized or decentralized should an energy system be?
19. How to correct the misalignment of incentives for flexibilization in the sense that the market structures and grip operating structures are not at all pulling on the same string (or maybe the same string, but in different directions)?
20. *What are the impacts of sets of fully flexible co-generation plants with heat storage, electric heaters, and district heating?*

Other stakeholders

1. Hydrogen vs. Electricity: coexist or compete?
2. How would a cost-optimized integrated model (assuming conversion between different sectors such as electricity, heating, and mobility) with optimal use of storage outside the electricity sector (e.g., thermal, charging flex of vehicles, etc.) differ from one that does not/only partially use these synergies?
3. *Is there a comparative advantage of storage vs interconnections, and how does it look like?*
4. What are the impacts and opportunities on digitalization and flexibilization in the energy sector?
5. Which technologies prevail in which scenario?

6. *What are the pros and cons of electrical storage (battery) and hydrogen in comparison?*

Mobility

Policymakers

1. *What kind of vehicles will be used in the future: electric, hybrid, petrol, or diesel? What are the realistic scenarios?*
2. What level of CO_2-emissions can we expect from the transport sector in the future?
3. What level of other air-polluting emissions can we expect?

Energy industry

1. *How high is the need for electrification in the mobility sector?*
2. *What is and might be the role of sustainable biofuels in the mobility sector?*
3. *What are the life cycle emissions, carbon footprint, and the total cost of ownership of vehicles?*

Non-governmental organizations (NGOs)

1. What is the availability, sustainability, and potential for bioenergy in mobility?
2. How can active and low energy or public transport mobility be increased?
3. *What impact has the electric vehicle charging infrastructure?*
4. What technology options are suitable for different transport modes (passenger transport, heavy goods vehicle, light goods vehicles, etc.)?
5. *How can we secure high accessibility of electric vehicle charging infrastructure?*

Research, Innovation & Consultancy

1. What is the best way to foster electro-mobility?
2. How will the implementation of mobility policy impact total emissions of air pollutants?
3. How to prioritize direct use of electricity (e-mobility) or indirect use (e.g., hydrogen)?
4. What is the impact of policy frameworks on technology development?
5. Are pedestrians considered in energy models, and how do different mobility scenarios affect them?
6. *How high are the energy efficiency gains of electric alternatives vs. alternative fuels (ratio of final energy consumption vs. gross energy demand)?*
7. *How does the interplay between market development and policy look like?*
8. *What are the advantages/disadvantages of hydrogen versus electric mobility?*
9. How will the implementation of mobility policy influence the spatial and temporal patterns of pollutant emissions?
10. What is the future of private individual mobility?
11. How to achieve a modal split that is less wasteful of resources and energy?
12. How will transport trends change over time with the introduction of more public transport, car-sharing, etc. (multiple scenarios with increasing/decreasing shares of car ownership, for example)?
13. *Which price level is reachable for synthetic fuels?*
14. How to integrate the automobile sector's ability to switch to clean cars and car owners' preferences?
15. How to find solutions that work both for rural and urban areas - and that can induce behavioral changes?
16. How can transport assist in maintaining a secure and reliable energy system (e.g., vehicle to grid storage)?

Other stakeholders

1. What is the fuel consumption by kind of actors (non-resident, commuter, resident)?
2. *How will the electrical vehicle penetration rate develop?*
3. How much emission reductions can be achieved through mode switching?
4. What is the penetration rate of electric mobility?
5. *Are electric vehicles compared to hydrogen on heavy-duty transportation competitive?*
6. What are the measures that can deliver significant emissions savings in the short run?
7. What is the pollution level of transport?
8. *How high is and will be the cost of low carbon shipping?*
9. *What can emissions reductions be achieved in road freight, e.g., through alternative logistics*

arrangements?

<u>Buildings (heating/cooling)</u>

Policymakers

No questions stated.

Energy industry

1. *How can we push the standardization in the building sector?*

Non-governmental organizations (NGOs)

1. Is it technically, socially, politically possible to decarbonize the building sector?
2. What is the potential for non-tradition or non-incumbent technologies such as heat pumps?
3. How much will it cost to decarbonize the building sector?
4. *How are modern heating technologies be impacted by dark and calm weather?*
5. What is the potential for district heating or cooling?
6. How can we integrate electricity, heating, gas, hydrogen to cover the demand for energy in buildings?
7. What are the potential, costs, and barriers for zero energy buildings?

Research, Innovation & Consultancy

1. What are the additional electricity demand patterns and the effect on peak load demand resulting from the electrification of the heating/cooling sector?
2. How to cope with the renovation gap?
3. How can refurbishment be increased?
4. *What can be the role of passive energy systems, as appropriate to the circumstances and context?*
5. With increased aggregated penetration of RES, what would be the resulting share of RES in the cooling/heating sector with and without electricity storage?
6. How to cope with buildings and lifestyles?
7. How can the building sector play a more active role in the energy transition?
8. *What are social co-benefits and rebound in households in the heating transition?*
9. How would the electrification of the heating/cooling sector affect the electricity mix? Are there increased needs for reserves, and what is the role of imports due to the increased peak demand? What are the expected effects on electricity prices?
10. How to cope with affordable buildings?
11. How can 'locked-in' technologies such as oil be phased out?

Other stakeholders

1. How can we best couple thermal and electric building models and cost-optimize them?
2. *What are good solutions for accommodations?*
3. What is the energy consumption by sector?
4. Can zero-carbon energy supplies be a cheaper way of decarbonizing buildings than deep retrofit?
5. What is the isolation level of buildings?
6. How feasible/competitive would it be to use hydrogen in gas distribution networks for building heat?
7. What is the penetration rate of new technologies?

<u>Industry (process heat)</u>

Policymakers

1. How to minimize stranded investments in the industry sector while decarbonizing the sector and the energy system?
2. What is the cost in different industry sectors to reduce process emissions?
3. How far and how quickly can renewables get us net zero in the industrial sector?
4. What is the best way to coordinate investment decisions in the industry in order to take into account energetic interdependencies? What is the appropriate role of different government levels (national, regional, and communal)?
5. Are there faster and better non-energy sector solutions to decarbonizing the industrial sector (instead

of, e.g., CCUS). Rather than using technologies to decarbonize a given output/ product, can we replace the product/use altogether with a more sustainable alternative? Thinking outside the box and more holistically.

Energy industry

No questions stated.

Non-governmental organizations (NGOs)

1. Can demand be disaggregated by temperature for heat demand, e.g., steam, high, medium & low-temperature process heat?
2. What potential is there for fuel switching in process heat demand?
3. What is the potential for renewable process heat?

Research, Innovation & Consultancy

1. How can potential synergies for integration be found?
2. *What is the potential of power-to-heat in the industry?*
3. How can we integrate solar energy?
4. *How high is the potential for heat recovery and utilization of industrial cogeneration (excess) heat for space heating?*
5. How can we integrate biomass energy?
6. *What is the potential of co-generation of heat and local ('cold') district heating grids?*

Other stakeholders

No questions stated.

Agriculture

Policymakers

No questions stated.

Energy industry

No questions stated.

Non-governmental organizations (NGOs)

No questions stated.

Research, Innovation & Consultancy

1. What role can bioenergy play in a future, climate-neutral energy system?
2. What contribution of biogas production utilities for energy generation could be?
3. How can the greenhouse gas emissions from agriculture be reduced?
4. Should biofuels of 1st generation be phased out?
5. Which agricultural emissions will be hard/ impossible to reduce?
6. What contribution of biofuels should be in the future (1st, 2nd + generations)?

Other stakeholders

No questions stated.

Other sector(s)

Policymakers

1. *How can we achieve an economy-wide perspective, taking into account the 'system' dimension and co-dependencies?*
2. *How can we develop a better grasp of the technological dimension (lock-in, technological risk, etc.)?*
3. *How can we develop a better understanding of the drivers/triggers of changes?*

Energy industry

1. *What is state of the art in gas-related infrastructures?*
2. *How can the security of supply for gas power plants be reached?*

Non-governmental organizations (NGOs)

No questions stated.

Research, Innovation & Consultancy

1. *How can further offshore wind (50km+) play a bigger role in decarbonization in comparison to onshore wind, with a key focus on public acceptability, scalability, and environmental impact?*
2. *How could biorefineries (energy +material use of biomass) help to transform the energy system?*

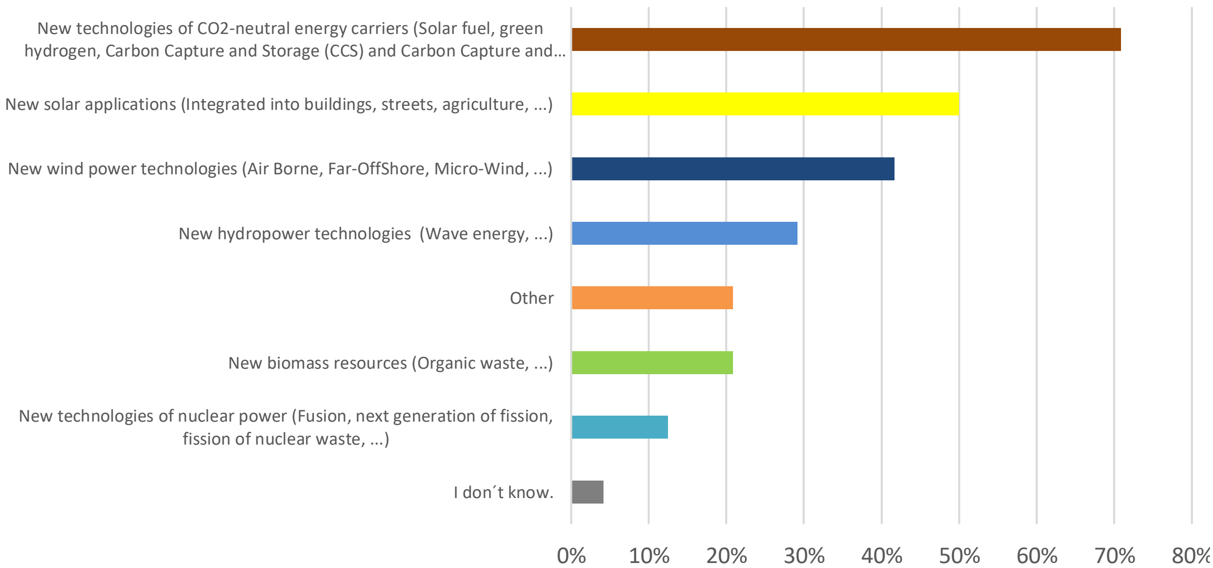
Other stakeholders

No questions stated.

B13 | You stated that the development of new technologies and services is very important to you. Which innovations in the electricity production sector should be included in energy models?

N: 24 (voluntary, multiple choices, up to 3 answers, figure sorted by total share)

Survey participants who indicated their interest in new technologies in question B3 were asked a follow-up-question given different innovative technology options. Its respondents see CO2-neutral energy carriers (like solar fuel, green hydrogen, Carbon Capture and Storage, and Utilization from coal and gas) as the most pressing modeling topic (71%). Besides, every second respondent wants to see new solar applications like PV-integration into buildings and streets or combination with agriculture (50%). These options were followed by new wind power technologies, including, e.g., Air Borne, Far-Off-Shore, and Micro-Wind (42%) and new hydropower possibilities like, e.g., wave energy (29%). New biomass resources and innovative nuclear power, like, e.g., atomic fusion, received the least attention (21% and 13%). Overall, technology preferences were strongly influenced by the scientific community (14 out of 24 respondents). As one policymaker, four energy industry representatives, and no NGO representative participated, we cannot analyze group-differences on a sound basis and, therefore, only include the aggregated figure.



One participant missed *"gas engines (e.g., for cogeneration) running on natural gas, biogas, biomethane or hydrogen"* as further innovative energy production technologies. Four further responses included energy storage and P2X-technologies, system integration technologies, and new energy transmission options like e.g., superconductors.

B14 | Given your sector-specific working context, which innovations should be included in energy models? If any, please describe the emerging technologies, services, and other innovations briefly.
N: 14 (voluntary, free text)

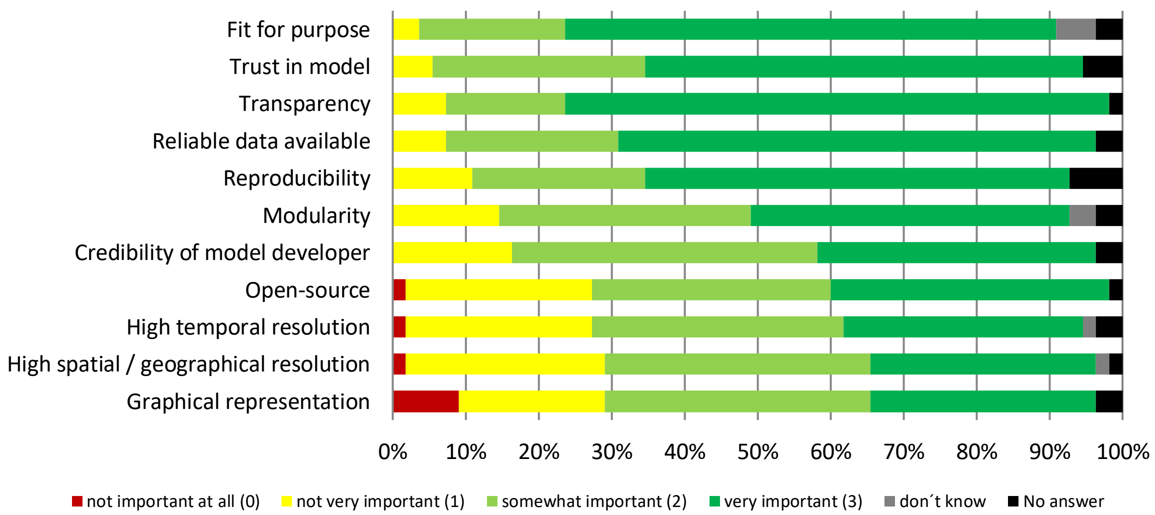
Participants emphasized the following innovative technologies and services to be integrated into models (extracted from the statements by the study authors): concentrating solar power, gas engines (i.e., internal combustion engines of up to 20 MW each) with converting natural gas or biogas into electricity & heat/cold (cogeneration or trigeneration) [better and not equivalent with traditional large and less flexible gas power plants based on the turbine technology (ex. CCGTs)], biogas facilities, biorefineries, exhausted heat, prosumer storage systems, hydrogen, batteries, P2X, direct CO2 air capture and storage, liquid air energy storage, smart energy efficiency measures, micro flexibilization, digitalization of demand energy management, demand-response and corresponding business models, electric grid infrastructure as commons, larger capacity transmission technology/medium voltage, and high current superconductors.

C Model design (and data)

Survey participants interested in the model design (as indicated in A13) received the following question section.

C1 | How important are the following model conditions for the use of models or their results in your work?
N: 55 (voluntary, Likert scale, figure sorted by total share of "not important at all" and "not very important")

The respondents showed a clear tendency towards the overall importance for all predefined answer options, as the sum of "somewhat important" and "very important" was even in the lowest case above 67%. Transparency, trust in models, and reliable data availability had the highest support rates (91%, and twice 89%). Group-specific differences were observable but relatively small and no finding contradicted the overall result. Only four policymakers and four NGO representatives contributed to the question, reducing the representativeness for these groups.



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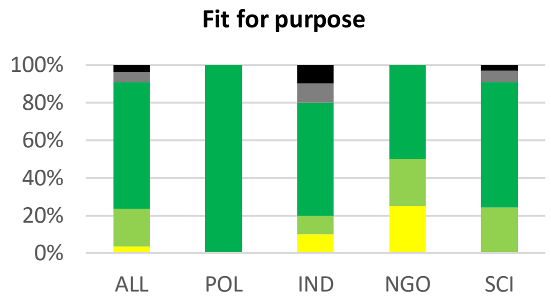
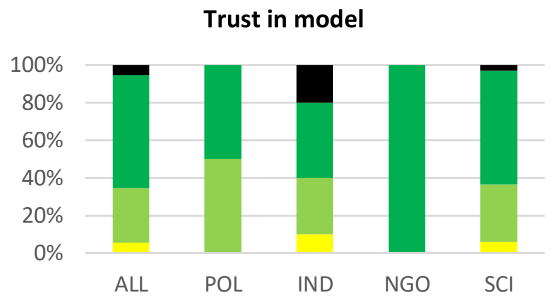
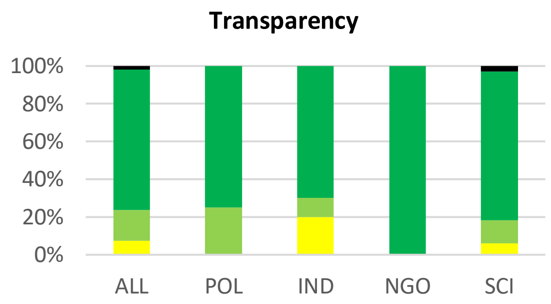
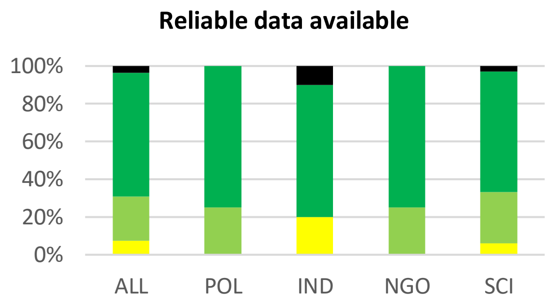
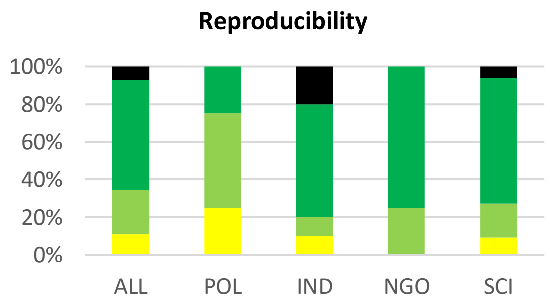
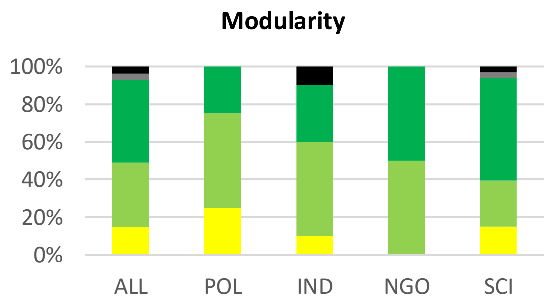


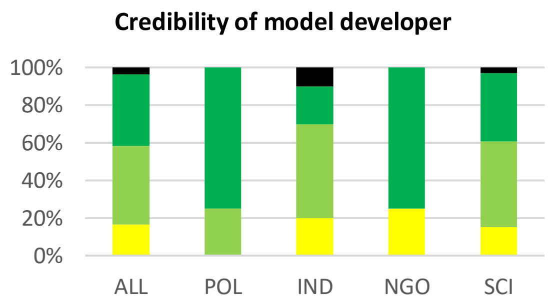


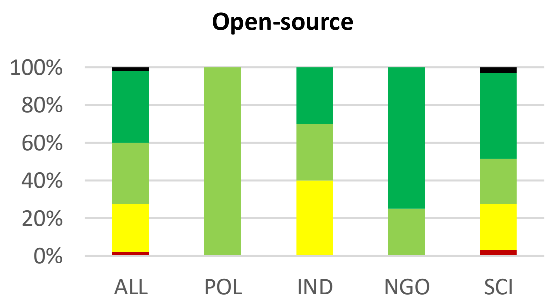


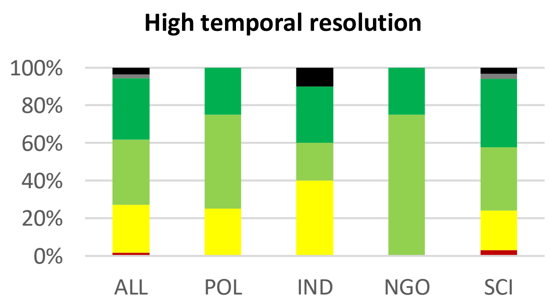


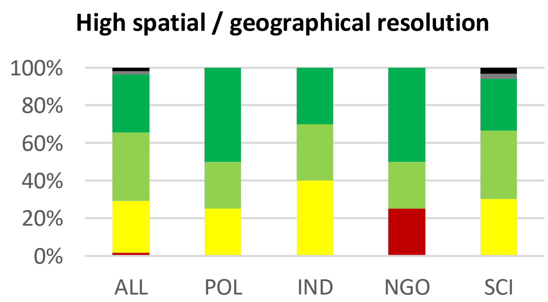


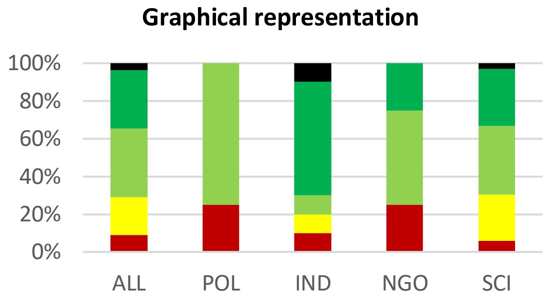








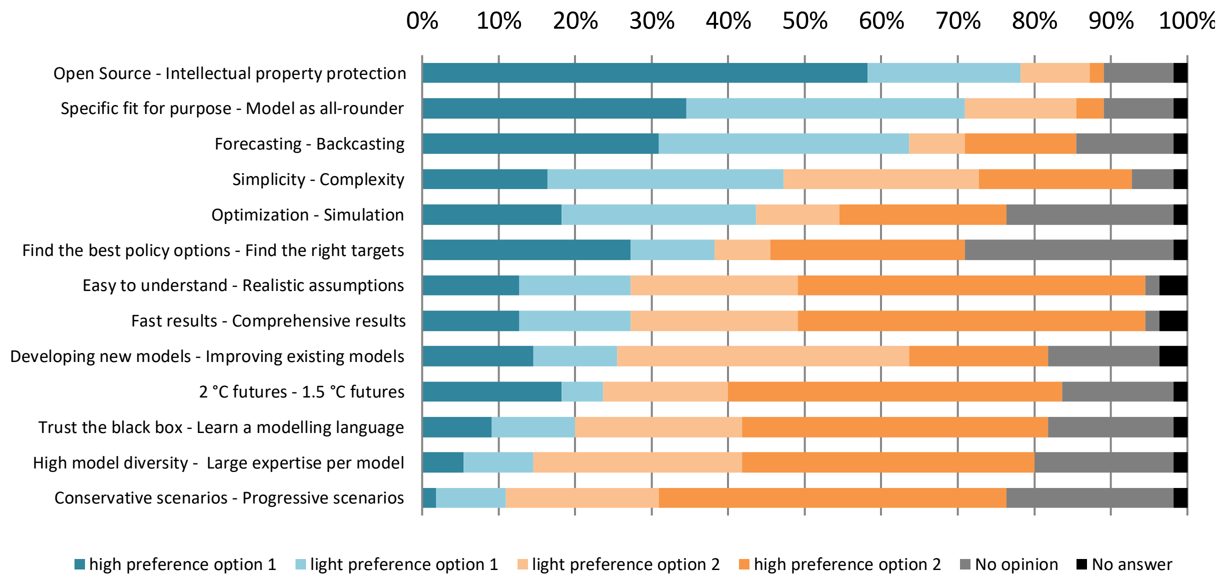




C2 | Which model feature/quality is more important? Please choose in each pair the more meaningful to you.

N: 55 (voluntary, Likert scale, figure sorted by total share of "not important at all" and "not very important")

Respondents had the chance to indicate their preferences regarding different design trade-offs, which modelers usually deal with and decide about during the model development and application. Here, they need to decide in which direction a model should develop, e.g., whether it should be a simple or a complex model, optimization or simulation model, and so on. Overall, we found clear tendencies towards one of the options for most of the predefined trade-offs. The majority of respondents preferred existing, fit-for-purpose, realistic, open-source models, and comprehensive, progressive, and 1.5°C scenarios. However, for some basic decision, the preferences seemed less clear, when the sum of high and light preferences are compared, like, e.g., for simplicity versus complexity (47% versus 45%), finding the best policy options versus finding the right targets (38% versus 33%), and optimization versus simulation (44% versus 33%). Group-specific differences were observable (see below). Again, only four policymakers and four NGO representatives contributed to the question, reducing these groups' representativeness.



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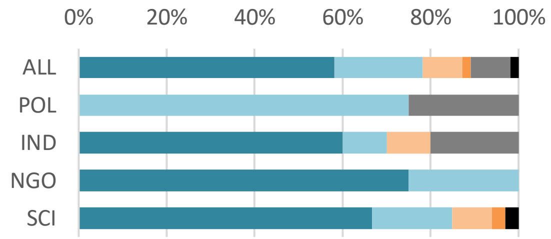
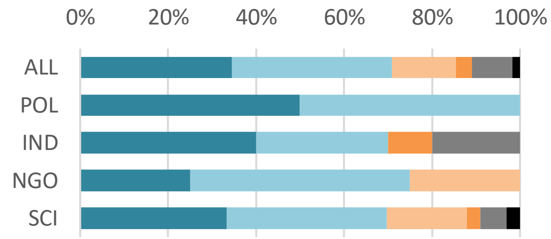
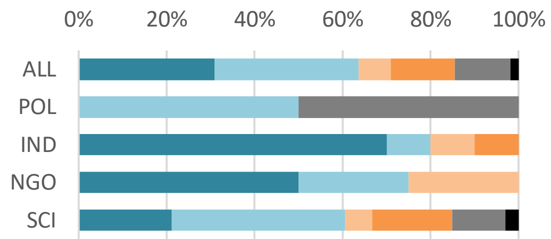
Open-source – Intellectual property



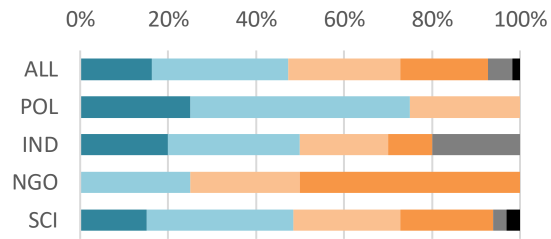
Specific fit for purpose – Model as all-rounder



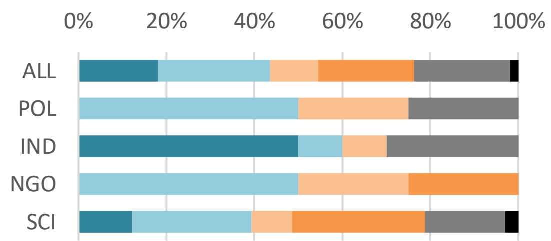
Forecasting – Backcasting



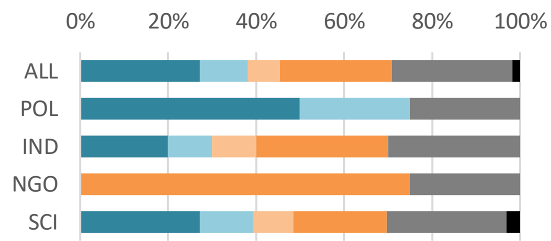
Simplicity – Complexity



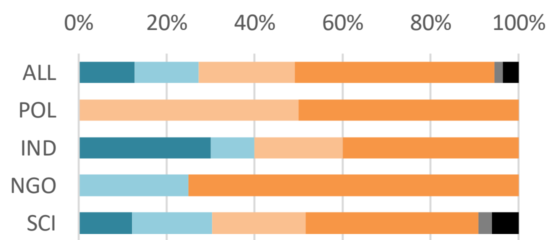
Optimization – Simulation



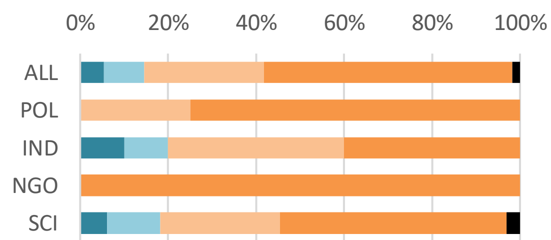
Find the best policy options – Find the right targets



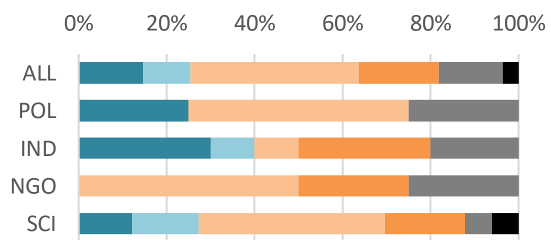
Easy to understand – Realistic assumptions



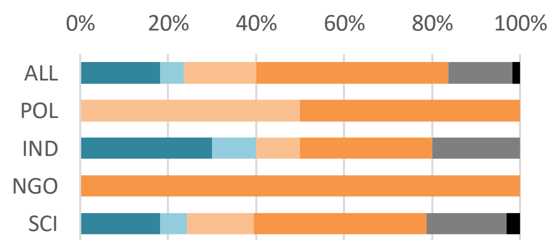
Fast results – Comprehensive results



Developing new models – Improving existing models

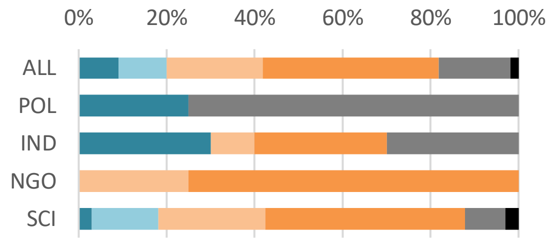


2°C futures – 1.5°C futures

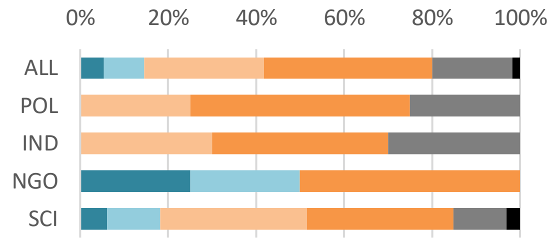


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

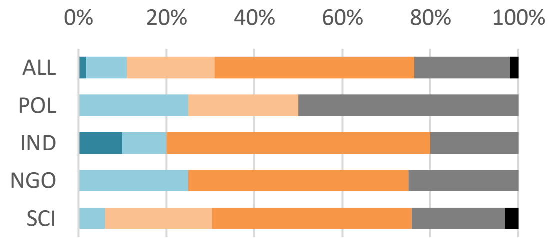
Trust the black box – Learn a modeling language



High model diversity – Large expertise per model



Conservative scenarios – Progressive scenarios

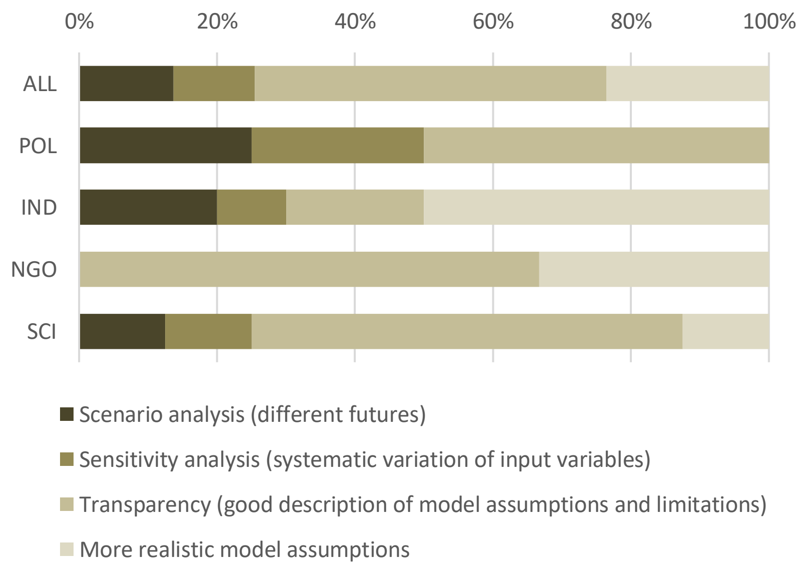


C3 | How important are the following measures to reduce model uncertainty? Please order them by importance, with the most important on top.

N: 51 (voluntary, ranking)

Participants were asked to rank four widespread solutions of uncertainty management in modeling by their importance, including scenario analysis (different futures), sensitivity analysis (systematic variation of input parameters), transparency (good description of model assumptions and limitations), and model improvement by the implementation of more realistic model assumptions. Focusing on the solutions that were ranked highest by respondents, transparency is most important (51%), followed by realistic model assumptions (24%), scenario analysis (14%), and sensitivity analysis (12%). The well-represented fraction of the scientific community (32 of 55 respondents) overall determined in no small extent the cross-group result. However, differences between the groups exist. For example, none of the policymakers ranked the highest realistic model assumption, while NGO representatives did entirely subordinate scenario and sensitivity analysis.

Ranked 1st place



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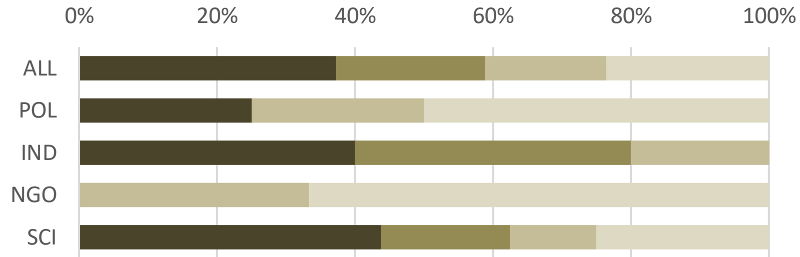
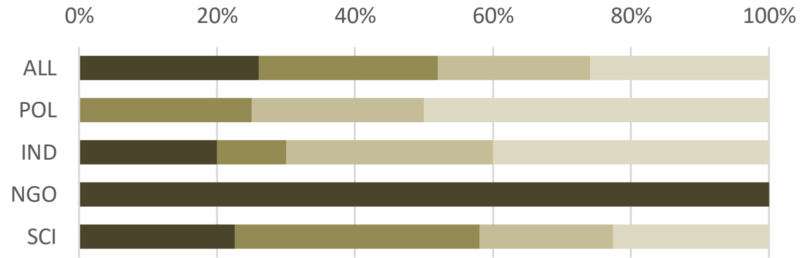
Ranked
2nd place



Ranked
3rd place



C4 | Regarding the previous question, did we miss to include aspects to deal with uncertainty in modeling that are important to you?
N: 8 (voluntary, free text)

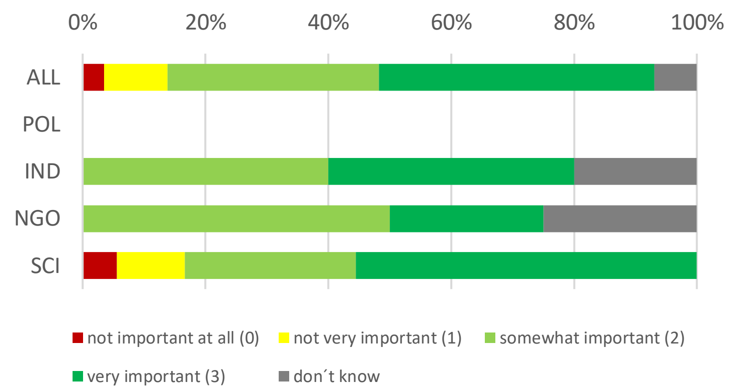
Eight participants who answered the previous question (C3) responded to this follow-up question about options for managing uncertainty in modeling. On the one hand, they emphasized general and specific aspects of the suggested solutions and, on the other, added different solutions. A respondent stated as a broad aspect, "[…] that uncertainty comes in many flavors, and each has its own appropriate set of remedial actions." Besides, specification means, for example, that transparency should be operationalized as an open-source of models, code, and data on public platforms (like, e.g., GitLab), as it assures for quality. Further solutions for uncertainty management were the explicit modeling and presentation of uncertainty (as a model output), and the use of stochastic models. However, stochasticity was seen quite critical by another respondent: "In general, the way people deal with stochasticity is overly simplistic; either brute force scenarios or cherry-picked scenarios. Sampling techniques like genetic algorithms, and Latin hypercube (and the combination of both), should be widespread because those sample more evenly, more representative (likely) scenarios."

D Modeling process

Survey participants interested in the modeling process (as indicated in A13) received the following question section.

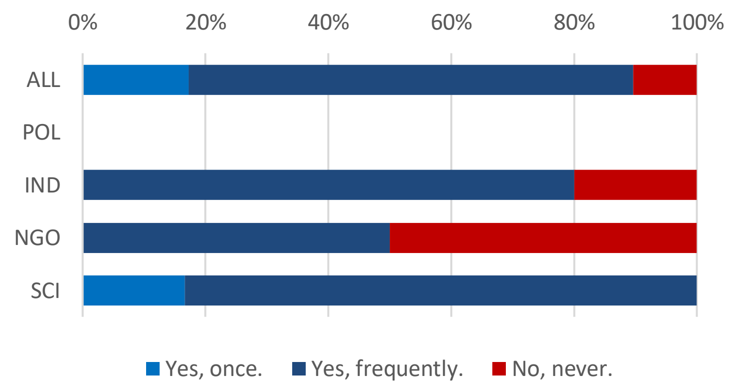
D1 | How important is your involvement in conceptually developing or improving models for you?
N: 29 (mandatory, Likert scale)

Participants who either never had worked with models (A306) or were indirectly involved in modeling so far (A302, A304, and A305) received this question. Overall, a high share likes to be involved in the conceptual development or improvement of models (79%). Almost half of the respondents stated even that their involvement is "very important" for them (45%). Group-specific differences are relatively small; however, the energy industry and NGO representatives signaled stronger interest than the scientific community. The overall result is strongly influenced by the large share of scientific contributors (19 of 30 respondents). As policymakers were not interested in contributing to the modeling process (as indicated in A13), no group-specific data is available.



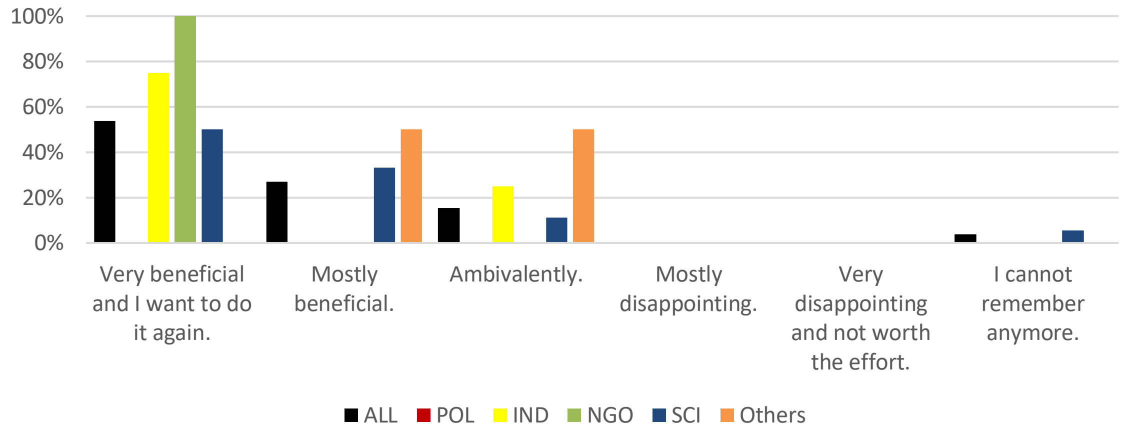
D2 | Have you ever been involved in the development or improvement of models?
N: 29 (mandatory, single choice)

All participants who were asked about the importance of their involvement (D1) were also asked about their past involvement in the modeling process. A large share of 89% had already contributed to the development or improvement of models, 72% even frequently. Scientists were most experienced (83% frequently), followed by the energy industry (80%) and NGOs (50%). Again, as policymakers were not interested in contributing to the modeling process (as indicated in A13), no group-specific data is available.



D3 | When looking back, how useful was the involvement in this process for you?
N: 26 (mandatory, single choice)

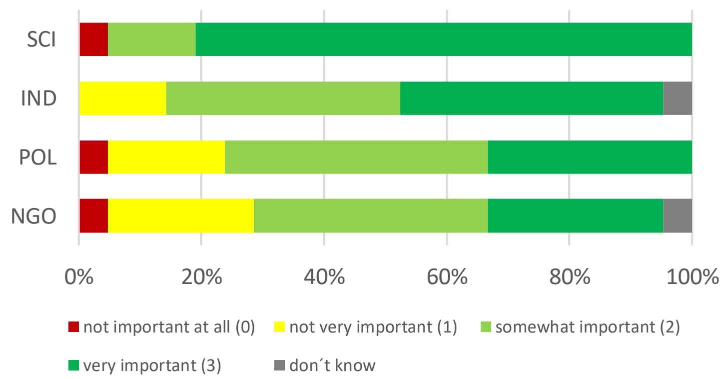
Participants who neither had worked with models (A306) nor were involved in modeling so far as result analysts, writers, readers and commissioners of model-based studies (A302, A304, and A305) and had contributed once or frequently to model development and improvement (D201 OR D202) were also asked about their satisfaction with their involvement. A large majority of respondents were satisfied with their involvement. About every second found it very beneficial and would like to contribute again (54%), and about every fourth mostly beneficial (27%). Although no respondents were mostly or very disappointed about the modeling process, some assessed their involvement as ambivalently (15%). While all four NGO representatives were very satisfied, one energy industry representative and two scientists had an ambivalent relation to the process. However, these numbers might be too small to be representative of these groups. As policymakers were not interested in contributing to the modeling process (as indicated in A13), no group-specific data is available.



D4 | How important for you is involvement of the following groups in your model development and improvement process?

N: 21 (mandatory, Likert scale, figure sorted by total share of "not important at all" and "not very important")

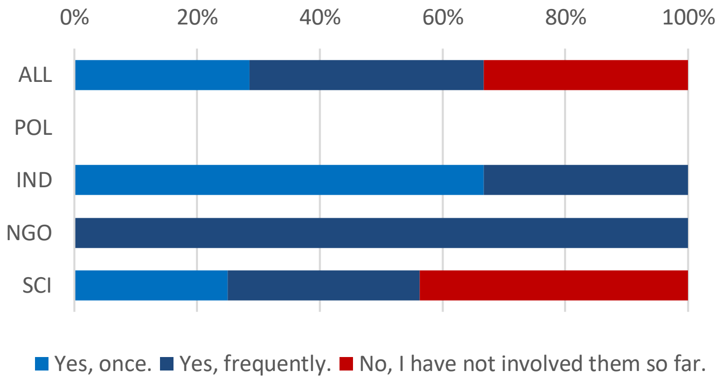
Participants who develop models technically or run and apply them (A301 and A303) were, on the contrary, asked about their satisfaction with the involvement of different stakeholder groups. Overall, the majority of modelers say the involvement of each group as positive (range of the sum of "somewhat important" and "very important" between 67% and 95%). Importantly to note, four out of five respondents assess the involvement of the scientific community as "very important" (81%), while these shares are significantly lower for the other stakeholder groups (29-43%).



D5 | Have you involved external stakeholders in your model development so far?

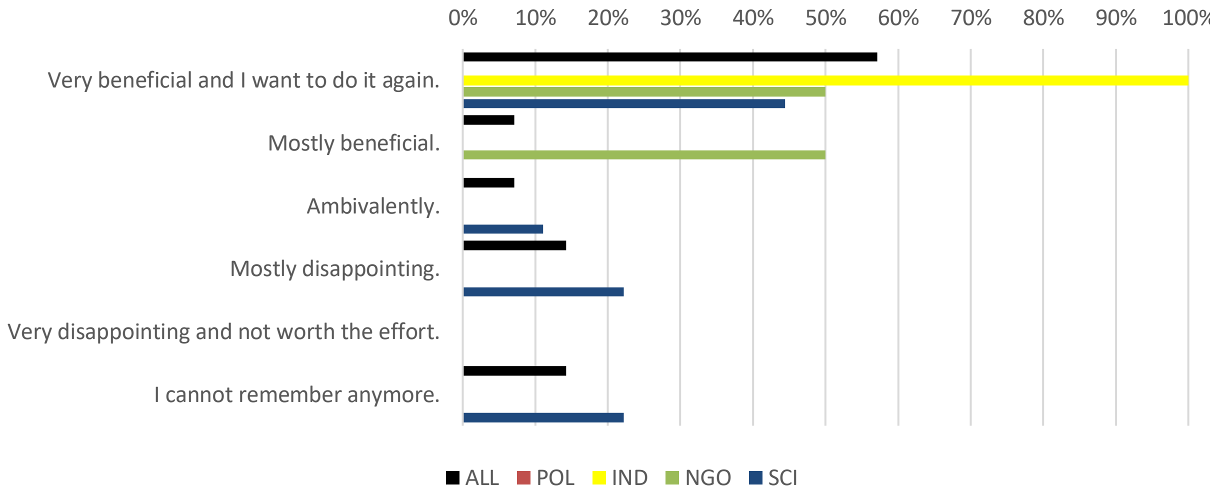
N: 21 (mandatory; single choice)

Participants who develop models technically or run and apply them (A301 and A303) also received this question about their orientation towards participatory processes in modeling. About every third respondent has not involved stakeholders so far (33%), involved them once (29%), and frequently (38%). All modelers with a background in the energy industry and NGOs that responded to the question have involved other stakeholders. Still, the numbers are too small to be representative of these groups. As policymakers were not interested in contributing to the modeling process (as indicated in A13), no group-specific data is available.



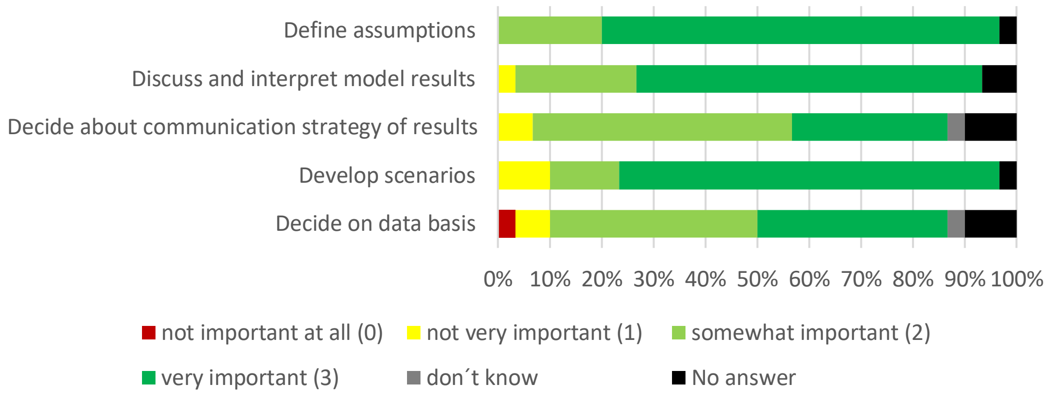
D6 | When looking back, how beneficial was the involvement of external stakeholders for your work?
N: 14 (mandatory, single choice)

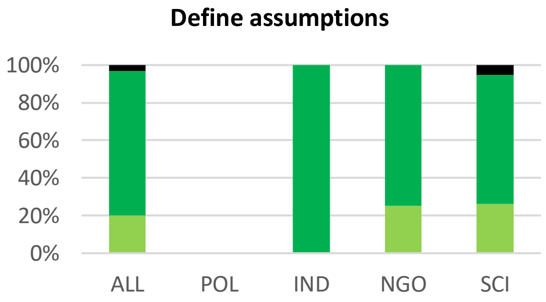
Participants who develop models technically or run and apply them (A301 and A303) and involved external stakeholders in their model development or improvement were asked about their satisfaction with the participation. Many of all respondents found the involvement very and mostly beneficial (64%). Two respondents were mostly disappointed (14%), and one arrived at an ambivalent judgment (7%). Group differences seem large; however, the numbers of the energy industry (3) and NGO representatives (2) were too small for a sound analysis. As policymakers were not interested in contributing to the modeling process (as indicated in A13), no group-specific data is available.

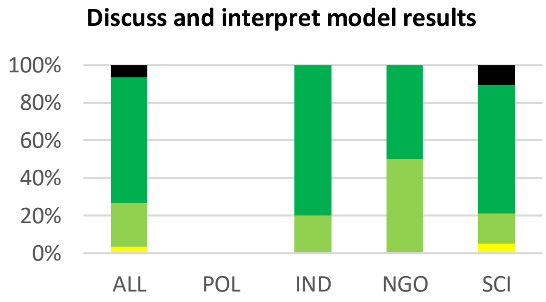


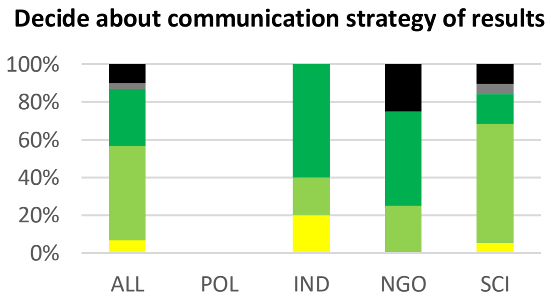
D7 | In the process of the model development or improvement, how important is the exchange about the following aspects between model developer and external stakeholders for you?
N: 30 (voluntary, Likert scale, figure sorted by total share of "not important at all" and "not very important")

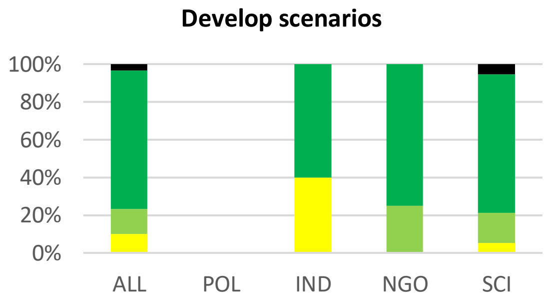
All participants interested in the modeling process (as indicated in A13) were asked which major topics should be discussed with involved stakeholders. All topics ranging from the definition of assumptions, discussion, and interpretation of model results, decision about community strategies of results, development of scenarios, to the decision about the data basis received strong support. The sum of "somewhat important" and "very important" lay in all cases in a range between 77% and 97%. With a focus only on the "very important" shares, a top 3 becomes more obvious: defining assumptions (77%), developing scenarios (73%), and discussing and interpreting model results (67%). Group-specific differences are rather small, while the overall result is strongly influenced by the large share of scientific contributors (19 of 30 respondents). However, for example, it is "very important" for all energy industry representatives to exchange between the model developer and external stakeholder about defining assumptions and deciding about the data basis. Again, as policymakers were not interested in contributing to the modeling process (as indicated in A13), no group-specific data is available.

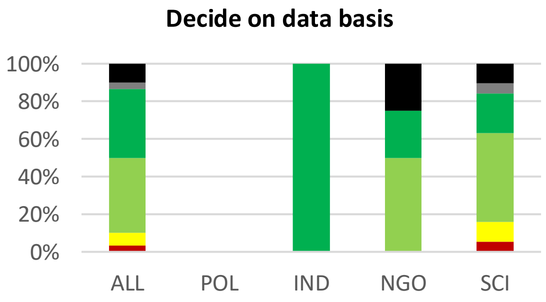












This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

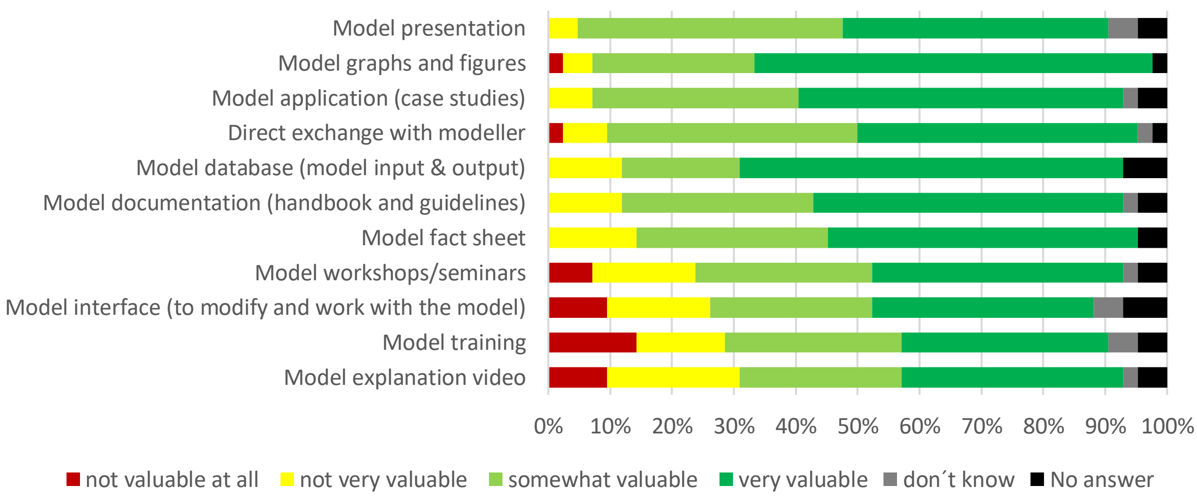
E Model outreach

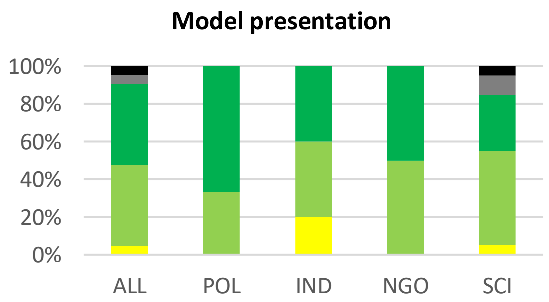
Survey participants interested in the modeling outreach (as indicated in A13) received the following question section.

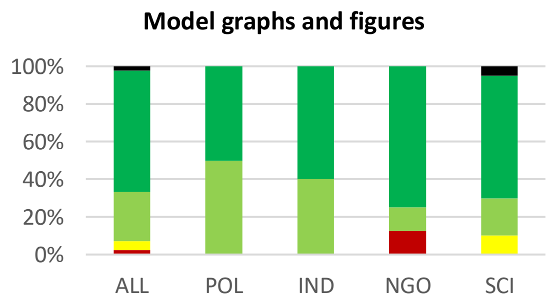
E1 | How valuable are the following forms of model communication for you?

N: 42 (voluntary, Likert scale, figure sorted by total share of "not important at all" and "not very important")

All question section E participants were asked about the value of different types of model communication to them. A majority of respondents found all predefined options as valuable; the sum of "somewhat valuable" and "very valuable" replies ranged from 62% to 90%, with model graphs and figures being most favored (90%), followed by case studies of model application, model graphs and figures, and the direct exchange with modelers on the second place (each with 86%). However, another ranking exists when taking into account "very valuable" replies only. Then, model graphs and figures (64%), model databases with input and output (62%), and case studies (52%) are the most desired communication types. Differences between the groups are relatively small for each communication form and do not oppose its overall result. However, the group-specific ranking can differ from the joint perspective.







Model application (case studies)

Direct exchange with modeler

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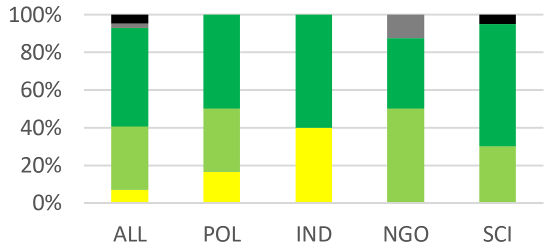
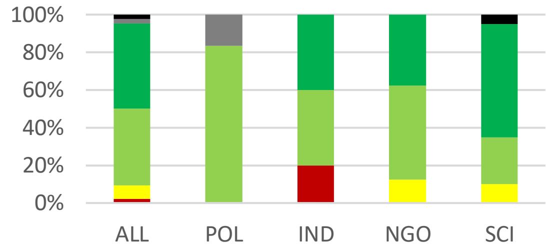
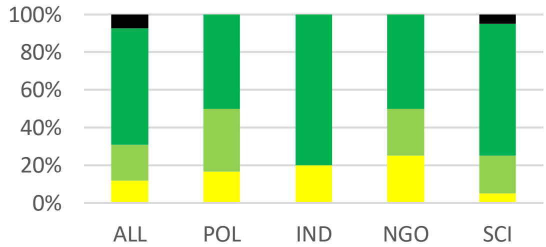
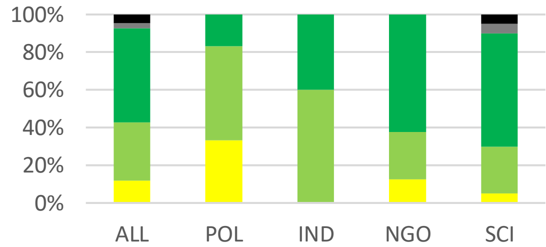




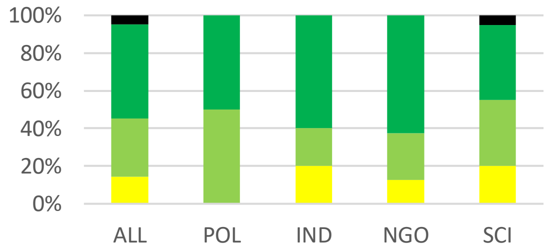
Model database (model input and output)



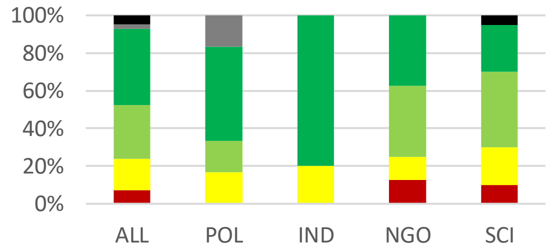
Model documentation (handbook and guidelines)



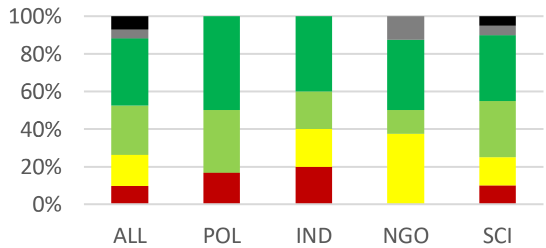
Model fact sheet



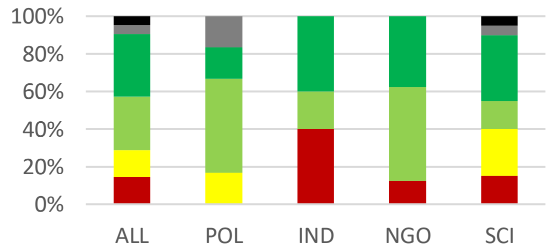
Model workshops/seminars



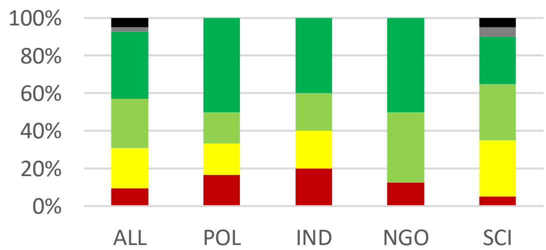
Model interface (to modify and work with the model)



Model training



Model explanation video



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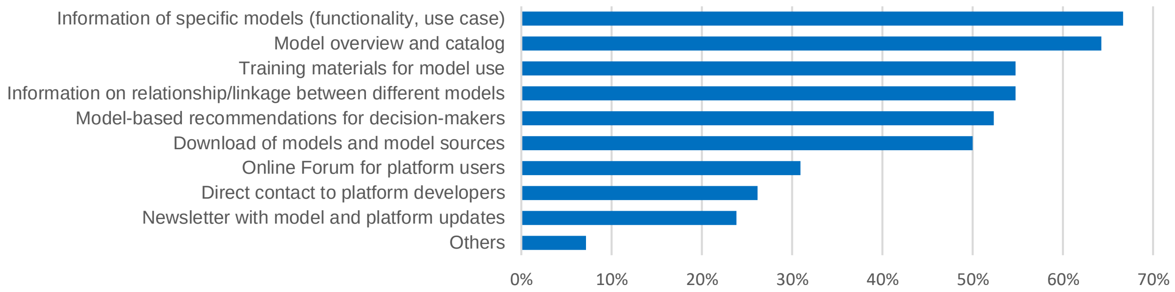
E2 | SENTINEL and openENTRANCE will each build a model platform that documents different models. What is essential for you to use it?

N: 42 (voluntary, multiple choices, minimum 1, figure sorted by total share)

The four essential predefined aspects mostly were chosen by the respondents were: information about the functionality and use cases of specific models (67%), model overview and catalog (64%), training materials for the model application, and description of the relation and linkage of different models on the platforms (55%). According to the respondents' views, an online forum for the platform users, the direct contact to the platform developers, and newsletters would be least relevant; only every third to fifth evaluated them as essential.

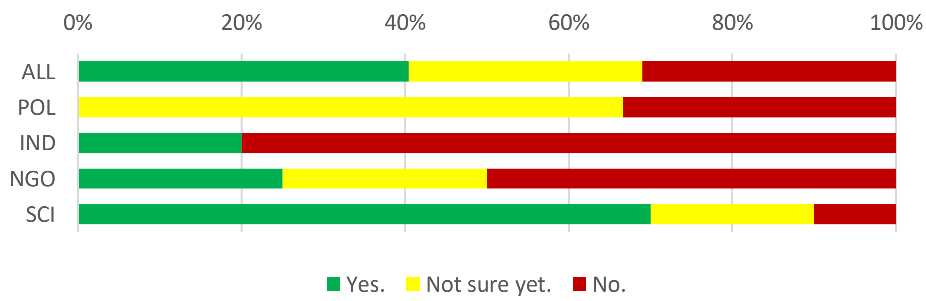


Besides these predefined aspects, respondents see the need for "other" essential platform assets. One respondent would also like to see a description (and perhaps metrics) of the communities associated with each model and the options for engagement", and another participant emphasized the importance of the possibility to download model results data.

E3 | Would you be interested in using that platform directly as a modeler?

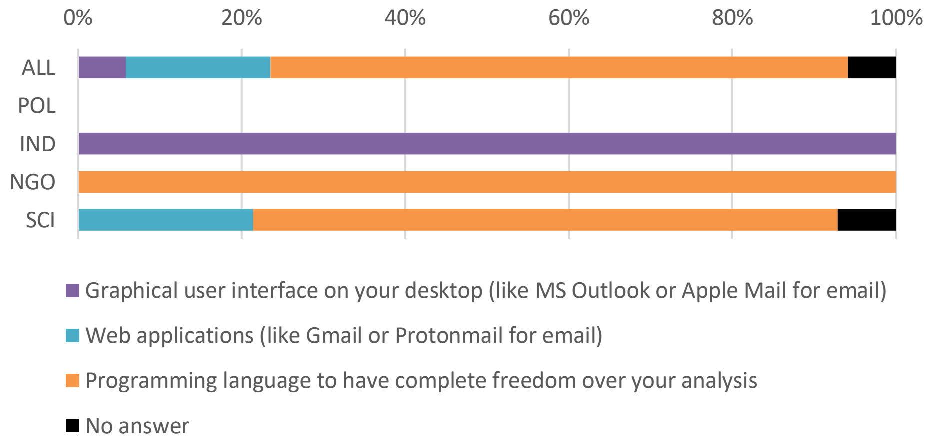
N: 42 (mandatory, single choice)

About 40% of all participants interested in model outreach was sure that they would like to use the model platform directly. If all respondents, who are not sure about their use yet, could be convinced, it is even about 60%. Most potential users connect to the scientific community, considering their high number of replies (20 of 42) and their immense interest in the platform (70-90% of respondents). Modelers in NGOs were interested less (25-50%), followed by the energy industry (0-20%). The likelihood that policymakers would use a modeling platform directly seems relatively small, as 67% were unsure, and no respondent sure about the platform use.



E4 | What kind of software do you prefer to use for modeling?
N: 17 (voluntary, single choice)

Participants who were already sure to use the model platform (as indicated in E3), were asked about their preferences regarding the implemented software solution(s). A large majority wants to use a programming language as a basis of interaction (71%), less prefer a web application (18%) or a graphical user interface on their desktop (6%). The large group-specific differences need to be reflected with the very small number of energy industry and NGO representatives who received this question (1 and 2). As policymakers were not interested in the platform use, group-specific data is not available.

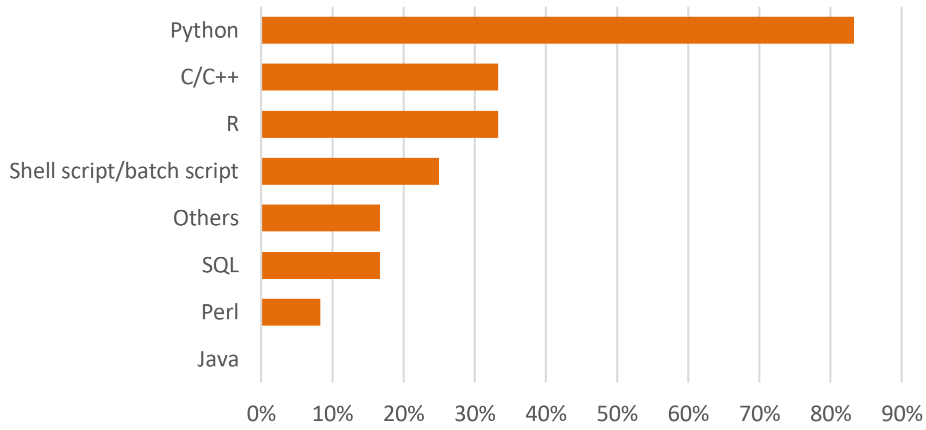


E5 | Which graphical interface do you prefer?
N: 2 (voluntary, single choice)

This question was asked to participants who would like to work with a graphical user interface to interact with the platform (as indicated in E4). Excel/Libre office received two votes, all other answer options none. However, the response rate is too low to count as a meaningful result.

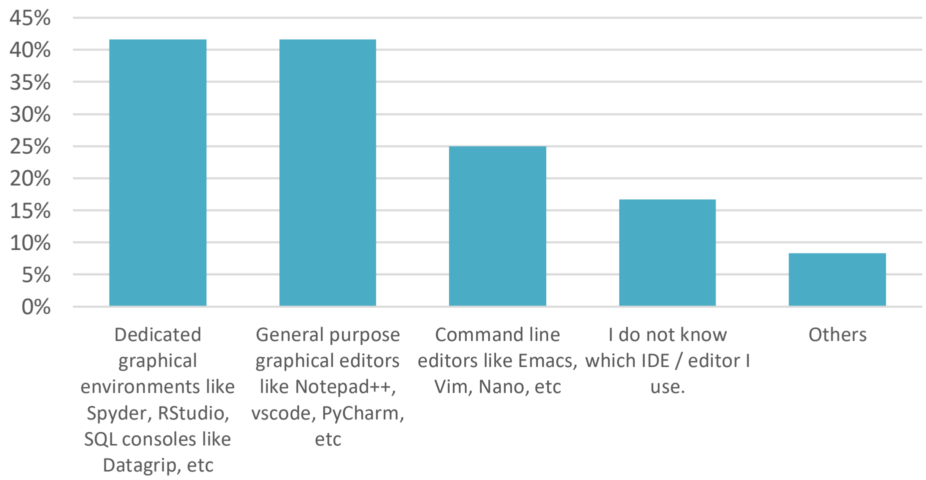
E6 | Which programming languages do you use in your analysis?
N: 12 (voluntary, multiple choices, figure sorted by total share)

This question was asked to participants only who want to use a programming language to have complete freedom over their analysis (as indicated in E4). Python is used most often for analysis by the respondents (83%), while every third modeler also uses C/C++, and R (both with 33%). "Other" languages were VBA, MATLAB, and GAMS (each with 1 mention).

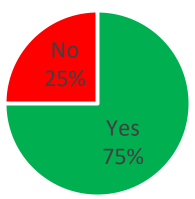


E7 | What integrated development environment (IDE) / editor do you use for your programming needs?
N: 12 (voluntary, multiple choices, figure sorted by total share)

This technical question was asked to participants who would like to use a programming language to complete freedom over their analysis (as indicated in E4). Nine scientists and three NGO representatives replied. Five of the twelve respondents indicated that their favored integrated development environment (IDE) / editor are dedicated graphical and general-purpose graphical editors (both with 42%). Every fourth user prefers the command line (25%), and two respondents admitted that they did not know which IDE they use (17%).



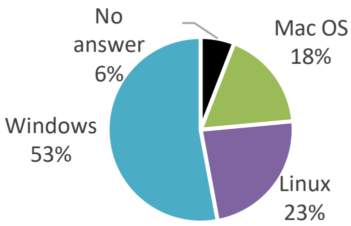
E8 | Are you familiar with the command line terminal?
N: 12 (voluntary, single choice)



This technical question was asked to participants who would like to use a programming language to have complete freedom over their analysis (as indicated in E4). The majority of the twelve respondents are familiar with the command line (75%).

E9 | What Operating System do you prefer for modeling and analysis?

N: 17 (voluntary, single choice)



This question was only asked participants who were already sure that they would like to work with the modeling platform (as indicated in E3). Every second modeler uses Windows (53%), followed by Linux (23%) and Mac (18%) as their preferred operating systems.

E10 | Is there any other online modeling platform that you use?
N: 6 (voluntary, free text)

All participants of question section E except respondents without model and modeling experience (as indicated in A3) were asked to point to existing modeling platforms. These examples could then serve the SENTINEL and openENTRANCE platform developers as role models and the corresponding developers as valuable discussion partners. Five of the six respondents to the question were part of the scientific community. Respondents recommended (some as 'key tools') the following initiatives:

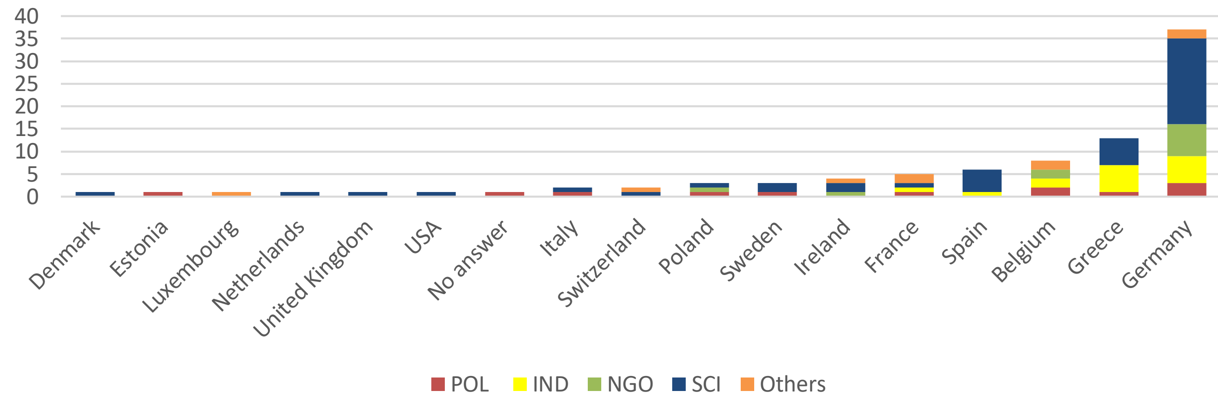
- GitHub
  (https://github.com/)
- GitLab
  (https://about.gitlab.com/)
- the Open Energy Modeling Initiative
  (https://openenergy-platform.org/)
- the open energy mod list/wiki
  (https://wiki.openmod-initiative.org/wiki/Main_Page)
- the Strategic Energy Roadmap Scenario Explorer
  (https://www.set-nav.eu/content/set-nav-scenario-explorer)
  the project Integrating Integrated Assessment Models
  (http://paris-reinforce.epu.ntua.gr/main)

F Others and demographic data

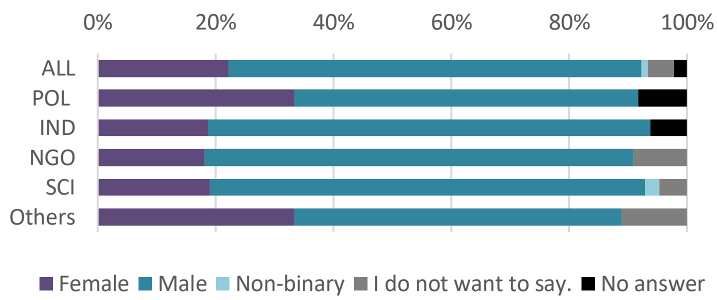
F1 | What is your country of residence?
N: 90 (voluntary, single choice; figure sorted by total number)

A large proportion of participants came from Germany (41%), followed by Greece (14%), Belgium (9%), Spain (7%), and France (6%). The country-specific distribution of stakeholders differs, with German stakeholders having the largest influence on the survey's overall outcome.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

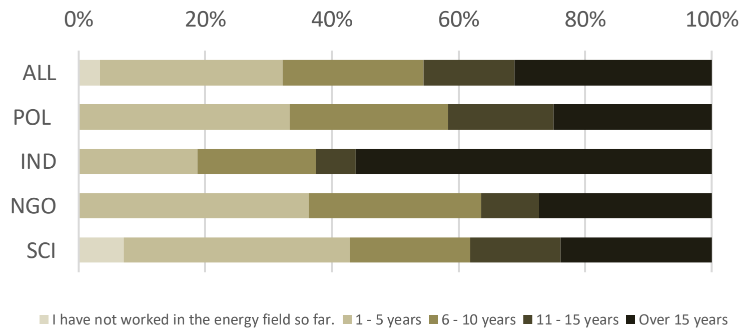


F2 | What is your gender?
N: 90 (voluntary, single choice)



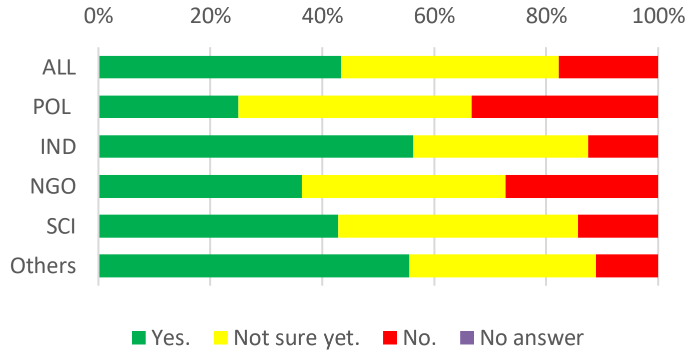
About 22% of participants were female and 70% male, while about 8% did not indicate. Group-specific differences were relatively small.

F3 | How long have you been working in the energy field?
N: 90 (voluntary, single choice)



Almost all participants have a working background in the energy field; however, the duration differs substantially. About one third have worked (each) between 1-5 years (29%), between 6-15 years (36%), and over 15 years (31%). The longest background in the energy sector can be found in the survey sample among energy industry representatives.

F4 | Would you be interested in participating in a stakeholder workshop on user needs?
N: 90 (voluntary, single choice)



In sum, a large share of survey participants was also interested in taking part in a SENTINEL workshop about user needs (43%). Almost as many had not decided yet (39%), every fifth was not interested (18%). Group differences were small, although energy industry representatives were most motivated in attending the workshop (56%).

F6 | Would you like to add further aspects to the survey, that we didn't mention? Help text: Please use the text box if you have general comments on the questionnaire.
N: 7 (voluntary, free text)

Seven participants gave feedback and added further aspects to the survey. All constructive statements pointing to aspects that should have been addressed (more) in the survey are summarized in the following list (structured by the study authors according to the statement´s need category):

Model content
- Smart systems as upcoming modeling challenge
- Modeling and planning hydrogen networks roll-out
- Finer-grain decision behavior by households as well as commercial actors
- Consideration of social aspects in modeling - public support/opposition, use of Just Transition funds

Model design
- Use of robust (least-regret) models
- Coherence between national, TYNDP, and TEN-E modeling
- Ability to run models or model components within developer languages such as Python, GAMS, or R for (1) lower barriers and ease of use, (2) ability to vary inputs adapted to national circumstances, new data, or external model output, (3) expansion of model user base, (4) building confidence and 'sanity checking', and (5) understanding model risk and ranges of validity.
- Data (!): technical, legal, and semantic operability including licensing, as well as distributed data architectures (including projects like data bus, Icebreaker One Open Energy web of data, and LF Energy)

Modeling process
- Need for scenarios reflecting policy objectives and even approved by policymakers
- Influence of stakeholder interests (including national governments, TSOs) in the modeling process
- Modeling transparency and oversight/guidance by policymakers and regulators, additional power to ACER

Model outreach
- No questions related on the current status quo of stakeholder engagement satisfaction in the European commission model development.

Appendix D: Online survey – detailed questionnaire

A Personal background, model use, and general demand

A1 Which stakeholder group would you count yourself among? [single choice, mandatory] If our groups do not match your profile, please let us know your area of activity in the "other" field.

- Policymakers
- Energy industry
- Non-governmental organization (NGO)
- Research, Innovation & Consultancy
- Other: ______________________

A2 What levels are you working at? [multiple choices, voluntary]

- Global
- EU
- National
- Regional
- Local (e.g., municipality)

A3 In what context do you work with models? [multiple choices, at least one answer, mandatory]

- A301 I develop models technically.
- A303 I apply and run models.
- A304 I analyze the results of model runs, write model-based studies, or give model-based advice.
- A302 I provide model developers with ideas for model improvement, or commission model-based studies.
- A305 I read model analysis and model studies.
- A 306 I have never used models or model results before.

A4 How long have you been working with models (as you indicated in the previous question)? [single choice, voluntary]

- Never
- 1-3 years
- 4-6 years
- More than 6 years

A5 All A3-groups except A306: You stated above that you work with energy models in one way or another. With which kind of models in terms of model topics and model type have you worked (as indicated above) so far?[28] [multiple choices, voluntary]

- *A501* Strategic energy system planning models
- *A502* Integrated assessment models
- *A503* Life cycle assessment models
- *A504* Emission inventory/air pollution models
- *A505* Social metabolism assessment models
- *A506* Electricity market models
- *A507* Transportation models
- *A508* Building models

[28] Italic conditions at the beginning of a questions like "*All A3-groups except A306:*" were not displayed to the participants.

- *A509* Macroeconomic equilibrium models
- *A510* Simulation models
- *A511* Optimization models
- *A512* Agent-based models
- *A513* System Dynamic models
- *A514* Multicriteria analysis
- *A515* Geographical information systems (GIS)
- *A516* Others: ________________
- *A517 I don´t know.*

A6 If chosen at least one answer of A501 to A516 You stated above that you use specific models or model results in your work. Which models or of which models exactly? Please type in the model abbreviation(s). *Help text*: You can leave the field blank. [multiple choices, voluntary]

- Model name(s): _________________________________

A7 All A3-groups except A306: Related to that, how often do you use models or modeling results? [single choice, voluntary]

- *A701* Daily
- *A702* Weekly
- *A703* Monthly
- *A704* Occasionally

A8 If chosen A306 OR A703 OR A704: What are the reasons that you do not or not often use model results? [multiple choices; voluntary]

- I don't have the time needed to search for model studies.
- I don't have the knowledge to use models.
- I have difficulties in interpreting model results.
- I don't have access to appropriate models.
- I am very critical of models and their assumptions.
- Other methods and tools are more appropriate to answer my questions.
- Others: ______________

A9 In your opinion, how important are models for…? [matrix; Likert scale: not important - very important, don´t know; mandatory]

… the energy transition as a whole
… policymaking in the energy transition

A10 All A3-groups except A306: For what purpose are you using models in your work? [multiple choices; voluntary]

- Agenda/Target setting of certain policy
- Policy/measure formulation
- Ex-ante-assessment of policy impacts
- Strategy development
- Policy implementation
- Ex-post-evaluation/monitoring of implemented policy
- Local energy planning

- Energy system operation
- Informing/Lobbying in politics
- Others: ________________
- None of the purposes above

A11 All A3-groups except A306: Where do you see the demand for additional or improved models helping you in your work? [multiple choices; voluntary]

- Agenda/Target setting of certain policy
- Policy/measure formulation
- Ex-ante-(impact-)assessment of policy
- Strategy development
- Policy implementation
- Ex-post-evaluation/monitoring of implemented policy
- Local energy planning
- Energy system operation
- Informing/Lobbying in politics
- Others: ____________________
- I don´t know.

A12 What time horizon(s) are you dealing with in your energy-related work? [multiple choices; voluntary]

- Hours
- Days
- Weeks
- Months
- Years
- Short-term (up to 2025)
- Medium-term (2030, 2040)
- Long-term (2050 and beyond)

A13 In our projects, we want to improve models in all possible directions. In which field(s) do you want to contribute to the model improvement? Your choice here will determine how many questions you will be asked in total. *Help text:* Please select all answers that apply to your interests. Please select all fields that apply to your interests. Each selected field will take about 10 minutes of your time. [multiple choices, mandatory]

- *A1301* **Model content** (aspects to be incorporated, questions to be answered by models, etc.)
- *A1302* **Model design** (level of detail in models, trade-offs in modeling, etc.)
- *A1303* **Modeling process** (procedure of model development, whom to involve in the process, etc.)
- *A1304* **Model outreach** (best options to communicate with target audience, elements of the model platforms, etc.)

B Model content [if chosen A1301]

B1 How important are the following aspects for the energy transition? [Likert scale: not important - highly important, don´t know; random order in LimeSurvey; voluntary]

- Resilience & security of supply
- Low-hazard technologies

- Nature protection
- Human health
- Energy efficiency
- Climate-neutrality
- Social acceptability
- Affordability
- Cost-efficiency
- Free energy trade between countries

B2 Regarding the previous question, did we miss to include aspects that are important to you? If any, please describe the aspects briefly. [open field; voluntary]

____

B3 Which of the following factors do you think should receive more attention in energy models? [multiple choices, minimum 1, maximum 5; mandatory]

- *B301* Development of new technologies and services
- *B302* Impact on the environment and natural resource use
- *B303* Potential supply restriction of raw materials and components for energy technologies
- *B304* Behavior, lifestyles, and heterogeneity of consumers
- *B305* Behavior and heterogeneity of investors
- *B306* Social acceptance and public opposition
- *B307* Social impact of the transition (e. g., gain and losses of energy jobs, changes in energy poverty)
- *B308* Cultural contexts (e.g., behavioral differences between countries)
- *B309* Policy impact/implications of different policy options
- *B310* Political dynamics (e.g. impact of climate change and renewable energy deployment on elections)
- *B311* Economic preparedness (e.g., scaling up of energy industry)
- *B312* Total costs and investment costs (including external costs)
- *B313* Shock events (e.g., natural hazards, societal catastrophes)
- *B314* Others: ____________________ [3000 signs]
- *B315* I don´t know.

B4a If chosen B304 OR B305 OR B306 OR B307 OR B308 OR B310: You stated that social aspects should receive more attention in models. What **social aspects** would you like to see integrated into energy models? [multiple choices; maximum 3; voluntary] *Help text:* Your answers here will especially help in developing QTDIAN in SENTINEL, a model toolbox focusing on social aspects of the energy transition.

- *B401* Social storylines and scenarios
- *B402* Technical potential based on social acceptance of energy technologies and infrastructures
- *B403* Social drivers and barriers of innovation diffusion
- *B404* Impact of social issues on politics and policies (e.g., social movements)
- *B405* Dynamics of social acceptance and individual attitudes towards energy technologies (e.g. habituation)
- *B406* Rebound effects in energy demand
- *B407* Optimization of acceptance instead of costs
- *B408* Co-benefits of prosumerism and community energy
- *B409* I don´t know.

- *B410* Others: ______________________

B4a2 *If chosen (A301 OR A302) AND (B304 OR 305 OR 306 OR 307 OR 308 OR 310)*: To what extent are these **social aspects** already integrated into **your energy model**? [Dual matrix / Likert scale: not relevant - relevant; hard to say; not integrated - highly integrated; hard to say; voluntary]

- Social storylines and scenarios
- Technical potential based on social acceptance of energy technologies and infrastructures
- Social drivers and barriers of innovation diffusion
- Impact of social issues on politics and policies (e.g., social movements)
- Dynamics of social acceptance and individual attitudes towards energy
- Rebound effects in energy demand
- Optimization of acceptance instead of costs
- Co-benefits of prosumerism and community energy

B4b If chosen B302 OR B303: You stated that environmental or resource issues should receive more attention in energy models. What **environmental factors** would you like to see integrated into energy models more in the future? [multiple choices, maximum 3; voluntary] *Help text:* Your answers here will especially help in developing ENVIRO in SENTINEL, a model focusing on environmental aspects of the energy transition.

- Raw material demand
- Other industrial inputs
- Water use and/or wastewater generation
- Air pollution
- Solid waste generation
- Dissipated heat
- Greenhouse gas emissions
- Loss of biodiversity
- Soil contamination
- Ozone depletion
- Others: _____________
- I don´t know.

B4b2 *If chosen (A301 OR A302) AND (B302 OR B303)*: To what extent are these **environmental aspects** already integrated into **your energy model**? [Dual matrix/Likert scale: not relevant - relevant; hard to say; not integrated - highly integrated; hard to say; voluntary]

- Raw material demand
- Other industrial inputs
- Water use and/or wastewater generation
- Air pollution
- Solid waste generation
- Dissipated heat
- Greenhouse gas emissions
- Loss of biodiversity
- Soil contamination
- Ozone depletion

B5 Which sector(s) is/are currently of main focus in your **working context**? [multiple choices, maximum 3; voluntary]

- *B501* Electricity
- *B502* Buildings (Heating/Cooling)
- *B503* Industry (Process Heat)
- *B504* Mobility
- *B505* Agriculture
- *B506* Sector-coupling, digitalization, and system flexibilization
- *B507* Other sector(s)
- *B508* I do not know.

B6 If chosen B501: You stated above that **electricity** is currently the main focus. Please list up to three questions (your 'Top 3') regarding this sector that should be answered by energy models. *Help text:* If any, please use the fields to write down the questions. [open fields; voluntary]

- ____________________________________
- ____________________________________
- ____________________________________

B7 If chosen B502: You stated above that **heating/cooling in buildings** is currently of main focus. Please list up to three questions (your 'Top 3') regarding this sector that should be answered by energy models. *Help text:* If any, please use the fields to write down the questions. [open fields; voluntary]

- ____________________________________
- ____________________________________
- ____________________________________

B8 If chosen B503: You stated above that **process heat in the industry** is currently of main focus. Please list up to three questions (your 'Top 3') regarding this sector that should be answered by energy models. *Help text:* If any, please use the fields to write down the questions. [open fields; voluntary]

- ____________________________________
- ____________________________________
- ____________________________________

B9 If chosen B504: You stated above that **mobility** is currently of main focus. Please list up to three questions (your 'Top 3') regarding this sector that should be answered by energy models. *Help text:* If any, please use the fields to write down the questions. [open fields; voluntary]

- ____________________________________
- ____________________________________
- ____________________________________

B10 If chosen B505: You stated above that **agriculture** is currently of main focus. Please list up to three questions (your 'Top 3') regarding this sector that should be answered by energy models. *Help text:* If any, please use the fields to write down the questions. [open fields; voluntary]

- ____________________________________
- ____________________________________
- ____________________________________

B11 If chosen B506: You stated above that **sector-coupling, digitalization, and system flexibilization** are currently of main focus. Please list up to three questions (your 'Top 3') regarding these aspects that should be answered by energy models. *Help text:* If any, please use the fields to write down the questions. [open fields; voluntary]

- ______________________________________
- ______________________________________
- ______________________________________

B12 If chosen B507: You stated above that some **other sector(s)** are currently of main focus. Please list up to three questions (your 'Top 3') regarding this sector / these sectors that should be answered by energy models. *Help text:* If any, please use the fields to write down the questions. [open fields; voluntary]

- ______________________________________
- ______________________________________
- ______________________________________

B13 If chosen B301 AND B501: You stated that the development of new technologies and services is very important to you. Which innovations in the electricity production sector should be included in energy models? [multiple choices, maximum 3; voluntary]

- New solar applications (integrated into buildings, streets, agriculture, ...)
- New wind power technologies (Air Borne, Far-Off-Shore, Micro-Wind, ...)
- New hydropower technologies (Wave energy, ...)
- New biomass resources (organic waste, ...)
- New technologies of CO_2-neutral energy carriers (solar fuel, green hydrogen, Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) of coal and gas, ...)
- New technologies of nuclear power (fusion, next generation of fission, fission of nuclear waste, ...)
- Others: _______________________________
- I don´t know.

B14 If chosen B301: Given your sector-specific working context, which innovations should be included in energy models? If any, please describe the emerging technologies, services, and other innovations briefly. [open field; voluntary]

___________________________ (3000 signs)

C Model design [if chosen A1302]

C1 How important are the following model conditions for the use of models or their results in your work? [Likert scale: not important <-> very important, don´t know; voluntary]

- Fit for purpose
- Trust in model
- Credibility of model developer
- Open-source
- Transparency
- Reproducibility
- Modularity
- High temporal resolution
- High spatial / geographical resolution
- Reliable data available
- Graphical representation

C2 Which model feature/quality is more important to you? Please choose in each pair the more meaningful to you. [four-point scale for each pair; random order in LimeSurvey; voluntary]

Complexity	o	o	o	o	Simplicity	o No opinion
Open-source	o	o	o	o	Intellectual property protection	o No opinion
Easy to understand	o	o	o	o	Realistic assumptions	o No opinion
Fast results	o	o	o	o	Comprehensive results	o No opinion
High model diversity, but small expertise per model	o	o	o	o	Only few models, but large expertise per model	o No opinion
Developing new models	o	o	o	o	Improving existing models	o No opinion
Optimization	o	o	o	o	Simulation	o No opinion
Specific fit for purpose	o	o	o	o	Model as all-rounder	o No opinion
Trust the black box	o	o	o	o	Learn a modeling language	o No opinion
Conservative scenarios	o	o	o	o	Progressive scenarios	o No opinion
1.5°C futures	o	o	o	o	2°C futures	o No opinion
Find the best policy options	o	o	o	o	Find the right targets	o No opinion
Forecasting (investigate possible futures)	o	o	o	o	Backcasting (define steps backwards from a desired future)	o No opinion

C3 All A3-groups except A306: How important are the following measures to reduce model uncertainty? Please order them by importance, with the most important on top. [ranking; random order in LimeSurvey; voluntary]

- Scenario analysis (different futures)
- Sensitivity analysis (systematic variation of input variables)
- Transparency (good description of model assumptions and limitations)
- More realistic model assumptions

C4 All A3-groups except A306 AND only if someone ordered C3: Regarding the previous question, did we miss to include aspects to deal with uncertainty in modeling that are important to you? If any, please describe the aspects briefly. [open field; voluntary]

____

D Modeling process [if chosen A1303]

D1 If chosen A302 OR A304 OR A305 OR A306: How important is **your involvement** in conceptually developing or improving models for you? [Likert scale: not important - very important; don´t know; mandatory]

D2 If chosen A302 OR A304 OR A305 OR A306: Have you ever been involved in the development or improvement of models? [single choice; mandatory]

- *E201* Yes, once.
- *E202* Yes, frequently.
- *E203* No, never.
- *E204* I cannot remember anymore.

D3 If chosen (A302 OR A304 OR A305 OR A306) AND (D201 OR D202): When looking back, how useful was the involvement in this process for you? [single choice; mandatory]

- Very beneficial and I want to do it again.
- Mostly beneficial.
- Ambivalently.
- Mostly disappointing.
- Very disappointing and not worth the effort.
- I cannot remember anymore.

D4 If chosen A301 OR A303: How important for you is involvement of the following groups in your model development and improvement process? [Likert scale: not important - very important; don´t know; mandatory]

- Policymakers
- Energy industry
- Non-governmental organizations (NGOs)
- Research, Innovation & Consultancy

D5 If chosen A301 OR A303: Have you involved external stakeholders in your model development so far? [single choice; mandatory]

- *E501* Yes, once.
- *E502* Yes, frequently.
- *E503* No, I have not involved them so far.
- *E504* I cannot remember anymore.

D6 If chosen (A301 OR A303) AND (D501 OR D502): When looking back, how beneficial was the involvement of external stakeholders for your work? [single choice; mandatory]

- Very beneficial and I want to do it again.
- Mostly beneficial.

- Ambivalently.
- Mostly disappointing.
- Very disappointing and not worth the effort.
- I cannot remember anymore.

D7 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?
[Likert scale: not important <-> very important; don´t know; voluntary]

- Decide on data basis
- Define assumptions
- Develop scenarios
- Discuss and interpret model results
- Decide about communication strategy of results

E Model outreach [if chosen A1304]

E1 How valuable are the following forms of model communication for you?
[Likert scale: not valuable at all - very valuable; don´t know; voluntary]

- Model documentation (handbook and guidelines)
- Model fact sheet
- Model database (model input & output)
- Model presentation
- Model explanation video
- Model application (case studies)
- Model graphs and figures
- Model interface (to modify and work with the model)
- Model workshops/seminars
- Model training
- Direct exchange with modeler

E2 SENTINEL and openENTRANCE will each build a model platform that documents different models. What is essential for you to use it? [multiple choices; at least one; voluntary]

- Model overview and catalog
- Download of models and model sources
- Newsletter with model and platform updates
- Information of specific models (functionality, use case)
- Information on relationship/linkage between different models
- Model-based recommendations for decision-makers
- Training materials for model use
- Online Forum for platform users
- Direct contact to platform developers
- None of these options
- Other:______________________

E3 Would you be interested in using that platform directly as a modeler? *Help text:* If you choose 'Yes', you will further be asked about your technical needs regarding the platform. [single choice; mandatory]

- *E301* Yes.
- *E302* No.
- *E303* Not sure yet.

E4 If chosen E301: What kind of software do you prefer to use for modeling? [single choice; voluntary]

- *E401* Graphical user interface on your desktop (like MS Outlook or Apple Mail for email)
- *E402* Web applications (like Gmail or Protonmail for email)
- *E403* Programming language to have complete freedom over your analysis
- *E404* Other: __________

E5 If chosen E401: Which graphical interface do you prefer? [single choice; voluntary]

- Excel/LibreOffice
- MS Access
- SPINE toolbox
- Other: __________

E6 If chosen E403: Which programming languages do you use in your analysis? [multiple choices; voluntary]

- Python
- R
- C/C++
- SQL
- Perl
- Java
- Shell script/batch script
- Other: ____________

E7 If chosen E403: What integrated development environment (IDE) / editor do you use for your programming needs? [multiple choices; voluntary]

- Dedicated graphical environments like Spyder, RStudio, SQL consoles like Datagrip, etc.
- General purpose graphical editors like Notepad++, vscode, PyCharm, etc.
- Command line editors like Emacs, Vim, Nano, etc.
- Other: ________
- I do not know which IDE / editor I use.

E8 If chosen E403: Are you familiar with the command line terminal? [single choice; voluntary]

- Yes.
- No.

E9 If chosen E301: What Operating System do you prefer for modeling and analysis? [single choice; voluntary]

- Windows
- Mac OS
- Linux
- Other: ____________

E10 All A3-groups except A306: Is there any other online modeling platform that you use? Help text: If any, please insert the platform name or link to the platform. [open field; voluntary]

____

F Others and demographic data

F1 What is your country of residence? Help text: The list includes all member states of the European Union. If you come from outside the EU, please use the 'other' field. [single choice; dropdown menu; voluntary]

- Austria
- Belgium
- Bulgaria
- Croatia
- Cyprus
- Czechia
- Denmark
- Estonia
- Finland
- France
- Germany
- Greece
- Hungary
- Ireland
- Italy
- Latvia
- Lithuania
- Luxembourg
- Malta
- Netherlands
- Poland
- Portugal
- Romania
- Slovakia
- Slovenia
- Spain
- Sweden
- United Kingdom
- Other: ____________

F2 What is your gender? [single choice; voluntary]

- Female
- Male
- Non-binary
- I do not want to say.

F3 How long have you worked or have been working in the energy field? [single choice; voluntary]

1. 1 - 5 years
2. 6 - 10 years
3. 11 - 15 years

4. Over 15 years
5. I have not worked in the energy field so far.

F4 Would you be interested in participating in a stakeholder workshop on user needs? [single choice; voluntary]

- *F401* Yes.
- *F402* Not sure yet.
- *F403* No.

F5 If chosen F401 or F402: We are glad that you are potentially interested in our workshop. If you would like to be invited please leave us here your contact data. [open fields; voluntary]
First name: ______________________
Last name: ______________________
Email address: ___________________________
(*Help text:* Your personal data will not be linked to the questionnaire.)

F6 Would you like to add further aspects to the survey, that we didn't mention? *Help text:* Please use the text box if you have general comments on the questionnaire. [open field; voluntary]

________________________________ (3000 signs possible)

F7 We would like to inform you about our results once we completed analyzing the survey data. If you agree to hearing from us again, please enter your contact email address below. [open field; voluntary]

Email address: _____________________
(*Help text:* Your personal data will not be linked to the questionnaire.)

Appendix E: Online workshop - Agenda

AGENDA

Opening plenary session: Your user needs for SENTINEL

12:30-13:30 User demands of energy models: presentation of first SENTINEL results + harvesting your input

Moderator: Prof. Dr. Anthony Patt (ETH Zürich) | Presenter: Dr. Diana Süsser (IASS)

Join us for a presentation of our findings of user needs, derived from interviews and an online survey conducted with energy stakeholders, and a live-poll-driven prioritization of needs. We aim at a mutual understanding and consensus about priorities of cross-model user needs. The results of the session and the whole day will be visually recorded.

13:30-13:45 Break

Parallel breakout sessions: Your stakes in European policymaking

In virtual breakout world cafés, we look deeper into the essential challenges of today's energy models, intending to assist policy- and decision-making. Different SENTINEL modeling teams will host these sessions, and use different open online tools for collective mind mapping and prioritization. Each session will start with an introduction round. **Thanks for your great interest in our sessions!**

13:45-14:40 Meet the models and modelers – round I

Session 1: Social and policy aspects in energy models

Hosted by: Prof. Dr. Johan Lilliestam and Dr. Diana Süsser (IASS)

While social and behavioral aspects have been often neglected in models, we would like to receive your insights on social drivers and constraints of the energy transition. Which social aspects you think should be (more) reflected in models? Furthermore, we want to present and discuss our concept of the QTDIAN modeling toolbox that deals with them.

Session 2: Including environmental aspects in energy system models

Hosted by: Dr. Cristina Madrid López and Nicholas Martin (Universitat Autònoma de Barcelona)

We will gather your insights about the new module ENVIRO, which integrates social metabolism and life cycle assessment. ENVIRO aims to inform energy system models about environmental impacts, constraints or other challenges. We will introduce you to the current trends in environmental assessment and reflect with you on the following questions: What environmental challenges should be considered in energy system models? How can such challenges be included in these?

Session 3: Modeling energy demand and supply

Hosted by: Dr. Souran Chatterjee and Prof. Dr. Diana Urge-Vorsatz (Central European University); Dr. Jakob Zinck Thellufsen (Aalborg University)

In session 3, we will explore with you planned measures to improve existing energy demand and energy supply models. How important are the issues of sector-coupling, decentralization and flexibility, and what other issues should we approach?

Session 4: Modeling the economic impacts of the energy transition

Hosted by: Tarun Khanna (Hertie School) and Jakob Mayer (University of Graz)

This session outlines improvements being envisaged for the three economic impact models participating in the SENTINEL project: an agent-based model, a power-system optimization model and a macroeconomic model. These models capture aspects of the energy transition such as affordability, security of supply and sustainability. To meet the arising requirements, these models are improved individually but also linked to each other in order to increase the comprehensiveness of assessments. Based on the presentation, we interactively discuss solved and pending challenges and invite you to share your experience and opinion about the adopted approaches.

Session 5: Designing the model platform of SENTINEL

Hosted by: Suvayu Ali (ETH Zürich) and Andrzej Ceglarz (Renewables Grid Initiative)

Session 5 is dedicated to the SENTINEL open-source modeling platform. We want to discuss which particular *technical and collaborative challenges* we are facing in model development. What makes a modeling platform successful from a technical point of view? How can we build a modelers network around the platform?

14:40-14:50 Break

14:50-15:45 Meet the models and modelers – round II

In a second round of work cafés, you have the chance to discuss your needs regarding specific models, as we keep the same sessions, but reshuffle their participants.

15:45-16:00 Break

16:00-16:30 Plenary session: Summary of breakouts + collecting further perspectives, and SENTINEL's next steps

Moderator: Prof. Dr. Anthony Patt (ETH Zurich) | Presenters: hosts of breakout sessions

In the final session, we will all come together again to summarize and reflect upon key user needs identified within the parallel sessions, to ensure all your relevant issues are reflected. We will use ZOOM annotation and live-polls to capture final needs and collect your feedback. We will end with an outlook of next steps within the SENTINEL project, and opportunities to stay connected with you.

Appendix F: Online workshop - Visual recording

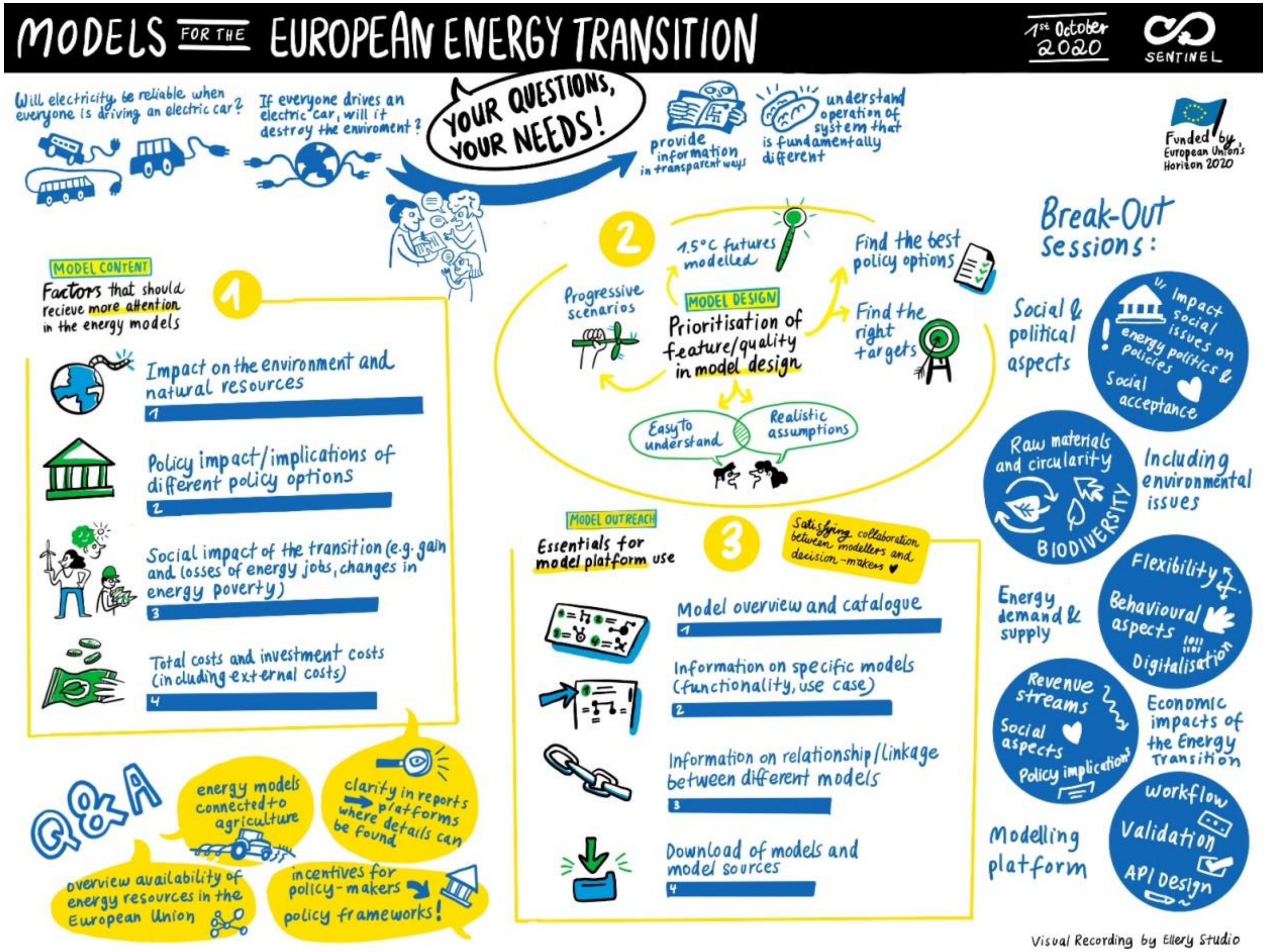


***Figure 27:** Sketchnote of the opening and closing plenary sessions*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

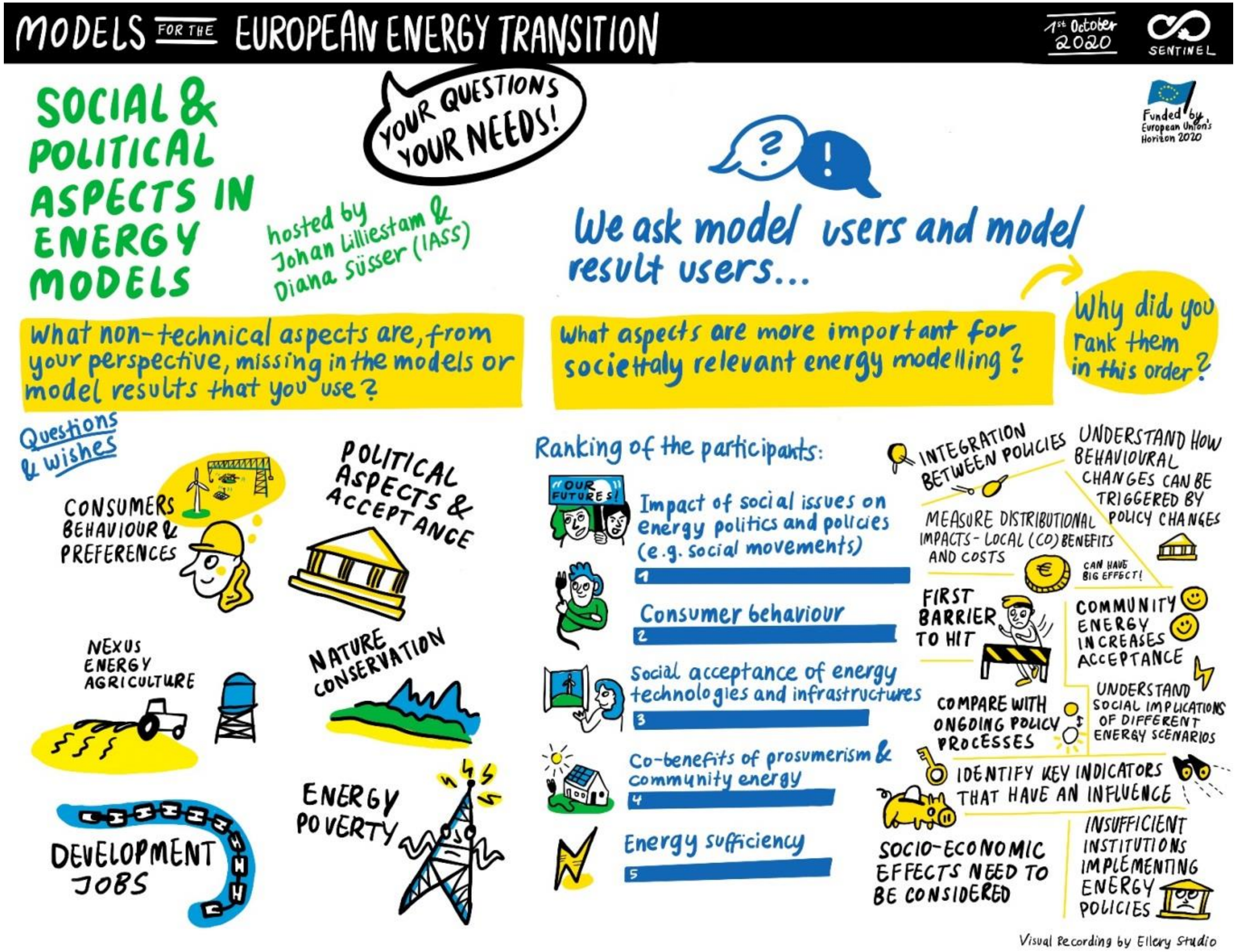


Figure 28: *Sketchnote of 'Social and policy aspects in energy models' (Breakout Session 1)*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

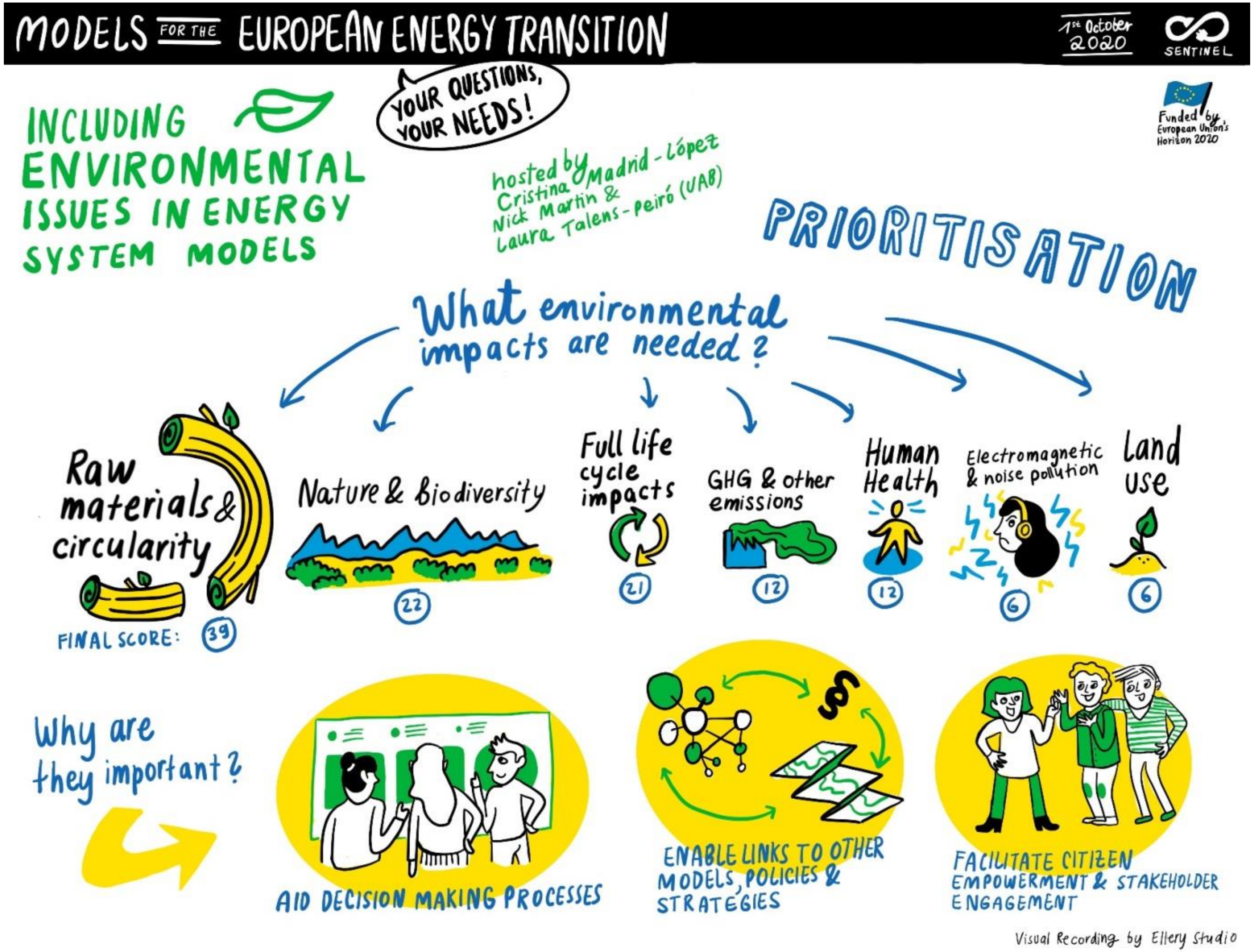


Figure 29: *Sketchnote of 'Including environmental aspects in energy system models' (Breakout Session 2)*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

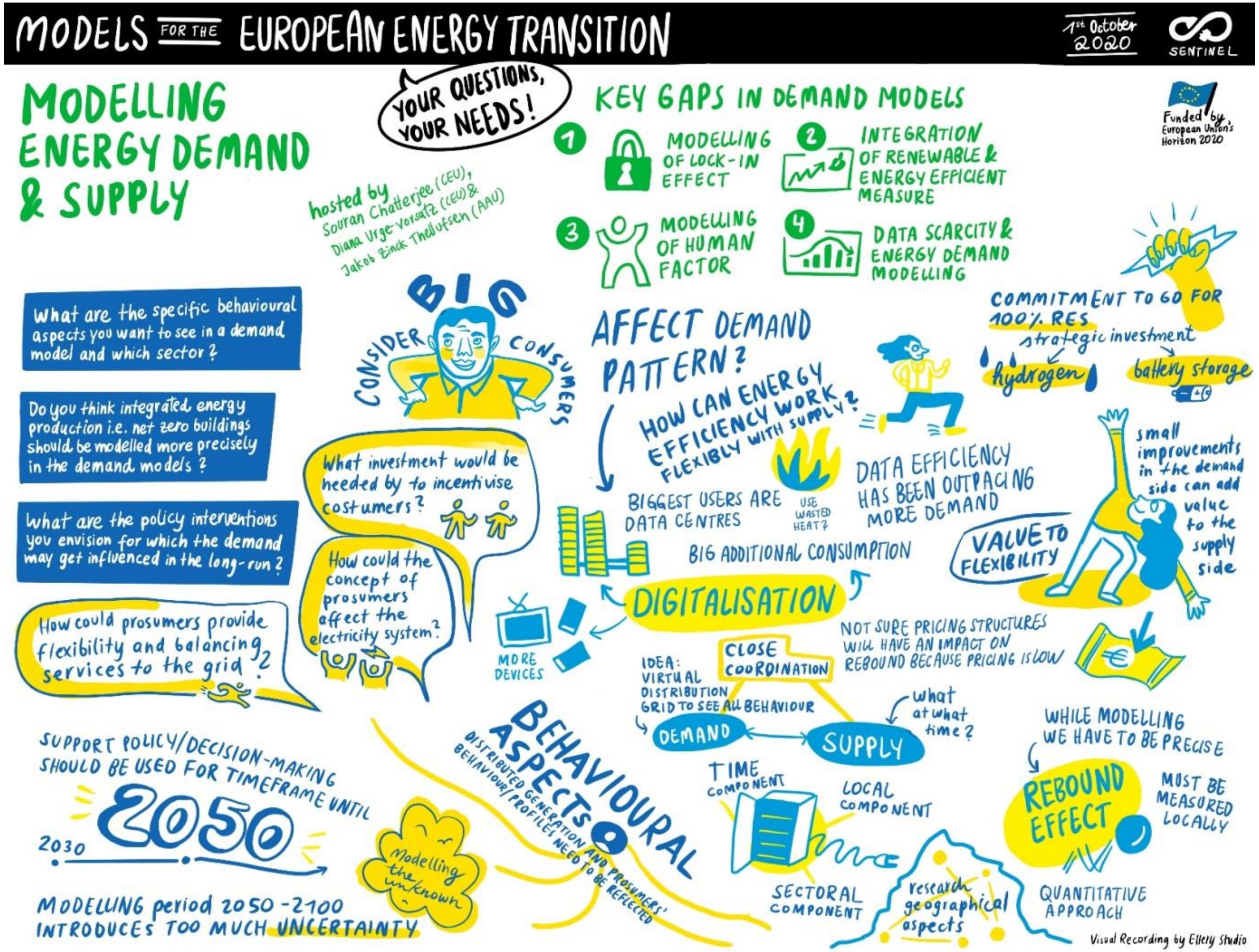


Figure 30: *Sketchnote of 'Modeling energy demand and supply' (Breakout Session* 3)

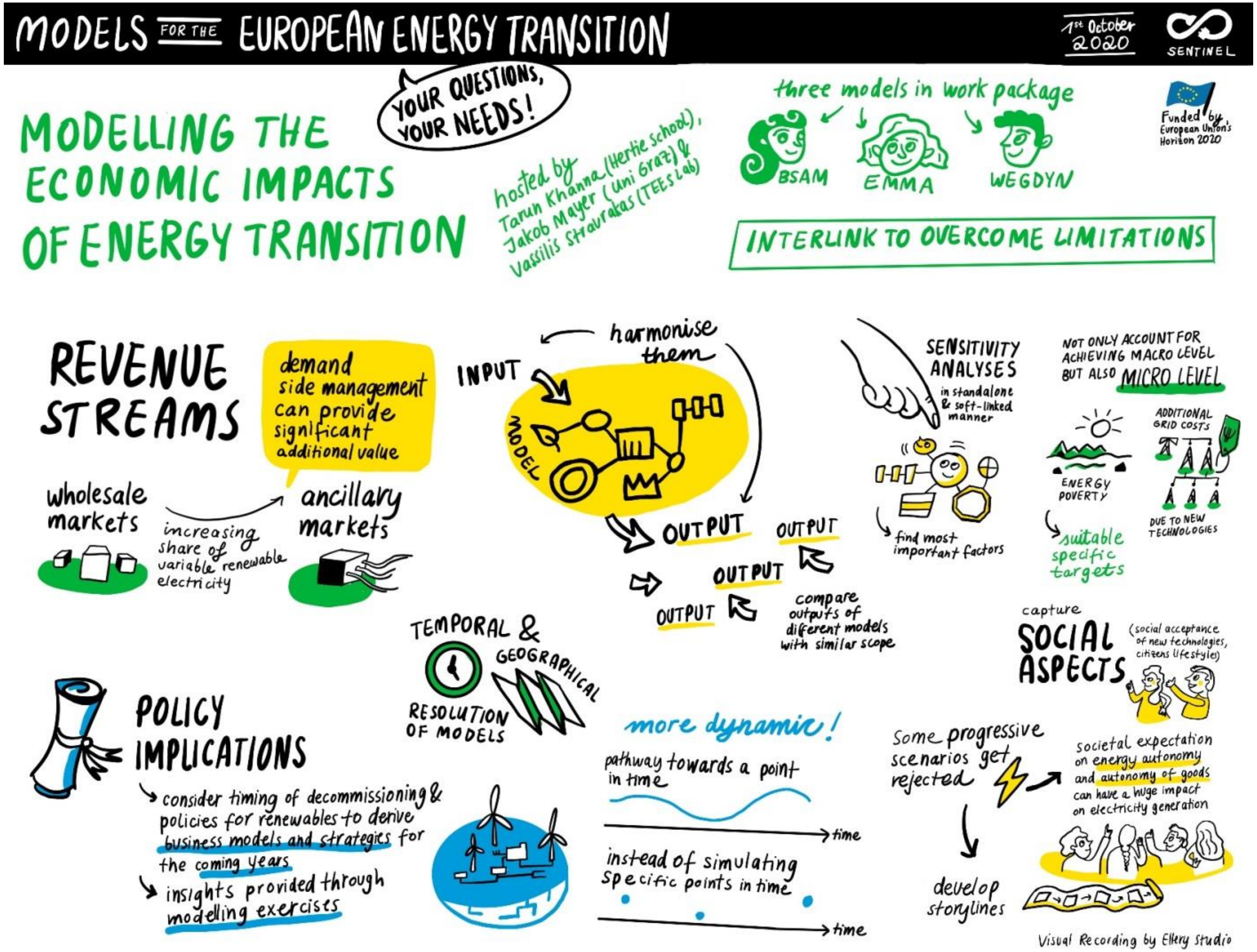


Figure 31: *Sketchnote of 'Modeling the economic impacts of the energy transition' (Breakout Session 4)*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089.

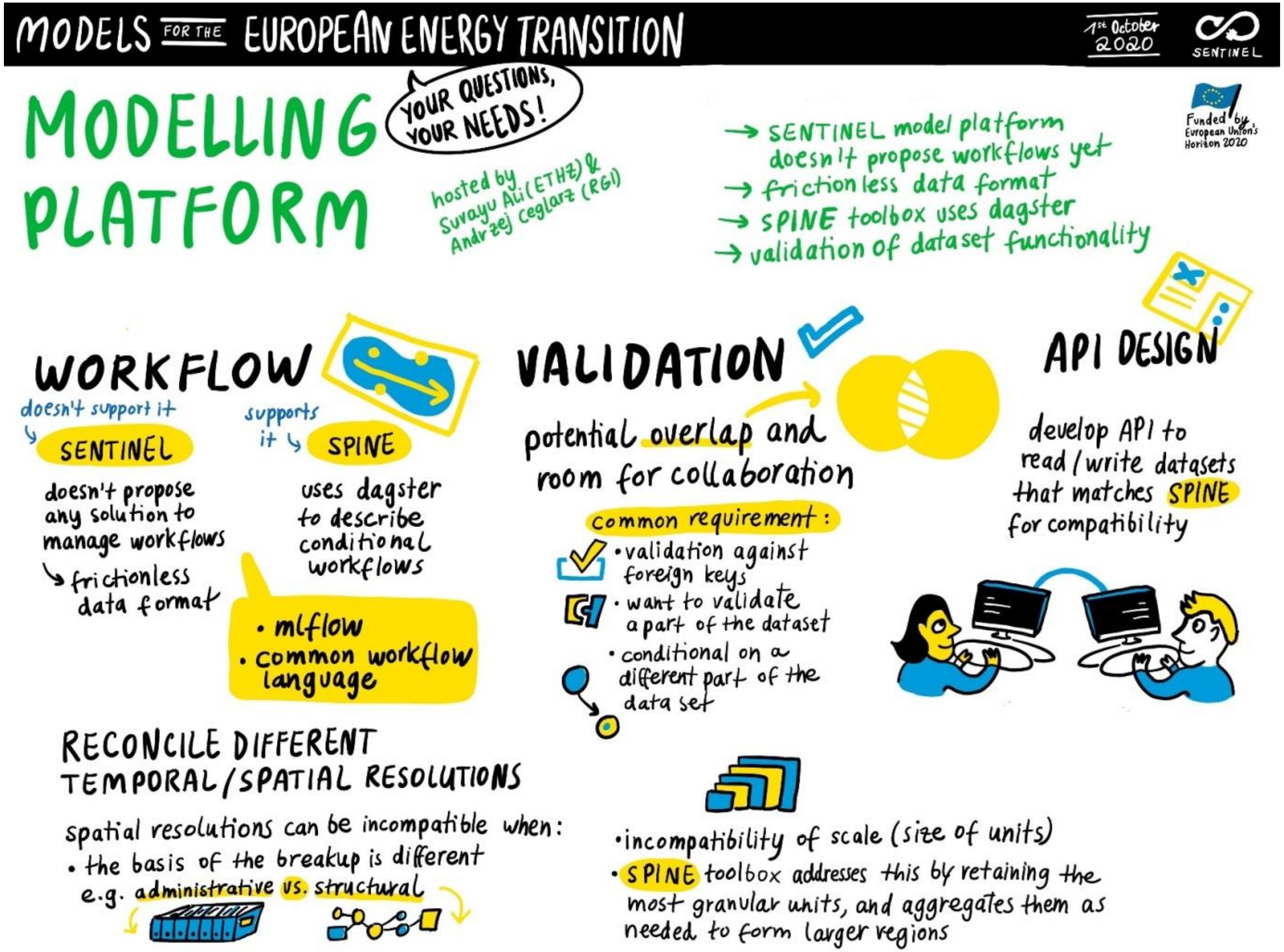


Figure 32: *Sketchnote of 'Designing the model platform of SENTINEL' (Breakout Session 5)*

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