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Existing tools, user needs and required model adjustments for energy demand modelling of a carbon-neutral Europe

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A R T I C L E I N F O

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A B S T R A C T

To achieve the European Union's target for climate neutrality by 2050 reduced energy demand will make the transition process faster and cheaper. The role of policies that support energy efficiency measures and demand-side management practices will be critical and to ensure that energy demand models are relevant to policymakers and other end-users, understanding how to further improve the models and whether they are tailored to user needs to support efficient decision-making processes is crucial. So far though, no scientific studies have examined the key user needs for energy demand modelling in the context of the climate neutrality targets. In this article we address this gap using a multi-method approach based on empirical and desk research. Through survey and stakeholder meetings and workshops we identify user needs of different stakeholder groups, and we highlight the direction in which energy demand models need to be improved to be relevant to their users. Through a detailed review of existing energy demand models, we provide a full understanding of the key characteristics and capabilities of existing tools, and we identify their limitations and gaps. Our findings show that classical demand-related questions remain important to model users, while most of the existing models can answer these questions. Furthermore, we show that some of the user needs related to sectoral demand modelling, dictated by the latest policy developments, are under-researched and are not addressed by existing tools.

1. Introduction

The European Union (EU) has committed to become climate neutral by 2050 [1] and has reinforced its emissions targets for 2030, committing to reduce greenhouse gas (GHG) by at least 55% compared to 1990 [2]. This requires unprecedented changes throughout the energy system, including increased penetration of renewable and carbon-neutral energy sources while reducing the energy intensity of the economy [3]. However, decarbonisation efforts have so far focused mainly on supply-side measures, notably the expansion of renewable power, while demand-side policies have received less attention [4,5]. Although final energy consumption slightly decreased by 2% between 2000 and 2015 in the 27 member states and the United Kingdom (UK) [6], studies conducted by the European Commission in the context of the “A Clean Planet for all” long-term strategy [7], present least-cost pathways that require significant cuts to final energy consumption in view of meeting the emission cap targets. These pathways lead to 21% decrease of total final energy consumption, between 2015 and 2050, with reduction of up to 60% in road transport and 40% in households.

Increasing energy demand thus, would further increase the challenge of meeting climate neutrality goals, as end-user demand determines the expanse of the energy system [8]. At the same time, increasing efficiency alone is not enough to achieve full decarbonisation: for this to happen, all energy consumed must be carbon-free, so reducing energy demand is only a helpful policy if it makes the transition to renewables easier, faster or cheaper [9,10] – and there are many reasons to believe that

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lowering energy demand would ease the pressure on a multitude of other sustainability issues beyond GHG emissions, particularly when non-GHG sustainability issues are also considered. It is therefore essential to develop and update energy demand models (EDMs) to provide scientifically robust insights for policymakers and other relevant stakeholders regarding future end-use demand scenarios.

EDMs are often used as ex-ante tools to explore options, policy strategies and instruments to support efficient decision-making. As the requirements and technical capacities for modelling have increased, numerous EDMs have been developed, for scientific purposes, consulting, and direct policy advising. However, it is not clear if these models grow in terms of details and mathematical sophistication to examine scenarios for climate neutrality [11]. To make energy models including EDMs more relevant and useful, models must be tailored to the needs of their users [12], and increase the likelihood of model results being used in practice [13]. EDMs, like all mathematical models, are often developed and improved based on the modellers' "normative" assumptions, such as the goal of cost optimisation and the rational behaviour of market actors; however, this subjective understanding of reality does not coincide with actual reality [14]. As the transition to renewable energy changes the "real-world" energy system, modellers are becoming aware of new challenges that must be incorporated in models to make them useful tools for studying energy systems. Therefore, it is important to identify the gaps between the "realities" demand models model today and the needs of EDMs users.

Scholars have investigated user needs for energy models, but only with a focus on system and supply models [15–17]. To the best of our knowledge, no study has yet focused on user needs for energy demand modelling. However, some of the user needs identified for the system models may also be relevant for demand models. For instance, Chang et al. [18] investigated recent trends in energy system modelling, including some system models with endogenous demand modules, and found gaps in high-resolution energy demand representation in all sectors, as well as in the openness and accessibility of demand modules. Also, Süsser et al. [19] found a high need among users of model results to better integrate behavioural and lifestyle aspects in modelling, which directly affects energy demand modelling. This lack of scientific attention to energy demand modelling may lead to a lack of information on the impact of demand-side measures, reflecting the often-hesitant implementation of measures. Nonetheless, changes to the demand side are likely to be as profound as those to the supply side [20], and supply-/demand-side measures will strongly interact. Demand-side measures directly affect consumers, so their societal and economic effects can be even larger [21,22]. Therefore, we see a large and increasing requirement for a deeper understanding of energy demand, including demand-side management and demand-response options that can provide insights into balancing fluctuations in renewable power supply at different time scales and provide direction to further improving EDMs in the context of countries or continents striving for climate neutrality [23–25].

In this article, we address the gap between the needs of different stakeholders to advance modelling tools and the results provided by existing EDMs. We ask the questions: What aspects do different stakeholder/user groups think that should be better represented by EDMs to improve future energy demand estimates in the context of the climate neutral transition in the EU? and what are the user needs that are presently not addressed by the existing EDMs? To answer these questions, we use a multi-method approach, consisting of an online survey, online stakeholder meetings and workshops, and an extensive review of existing EDMs. Our novel contribution to the scientific literature is threefold: First, we show general and sector-specific user needs that EDMs should address according to modellers and different stakeholder groups. Second, we provide an overview of existing EDMs and their main characteristics and capabilities. Third, we compare these needs with what is captured by existing modelling tools to discuss key gaps in existing tools and hence, user needs that are yet to be incorporated into EDMs.

2. Methods

We first investigate the needs of different stakeholder groups towards the further improvement of EDMs in support of efficient decision-making on the road to climate neutrality by 2050 in the EU. We then provide an overview of the status-quo of existing EDMs. To do so, we conducted an online survey as well as online stakeholder meetings and thematic workshops, and a review of existing energy demand modelling tools. Interacting with different users of models and model results enabled us, first, to understand and identify the different user needs, and, thus, demonstrate the direction in which EDMs need to be improved to be relevant to their users. We also conduct a review of existing energy demand modelling tools, focusing on current approaches and characteristics to give a full understanding of their capabilities and identify their limitations and gaps. Fig. 1 provides an overview of the multi-method approach we followed.

We systematically analyse, compare and present the user needs, limitations and gaps of existing EDMs. To do this, we adapted the original categories defined by Süsser et al. [19] as an analytical framework to categorise and analyse user needs about energy system models: I. *what* to model ("**content**"), II. *how* to design the model ("**design**"), and III. *how* to communicate with modellers and model users ("**outreach**"). Note that from the original set we excluded the "Modelling process" category as this was out of the scope of our study (Fig. 2).

2.1. Online survey

We first conducted an online survey to identify general user needs relevant to modelling. By "general" we refer to user needs that are relevant for overall energy demand modelling irrespective of sectors. The online semi-quantitative questionnaire included different types of questions [26]: single and multiple choice,[1] Likert-like scales[2] and free-text boxes. Some questions were mandatory, others voluntary. Since we distributed the survey among national and European organisations and individuals via private and public online channels, the survey population was based on a non-probability sample [27]. We surveyed both modellers and users of model results from four stakeholder groups: research (42), policymaking (12), energy industry (16), and non-governmental organisation (NGOs) (11). We received 90 completed survey responses, from which, we only present user needs specifically relevant for energy demand modelling. More detailed survey results are reported in Gaschnig et al. [28]. The survey questionnaire and anonymised aggregated data are openly available at Zenodo [29].

2.2. Stakeholder meetings and workshops

Since the survey's sample size was too small to reach saturation, as a second step, we conducted stakeholder meetings and workshops to further complement the survey and strengthen our findings. We kicked-off with a Europe-wide workshop to discuss energy modelling expectations for the European energy transition to climate neutrality. The workshop was implemented online due to the COVID-19 pandemic, as were most stakeholder engagement activities at the time [30]. The objectives were to discuss, verify, and prioritise the preliminary set of general user needs, as identified through the survey, directly with different stakeholders, and to identify a preliminary set of sector-specific user needs. 23 stakeholders with a background in energy systems and energy demand modelling participated in the workshop, from research,

[1] Survey participants chose between multiple given answers, e.g., select the most relevant or correct statement.

[2] Survey participants had to rank the importance of different aspects, e.g., from not important to highly important.

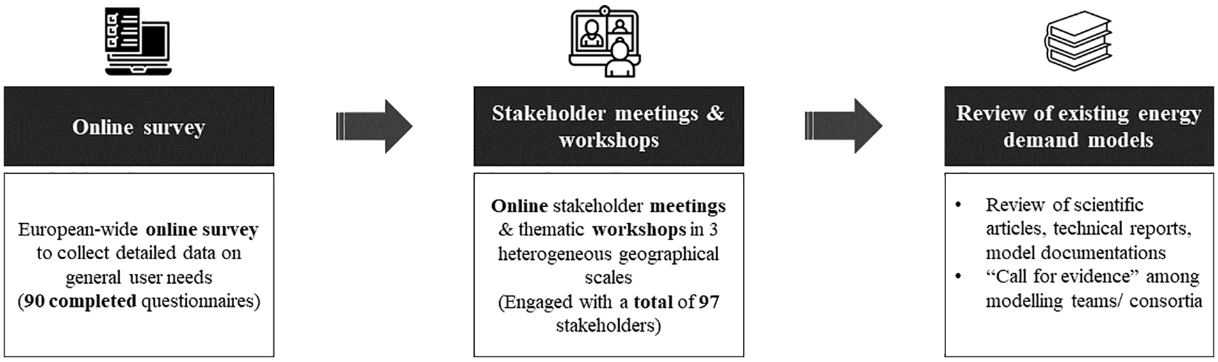

Fig. 1. Overview of the multi-method approach followed.

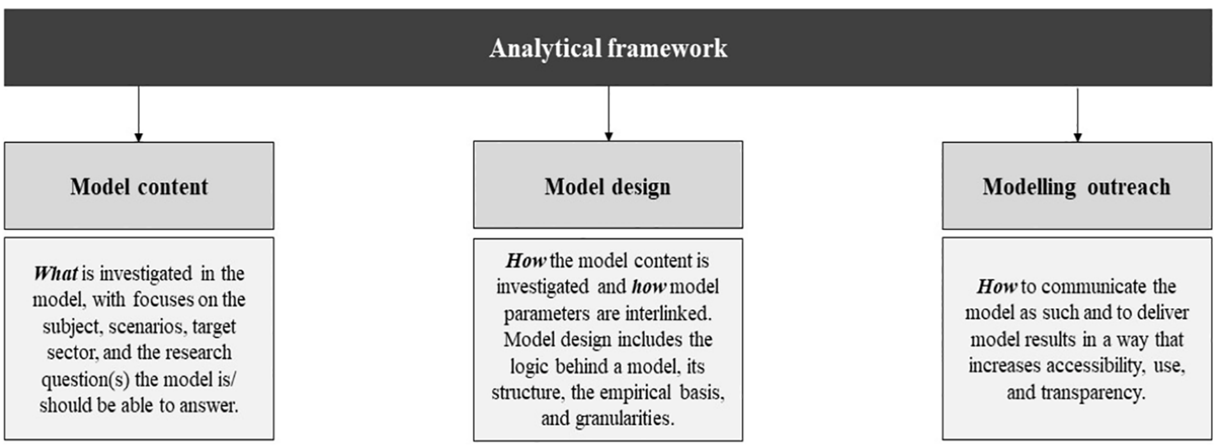

Fig. 2. Structural framework for the analysis of user needs on the road to climate neutrality and of limitations/gaps of existing energy demand models (as adapted from [19]).

policymaking, energy industry, and NGOs, [28]. The workshop consisted of two plenary sessions and five breakout sessions of two session rounds, which allowed participants to join to different sessions (see Table S1, in Supplementary material). Here, we report on the findings from the breakout session "Modelling energy demand and supply", which was specifically dedicated to user needs in energy demand and supply modelling, and the interaction of the two. The workshop session allowed us to validate our set of general user needs and expand on a preliminary set of sector-specific user needs.

To discuss and solidify our set of sector-specific user needs, we then conducted, thematic case study workshops and meetings with key stakeholders in three heterogeneous geographical scales, namely: 1. national (Greece), 2. regional (Nordic countries), and 3. continental (EU member states, Switzerland, and UK) to further enrich our findings with more contextual requests on energy demand modelling towards climate neutrality. We selected these cases as representatives of different spatial scales of the European energy transition and geographical contexts with different demographic, economic, energy and climate characteristics, and governance levels. Considering that all the EU's national energy systems will need to be coordinated in the future to make Europe climate neutral by 2050, we also considered the level of the integration potential. For the national case, we conducted interviews and focus groups, following a semi-structured guideline, with 33 stakeholders. For the regional and the continental cases, we conducted two stakeholder workshops of a similar format as the European-wide workshop above, with plenary and parallel sessions; each event had one breakout session dedicated to energy demand modelling. Due to COVID-19 implications, all these activities were held online. Overall, we engaged with more than 70 stakeholders from research, policymaking, energy industry, and NGOs, with a background in energy systems and energy demand modelling (see Table S1, in Supplementary material). We recorded and transcribed the feedback received from the interviews, focus groups, and workshops. All research concerning the national case was conducted in Greek, while for the other two cases it was conducted in English. Presented quotations in the case of Greece have been translated by the authors. More information on these stakeholder engagement activities is presented in Stavrakas et al. [31].

2.3. Review of existing energy demand models

As a final step, we conducted an extensive review of existing EDMs to understand their characteristics and capabilities and to identify their limitations and gaps on the road to climate neutrality. We reviewed scientific articles, technical reports, and model documentations. We searched the following scientific databases: Science Direct, Google Scholar, the Central European University (CEU) and the Imperial College London (ICL) databases, as well as Google. We used the following search strings: "energy demand models," "EU climate neutrality and energy demand," "energy demand and supply models," and, "energy system models." These search strings yielded a total of 21,899 studies as of June 2021 (9514 from Science Direct, 9430 from Google Scholar, 4461 from ICL database, and 1345 from CEU database). After removing duplicates, abstracts and then manuscripts were reviewed for eligibility using the five criteria listed below:

1) models must endogenously calculate future energy demand;

2) models must have granularity across sectors or systems, technologies, and/or fuels, with input assumptions and a validated method; as opposed to purely econometric projections;
3) models must document their method and input data in a report or in a scientific journal article; and
4) models must project energy demand for different future scenarios;
5) models must include European Union and/or UK in their spatial coverage. Models with global coverage are included if they provide specific results for European Union and/or UK. We reviewed system models with an endogenous energy demand module in addition to standalone sector-specific demand models, to derive a comprehensive review of models that calculate energy demand based on different approaches, and temporal, sectoral, and geographical coverages.

To complement our literature review, we also circulated a 'call for evidence' among different EU modelling consortia: "Sustainable Energy Transitions Laboratory (SENTINEL)[3]" consortium, the "Energy Demand changes Induced by Technological and Social innovations (EDITS)[4]" consortium, and the "Energy and Social Science Network (EASSN).[5]" Our objective was to gather information about existing EDMs with a focus on the building, transport, and industry sectors to understand the "status quo" in energy demand modelling and identify the main limitations and gaps of EDMs in terms of their capabilities to address the identified user needs. We therefore stopped adding demand models in the list, (especially system models with a demand module) when they added no new features to any of the categories in Fig. 2. Altogether, we derived a list of 39 EDMs.

3. User needs towards climate neutrality by 2050 in the European Union

Based on our approach and the analytical framework presented, we identified the user needs of what EDMs should model, how EDMs should be designed or further developed EDMs to cover the required content, and how to communicate modelling results to modellers and model users (Fig. 3).

3.1. Model content

Stakeholders indicated the directions in which EDMs should be further developed and the research questions to which modellers should apply their models, so that models and model results have a meaningful impact on decision-making for the transition to climate neutrality. Our survey findings show that most stakeholders, regardless of their group, are concerned with the electricity system (Fig. 4). One survey respondent raised the question: "*Can we rely on renewable electricity to meet the demand in the EU until 2050*?" However, the focus also shifts to heating and transport sectors, which are expected to be largely electrified [32,33]. A stakeholder asked: "*What are the additional electricity demand patterns and the effect on peak load demand resulting from the electrification of the heating/cooling sector*?" EDMs therefore need to consider different sectors and also issues of sector coupling, digitalisation, and flexibility. Our workshops revealed that new energy technologies, such as renewable gases and green hydrogen should also be included in demand modelling in the context of sectoral transitions.

We find that stakeholders are particularly interested in the demand-side measures needed to achieve decarbonisation targets. Stakeholders called for models that provide a better understanding of the impacts of energy efficiency improvements and behavioural/lifestyle changes on energy demand. The first aspect refers to the need to include measures such as the development of energy performance standards for buildings, the labelling of appliances, fuel economy standards for road transport, CO_2 taxation for air transport, and the application of cogeneration for industry, to assess the impact of different policy options. On the other hand, reducing final energy consumption depends not only on improving overall energy efficiency but also on measures to reduce or optimise service demand, such as the heating behaviour and comfort, the distances travelled by cars and the use of energy-related appliances [34]. Behaviour, lifestyles and heterogeneity of consumers was the second most prominent issue raised when survey participants were asked what factors do they think should receive more attention in energy models (Fig. 5). According to the stakeholders, energy models should quantitatively assess behavioural and lifestyle changes of consumers. One survey respondent asked: "How will demand profiles change?" To answer this question, EDMs need to draw on empirical results from social science research to better understand energy sufficiency policies [35] and the appropriateness of certain measures in certain regions or countries based on public perceptions and acceptability.

Building on our survey results and the insights from the Europe-wide workshop, our thematic case study workshops and meetings allowed us to shed light into sector-specific user needs in the building, transport, and industry sectors.

3.1.1. Buildings

Stakeholders identified several gaps and needs that are essential for modelling energy demand in the building sector and explore transition pathways towards a climate neutral economy in Europe. Some needs, such as standardisation and labelling of buildings, or the role of energy efficiency in reducing energy demand, have been well-known for some time. However, one of the major questions that was raised by almost all the stakeholders was "*how can the standardisation of the building sector be further pushed*," focusing on assessing and prioritising the saving performance of energy efficiency measures, especially of emerging ones, also considering the concept of "smart buildings," which has gained a lot of interest recently. Stakeholders questioned whether "*zero-carbon energy supplies can be a cheaper way of decarbonising buildings than deep retrofits*," suggesting more comparative scenarios and cost-benefit analyses on that front. In this context, another important issue that was raised by stakeholders is exploring "*what are the potential costs, and barriers for nearly zero energy buildings (NZEB)*," as for example, in the case of the Nordic region, where stakeholders acknowledged that "*there is still not enough emphasis on the need for international building certifications like passive houses or nearly-zero energy buildings*."

Assessing the nexus between renewable energy sources and energy efficiency in the building sector is another significant issue that EDMs should be able to address. Many stakeholders were interested in "*the optimal energy efficiency investments in buildings in order to achieve cost effective synergies between renewable energy sources and the electrified heating and cooling sector*." For example, stakeholders asked "*What should be the level and the timing of financing combined renewable energy sources and energy efficiency measures in different types of buildings in the residential sector with the least possible costs*?" Furthermore, stakeholders also wanted to look into the contextual opportunities for heat pumps and district heating/cooling to increase energy efficiency in buildings without the thermal comfort of occupants being compromised.

While stakeholders consider the performance assessment of different technologies for the building sector decarbonisation as an important issue, preserving indoor comfort is considered equally important to them, highlighting that "*having a warm and comfortable home is as important as achieving energy savings through renovation measures*." Existing models often neglect such aspects, and so further research is required for EDMs to address occupants' comfort, health, and well-being in a more scientifically robust and consistent way. In this context, integrating socio-technical transitions in EDMs (i.e., behaviour, social risks and opportunities, transition dynamics, and heterogeneity across

[3] https://sentinel.energy/.
[4] https://iiasa.ac.at/web/home/research/researchPrograms/Energy/Research/EDITS/EDITS.html.
[5] https://www.jiscmail.ac.uk/cgi-bin/webadmin?A0=EASSN.

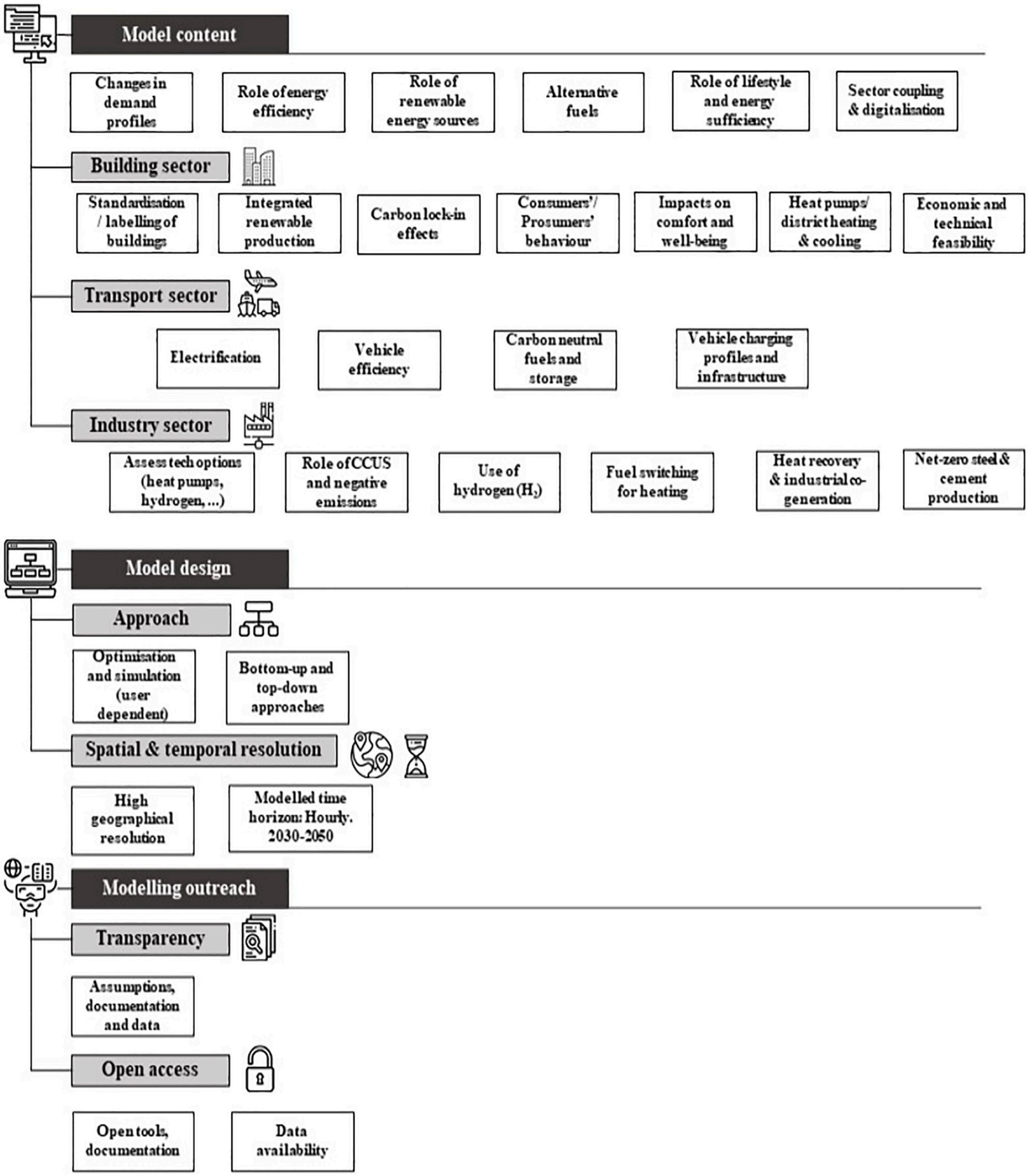

Fig. 3. Summary of the identified user needs in the field of energy demand modelling categorised across the three analytical categories.

and within societies) is an important aspect raised by both the literature and stakeholders [36]. EDMs should address more social and behavioural aspects of the energy transition (including for heating/cooling), which could create further opportunities for active consumer participation, e.g., prosumerism, etc. [37]. This is also validated by our online survey, which found that the top three social aspects which should be further analysed by energy models in general are: co-benefits of prosumerism and community energy, drivers and barriers of social innovations' diffusion, and dynamics of social acceptance and individual attitudes [19]. When it comes to demand modelling, the key issues of scenario development and definition of model inputs/outputs should be resolved to improve modelling of human behaviour, including the role of attitudes, preferences, and acceptance of energy technologies. "*Behaviour, lifestyle, and heterogeneity of citizens/consumers*," with a special focus on understanding "*how policy changes can trigger behavioural changes*," are critical aspects according to stakeholders that existing EDMs have not adequately addressed so far.

Furthermore, stakeholders identified the need to consider the carbon lock-in effects while modelling energy demand. For the building sector, particularly, lock-in effects are crucial as investment in long-lasting built

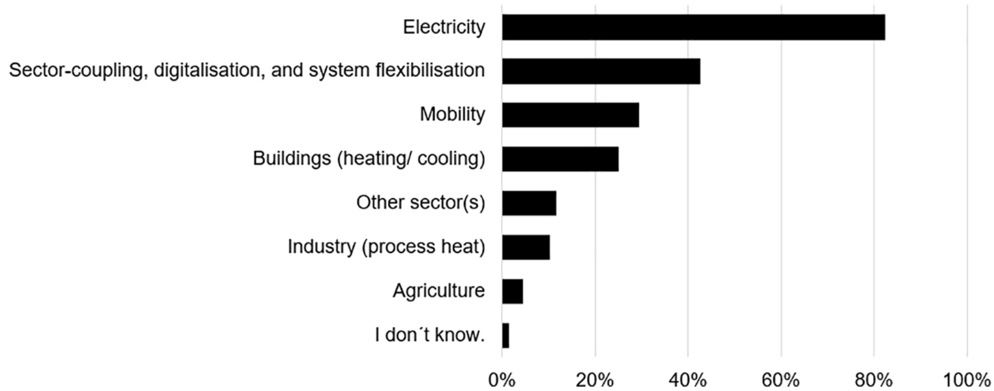

Fig. 4. Answer to the question: Which sector(s) is/are currently of main focus in your working context? [multiple choice, maximum 3, $n = 68$].

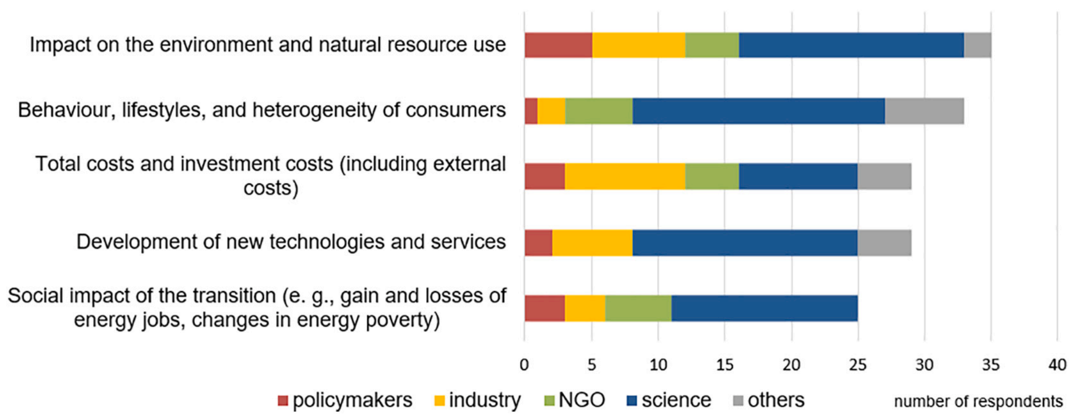

Fig. 5. Top 5 answered issues to the question: Which of the following factors do you think should receive more attention in energy models? [multiple choice (minimum 1, maximum 5 aspects), optional question].

infrastructure impacts energy demand patterns for a considerable length of time after their development [38].

3.1.2. Transport

With fossil CO_2 emissions from road transport still growing in Europe [39], stakeholders pointed out the importance of decarbonising this sector for meeting emission reduction targets. In alignment with impact assessments accompanying the release of the 2030 and 2050 objectives [34,40], stakeholders highlighted the "*significant role*" that electrification would have in limiting emission from final energy uses. They also posed questions regarding "*the impacts of the electrification for this final energy use on the full energy system*", considering that scenarios forecast that electricity will become the main fuel for transportation in a climate neutral horizon by 2050 [39]. Stakeholders suggested that models should not only account for a yearly dimension, but they need to be able "*to forecast hourly demand*", contributing to understanding changes "*in amplitude and shape of load curves due to different assumptions for vehicle charging profiles*." Users have also specifically emphasised the development of the associated infrastructure and how additional storage could facilitate the control of power flows, as well as voltage, phase imbalances and frequency of the electric grid. Given that battery electric vehicles are expected to be the preferred option to meet the decarbonisation targets for passenger transport, users stressed the need for models to employ "*representative inputs for fuel economy*" for these units. Stakeholders also underlined the "*challenges that freight transport would go through*" in reducing GHG emissions, posing the question of "*how energy models can be employed for essaying different technology options, including battery, hydrogen, power to fuels, and hybrid fuelled units*."

Finally, the EU established post-2020 and post-2030 standards for new units in terms of fuel consumption per travelled distance in view of strengthening its climate change mitigation targets [41]. These standards were set before the approval of the European Green Deal [40] and the 2030 updated GHG emission cuts [42]. Users suggested that models should account for possible "*fuel economy evolution beyond 2030*", being able to incorporate learning curves for both internal combustion and electric vehicles.

3.1.3. Industry

When it comes to the industry sector, stakeholders underlined "*the need of modelling specific pathways for different industry types*," considering the differences in terms of energy consumption patterns and consequent GHG emissions. They also highlighted the need to consider both combustion and process emissions when modelling industrial decarbonisation. Several technology options are foreseen to be incorporated within this final energy use [34], with stakeholders stressing the role of "*heat pumps, carbon capture utilisation and storage, heat recovery and industrial co-generation, use of hydrogen, and net zero steel and cement production*." It is expected that heat pumps will be introduced to partially replace fossil fuel employed for low enthalpy heat generation [34,43], particularly substituting natural gas in Western European countries and natural gas, coal and fossil liquid fuels in Eastern Europe. It is envisaged that this technology incorporation will be mostly focused on light industries and/or for liquid fluid heating.

Stakeholders also underlined the role of carbon capture utilisation and storage (CCUS) technologies, particularly, in the context of emission reduction for steel, clinker production, and chemical manufacturing. Post-combustion CO_2-capture processes are envisaged to be incorporated downstream blast furnaces for pig iron production, while pre-combustion and calcium looping technologies could be applied in cement industries and for decarbonising hydrogen (H_2) production from natural gas respectively [44,45]. Steam methane reforming is currently the most widely used route for chemical industries using H_2 as feedstock [46]. "*Deployment of these technologies will rely on regional or national feasibility and capacity for CO_2 transport and storage, aspects that stakeholders considered relevant to be accounted for when developing scenarios or pathways involving a wide penetration of these processes*." Some users also highlighted the potential of CO_2 utilisation routes for the production of fuels and chemicals, and for the enrichment of agriculture greenhouses.

Users also pointed out the role of biomass feedstock in industrial and energy conversion facilities with installed CCUS units as a way to enable "*negative emissions*", partially contributing to compensate for residual emissions from certain final uses. They underlined the need for "*modelling tools to be able to explore such interactions when simulating demand-side decarbonisation pathways*." The use of H_2 as an alternative low-carbon fuel and the environmental trade-offs associated with its production mechanisms are currently the main subject of ongoing debate [47]. Stakeholders have highlighted the importance of H_2 "*in reducing emissions from the industrial sector and replacing fossil fuels both as energy vectors and feedstock for certain processes like steel production*." Furthermore, they have also reflected on the use of H_2 to intermittently store renewable-based electricity, being necessary to account for the integration of the supply and demand side when modelling H_2 penetration across final energy uses.

Finally, efficiency improvement is critical to reaching lower emissions, and, at industrial level, this can be realised by enabling thermal integration of streams and possible in-situ generation of heat and power-using hot flue gases or high temperature streams as source of heat for working fluids in power cycle. Several countries have developed policies aimed at encouraging this type of practice as well as biomass-based heating systems [48,49].

3.2. Model design

During the modelling process, modellers must not only make decisions about the model content but also often make fundamental (and to a certain degree irreversible) decisions about their model's design., especially when it comes to new models completely developed from scratch. Such decisions include the appropriate level of complexity, whether it should be an optimisation or a simulation model, granularity, with respect to spatial, temporal and sectoral coverages.

The survey results show that respondents work with, or use results of, different types of models (Fig. 6). It is noticeable that energy industry and NGO users work more with electricity markets and energy planning models, while policymakers work more with integrated assessment models and macro-economic equilibrium models in comparison to other stakeholder groups. The respondents stated to work with different EDMs, or energy systems models with a strong demand component, such as Energy, Economics and Policy (Enerpol) model, Energy Transition Model (ETM) etc.

In addition to the models used, we also asked them about their preferences for model designs. We find no clear preference for optimisation or simulation models – but a preference for optimisation especially among industry actors (Fig. 7). Furthermore, we find a balanced opinion when it comes to the question if models should be rather simple or more complex. However, while more complexity may be needed to address the content-related user needs of above,: stakeholders stated that EDMs should be capable of accounting for the impacts of demand-side measures, highlighting the need for combining bottom-up and top-down approaches.

In addition, more complex EDMs may be the result to deal with high spatial and temporal resolutions, as stakeholders consider this important for the use of models (Fig. 8). Models are specifically needed to assist model users in mid-term time horizons of the energy transition. The online survey reveals that almost three-third of the stakeholders deal with medium-term (2030, 2040) and more than 50% with long-term time horizons (2050 and beyond up to 2100) in their work (Fig. 9). To assist decision-makers, EDMs must adapt their emission caps to the new climate change mitigation targets for 2030 and 2050 in the context of

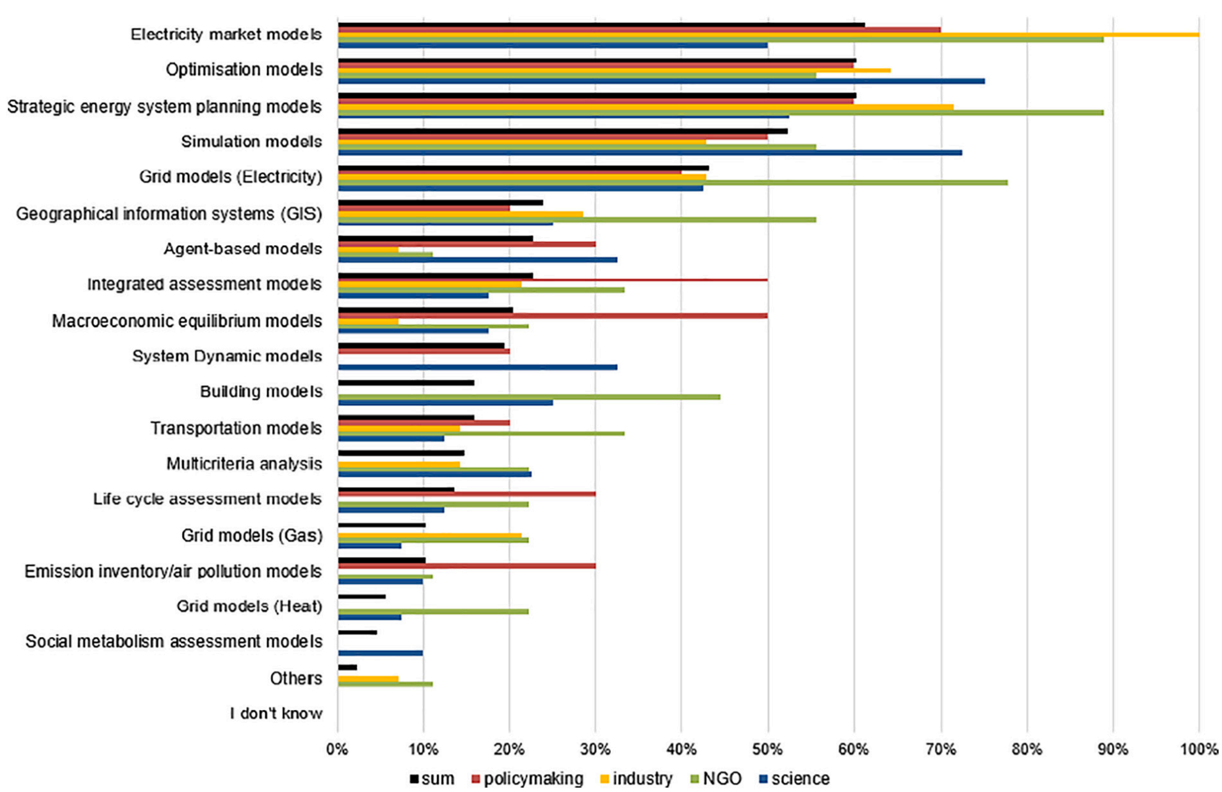

Fig. 6. Answer to the question: With which kind of models in terms of model topics and model type have you worked (as indicated above) so far? [multiple choice, voluntary, $n = 88$].

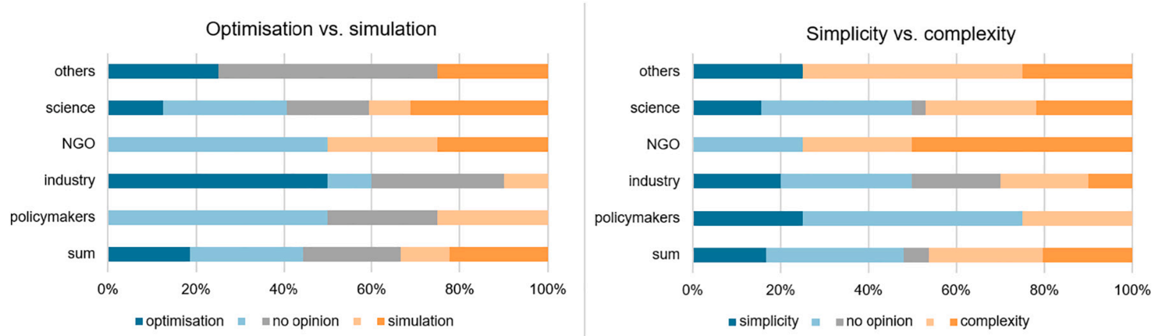

Fig. 7. Answer to the question: Which model feature/quality is more important to you? Please choose in each pair the more meaningful to you [note: we presented a four-point scale for both pairs].

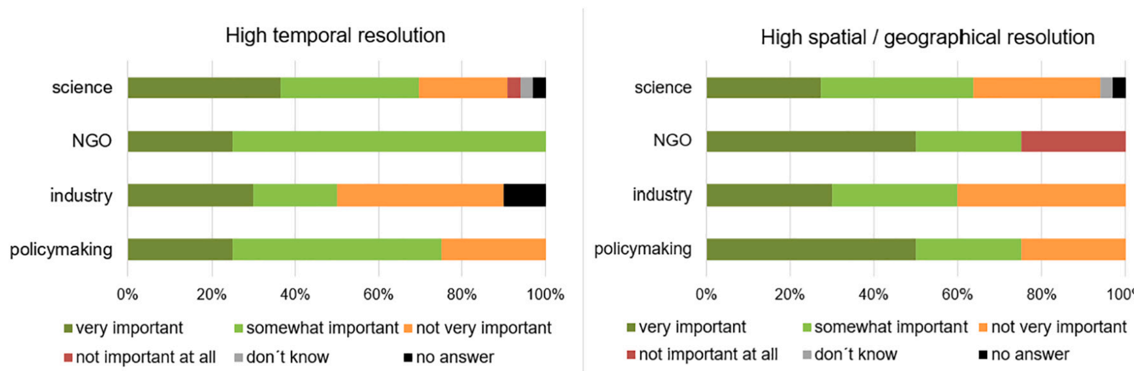

Fig. 8. Answer to the question: How important are the following model conditions for the use of models or their results in your work? [Likert Score: not important ⟨–⟩ very important, don't know; voluntary; $n = 55$].

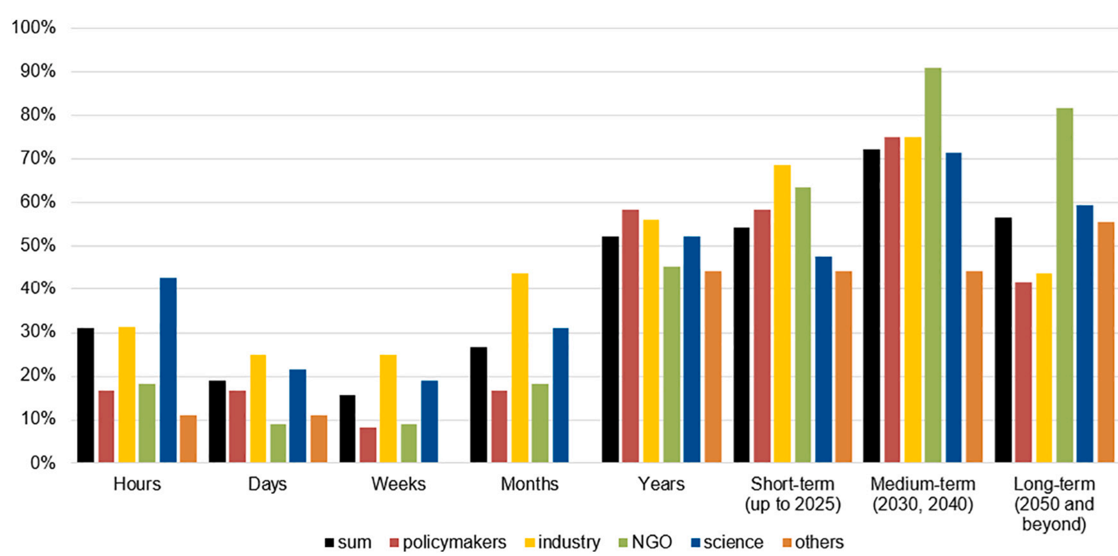

Fig. 9. Answer to the question: What time horizon(s) are you dealing with in your energy-related work? [multiple choice; voluntary, $n = 90$].

the “Fit for 55” and the European Green Deal strategy [2,50]. It is noticeable that especially NGOs tend to deal with longer timeframes than other stakeholder groups. Furthermore, we find that stakeholders also need demand modelling results at shorter time resolutions, as sector coupling, fuel swapping in final energy uses, and modifications in efficiency will lead to changes in the future demand profiles; not only in terms of absolute numbers but also in their shape [51,52]. This seems of specific interest to actors from industry and partly scientists. As power demand becomes more volatile and supply largely dependent on intermittent renewable sources, the analysis of load curves becomes crucial for the design of future energy systems. Most impact assessment models focus on the annual dimension, reporting power demand and generation at that scale and partially, or completing ignoring the hourly dimension and its consequences for security of supply. Therefore, EDMs need to fill this gap and contribute to ensuring supply security.

3.3. Modelling outreach

Our results also identified needs regarding modelling outreach to increase the usefulness of the models (Fig. 10). Most survey respondents consider transparency to be very important or somewhat important; equally so across all stakeholder groups. Respondents emphasised the need for a better understanding of the assumptions underlying the modelling philosophy, as well as the input data and how it is processed internally. For example, stakeholders expressed a specific need for access to detailed and further disaggregated data on fuel consumption in various major final energy uses, and criticised the fact that this is not the case for official scenarios such as the previous "EU Reference Scenario" [53]. Furthermore, users stated that it is of great value to them to have open access to the tools and the input data of the modelling runs. One survey respondent stated that "*open source has a quality assurance function.*" Increased transparency and openness also allow for reproducibility of calculations and analysis of possible causes for differences in the outputs, when comparing the results of different models. This was especially valued by scientists and NGO representatives. Additionally, although the reproducibility of the model results is important to all stakeholders, it was noticeably less important to policymakers than other stakeholder groups.

Modelling exercises should streamline the use of input data and assumptions, as stakeholders acknowledged that the level of available information, especially on residential buildings, is considered as "*not very high*" or "*scarce*"; there "*is a lack of information about residential buildings and their energy performance details*," as no obligation exists to collect data about the residential building stock and building owners are not requested to inform the municipality about energy-efficiency measures implemented.

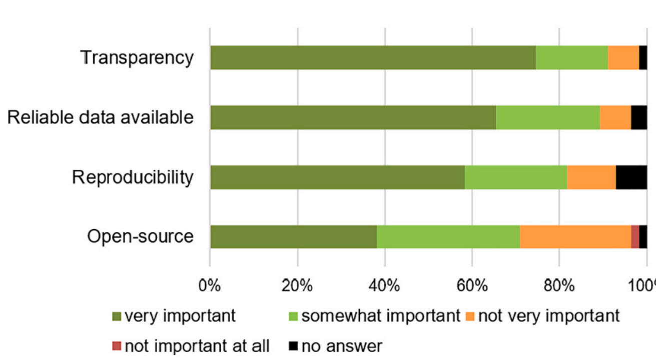

Fig. 10. Answer to the question: How important are the following model conditions for the use of models or their results in your work? [Likert Score: not important ⟨–⟩ very important, don't know; voluntary; $n = 55$].

4. "Status quo" of existing energy demand models

Based on the selection criteria described in Section 2.3, we selected a list of 39 EDMs in Table 1 for further review to identify main limitations and gaps with respect to modelling energy transitions. A detailed list of the EDMs presented and their description are provided in Table S2 in Supplementary material.

4.1. Model content

The key outputs of these models are end-use-specific service demand, and total energy demand, split by specific end uses. Models provide a wide range of outputs due to various scenario-related assumptions and different methodologies used. Most of the existing models, (38 out of 39, 97%) calculate energy demand profiles for different sectors or end-uses or systems, and all of them incorporate energy efficiency either through scenarios or through input data and/or assumptions. Some models generate results for baseline or reference scenarios, which consider existing policies, and then, compare these with additional scenarios of different carbon emission targets to give a direct comparison on the outcome of different actions. Thus, the magnitude of final energy demand may change among different models once scenario-related assumptions alter, but the trend about energy demand remains the same.

In the "FTT: Heat" model, for instance, scenarios are based on the share of renewables in heating of residential buildings, deep decarbonisation and strict carbon taxes. While this model incorporates a share of at least 10% for heating from clean energy by 2030 in the EU, this value is more ambitious (i.e., 27%) in the "2030 Quota EU" scenario of the "Invert/EE-Lab" model [66]. For the transport sector [77], the models "REMIND", "WITCH-T" and "GCAM" show that this sector can achieve up to 90% emission reduction globally by end of century, by implementing fuel efficiency, with the use of carbon capture and storage (CCS) technologies. However, it must be emphasised based on their results that this reduction can only be achieved in case of strict carbon taxing. Otherwise, global emissions are likely to be reduced only after 2080. Once all sectors are considered, industry and transport were projected to be the largest pollutants in terms of CO_2 by 2050 in the EU, based on the analysis with the PRIMES full system model [94]. Furthermore, results refer to significant growth in electricity among the different fuel types, considering the period 2010–2050.

The scenario review is unable to conclude whether these ambitious scenarios are compatible with the transition to climate-neutrality as no EDM scenario includes transition to climate neutrality. One key reason is likely that demand-side measures alone cannot suffice to achieve climate neutrality, and hence, supply side measures should be considered as well while designing scenarios towards climate neutrality. Nevertheless, many energy efficiency measures are supportive of full decarbonisation, because they reduce the amount of energy to decarbonise. Thus, EDMs need further development and more close integration with system models to be able to identify synergies or trade-offs between demand- and supply-side policies. Findings from Tables 1 and S2 (see Supplementary material) further reveal that although many of the existing scenarios of the EDMs show the potential of different energy efficiency measures and renewable technologies, there is no model that investigates both the economic and technical feasibility of this nexus in an integrated manner. The latter is required to have accurate energy demand estimates, especially considering the new European targets dictated by the recent policy developments. Lastly, although behavioural and lifestyle-related changes in demand have lately been gaining importance within the modelling community, so far only 7 out of 39 (18%) models incorporate either lifestyle or behaviour changes while calculating energy demand.

4.2. Model design

4.2.1. Method

Existing EDMs take different methodological approaches, which determine determines how detailed a model can be while calculating demand. Most (80%) of the models rely on three main methodological approaches: top-down, bottom-up, and a combination of top-down and bottom-up approaches which is perceived as a hybrid approach. Top-down approach assesses the economy-wide potential of climate change policies or measures by using a globally consistent framework and by capturing macro-economic feedbacks. The bottom-up approach on the other hand, incorporates extensive data on technologies and costs, allowing for detailed descriptions of energy consumption [62]. Both approaches put different weights on aspects when it comes to market and technology description, representation of macroeconomic measures and aggregation of energy sectors. The methodology used depends on the modelling objectives, therefore, the top-down and bottom-up models can be even further categorised into econometric, statistical, technological, and engineering models [100].

Models employing a simulation method parameterise the components of the energy system with equations and fine-tuned variables. By

Table 1
List of the existing energy demand models analysed in the context of this study.

Building sector

	Model name (reference)	Modelling method/ approach	Timespan	Geographical coverage	Scenario description
1	The Built Environment Analysis Model (BEAM2) [54]	Simulation (bottom-up)	2012–2050	Global	3 scenarios (Track 1, 2, 3): retrofit rate, CO_2 emission, final energy use and reduction, total costs
2	The Behavioral change in energy consumption of Household (BENCH) model [55]	Agent-based simulation (bottom-up)	User-defined (until 2020/2030)	Regional (EU nations)	6 experiments: household attributes, psychological factors, learning and social network
3	The Bottom-Up ENergy Analysis System (BUENAS) model [56]	Simulation (bottom-up)	2005–2030	Global	2 scenarios (Business-As-Usual, Best practice): energy efficiency of equipment
4	Dynamic high-Resolution dEmand-sidE Management (DREEM) model [57]	Simulation (bottom-up)	User-defined (until 2030 or 2050)	Regional	2 scenarios (Business-As-Usual, Flexibility through provision of services to the grid): availability of solar PV, electricity storage installations, smart thermostat and advanced control device
5	Energy Demand Generator (EDGE) model [58]	Simulation (bottom-up)	2010–2100	Global	5 scenarios (Shared Socio-Economic Pathways): population, income per capita, cooling and heating degree days
6	Future Technology Transformations' (FTT): Heat model [59,60]	Simulation (bottom-up)	Until 2050	Global	3 scenarios: carbon tax, capital subsidy on renewable heating technologies, kick start procurement policies for renewables-based heating technologies
7	High efficiency Building (HEB) model [61,62]	Simulation (bottom-up)	2022–2060	Global	4 scenarios (Frozen, Moderate, Deep, Net-zero): accelerated retrofit rate, energy efficiency measures and shares of different building vintages, onsite solar energy production
8	Invert/Accounting [63–65]	Simulation (bottom-up)	2010–2055 (2080)	Regional (EU nations)	Unknown
9	INVERT/EE-Lab [66]	Simulation (bottom-up)	2010–2055 (2080)	Regional (EU nations)	3 scenarios (Current Policy, Gradual Quota MS, 2030 Quota EU): share of renewable energy sources in heat/cooling fuel mix, certificate trade, subsidies,
10	Invert/Opt [63–65]	Optimisation (bottom-up)	2010–2055 (2080)	Regional (EU nation)	Unknown
11	TIMER-Residential Energy Model: Global (TIMER-REMG) [67]	Simulation (bottom-up)	1971–2100	Global	3 scenarios (High demand – low efficiency, Low demand – high efficiency, Medium demand and efficiency): efficiencies for heating, cooling, cooking and appliances
12	TIMER-Services [68]	Simulation (bottom-up)	1971–2100	Global	5 scenarios (Shared Socio-Economic Pathways): service sector energy use, CO_2 emissions to global population, cooling and heating degree days, fuel prices and sector's activity driver

Transport sector

	Model name (reference)	Modelling method/ approach	Timespan	Geographical coverage	Scenario description
1	Assessment of Transport Strategies- (ASTRA) model [69,70]	Simulation (bottom-up)	Until 2050	Regional (EU nations)	4 scenarios: timing of the uptake of vehicles with connected and automated driving, model of personal mobility, spatial distribution, cost
2	Battery electric vehicles potential (BEVPO) model [71]	Simulation (bottom-up)	User-defined (various)	Regional (EU nations)	6 scenarios (pp1-pp5a): location, availability and nominal power of charging stations
3	Multi-Agent transport Simulation (MATSim) [72]	Agent-based simulation (bottom-up)	Until 2030	Global	User-defined scenarios
4	PRIMES-TREMOVE [73]	Simulation (bottom-up)	2000–2050	Regional (EU nations)	3 scenarios (Business-As-Usual, TEC_Nopol, TEC_CO2pol): technoeconomic development of batteries and fuel cells, CO_2 emission regulations on cars
5	Transport Integrated model of Europe (TRIMODE) [74]	Simulation (bottom-up)	2015–2050	Regional (EU nations)	Unknown number of scenarios for the following policy scopes: network flows, taxation, infrastructure charges, fuel mix, GHG emission, energy efficiency, electric charging network
6	Transport European Simulation Tool- (TRUST) [75]	Simulation (bottom-up)	2016–2050	Regional (EU nations)	Unknown number of scenarios for the following policy scopes: road charging, energy taxation, infrastructure changes, speed limits, technology, driver and port regulations
7	UK Transport Carbon Model (UKCM) [76]	Simulation (bottom-up)	Until 2050	National (UK)	5 scenarios (Reference, Fuel Duty, Speed Limit, Electric Vehicles, Integrated Package): cost of fuels, speed regulations, availability of electric vehicles
8	World Induced Technical Change Hybrid- Transport (WITCH-T) model [77]	Simulation (hybrid)	Until 2100	Global	5 scenarios (Shared Socio-Economic Pathways): vehicle number, travel intensity, fuel efficiency improvement rate, battery learning progress factor

Industry sector

	Model name (reference)	Modelling method/ approach	Timespan	Geographical coverage	Scenario description
1	FORECAST [66]	Simulation (bottom-up)	Until 2050	Regional (EU nations)	Two scenarios (Reference, Transition): energy taxes, emission trading schemes, technology subsidizes, energy performance standards

System models					
	Model name (reference)	Modelling method/ approach	Timespan	Geographical coverage	Scenario description
1	Calliope/Euro-Calliope [78]	Optimisation (top-down)	User-defined (typically until 2050)	Regional (EU nations)	User-defined scenarios
2	Demand for Energy Services, Supply and TransmIssioN in EuropE (DESSTINEE) [20,79]	Simulation (top-down)	Until 2050	Regional (EU nations)	It includes a scenario generator by considering: population, economic growth, improvements of the building envelope, heat pumps, and electrification of the transport fleet
3	Energy Market Liberalisation in Europe (EMELIE-ESY) model [80]	Partial equilibrium	2010–2050	Regional	Different scenarios (usually 10) are used based on assumptions for technology availability/efficiency (e.g., CCS) and policies (e.g., nuclear energy, renewables, emission reduction)
4	EnerPol [81]	Optimisation	2010–2050	Regional (Europe, North America, Asia and Africa)	4 scenarios by implementing: different share of hydropower, transmission capacity, number of gas and nuclear plants and energy efficiency
5	Enertile [82–84]	Optimisation (hybrid)	Until 2050	Regional (EU + ME + NA)	8 scenarios by considering: flexibility options for electricity in district heating, heat pumps in buildings, electric vehicles
6	Energy Transition Model (ETM) [85]	Simulation	Until 2050	User-defined (Cities-regional)	Beyond some default country-specific scenarios, it allows user-scenarios based on (optionally): energy use and imports, CO_2 emission, costs, share of renewables, technological mix
7	Global Change Assessment Model (GCAM) [86]	Optimisation (top-down)	Until 2100	Global	User-defined scenarios by considering: carbon prices, amount of emission, energy production standards, land-use standards and constraints
8	The General Equilibrium Model for Economy-Energy-Environment (GEM-E3) [87]	General equilibrium	Until 2100	Global	Enables for activating “switch” parameters for scenario definitions, including environmental “switches” and budget balancing instruments.
9	Low Emissions Analysis Platform (LEAP) model [88]	Simulation (hybrid)	User-defined (usually 20–50 years)	Global	User-defined scenarios by considering: emission, energy prices and efficiency
10	Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) [89–91]	Optimisation (hybrid)	User-defined (usually 50–100 years)	Global	User-defined scenarios by considering: bounds and taxes on emission, and bounds on deployment of new technologies
11	POLES (Prospective Outlook on Long-term Energy Systems) [92]	Partial equilibrium (top-down)	Until 2050	Global	Unknown number of scenarios; they translate the following policy dimensions: population, economic growth, discount rates on energy investments, accessibility of energy resources, pricing of GHG emissions. Renovation rates, subsidy on energy fuel
12	Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIa) [93]	Partial equilibrium (hybrid)	Until 2050	Regional (EU nations)	Unknown number of scenarios intents to assess the following policy dimensions: technological standards, technology prices, finance, energy efficiency, behavioural changes, feed-in tariffs, investment incentives for renewables, CO_2 emission trading
13	Price-Induced Market Equilibrium System (PRIMES) [94]	Partial equilibrium (hybrid)	Until 2050	Regional (EU nations)	6 scenarios (Reference, EUCO17-40): emission trading schemes, use of biofuels, support of renewables in heating, energy efficiency level of buildings, support of heat pumps, technologies in the industry, emission and energy efficiency standards for cars and trucks
14	REgional Model of Investment and Development (REMIND) [77,95]	Optimisation (hybrid)	Until 2100	Global	5 scenarios (Baseline, 2 °C with carbon price only, 2 °C with additional sustainability policies, 1.5 °C with carbon price only, 1.5 °C with additional sustainability policies): initial carbon price, carbon price, nuclear phase-out, energy use
15	Regenerative Energy Model (REMod) [96]	Optimisation	Until 2050	Regional (EU nations)	4 scenarios (Reference, Persistence, Non-acceptance, Sufficiency) based on: use of new technologies in the private sector, resistance to the expansion of large infrastructures and societal behaviours
16	The Targets IMage Energy Regional Model (TIMER) [97]	Simulation	Until 2050	Global	Different scenario files are used (suitable for incorporating SSP scenarios) based on the following drivers: population, GDP, environmental and other policies, technological changes and lifestyle parameters
17	The Integrated MARKAL-EFOM System (TIMES) [98]	Optimisation	User-defined (usually multiple years)	Local–Regional	4 scenarios (Carbon tax, Cap-and-trade-on CO_2, Portfolio standard, Subsidies for some classes of technologies): population, GDP, number of households, supply curves, trade, subsidizes, taxation
18	World Energy Model (WEM) [99]	Simulation (hybrid)	Until 2050	Global	4 scenarios (Net zero emission by 2050, Announced Policies, Stated Policies, Sustainable Development): technology cost and learning, energy prices and affordability, investments

doing so, simulation models can assess the potential impacts associated with the incorporation of energy efficiency technologies and policies within a particular or several end-uses. As a special subcategory, there are agent-based simulation models designed for taking the various behaviours and decisions of entities within the energy system into account. The other main technique of optimisation is applied when models are used to forecast the technology and fuel basket that minimise cost to fulfil certain reduction targets [101]. Optimisation models include mathematical representations of one or more factors needed to be optimised in the form of objective equations and solves the given problem by linear programming, mixed integer linear programming, non-linear programming and dynamic programming techniques [102]. Some tools consider a macro-economic approach, modelling energy demand as a part of the whole economy and further analysing the impact of the energy transition. In that case, these models use an equilibrium approach [100]. Based on completeness of the representation of the economy, equilibrium can be divided into general and partial equilibrium model.

Findings from Table 1 reveal that 90% of the sectoral models use a bottom-up approach, whereas 55% of the system models use top-down or hybrid approach. The reviewed bottom-up building sector models usually rely on the detailed knowledge of various parameters for individual buildings, including thermal properties (e.g., u-values, heat gain, thermal inertia), construction materials, technological parameters of appliances, boilers or heat pumps and behaviour of occupants. The transport models incorporate travelling time and costs, fleet technologies, infrastructure, emission factors and distribution of electricity charging stations (see Table S2 in Supplementary material). However well, these sectoral models address the most essential user needs (e.g., integrated renewable production: “HEB”, consumer's behaviour: “DREEM”, heat pumps: “EDGE”, electrification: “BEVPO”), there is no such model that could cover all aspects, mainly because of the complexity of the whole world, the combination of extreme breadth and depth.

Due to the more generalised approach in top-down models, they have coarser spatial and temporal representation (e.g., annual and regional/global) and end-use level (e.g., total heating energy) (see Table 1). The reviewed whole system models apply a substantial collection of input data for socioeconomic factors (e.g., population, gross domestic product (GDP), mobility, number of households,), energy balances (e.g., demand, supply, generation,), energy resources (diversified by components) and emissions. In most cases these models also use historical data for initialising the projections and framing the results. A common approach among system models is for dynamic interactions within the energy system to be modelled via agents (e.g., “POLES”, “POTenCIA”, “PRIMES”,). Agents in these modelling tools usually represent industries, services, households, or other entities/actors of the energy system, and intend to minimise (maximise) their costs (profits) for energy consumption, based on individual choices driven by habits, risk, availability and reliability of technologies. Furthermore, some of these models (22% of the system models) tend to use partial equilibrium (e.g., “PRIMES”, “WEM”,), or optimisation (33% of the system models) (e.g., “Enertile”, “GCAM”, etc.) method, with limited granularity (sectoral and temporal) and complexity in their design. The developers of such models must find the balance between the complexity of sectoral representation and computational costs, to exploit the benefits of interlinking system and sectoral EDMs.

Overall, bottom-up is the most common approach among sectoral EDMs, which may be related to the fact that incorporating detailed technological and socio-economic inputs allows for effective representation and estimation of long-term intra-sectoral changes. On the other hand, due to the spatial inhomogeneity and limited accessibility of such highly granular data for the entire energy sector, model developers must make compromises and follow top-down or hybrid approaches in compiling their tools. As a result, several system EDMs generalise and simplify their assumptions on the dynamic of technological progress and preferences of different actors.

4.2.2. Spatial and temporal resolution

By analysing the findings from Tables 1 and S2, we found that more than one-third of the reviewed models have global coverage, mostly designed for calculating the energy demand in the building and transportation sectors. Many of the sectoral models, precisely, 45% of the sectoral models also have global coverage, whereas half of the system models, due to their greater complexity and data requirements, are typically used for regional and country-level analysis. In general, the modelling period of global models is longer than for regional models, typically covering four or five decades. On the higher end, we can find the “TIMER-REMG” and “EDGE” models that can produce outputs for the period from 2071 to 2100. Since the certainty of projections becomes lower, further into the future, most models are less ambitious in terms of temporal span and give a closure to their predictions at 2050 (e.g., “BEAM2”, “HEB”, “TRIMODE”, “DESSTINEE”). This is especially valid for full system models since all reviewed examples limit their temporal coverage until the middle of this century. Nevertheless, the temporal resolution (size of time steps) for system models can be very different. The “Calliope” and “DESSTINEE” models, for example, provide hourly resolution, which lets the user examine the demand profiles in particularly high detail. Other models offer outputs with yearly (e.g., “POTenCIA”) or multiannual (e.g., “POLES”) resolution. Most subsector models (especially global models) also run simulations with yearly resolution.

As it is identified by many stakeholders, having simulations with fine spatio-temporal resolution is very important for many research questions [20]. However, only 17% of EDMs, majority of them are system models, have the capability to provide modelling outputs at hourly time steps, giving insight into the intra-annual characteristics of energy consumption and CO_2 emissions. Additionally, this could lead to a consistent calibration and development of modelling tools by using, for example, hourly electricity consumption or meteorological proxy data. In their spatial granularity, most models rely on statistical data available on regional or country-level. However, it is highly desired to disaggregate this data further with different techniques. Coarsely aggregated data for the most important inputs could risk masking the most essential aspects in terms of climate variables, fuel availability and elements in the economic matrix, giving undesired uncertainties associated with the modelled energy demand and supply. Detailed geographic information system (GIS) data offer a promising option to obtain higher granularity data for several modelling inputs (e.g., climate-dependent or building footprint data) [103]. However, it must be noted that the wider application of GIS data in EDMs could be inhibited by the accessibility and the high pre-processing time of such data sets.

4.3. Modelling outreach

Most of the EDMs (81% of the sectoral models, and 56% of the system models) are closed-source, or their transparency status is not disclosed/found, making it difficult to explicitly compare results. In most of the cases, model assumptions, mathematical equations, level of aggregation, and sectoral coverage are also not open, which makes these models a “black box” [104]. Model transparency provides a mutual opportunity for both modellers and users to exchange knowledge through a transparent modelling framework (i.e., feedbacks via a public platform) that fosters user accessibility and replicability of the models [13,105]. The closed-source (or commonly called “proprietary”) publicity status of energy models could stem from many factors, such as the presence of restricted or commercial data in the input assumptions or the need to provide permanent quality control and additional support for users (e.g., developing graphical user interfaces). However, providing partially or fully open licences for models is still recommended over closed models for many reasons. For instance, on the developer side, it may be the valuable feedback given from experienced users or stakeholders, which can generate a positive loop by contributing to improving the source code, or the input dataset of the earlier model releases. On the other hand, on the user side, open-source models ensure greater flexibility and customisation of each modelling component and foster greater trust in the model's methods.

Finally, despite the best efforts of a model's developers, any model has limitations in its ability to fully reproduce all the components for which it was designed. Shortcomings may stem from an incomplete knowledge of the energy sector itself and its interaction with other sectors and systems (e.g., economy, climate,). Given that these interactions are highly non-linear, there is a limited chance to mathematically formulate them without making significant simplifications. The complete description of the energy sector requires an unmanageable amount of data, much of which is simply not recorded, and so simplifications are required in any model. When it comes to the complexity of each model, this is highly influenced by the research questions the model has been developed to answer. Among the reviewed models, the sector models are, by their nature and narrow scope, the most comprehensively detailed. Nonetheless, unlike the full system models, they are only capable of providing estimations on a narrow spectrum of the processes of the different sectors. Conversely, due to many simplified assumptions and uncertainties of the future interactions between different sectors, full system models can primarily inform us on the expected trends, but with less reliability and granularity.

5. Discussion and conclusions

Our findings show that classical questions in the field of energy demand modelling, such as “how will overall demand develop,” “how will demand profiles change,” or “how will energy efficiency policies contribute to meeting climate targets” remain important for model users. In this context, some of the general needs such as modelling energy demand for the “time periods of 2030 and 2050,” or modelling the “role of energy efficiency” are already considered in most of the existing EDMs. Similarly, some of the sectoral user needs such as “standardisation or labelling of buildings” or “vehicle efficiency” are incorporated in 86% and 67% of the building and transport sector demand models respectively. However, some user needs such as “sector coupling”, and “the role of renewable energy sources”, are generally only considered by system models with an endogenous demand module and usually not by sectoral demand models. However, these system modules often use a top-down or hybrid approach with simplified assumptions to model energy demand, and hence, they often provide estimations on broad scope across all sectors but with limited detail. Besides, due to uncertainties of the future interactions between different sectors, system models can primarily inform decision-makers on the expected trends, with less reliability on the precise magnitude or detailed granularity.

Table 2 synthesises our results in terms of the user needs identified and the capabilities of existing EDMs, while it presents key gaps in the field of energy demand modelling, in other words, the user needs which are not addressed by existing EDMs.

Several key sectoral user needs, such as “lock in effects” in the building sector (only 1 or 7% of the building demand models incorporates this need), “carbon neutral fuels and storage” in the transport sector, “assessing technology options”, and “Role of CCUS and negative emissions” in the industry sector, remain under-researched, and, hence, are often not incorporated by most of the EDMs. These user needs are, in most of the cases, not considered due to unawareness of the impact of the aspects on final demand, data unavailability, and methodological challenges. These knowledge gaps and challenges do not make these user needs any less significant, though. For instance, future EDMs need to explicitly acknowledge system dynamics, including the lock-ins that arise especially from infrastructure dependence (e.g., investment in long-lasting built infrastructure such as buildings, land-use patterns) and long-lived assets (e.g., buildings), but also systemic lock-ins (e.g.,

Table 2
Summary of key gaps. Index: Yes = Majority of the models incorporate the specific user need as a model input. No = Majority of the models do not incorporate the specific user need in their model input framework.

Categories	User needs	Existing model capabilities (User need addressed)		Gaps for further development
		Sectoral model	System model	
Model content	Changes in demand profiles	Yes	Yes	Although most of the EDMs provide data on demand profiles, very few of them provide data on an hourly resolution. Models should provide data both on annual and hourly resolutions.
	Role of energy efficiency	Yes	Yes	Most of the EDMs do incorporate energy efficiency in their scenarios. However, energy efficiency technologies are constantly being developed and hence, scenarios should reflect the new technologies and measures accordingly.
	Role of renewable energy sources	No	Yes	Most of sectoral EDMs do not include renewable energy sources as they are only focused on the demand side. However, the system models do incorporate the renewable energy sources as they are designed to calculate the energy balance. However, the sectoral models do not consider the possibility of off-grid renewable sources which can reduce the net demand. Only two of the sectoral models (,“DREEM”, and “HEB”) consider the impact of renewable energy production and net demand in the building sector.
	Alternative fuels	No	Yes	Most system models incorporate the use of green and e-gases while calculating the energy balances. Sectoral models do not widely consider these gases as their modelling approach solely focuses on calculating energy demand.
	Role of lifestyles and energy sufficiency	No	No	Users require a well-designed indicator to calculate the whole impact of lifestyle changes to energy

(continued on next page)

Table 2 (*continued*)

Categories	User needs	Existing model capabilities (User need addressed)		Gaps for further development
		Sectoral model	System model	
				demand. There are a few sectoral models that incorporates some component of lifestyle changes, but no model so far incorporates lifestyle changes coherently.
	Sector coupling & digitalisation	No	Yes	Sectoral models by design are not capable of incorporating sector coupling. However, the sectoral models can incorporate digitalisation, but only for a particular sector (mainly buildings). However, most of the system models do incorporate sector coupling to calculate energy balance.
	Building sector			
	Standardisation/ labelling of buildings	Yes	No	Most sectoral models use standardisation/ labelling of buildings to calculate energy demand. Rates of standardisation are varied across scenarios. System models do not widely consider these aspects, as they use a top-down approach.
	Integrated renewable production	No	No	System models often consider the integrated renewable production as a part of energy supply; however, system models do not consider off-grid onsite production, which has a substantial impact on net energy demand. Most of the demand models do not consider integrated renewable production as they consider final energy demand and not the net demand.
	Consumers'/ prosumers' behaviour	No	No	Similar to lifestyle analysis, the consumer/prosumer behaviour also requires a well-designed indicator to calculate the whole impact of behavioural changes on energy demand. There are a few sectoral models (such as “DREEM”, “BENCH”) that incorporates some component of behaviour changes, but no model so far incorporates behavioural changes coherently.
	Heat pumps/ district heating & cooling	Yes	No	Most sectoral models use heat pumps/ district heating and cooling of buildings to calculate energy demand. Rates of these technologies' deployment are varied across scenarios.
	Impacts on comfort and well-being	No	No	Majority of the sectoral or system models do not consider the impacts of thermal comfort and well-being during energy demand calculations. However, users have identified the need to calculate and incorporate comfort and well-being as due to climate change, energy demand would substantially impact these aspects. Also, comfort has a significant relation with demand and vice versa.
	Economic and technical feasibility	No	No	None of the sectoral or system models reviewed investigates both the economic and technical feasibility of this nexus in an integrated manner. However, as identified by various stakeholders that feasibility will be a key issue in realistically modelling energy transition.
	Carbon lock-in effects	No	No	Most sectoral and system models do not calculate or even consider the potential of carbon lock-in due to energy inefficiency policies-related to the building sector. Modelling carbon lock-in can reveal the true potential of the cost of not going for an ambitious energy efficiency policy.
	Transport sector			

(*continued on next page*)

Table 2 (*continued*)

Categories	User needs	Existing model capabilities (User need addressed)		Gaps for further development
		Sectoral model	System model	
	Electrification	Yes	Yes	Most sectoral and system models tend to present highly aggregated results, accounting for power consumed among macro categories such as road transport, rail, aviation, etc. There is a gap, which a few tools try to fill, in terms of the electrification share of the different vehicle types (e.g., cars, buses, trucks, etc.).
	Vehicle efficiency	Yes	Yes	Models report results or conduct estimations considering aggregated values for efficiency increase. Few tools distinguish among vehicle types. Assumptions for post 2030 fuel economy standards are in general not very transparent.
	Carbon neutral fuels and storage	No	No	Figures for 'low carbon fuels' tend to be aggregated, including usages of different vectors, such as: H2, P2G (power to gas), P2L (power to liquids) and biofuels. Although both sectoral and system models do model efficiency of the vehicles, majority of these models does not include the use of carbon neutral fuels and its impact on the potential energy demand.
	Vehicle charging profiles and infrastructure	Yes	Yes	System models analyse the impact of road transport electrification on total final power consumption. Some of them study the influence on some assumptions for charging patterns on peak demand and hourly electricity prices. Some sectorial models enable to evaluate how different charging regimes could alter hourly power demand, distinguishing among different charging blends while allowing the assessment of different strategies for charging infrastructure.
	Industry sector			
	Assess technology options (heat pumps, hydrogen, …)	No	No	Some sectoral models present results for fuel usages across subcategories, however they do not distinguish between different enthalpy qualities for the heat produced. Most system models report results for the whole industrial sector, not disaggregating fuel consumption according to end uses.
	Role of CCUS and negative emissions	No	No	Sectoral models report captured CO2 for secondary activities or else figures for different industry types. On the other hand, only 11% of the system models tend to account for total captured or removed CO2, while a few models specify in what type of sources.
	Use of hydrogen (H2)	Yes	Yes	Sectoral models account for H2 usage in general, aiming for a disaggregation among key categories (at least for heavy industries). On the other hand, some system models present data for H2 consumption for the whole industrial sector. They may use different conventions, being sometimes not clear whether H2 is produced onsite.
	Fuel switching for heating	No	No	Some sectoral models present results for fuel usages across subcategories, however, they do not distinguish among different enthalpy qualities for the heat produced. On the other hand, most system models report results for the whole industrial sector, not disaggregating fuel

(*continued on next page*)

Table 2 (*continued*)

Categories	User needs	Existing model capabilities (User need addressed)		Gaps for further development
		Sectoral model	System model	
				consumption according to end uses.
	Heat recovery & Industrial co-generation	No	No	Sectoral models mostly consider self-generation as a way to reduce final energy consumption, reporting a decrease in the power consumption, or in other energy carriers. On the other hand, some system models present data for 'autoproducers', not distinguishing according to the type of facilities generating power and heat.
	Net-zero steel & cement production	No	Yes	Simulation based on bottom-up sectoral models allow to evaluate the impact of technology deployment, such electric arc production methods, or fuel swapping, on emissions from steel and cement production. Some system models report results for steel and cement industries in terms of usages for low-carbon energy carriers.
Model design	Optimisation and simulation (user dependent)	Yes	Yes	The developers of such models must find the balance between the complexity of sectoral representation and computational costs, to exploit the benefits of interlinking system and sectoral EDMs.
	Bottom-up and top-down approaches	Yes	Yes	Stand-alone sectoral models are much more detailed as they mostly use bottom-up approaches with certain macro parameters (e.g., GDP, population, etc.). Whereas system models often uses a top-down approach due to which it is difficult for the system models to gather detailed information about each of the sectors.
	High geographical resolution	Yes	Yes	Most of the EDMs has a detail spatial coverage including national, and regional data. However, the models should also include city-level demand data as city contributes majority of the emissions. Due to huge data requirements to model energy demand, it is often the case that for a single model it is impossible to calculate the complete sector-specific demand, given time- and resource-relevant constraints
	Modelled time horizon: Hourly. & 2030–2050	No	Yes	Due to methodological and data challenges, only a handful of sectoral demand models produce data with a detailed spatial disaggregation and hourly resolution. High temporal resolution is needed to understand whether renewable energy can generate the entire demand without any disruption at service and comfort levels. The temporal resolution needs to be at hourly scale as we also need to understand whether renewable energy can generate the entire demand without any disruption at service and comfort levels. However, both sectoral and system models calculate demand for both 2030 and 2050 time period.
Modelling outreach	Assumptions, documentation and data	No	No	Most of the EDMs are not open and hence, it is difficult for a user to use the existing scenarios and data. Especially, for the climate transition, it is important to understand different scenarios.
	Open tools, documentation	No	No	Although, a couple of system models are open, the
	Data availability	No	No	

(*continued on next page*)

Table 2 (*continued*)

Categories	User needs	Existing model capabilities (User need addressed)		Gaps for further development
		Sectoral model	System model	
				documentation and the user-friendliness of these models are often not transparent and hence, reproducibility of data by using these models often gets difficult.

renter-landlord problems in renovations). Models ignoring lock-ins and systemic inertia may find unrealistically optimistic solutions, detached from the realities experienced by the actor that needs to implement the changes. Similarly, the role of CCUS technologies as an emission abatement option in the industrial sector could not only influence sectoral GHG emissions but also facilitate the overall system's decarbonisation, when the technology is applied in biomass feedstock plants allowing negative emissions. Models are then required to account for these incorporations in the demand matrix aiming to provide a more representative and accurate insight of the future energy system in the context of different climate change mitigation scenarios. Our findings show that model users acknowledge these issues, but also that much work is still needed to truly integrate such solutions in EDMs.

Most of the existing models were constructed in the last decade, sometimes with roots going further back. In the last few years, the climate-political reality has changed; whereas 10 years ago the aim was to reduce energy system emissions, the aim today is to eliminate them. The latter challenge requires very fundamental changes in the energy system, far beyond the incremental patches that could suffice if the emissions were only to be reduced; for example, a power system with no gas power at all has very different challenges than one with some gas power. Not all models can solve the zero-emission problem and demand models have a key role to play to identify ways where radical demand reduction is necessary or possible, but also the ways in which is it not possible or necessary. To become more relevant to decision-makers, EDMs need to better reflect political realities by including recent-past trends, but also current and upcoming policies; if not, then policy advice generated will be either misguided or knock down already open doors. More importantly, models often (cost-)optimise to find the economically efficient demand profile, but in reality, standards and regulations will very likely remain and continue to be tightened, regardless of the “optimality” of this.

System models tend to use an optimisation approach to identify the least-cost fuel basket and technology deployment that is compatible with decarbonisation targets. This limits their geographical, temporal, and sectorial coverage, making it difficult to evaluate the impact of measures that can contribute to decreasing emissions from energy end uses. It becomes necessary to employ sectorial, and possibly simulation-based tools, which enable the assessment of emissions reduction potential of certain regulations and technologies. This has been highlighted by the different stakeholder engagement activities and by our literature review, which shows the need of models focusing on different sectors to answer key questions in terms of decarbonisation pathways.

Finally, the energy demand side is changing at least as radically as the supply side, but challenges are higher because there are several different ways in which demand may be reduced, and because the effects of demand-side measures on consumers, including citizens, are more direct than supply-side measures. Therefore, it is particularly important that models are designed to investigate the trade-offs between strategic choices. For example, many models investigate the need for demand-response or how it can be optimally used to balance fluctuating supply. Rarely are the trade-offs investigated, and especially not the non-economic ones, such as the social ones. There are strong trade-offs in demand-response, but they are rarely purely economic, and ignoring them may lead to model-based policy recommendations that turn out to be socially unfeasible. In addition, many stakeholders demanded for a better representation of behavioural changes and lifestyle in energy demand. However, national Energy and Climate Plans [106] and Long-Term Strategies [107] often focus on energy efficiency and renewable energy policies and only include some energy sufficiency policies, especially in the transport sector, e.g., modal shift policies, etc. [108]. Similarly, most EDMs rarely include financial incentives and fiscal instruments for sufficiency. This calls for further research to advance the understanding of the role of energy sufficiency, develop quantifications, and assess the impact of energy sufficiency policies in reducing energy demand.

As further research, we intend to show how different sectoral demand models can be upgraded and soft-linked to address all the identified demand-side user needs discussed in this study. The objective of the soft-linking approach is to calculate the total annual final energy consumption and corresponding GHG emissions until 2050, for each sector and type of end-use, in addition to producing hourly power demand profiles. The list of the identified user needs and discussion of required advancements of existing EDMs presented in this study can contribute to improve the energy demand modelling framework to better inform policymakers, researchers, and the public on the impacts of different decarbonisation measures, within several final end-uses, and their full system implications in view of a net-zero horizon. We provide the first comprehensive empirical study of user needs and identify gaps related to energy demand modelling. Our study provides a list of general and sectoral user needs, based on which the existing EDMs should be updated, or new ones can be developed to address remaining modelling gaps. Incorporation of these gaps and user needs will enhance the usefulness and policy impact of energy demand modelling. However, like any stakeholder input-based review study, our study also has some limitations. First, our review and call for evidence allowed us to arrive at a comprehensive overview of energy demand modelling tools. However, other tools might exist that we did not find or that were still under development and not publicised at the time of writing. In addition, we present a robust list of user needs based on our multi-method approach. We acknowledge, however, that the identified needs might be not the same across different European countries or outside of Europe. We held the workshops and meetings online, and the results we derived at might be different and/or less profound than results in physical meetings [30].

Nevertheless, this study adds new perspectives on various user needs in demand modelling and identifies key gaps with the existing demand models. We call for further research to explore user needs for demand modelling in specific country contexts and to advance EDMs according to the identified user needs.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2022.102662.

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