Trends in tools and approaches for modelling the energy transition

Chang, Miguel; Thellufsen, Jakob Zink; Zakeri, Behnam; Pickering, Bryn; Pfenninger, Stefan; Lund, Henrik; Østergaard, Poul Alberg

Published in:
Applied Energy

DOI (link to publication from Publisher):
10.1016/j.apenergy.2021.116731

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Applied Energy 290 (2021) 116731

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Trends in tools and approaches for modelling the energy transition

Miguel Chang [a,*], Jakob Zink Thellufsen [a], Behnam Zakeri [b,c], Bryn Pickering [d], Stefan Pfenninger [d], Henrik Lund [a], Poul Alberg Østergaard [a]

[a] Department of Planning, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark
[b] Energy Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria
[c] Department of Planning, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen, Denmark
[d] Department of Environmental Systems Science, ETH Zürich, Universitätstrasse 16, 8092 Zürich, Switzerland

HIGHLIGHTS

- Survey of current trends and challenges in energy system modelling tools (N = 54).
- Tool features, linkages, user accessibility and policy application were reviewed.
- Growing coverage of cross-sectoral synergies, open access, and improved temporal detail.
- Challenges in representing high resolution energy demand in all sectors.
- Key issues remain in understanding tool coupling, accessibility & perceived policy-relevance.

ARTICLE INFO

Keywords:
Energy system modelling tool
Energy models
Energy system analysis
Survey
Review

ABSTRACT

Energy system models are crucial to plan energy transition pathways and understand their impacts. A vast range of energy system modelling tools is available, providing modelling practitioners, planners, and decision-makers with multiple alternatives to represent the energy system according to different technical and methodological considerations. To better understand this landscape, here we identify current trends in the field of energy system modelling. First, we survey previous review studies, identifying their distinct focus areas and review methodologies. Second, we gather information about 54 energy system modelling tools directly from model developers and users. Unlike previous questionnaire-based studies solely focusing on technical descriptions, we include application aspects of the modelling tools, such as perceived policy-relevance, user accessibility, and model linkages. We find that, to assess the possible applications and to build a common understanding of the capabilities of these modelling tools, it is necessary to engage in dialogue with developers and users. We identify three main trends of increasing modelling of cross-sectoral synergies, growing focus on open access, and improved temporal detail to deal with planning future scenarios with high levels of variable renewable energy sources. However, key challenges remain in terms of representing high resolution energy demand in all sectors, understanding how tools are coupled together, openness and accessibility, and the level of engagement between tool developers and policy/decision-makers.

1. Introduction

The transition towards a decarbonized and sustainable energy system is expected to play a crucial role in halting the effects of global warming while furthering human wellbeing, security, and sustainable development [1]. Energy system models - mathematical representations of energy systems - are often needed to quantify the impacts of this transition, and plan potential pathways [2,3] due to increasing complexity. Numerous energy system modelling tools[1] are available, providing energy modelling practitioners and planners with a wide range of alternatives to represent energy systems according to different technical and methodological considerations, which can help inform policy- and decision-makers in their planning processes and policy recommendations [4,5]. These tools are in continuous development in

* Corresponding author.
E-mail address: miguel@plan.aau.dk (M. Chang).

[1] We refer to modelling tools as computational software, or modelling frameworks, that generate energy system models.

https://doi.org/10.1016/j.apenergy.2021.116731
Received 16 November 2020; Received in revised form 12 February 2021; Accepted 20 February 2021
Available online 11 March 2021

response to the emerging challenges in the energy transition and new technological breakthroughs [3,5]. For this reason, multiple efforts have been made in the energy modelling community to review the ever-changing pool of tools available to energy modellers, to classify their features, outline their applications, and point at the issues that these aim to tackle [4,6–8].

In this paper, we survey how these reviews have been conducted and what issues they address. Moreover, we show current trends found in energy system modelling tools by gathering some of their key features and applications, including their apparent role in decision-making support. To do this effectively, we have gathered inputs from tool developers to better assess some of the key considerations and to gather information that is not necessarily readily available from written academic sources or tool documentation.

The work presented here is divided into four parts. Section 2 gives an overview of different reviews and surveys of energy system models and tools, outlining how these reviews were conducted, their respective focus areas, and existing gaps in the literature. The purpose of this review is to not only identify emerging trends, but to also identify how some of the lessons learned in past reviews are captured. In Section 3, we detail the analytical approach followed in our survey of energy system modelling tools. In Section 4 we present the results from this survey and identify the key features and trends in tool developments. In Section 5, we put into perspective some of the emerging challenges and discuss potential ways forward.

2. Literature review

This section presents an overview of different reviews and surveys of energy system models and tools found in the literature. These are then categorized according to their respective focus areas and their review approach, to show existing gaps in the literature.

2.1. Background

Energy system modelling tools are used for assisting energy policy making and assessing different energy pathways [9]. The range of available energy modelling tools is significant and continuously expanding. Several studies have investigated the developments of the above with a focus on different aspects of these models and reported different challenges faced in the field of energy systems analysis. For instance, Connolly et al. [4] present an overview of computational modelling tools capable of analyzing the integration of renewable energy sources (RES) in energy systems at large, looking into survey responses from 37 model developers.

In Foley et al. [10], a literature review of system models with a focus only on the electricity sector is presented. Similarly, Després et al. [11] conduct a review of modelling tools focusing on the integration of variable renewable energy (VRE) mainly in the power sector. Mahmud and Town [12] reviewed modelling tools with a focus on the integration of electric vehicles in the energy system. More recently, in a study by Ringkjøb et al. [6], a thorough review of 75 energy and electricity system modelling tools is presented, assessing modelling scopes, characteristics and limitations, and validating most inputs with tool developers.

In addition to these broader overviews of energy system modelling tools, a relevant body of work exists about the underlying implications that models have on a broader energy planning level. In this regard, a key aspect to consider is the classification of the energy system model, and the choice of specific types of modelling frameworks according to the purpose of a given planning exercise.

Different classifications of energy system modelling tools have been discussed by a number of studies, which reflect upon the characteristics and challenges of bottom-up applications [8], the suitability of tools for decision support in local planning [13], as well as their applicability worldwide [14], their general effectiveness for energy planning purposes [15], their level of technical complexity [16], and the classification of modelling approaches with direct feedback from modelling tool developers [17].

Another critical consideration examined in the literature is the applicability of models in specific context-areas. This has been the case, for instance, in reviewing and narrowing down the applicability of various energy system modelling tools and their limitations for analyzing the energy transition in a European context [18], in a regional Nordic perspective [19], on a country-specific level [20,21], in developing world countries [22,23], in energy systems of urban scale [24–29], and standalone and grid-connected hybrid energy systems [30,31].

Over the past years, a number of studies have shifted the spotlight from a pure overview of modelling tools towards the study of emerging issues for energy system modellers and planners, as developers and users of such tools, under the context of climate change and the transition towards sustainable energy systems. For example, Pfenninger et al. [5] outline different modelling paradigms and emerging methodological challenges faced in the energy system modelling arena, highlighting the way current modelling methods could be revised by benefiting from cross-discipline and cross-sectoral synergies.

Similarly, Lund et al. [32] put into perspective the theoretical positioning with regards to selecting a modelling approach and how these should be considered when addressing and debating different future energy system scenarios based on sector integration.

Correspondingly, the complementarity of these modelling paradigms and approaches, and the potential to integrate models with different features for answering emerging research questions has also been a matter of recent study [33–35], as the focus towards more cross-sectoral integration [12,36–38] and socio-technical considerations becomes more apparent [39–43].

Meanwhile, Savvidis et al. [7] review and discuss the gaps between energy policy questions and modelling capabilities found in a selected sample of modelling tools. In addition to these, the openness of energy data and models have been discussed in a number of studies [44–48] and by expert groups. These include the *Open Energy Modelling Initiative* [45,49], which collects information on a growing number of open-source energy system models and frameworks in addition to open energy data; and combined efforts in the modelling community like the Energy Modelling Platform for Europe and other energy system modelling related projects [50–55].

However, some key gaps remain present. As pointed out by Hall and Buckley [20], the lack of clarity found in the literature about models' characteristics can hinder side-to-side comparisons. Moreover, the target audience and the main area of application of these modelling tools are not always explicit in the literature, often leaving these aspects open to interpretation [25]. Furthermore, potential misinterpretations or misrepresentations while reviewing modelling tools can arise if no form of dialogue with developers take place. Taking as an example the EnergyPLAN tool as portrayed in recent literature review studies, the tool is described as having an optimization methodology [56], geographical coverage [8] and being developed in a programming language [21] which do not necessarily correspond to the tool as described by its developers [57]. Thus, having open lines of dialogue, such as surveys and personal communication, can be a valuable approach when reviewing and validating the technical characteristics of modelling tools, as has been shown in past studies [4,6,16,17].

Nonetheless, this more direct review approach has had limited use when probing aspects such as the policy relevance of the tools, the ability to couple multiple modelling tools to answer complex research questions, or the level of accessibility of the tools with a perspective on not only the licensing but also on the user interaction. This becomes especially crucial as the value of modelling tools and scenarios for decision support is not always fully appreciated by energy planning practitioners and decision-makers [58], despite the intent of models and tools to be relevant for decision-support [59].

2.2. Classification of energy system modelling reviews

As described in the previous section, the current landscape of reviews assessing energy system modelling tools is quite vast. To better understand how these studies have been conducted and their focus areas, we have put forth a classification scheme of these reviews. This classification scheme also has the purpose of outlining new potential focus areas to survey modelling tools, and potential areas of actionable research. At the same time, it provides a useful view into past research that has listed some existing modelling tools, including their attributes and applications.

For this, we have used a modified and expanded categorization scheme compared to that initially proposed by Savvidis et al. [7], where the reviews were catalogued into four groups based on their underlying purpose.

In the present study, we reformulate the four original categories with additional details and propose three new additional categories based on recurring themes found in previous literature but not explicitly mentioned in the previous categorization effort. Namely, these new categories cover reviews that examine real-life policy application of the tools, model linking, and the transparency, accessibility and usability of the tools. In addition to this, we contextualize these studies in terms of their review approach, as well as their area of application and delimiting scope. This allows identifying existing trends and new potential study areas while putting in perspective how modelling lessons are gathered, and how future review exercises can potentially be conducted.

In this paper, the categories considered are divided as follows, considering their corresponding purpose(s):

- Category 1 [Descriptive overview]: Provide descriptive overviews of the technical features of modelling tools, such as their methodological approach, mathematical formulation, and resolution (spatial, temporal, techno-economic, sectoral).
- Category 2 [Classification]: Provide a new classification scheme, and/or focus on grouping modelling tools to provide an overview of existing modelling typologies (based on their technical attributes or modelling approaches).
- Category 3 [Practical application]: Identify the use of energy system modelling tools based on previous applied studies, and to identify areas of suitability for addressing current and future issues based on the tools' modelling capabilites.
- Category 4 [Inter-comparison & suitability]: Compare modelling features side-by-side in order to identify the suitability for a particular application.
- Category 5 [Transparency, accessibility & usability]: Identify transparency and licensing/accessibility of the modelling tool, outlining issues such as result reproducibility, validation and testing, and open source code, and the user interaction with the tool.
- Category 6 [Policy relevance]: Identify policy-relevance of modelling tools based on real-world applications and policy-making case studies[2].
- Category 7 [Model linking]: Identify combined capabilities of modelling approaches through the linking of modelling frameworks.

It is apparent that these categories are not mutually exclusive. In fact, most reviews fell into more than one single category. It is also important to note that there is a degree of overlap between the categories, where some elements of one category could be sub-categorized within another due to some of the studies having more general purposes. However, a degree of differentiation is needed to zero in on the key issues and insights contributed by the reviewed literature. For instance, when considering reviews of the modelling tools' practical application (category 3), an overlap with potentially reviewing their suitability to access policy applications. However, the latter warrants deeper analysis to determine actionable research and real-life application of the reviewed tools, as conveyed by Category 6.

In addition to these categories, we have categorized the reviews by their focus area and delimitating scope, by outlining whether the reviews focused on – for example – urban scale modelling tools, power sector models, bottom-up tools, socio-technical energy transition (STET) models, etc. Similarly, the review approach was also outlined. Here, we noted three distinct approaches: literature reviews, reviews with developer/user inputs (from survey questionnaires, presentations, or review validation with tool developers), and web searches. Concretely for the last approach, the review paper by Markovic et al. [24], presented results without further procedural description and solely referencing websites.

A summary of the categorization, focus and approach of the reviews is seen in Table 1.

As observed in Table 1, several purposes can be identified in previous review studies of energy system models and tools. This survey shows that a clear majority of the studies provide some type of descriptive overview (Category 1) of the features found in models and tools, while also providing classification schemes (Category 2) or prescriptive narrowed-down lists of tools suitable to address a specific issue or scope of analyses. In general, these reviews are useful at mapping the technical aspects and considerations for modellers to select a tool and to pinpoint issues within specific modelling approaches. This is especially the case when these tools are assessed in tandem with applied case studies, where their application provides further insight into how the tools are able to tackle questions about the energy system and different energy policy scenarios.

Although dialogue with tools developers is often suggested by a number of reviews to improve clarity on modelling purpose and scope, assumptions and categorizations; the reviews are not always conducted in such ways. Instead, as seen in Table 1, most of these studies rely on reviewing the existing literature to formulate their interpretation of modelling features or to assess the applicability of models or their policy-relevance.

In more recent years, the issues of transparency and model accessibility have come into focus, being key issues covered by a growing number of studies. This often refers to having open access to a model or to a modelling framework's underlying mathematical formulation - i.e. making the underlying software code in some tools being open source. However, the broader accessibility of the tools in terms of the readiness with which end-users can use tools to construct an energy system model and generate energy system scenarios is not commonly evaluated in previous studies.

Moreover, from this survey we have seen that the policy relevance of the modelling tools is often evaluated in terms of the tool's capabilities to assess the impacts of current policy and potential future developments in academic studies. Given the technical features found in the current landscape of modelling tools, evaluating techno-economic aspects of policy implementations could be routinely performed. However, the focus has been more limited in terms of reviewing the tools used for official policy-making – including both whether the tools have been used directly or as a reference to support official policy choices and their subsequent impact on official planning and decision-making processes. Finding out about these types of applications requires going beyond the tools' technical documentation, and sometimes even beyond written academic outlets. While, this information might be available in official documents, it becomes increasingly complicated to compile when considering the multitude of national, regional and local official plans (often only published in their local language) documenting the use of

[2] While the technical features of some energy modelling tools enable the analysis of policy relevant questions, the actual use of these to support official policy is more limited. Here, we refer to reviews that follow up on whether the modelling tools have been used to support official (government) policy, rather than their ability to technically evaluate policy and generate insights solely on an academic level.

Table 1
Overview of the 42 review articles surveyed with their corresponding classification and review method, sorted by year of publication.

Source	Category							Focus topic	Spatial/Technical/Access delimitation	Review method	Year published
	1	2	3	4	5	6	7				
Van Beeck [13]	X	X		X				Classification of tools for local energy planning	Local	Literature review	1999
Jebaraj and Iniyan [14]	X		X					Review of energy models' applications	Global	Literature review	2006
Connolly et al. [4]	X			X				Suitability of tools for modelling integration of renewables	Local/National/Regional	Survey questionnaire	2010
Bhattacharyya and Timilsina [22]	X			X				Comparison of suitable tools for developing countries	Developing countries	Literature review	2010
Mundaca et al. [60]	X		X			X		Review of tools for evaluating energy efficiency policies	Bottom/up energy economic models	Literature review	2010
Foley et al. [10]	X		X					Overview of tools for electricity system modelling	Electricity sector models	Literature review	2010
Unger et al. [19]	X	X	X				X	Coordinated use of modelling tools	National/Regional	User inputs, Literature review	2010
Mendes et al. [61]	X		X	X				Review of integrated community energy system tools	Local (district/ community)	Literature review	2011
Markovic et al. [24]	X			X				Tools suitable for modelling urban energy systems	Local (urban/district)	Web searches	2011
Manfren et al. [62]	X	X		X				Tools for distributed generation projects	Local (urban/district)	Literature review	2011
Keirstead et al. [25]		X	X					Review of urban energy system models approaches	Local (urban/district)	Literature review	2012
DeCarolis et al. [63]	X		X		X			Modelling results transparency and reproducibility	Energy economic optimization	Literature review	2012
Mirakyan and De Guio [64]	X		X	X				Tools & methods for integrated energy planning in cities	Local (urban/district)	Literature review	2013
Pfenninger et al. [5]	X	X	X			X		Modelling categories and outline emergingchallenges	National	Literature review	2014
Allegrini et al.[26]	X		X	X				Modelling approaches and tools for district-scale systems	Local (urban/district)	Literature review	2015
Huang et al. [65]	X	X	X	X				Modelling approaches and tools for community systems	Local (urban/district)	Literature review	2015
Van Beuzekom et al. [27]	X		X	X				Suitable optimization tools for urban development	Local (urban/district)	Literature review	2015
Li et al. [39]	X		X					Review of socio-technical energy transition models	STET models	Literature review	2015
Despres et al. [11]	X	X	X					Energy modelling tool typologies for renewable integration	Power sector	Literature review	2015
Hall and Buckley [20]	X	X	X					Systematic review of energy models and classification	National (UK)	Literature review	2016
Olsthoorn et al. [36]	X	X						District heating systems and integrated storage	Local (urban/district)	Literature review	2016
Mahmud and Town [12]	X		X					EV modelling	EV modelling included	Literature review	2016
Lund et al. [66]		X	X			X		Modelling approaches and planning support	Simulation/optimization	Literature review	2017
Ringkjøb et al. [6]	X	X	X	X	X			Renewable energy integration	Active models (2012<)	Lit. review, developer inputs	2018
Lopion et al. [21]			X					Historical trends in energy system models' development	National	Literature review	2018
Müller et al. [17]		X				X		Discussion of approaches and categories of energy	EU developed models	Developers' presentations	2018
Crespo del Granado et al. [33]		X	X					Review of nexus between energy and economic models	Economic/bottom up models	Literature review	2018
Lyden et al. [67]	X		X	X				Community-scale energy systems with storage & DMS	Local (district/ community)	Literature review	2018
Morrison [46]					X			Modelling transparency, reproducibility and openness	Open modelling projects	Literature review	2019
Oberle and Elsland [47]	X	X	X		X			Suitability and application of open access models	Open access models	Literature review	2019
Ferrari et al. [28]	X		X	X				Suitability of tools for urban energy planning	Local (urban/district)	Literature review	2019
Scheller and Bruckner [29]	X	X		X				Optimization models & approaches for municipal systems	Local (urban/district), ESOMs	Literature review	2019
Savvidis et al. [7]				X		X		Suitability of models to answer policy questions	Active, policy relevant models	Literature & expert review	2019
Groissböck [48]	X		X	X	X			Review of tools for power system modelling	Open access tools	Literature review	2019
Abbasabadi and Ashsayeri [68]	X	X	X					Outlook of modelling approaches in urban energy systems	Local (urban/district)	Literature review	2020
Hirt et al. [34]	X		X				X	Applied cases of linking energy system and STET models	STET models	Literature review	2020
Prina et al. [8]	X	X		X				Classification of bottom-up energy models	Bottom-up models	Literature review	2020
Ridha et al. [16]		X		X				Profiles and categorization based on modelling complexity	Available data in MODEX database	Survey questionnaire	2020

(continued on next page)

Table 1 (*continued*)

Source	Category							Focus topic	Spatial/Technical/Access delimitation	Review method	Year published
	1	2	3	4	5	6	7				
Weinand et al. [31]			X	X				Suitability of modelling autonomous systems	Local (district/ community)	Literature review	2020
Musonye et al. [23]	X		X	X				Suitability of modelling in Sub-Saharan African context	National/Regional (Sub-Saharan Africa)	Literature review	2020
Fattahi et al. [35]	X	X	X				X	Linking of modelling approaches	National	Literature review	2020
Klemm and Vennemann [56]	X		X	X				Suitability of tools for modelling district energy system	Local (urban/district)	Literature review	2021

energy system modelling tools.

Finally, another recurring area suggested in the surveyed review articles is the application of interdisciplinary approaches, and model coordination and integration. However, few reviews try to map how tools have been coupled together beyond a specific set of modelling traditions [34]. This opens questions as to how model coupling is done, with which tools, and to what extent coupling approaches are used to answer specific energy planning questions.

2.3. Observed trends and findings in past energy system modelling reviews

Looking beyond the scope and methodologies of past reviews listed in Table 1, several trends and findings emerge from the literature over the past 10 years. In Connolly et al. [4], the typical application of different modelling tools is provided. While this study has a comparative nature, it outlines that – at the time – only seven energy system modelling tools were identified capable of modelling 100% renewable energy systems, four considering hourly time-steps and different sector coverage, and three with coarser (annual) temporal resolutions but with multi-year perspectives.

From there, several suitability studies have looked further into the technical descriptions of different energy modelling tools, having as main outcome shortlists of applicable tools that could address specific research cases. This has been predominantly the case of reviews looking into the suitability of energy system modelling tools to represent local scale energy systems (ie. Urban, district, community scale), though similar cases apply for other geographical scales. As early examples, Mendes et al. [61] identify a handful of tools highlighting the importance of hourly modelling and spatial scale flexibility to conduct their assessment; while Allegrini et al. [26] call for adequate representation of district heating, renewable energy and adequate integration of the urban microclimate and resulting effects on building demands when conducting energy system analyses. By contrast, studies conducted over the past 5 years incorporate into their model-finding exercises far more comprehensive criteria about high modelling details such as multiple sector representation, high spatial and temporal resolutions, uncertainty analysis, storage and demand side management representation [29,36,67]; but also user-friendliness [28] and openness of these tools [56]. Meanwhile, other studies point at a lack of representation of additional dimensions, like increased social aspects in energy system modelling tools [31].

Similar to Connolly et al. a decade ago, Foley et al. [10] also raised the issue of modelling renewable energy, finding that electricity system models were ill suited to properly consider energy storages, flexibility services and variable renewable energy sources. More recently, Ringkjøb et al. [6] found that several studies address the effects of integrating variable renewable energy sources to varying degrees, with models capable of representing grid expansion, storages and demand-side management technologies. However, representing the variability of these sources in long-term energy models was found as a challenge due to the coarser time-step of these modelling tools. Likewise, the integration of energy sectors was also found as an outstanding challenge to be address in model development. Prina et al. [8] also makes this point, after identifying the current status of bottom-up models in their spatial, temporal, techno-economic and sectoral resolutions. In their study, bottom-up modelling tools are found uncapable of addressing these four dimensions fully.

Similarly, in Lopion et al. [21], key trends are also examined around the development of energy system models over the last decades. In this review, they found new developments around increasing spatial and temporal flexibility of energy system models and state the need to have modelling efforts align to answering energy policy questions. This is also touched upon by Savvidis et al. [7], when reviewing gaps between modelling capabilities and technology-specific policies. From this study, the representation of the distribution grids, endogenous demands, the systems technical flexibility and policy constraints were found as areas of improvement for energy system models.

Other key areas found among recent reviews, include the prospect of expanding modelling dimensions to increase realism in addressing energy and climate challenges, and increasing modelling transparency. In the case of the former, linking energy system modelling tools with socio-technical energy transition approaches [34] or macro-economic models [33] has been found as a potential avenue for inter-disciplinarity and better representation of the energy system. Fattahi et al. [35], also highlights this potential, after noting the shortcoming of energy system modelling tools in generating insight about micro- and macro-economic aspects of the energy transition.

On the issue of transparency, much has been said in recent years. For instance, Morrison [46] and Pfenninger et al. [45] find that energy system models are lagging behind in adopting best practices for transparency, such as those found in the open modelling community, pointing out the need to enhance transparency of modelling analysis and reproducibility. Following from this, Oberle and Elsland [47] look into the current landscape of open access tools to outline their features, finding them technically suitable to address research questions regarding a variety of energy scenarios.

3. Methods

In this paper, we opted to review the features and applicability of energy system modelling tools by gathering inputs directly from tool development teams and key users. As seen in the literature review, some aspects of the tools and their applications can be overlooked, are rather difficult to come by from only analyzing publications or are altogether misinterpreted due to a lack of a common language found in the existing literature describing modelling tools. This becomes increasingly relevant when considering the application of some modelling tools outside the realms of academia, where modelling outputs can translate into local or national policy discussion in white or green papers (sometimes in their original language), while being less accessible to external inspection or by reviewing traditional sources and model documentation.

By establishing some line of dialogue, in this case through a survey questionnaire, we try to bridge this methodological gap and establish a common language to describe the tools and their applications from the developers and users own perspectives.

In this process, 137 different modelling tools were identified from the existing literature and survey studies referenced in the previous section. The conceptualization of the questionnaire took the work presented in Connolly et al. [4] as a starting point of inspiration, with several reconsiderations and new aspects added to the questionnaire presented in that study corresponding to new developments and considerations in the practice of energy system modelling and tool development.

A web-based questionnaire was designed on the SurveyXact platform, which then was sent to the developers of each tool identified.

From this survey, 54 complete responses where gathered, plus an additional six partially completed entries. Although, additional tools and model descriptions can be found in the literature, these are not considered in the following result interpretation in order to preserve the consistency of the analysis. It must be noted that the overall survey results, while not necessarily providing a comprehensive sample of all existing tools, are still indicative of general trends found in the energy system modelling field. The tools covered in the analysis ranged from commercially available software, to in-house proprietary developments, and open access, widely used modelling tools. In addition, a deliberate choice was made to only include one modelling tool in cases where multiple branch-out versions exist; for example, in the case of MARKAL-TIMES [69], and its family of models [70–74], or similarly in the case of OSeMOSYS [75] and GENeSYS-MOD [76]. The list of tools surveyed is presented in Table 2.

The survey questionnaire covered questions regarding the tools' access and licensing, user interface, methodological approach, mathematical formulation, spatio-temporal resolutions, sectoral representation, technical attributes and technology detail, and area of past application, including use for official policy-support. In addition to this, data regarding typical application of tools and descriptions from the respondents was also gathered.

An overview of the questionnaire is provided in Appendix A, while a summary of the inputs for the 54 modelling tools is provided in Appendix B as a supplementary data repository.

Table 2
List of the 54 modelling tools surveyed where full responses were gathered.

Modelling tools surveyed (completed questionnaire responses)
Balmorel [77]
Calliope [78]
COMPOSE [79]
DER-CAM [80]
DIETER [81]
Dispa-SET [82]
E2M2 - European Electricity Market Model [83]
EMLab-Generation [84]
EMMA [85]
EMPIRE[86]
Enerallt [87]
Energy Transition Model [88]
EnergyPLAN [57]
energyPRO [89]
energyRt [90]
EnergyScope [91]
Enertile [92]
ENTIGRIS [93]
ESO-XEL [94]
EUCAD [95]
EUPowerDispatch [96]
Global Energy System Model (GENeSYS-MOD) [76]
GridCal [97]
Homer Grid [98]
iHOGA [99]
IMAGE [100]
IMAKUS [101]
Integrated Whole-Energy System (IWES) model [102]
INVERT/EE-Lab [103]
LIBEMOD [104]
LIMES-EU [105]
LOADMATCH [106,107]
LUSYM [108]
Maon [109]
MESSAGEix [110]
National Energy Modeling system (NEMS) [111]
OpenDSS [112]
OptEnGrid [113]
POLES-JRC [114]
POTEnCIA [115]
PRIMES [116]
PSR – SDDP [117]
Pymedeas [118]
PyPSA[119]
RamsesR [120]
Regional Energy Deployment System (ReEDS) [121]
REMIND [122]
Sifre [123]
System Advisor Model [124]
TIMES [69]
TransiEnt Library [125]
UniSyD5.0 [126]
WEGDYN [127]
WITCH [128]

4. Features and trends in energy modelling tools

In this section, the results from the tool survey are presented with a focus on approach, scope, coverage, access, policy relevance and model coupling.

4.1. Approaches and formulation of the objective

As identified in the literature, several schemes exist to classify modelling tools according to their methodological approach and mathematical formulation [13,17,20,129]. In this study we examined the modelling tools under three broad categories according to their analytical approach: Simulation, Optimization and Equilibrium models. In the case of the latter, further subcategorizations were defined by model developers about their modelling tools, namely to clarify if these are computable general equilibrium (CGE) or partial equilibrium. In addition to the above, some simulation tools made further specifications to describe the novelty of their underlying methodology; for instance, by elaborating on their operation and iterative simulation approach [107].

In terms of the mathematical formulation, several objectives were identified across the sampled energy system modelling tools. More recurring across optimization modelling tools was the characterization of one or more purpose-fit objective functions, including the minimization or maximization of indicators such as total system costs, investment costs, dispatch costs, fuel consumption, system emissions, renewable energy penetration, and social welfare. In the case of simulation tools, the main approaches identified behind their mathematical formulation included scenario development, what-if analysis, multi-criteria analysis and agent-based analysis.

Irrespective of modelling approach and formulation, the definition of multiple objectives or purposes for a given single tool was readily apparent from the gathered data, as is the fact that a significant portion of the models can serve multiple purposes with their underlying formulation. Overall, we observed that most modelling tools can use multiple assessment criteria in their studies depending on the specific case and the underlying context, resulting in a wide range of choices as highlighted in [31,130].

4.2. Modelling scope: temporal, spatial, and technical resolution

4.2.1. Temporal resolution

The integration of high levels of variable renewable energy sources (VRES) poses a challenge for energy planning, which calls for models capable of representing the corresponding variability. Similarly, the level of detail used for modelling the energy system can also result in more accurate system representations capable of capturing synergies and resource availability that are spatially dispersed by nature.

The choice of temporal resolution used in energy system studies can have a significant impact on capturing the actual dynamics of a modelled system and adequately balancing supply and demand. This is illustrated, for example, by Poncelet et al. [131] when assessing the impact of temporal resolution in systems with high uptake of renewables, concluding that low temporal resolution can potentially underestimate operational costs and overestimate generation capacity.

Similarly, Deane et al. [132] determined that higher temporal resolutions are better able to capture system loads, the inflexibility of large thermal power units, and renewable energy generation; thereby assessing more accurately the corresponding system costs. Nonetheless, increasing the time resolution can be computationally expensive. Thus, temporal resolution should be selected with caution, especially when considering resolutions coarser than 1-hour to represent renewable generation fluctuations [133].

In the modelling tools sampled for this study, the 1-hour modelling time-step was the most frequently observed, as seen in Fig. 1. Other time-steps observed, although to a lesser extent, were the yearly and multi-year resolutions, as well as seasonal time-slices. In the "Other" category, the modelling tools were reported capable of adjusting their modelling time-step to even higher levels like minutes, seconds, or having user-defined steps, as well as having lower resolutions e.g. daily, using representative hours and hour-blocks and weekly resolutions. In addition, some tools had higher (hourly) resolutions in certain aspects of their system representation while using coarser (annual) resolutions for others.

Interestingly, modelling tool developers also highlighted that the capabilities of their models not always correspond to their typical application. For example, some tools although technically capable of operating with an hourly resolution, are typically used with other modelling time-steps, such as using a time-slice representation [69] or with a reduced yearly time-series produced from aggregation algorithms [76]. For some tools, this can be explained by the fact that high modelling resolutions and temporal detail can translate to higher computational effort and calculation times [5]. However, the choice of lower time resolutions can also driven by a lack of empirical high resolution data for future time horizons, or from the use coarser temporal detail of the energy demands represented in energy system modelling tools [134].

An additional temporal aspect considered is the time horizon of the modelled outputs, as seen in Fig. 1. This shows that a large majority of the modelling tools can provide more than just a single snapshot of the energy system, but rather have the capability to outline multiple stages of the energy transition by providing multi-year outlooks, with some being capable of having more than one fixed time horizon. This modelling capability is reflective of the intent to outline the pathways of policy scenarios and sequential decision-making [135], as seen – for example – for capacity expansion at a country level [136], to formulate energy policy at the EU level [137–139], or to assess regional and global decarbonization pathways [140].

On the other hand, a smaller yet significant share of the modelling tools surveyed can also use a 1-year modelling time horizon or even shorter-term horizons. This comes with the potential advantage of lower computational effort and less uncertainty due to the number of assumptions and data inputs going into the modelling. While less detailed in outlining potential energy transition pathways, the application of a 1-year time horizon can still outline end- and mid-point snapshots of technical developments or policy scenarios at selected years. This can provide high levels of detail of an energy system redesign to strive for, as illustrated in studies about urban energy transitions [141,142], national energy system redesigns [143–146], and regional studies [147–149]; in turn, acting as potential points for policy backcasting [150–153].

Putting these results into perspective, we can see that over the past decade advances have been made in how time is represented in modelling tools. Taking the study by Connolly et al. (2010) as an example, we can see that now a larger share of energy system modelling tools are capable of using hourly time-steps, compared to roughly half capable of such identified at the time for the 37 tools surveyed in that study [4]. In terms of the modelling time horizon, the results found in this survey are to an extent similar to those presented by Connolly et al. [4], which shows that most models surveyed then were already capable of handling multi-year time horizons, as well as yearly, and to a lesser extent coarser resolutions.

Similarly, Pfenninger et al. [5] raises the issue of higher temporal detail as a pending challenge in energy system modelling development. As seen today, increased development has been given to capture high temporal detail in the modelling tools surveyed.

4.2.2. Spatial and technical resolution

Across the surveyed modelling tools, a levelled distribution was observed between tools working with aggregate technical specifications and those capable of representing individual plants or energy system components. Out of the 54 tools surveyed, 31 reported using individual plant details, while 23 reported using aggregate technical details. This reflects – in part – the nature of the tools sampled since some of them are capable of modelling large spatial aggregations on the global and regional scale (and in some cases even at the urban level), where aggregate operational detail provides adequate representation of the energy system [154,155], having an overall less significant impact than the temporal resolution [131].

On the other hand, some of the tools working with finer operational detail are tuned based on the purpose and scope; for instance, to flexibly represent project-specific components [156,157] or set up to represent specific dispatchable units or plants [158,159].

Interestingly, the survey pointed that even if some of these tools are capable of representing individual plants and conversion units, the standard modelling representation for larger spatial scopes – like on a national scale – would still rely on aggregated values. This raises an interesting point when considering the features and intended flexibility of use, with the standard practical use of the tools.

4.3. Cross-sector coverage

As the global focus shifts towards higher penetration of renewable energy sources to decarbonize the energy system and to halt global warming, more effort has been put towards coupling the main energy sectors to benefit from their potential synergies. A vast range of reviews identify the challenges of integrating more renewable energy, mainly considering electricity sector [5,10,11]. However, as identified by Lund et al. [37], cross-sector integration can also be a pivotal aspect to incorporate larger shares of renewables, by facilitating additional flexibility in the energy system. This has been the subject of a number of studies (e.g. [149,159–162]), which have analyzed the potential of integrating the electricity, heat, transport and industrial sectors, and thereby allowing 100% renewable energy shares in future energy system scenarios.

The potential for sector coupling was investigated in the survey of modelling tools by looking into their sectoral coverage. This is shown in Fig. 2 and Table 3, and outlined in further detail in Appendix B.

As seen in Fig. 2 and Table 3, the inclusion of the electricity sector is shared across almost all the tools examined. For roughly half of these tools, it is furthermore possible to explicitly model both the transport sector and heating (including individual and district heating). However, it must be noted that when considering tools representing only the electricity vector, non-explicit approaches to represent scenarios where heating and transport are electrified can arise and, thus be partialy covered. Additional sector coverage is seen to a varying degree when looking at industry or cooling applications, and it is much less prominent considering biofuel production, being modelled by only one-third of the tools examined.

The common theme of the electricity sector is key to sectoral integration, since thermal, transport, and industry sectors are considered in the context of electrification in a smart energy system [163]. Indeed, it is

Fig. 1. Modelling time-step by time horizon of the 54 surveyed tools. Note that the sum exceeds 54 as some tools can operate with different user-defined time resolutions.

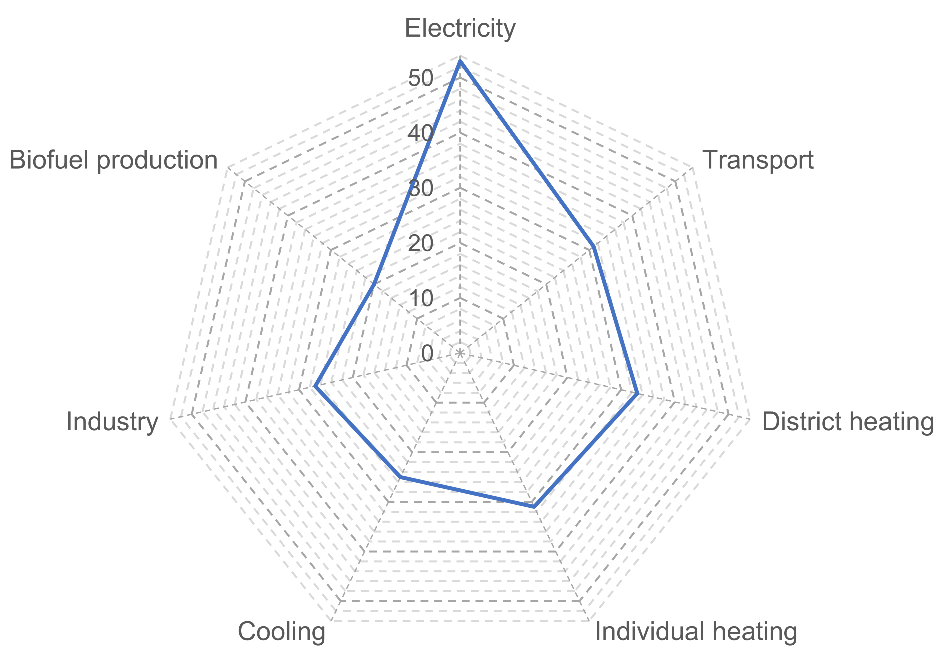

Fig. 2. Sector & end-use coverage in the 54 surveyed modelling tools.

expected that when incorporating these demands, the total electricity demand will markedly increase [160]. More importantly, however, these sectors can act as sources of demand response, having promising prospects to provide flexibility and improve the efficiency of the energy system [164]. This has been shown in prior studies when analyzing the potentials to shift industrial [165], thermal [166], and electric transport loads [167]. This flexibility can also be reaped within the electricity sector, by considering flexible demands responsive to the costs of generation dispatch, which could cover second priority loads. This can be done by covering these lower-priority demands in off-peak hours, or in the presence of excess electricity from fluctuating renewable sources when generation costs are lower [164,168,169]. In our survey, about 23 of the 54 models were capable of representing elastic demands responsive to supply costs (Fig. 3).

4.4. Demand representation

Common across all energy system models is the need to balance energy supply and demand. As seen in Fig. 3, energy demand is rarely a modelling outcome, but rather an exogenous input assumption, either as

Table 3
Sector coverage overlap by number of tools in the 54 surveyed modelling tools.

No. of sectors/ end-uses covered	Number of modelling tools	Sectors/end-uses excluded by number of tools
7	15	n/a (ie. all sectors covered)
6	5	biofuel production (3 tools), industry (1), cooling (1)
5	4	biofuel production (4), cooling (1), industry (1), district heating (1), transport (1)
4	7	cooling (5), biofuel production (4), individual heating (4), industry (4), transport (3), district heating (1)
3	3	biofuel production (3), cooling (3), industry (2), district heating (2), individual heating (1), transport (1)
2	8	biofuel production (8), cooling (7), industry (7), individual heating (6), transport (6), district heating (5), electricity (1)[a]
1	12	All but electricity generation (12)

[a] Partially covers electricity as contributions for heating purposes.

a static demand or with some elasticity. This requires that modellers represent energy demand for the variety of aforementioned sectors at the relevant temporal and spatial resolution of their modelling tool.

Focusing in on specific studies undertaken by some of the surveyed modelling tools, we see that the same data sources are often used, or that the hurdles to data acquisition are dealt with in similar ways.

In the European context, hourly electricity demands are readily available from the European Network of Transmission System Operators for Electricity (ENTSO-E) [170]. ENTSO-E data is used in several national scope studies [81,147,171–174], although others source data directly from relevant national bodies [133,166,175–177] or as a synthesis of ENTSO-E and national statistics, via the Open Power System database [178]. When data is unavailable for countries, or subnational regions are being modelled, scaling factors are applied based on aggregated demand statistics [147,179], relative population magnitudes [133,142,177], or additional economic parameters and weighting ratios [180]; in all such cases, it is not possible to verify validity.

The inclusion of additional sectors beyond electricity poses additional difficulties, since high resolution measured data is not readily available outside the electricity sector. Instead, national statistics are usually mapped to representative profiles of demand [161,175]. In the case of thermal demand, heating degree days or hours are used in this process, whereby the deviation of outdoor temperature from a reference temperature indicates a requirement for heating or cooling. Several projects have endeavored to simulate thermal demand using both bottom-up and top-down approaches [169–171], but their incorporation by energy modelling tools is currently limited.

Although sources exist to understand historical demand at some resolution, future demand is understandably unknown. Frequently, historical demand is used directly when modelling a scenario of a future energy system, without altering its magnitude or shape [172,175,181]. The same approach has been used when projecting further back in time than available data allows, whereby a single year is used to represent all historical years of interest [133]. Yet, it is clear that demand changes over time. Roadmaps for energy systems, such as the EIA international energy outlook [182], include estimations of the increase in demand and have been used to scale the magnitude of model input profiles accordingly [166,183]. However, the magnitude of demand is not the only element that will change, the profile shape is also variable. Indeed, at the high (one hour) temporal resolution we see to be increasingly important to modellers, the dynamics of demand are as important as variable renewables; the two may even be coupled [184,185]. As with thermal demand, reliance on demand modelling tools is key to understanding future profile shapes, but is underutilized. An example of how they could be used is shown in [171], where the DeSTINEE [186] simulation tool is used to estimate electricity demand in Italy for the year 2050, considering full electrification of heat and transport sectors.

4.5. Cross-platform modelling integration: Model coupling

With the expanding number of energy modelling tools available, and with these having different focus points, it is interesting to see to what extent different tools are linked with each other. By linking tools, more issues can potentially be scrutinized by investigating multiple aspects or to complement their methodological approach and coverage. This has been the case in studies looking into combining the capabilities of energy system modelling tools and demand modelling [187], energy system modelling tools with different technological and temporal resolution [188], and linking bottom-up and top-down modelling approaches [189].

Based on the survey of energy tools, the most common linking approach is the so-called "soft-linking" of tools: 33 of the 54 tools have been run with other tools, by applying an external workflow or a linking tool. Soft-linking is in the scope of this review, defined as a clear definition of an approach towards how inputs and outputs from different tools can be utilized in combination. Thus, soft-linking does not interlink source-code specifically between two tools to operate automatically

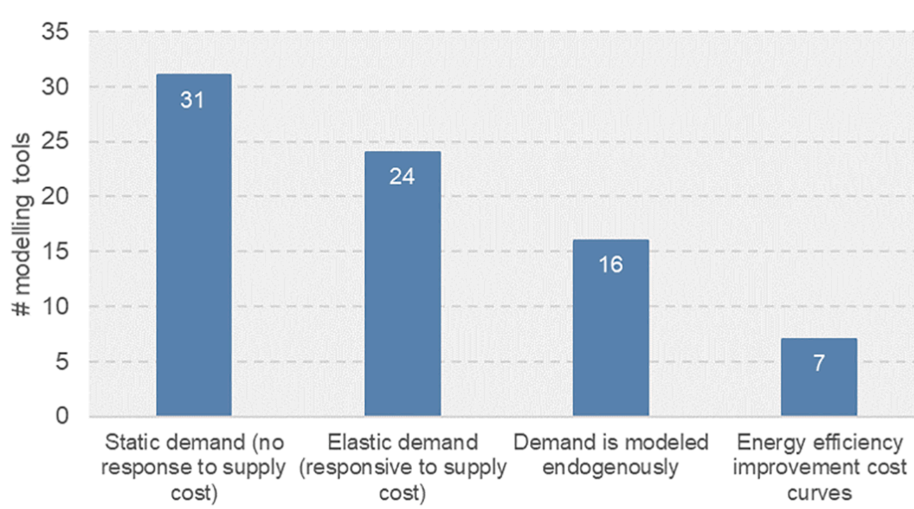

Fig. 3. Overview of how energy demands are handled across the 54 surveyed modelling tools. Note that the sum exceeds 54 as some tools can represent different energy demands in multiple ways.

together. An example of soft-linking could be the energy scenario of one tool modelled in another energy system tool that can capture a finer temporal resolution and sectoral or technological details.

If two or more tools are linked through their source code, we specify that as hard-linked tools. An example of this would be if the code of two or more energy system optimization tools are linked together in such a manner that they can be solved as a single, yet complex, optimization problem. Three of the tools in the survey have been hard linked to other tools. Five of the tools have been integrated into other tools, making new merged tools. The difference between an integrated tool and a hard-linked tool is as follows. In principle, with hard-linking, two separate tools still exist but linked to each other to exchange input/output data automatically. However, when two tools are fully integrated, the linked tools evolved into a new tool with a common set of input and output data. So, in total nine tools have been integrated with specific coding between tools. Out of all tools examined, 11 have not been linked to other tools, and for one the linking status was unknown for the tool developer. Further information regarding the type of tools connected between each other was not collected in the survey.

These results hint at a growing trend where complementary methodological approaches are used in tandem to leverage their capabilities and potential for additional insight. Fattahi et al. [35] present an example of this by reviewing the features and gaps of current energy system models and proposing a conceptual framework of how model coupling can take place between energy system modelling tools and regional models presenting infrastructure and resource constraints, electricity market, and macroeconomic modelling tools. Otherwise, more focused coupling efforts can also be found in the literature, including cases coupling top-down and bottom-up energy system modelling tools to gain insight about appropriateness of technology choices in the energy system and wider macroeconomic and welfare effects [189–191], linkages between technology-rich modelling tools and long-term planning ones to get more nuanced representations of the systems' sector coupling and flexibility options [159,192–194], coupling tools forecasting fuel and transport demands with energy system simulation tools [195], or even combined efforts linking spatial analysis [146,196], and behavioral aspects of end-user transport demands [197,198] with energy system modelling tools. Likewise, linking socio-technical transition aspects with energy system tools can prove beneficial to capture more realism in modelling [34].

In all, the coordinated use of modelling tools and different approaches opens a world of possibilities to capture greater detail of the real-world and its dynamics with the energy system. Moreover, this could help in tackling modelling uncertainty, as a better representation could be captured by linking approaches. However, increasing modelling realism should not trump the functionality of modelling tools. While it is certainly impossible and impractical to create and all-encompassing model [19], the added complexity of model coupling could also be detrimental for uptake by relevant users, or for an eventual use of modelling outcomes which are perceived as being too-complex [58]. At its core, the interpretability of modelling outcomes will be rooted in a clear understanding of the underlying modelling assumptions and formulations rather than the increase realism of integrated modelling tools [3]. Thus, a balance between modelling complexity and interpretability and usability is necessary when considering tool coupling exercises.

4.6. Tool usage: accessibility and transparency

There is a current trend and focus on openness of energy system modelling tools [44,46,47,199,200], which, as gathered by Oberle & Elsland [47], are well suited technically to model current challenges in the energy transition. As mentioned in Section 2, this open development is also one of the drivers behind the *Open Energy Modelling Initiative* [45,49], which gathers a growing number of open-source energy system models and frameworks. While this openness generates a natural exchange of knowledge between researchers and modellers and allows for a transparent modelling framework for modellers and users, it is essential to focus on user accessibility and third-party replicability [63].

As explored in other fields of study, prospective users of open access tools still require adequate levels of guidance to learn how to use these, and enable subsequent model implementations [201]. In some cases, this can be facilitated by dedicated graphical interfaces as opposed to direct manipulation of the source code, especially when considering occasional users[3] of a tool [202]. However, the selection of interface should accommodate the specific user-needs [203]. This is especially relevant as the uptake of energy system models as tools for decision-support can be hindered by the functionalities and complicatedness of use perceived by target users [28,58].

Therefore, we compare the tool openness with the tool's user interface. In Fig. 4, the same tool might appear more than once, but in total, 36 of the 54 models and tools surveyed can be free for other users. Of those, 22 are open source, and eight of these require additional commercial software or solvers to run. Only two freeware applications were reported which were not also open source, while 11 tools commercial (paid) software were identified. In addition, 11 tools were observed to be in-house tools that are not sold or provided to outside users. Moreover, 11 tools report being free under special conditions, or being available under request for academic purposes, and overlapping with some of the previous categories otherwise.

The open-source category, as well as most of the other categories, are to a large extent dominated by tools with direct coding options. For many of the tools, this is the only option to use the tool, although human-readable text interfaces are also available to more easily handle the code of some tools' code. In addition, under the "other" category for user-interface we identify that some tools can be used in diverse ways via other external applications such as Excel, Jupyter Notebooks, via bash controls, etc.

Within the non-open source tools, whether they are free or commercial, the share of tools with a dedicated graphical user interface is more significant, while there is a lower number of tools with web-based interfaces.

Many energy tools are dependent on mathematical solvers to operate and find solutions. Talking about the accessibility of free tools, it is important if a tool can operate on open-source/free solvers. Of the 37 tools that indicated they use a solver, 23 are dependent on commercial software while only 8 of these are reported as being open source. This potentially also limits the accessibility of such open and/or free tools, especially looking outside of academic settings with special educational licensing agreements to access some of these solvers.

4.7. Perceived policy-relevance

A key aspect of energy system modelling is the ability to quantify the impacts of changes in the energy system and in this manner contribute to the public debate, while also supporting decisions to guide the energy transition [5,32,204]. Although it is commonly understood that energy policies are political decisions, the use of energy system modelling studies is important to inform and substantiate the policy-making process [7].

In the survey, we attempt to quantify the number of tools that have made some policy contributions. We differentiate between those that have been used directly by an official governmental or public institution for guidance in official policy and indirectly by contributing to the discussion or used as a reference to contrast and/or validate official policies. An outline of this can be seen in Table 4.

Many of the surveyed tools have been used for policy support, both directly (e.g. PRIMES [205]) and indirectly, with some overlapping

[3] Casual or occasional users refers to those who are using a tool intermittently rather than having constant interactions, regardless of their level of expertise in the field of study for which the tool is applied.

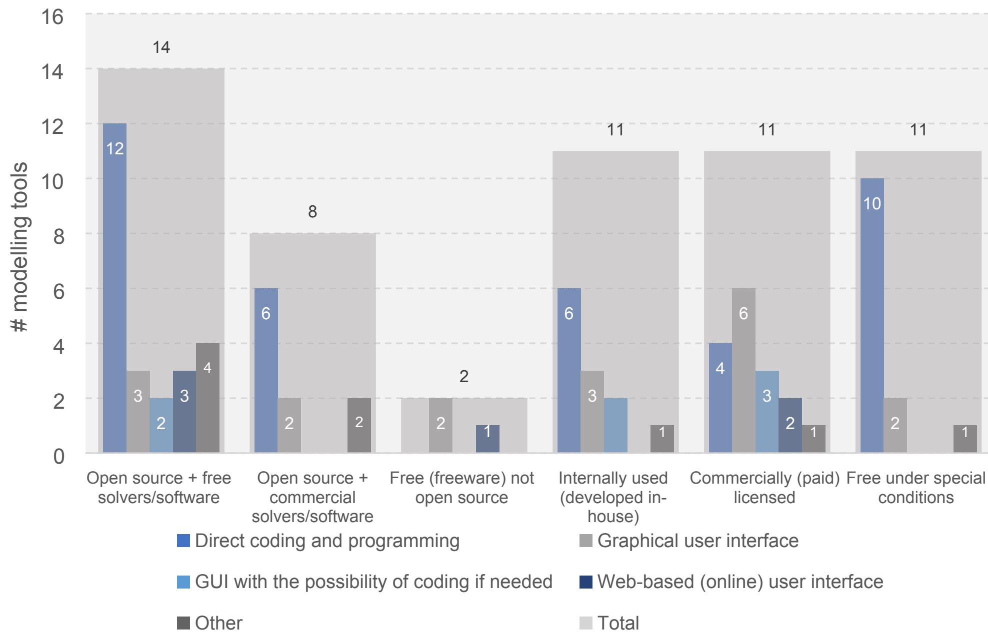

Fig. 4. Comparison of tool types with user-interface among the 54 surveyed tools. Note that the sum of each bar and the total exceed 54 as some tools can fall under multiple licensing/availability and user interface categories.

Table 4
Modelling tools and policy support status among the 54 surveyed tools. Note that the sum exceeds 54 as some tools have had more than a single policy-support application.

Use for policy-making and/or support	# of tools
No	8
Not known	16
Yes, directly	16
Yes, indirectly referred in a relevant official document	17

usage between these two categories (e.g. EnergyPLAN [206,207]). On the other hand, over a third of the models did not have any identifiable policy contribution. This could correspond to the fact that some of these tools are rather new in-house developments used within academic research, or they have been used for a limited scope of projects.

While this certainly shows a gap between modelling and policy, it does not reflect on the modelling potential of such tools to answer policy-related questions. It does however raise a question regarding awareness of modelling tool application beyond initial development, and the involvement of policy-makers in discussions about modelling features and results. Such an involvement could enrich the end-use of energy system models, particularly to produce scenarios answering policy-related questions [7,17]. Ultimately, having this interaction with policy-makers and putting the models to use in decision-support also serve as form of legitimacy and could be viewed as a real-world validation of the energy system model in question [59].

For this reason, it is important to understand the characteristics of the tools used for policy support applications. The attributes of these tools vary in terms of technical modelling characteristics, but also in their accessibility, target user-base and interfasing. In Fig. 5, an overview is presented of the different attributes found in those tools. From the results shown in Fig. 5, a few clear trends can be observed.

First, the tools used for policy-support tend to have high temporal resolution, relying mostly on hourly modelling. This has been specially the case for those tools reported to have direct policy applications, which responds to the need to model the energy system's dynamics when considering fluctuating demands and supply sources, as well as energy balancing. For the tools with indirect application, the hourly time resolution is apparently used as much as yearly resolutions. To a lesser extend, some tools also consider seasonal time-slices or multi-year resolutions to conduct their modelling.

In terms of modelling time-horizon, a multi-year outlook is seen to be most predominant among the surveyed tools with policy applications, while yearly horizons are less used. The ability to represent multiple years facilitates outlining long-term policy pathways, making it a valuable attribute when modelling transition scenarios for the energy system. On the other hand, 1-year horizons, while not explicitly modelling transition pathways, can still aptly model different end- and mid- point scenarios for the enegy system, making them equally valid tools for policy analysis and support.

As seen in Fig. 5, the ability to represent multiple energy sectors and end-uses is widely considered in the tools with policy applications. Here, the electricity sector seems to be slightly more well represented, however other key sectors and end-uses are also considered to an almost equal extent. Interestingly, those tools used indirectly for policy support report having higher representation of some of these sectors, with a slight edge on modelling transport, industry and cooling. By contrast, the overall number of tools surveyed, shown prior in Fig. 2, show a gap between modelling the electricity and other sectors and end-uses.

The energy demand representation in the tools used for policy support falls mostly under static demand representations, with elastic demands also being represented. On the other hand, endonegous demand modelling does not seem to be a common feature present in these models. This aligns with the discussion in Section 4.4. However, endogenous demand representations is slightly more predominant in the tools used for indirect policy support. On the other hand, we see that most of the energy system modelling tools with policy applications rely on connections with other tools, likely to supplement their modelling capabilities.

Finaly, regarding the access and use of the tool, it is possible to see some clear cut distinctions between the tools used directly and indirectly for policy support. For instance, while open source access seems to be a prefereed attribute in the observed tools, the use of commercial and non-open source freeware seems more prevalent in direct policy applications. Similarly, tools used for direct policy-support seem more likely to provide graphical user interfaces, in contrast with direct coding, mostly found in those modelling tools used indirectly for policy support

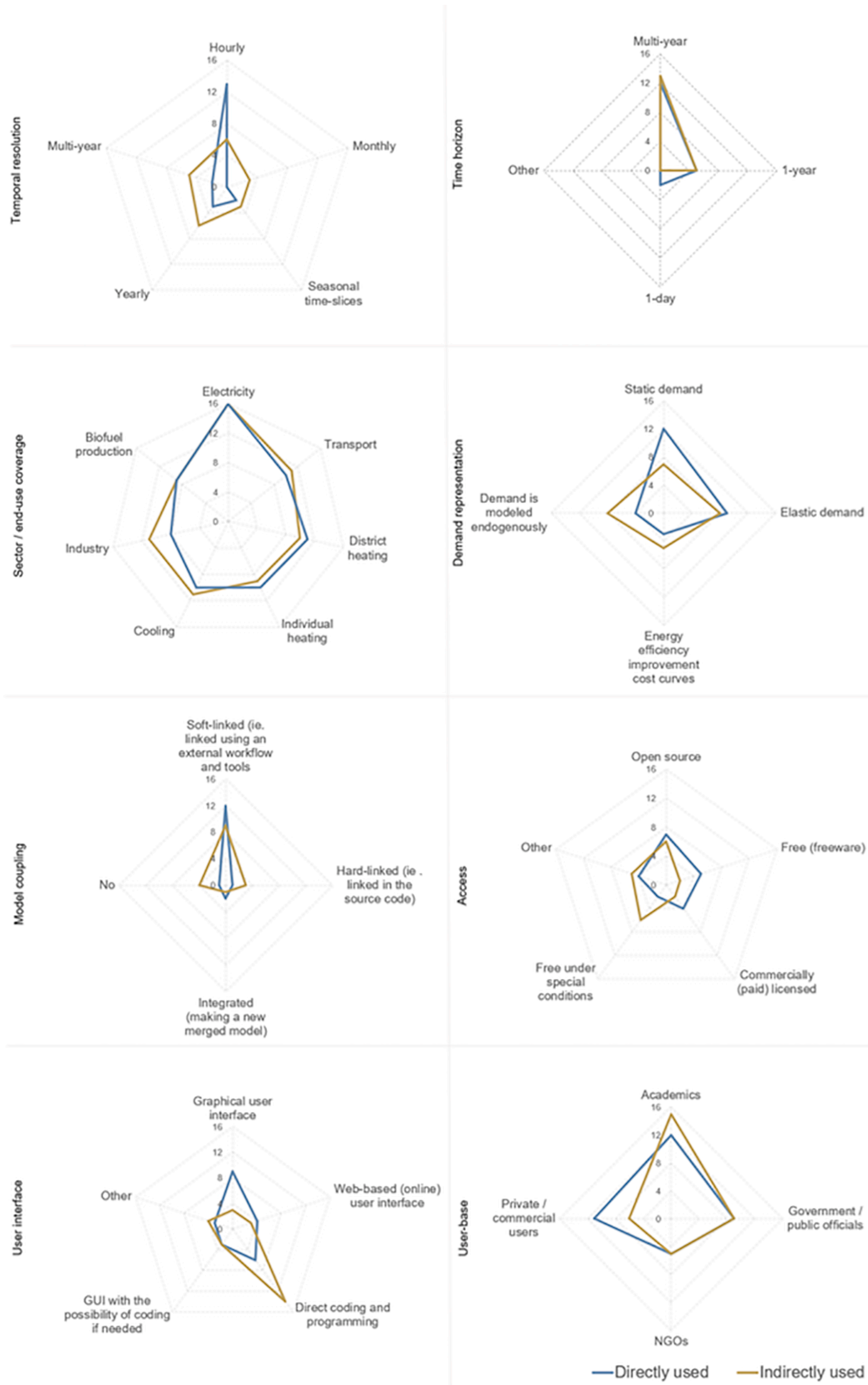

Fig. 5. Characteristics of the tools reported to be used directly (in blue) and indirectly (yellow) for policy support represented as radar plots of temporal resolutions, time horizons, sectoral coverage, demand representations, model coupling applications, access/licensing, type of user interface and user-base of the tools. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

applications. Ultimately, this could potentially be associated to the target user-base of the modelling tools as seen in Fig. 5, where we see that for direct policy support the main user-base consists of private/commercial users, as well as academics and government/public officials; while, academic users make up the main user-base of those tools used for indirect policy-support.

5. Summary and discussion

This study reviews recent trends in energy system modelling tools by surveying the existing literature and gathering inputs directly from tool developers about the features and applications of their modelling tools. Unlike previous review studies found in the literature, this contribution establishes a direct communication with modellers and developers of the tools through a questionnaire, to reflect the way these developers understand their tool under a common terminology, while also addressing issues that previous survey-based studies have not put much focus on, such as the factual policy-relevance of studies conducted by an energy system modelling tool, the accessibility, openness and usability of the tool, and possible model coupling applications. This reduces the risk of misinterpretation or biased assessment of different tools by relying on their published information, although with a limited sample of tools surveyed. Moreover, the survey offers an avenue to gather information about the real-world application of the tools directly from their developers.

This, of course, does not come free of downsides, like the potential exclusion in the current survey of some well-documented modelling tools, in cases where no responses were gathered for the questionnaire, or by considering representative 'members' from a family of models which might have different technical attributes to their source. Moreover, potential biases in the survey can arise as the majority of the past reviews, and the models survey stem from European research, which could hint at a focus on modelling specific aspect of European energy transition paradigms. Nonetheless, we recommend this line of dialogue with tool developers when conducting future review exercises in order to gather insight about the modelling applications of a particular tool or for validation purposes, and more generally to identify trends in the field of energy system modelling. From this, the following points appeared to be evident after the process of conducting the survey, including both literature reviews and modelling tools.

First, it is challenging to agree on a specific vocabulary that all tool developers reach consensus in the same way. For instance, multiple studies have focused on proposing new classification schemes and to categorize different modelling approaches or methodologies. While some of these categories are unambiguous, other descriptive labels assigned to tools might fall within an overlapping spectrum which is harder to define. This is not surprising as an overlap between modelling methodologies does exist; it highlights, however, the importance of communication between modellers when discussing different modelling methods and would be relevant when interpreting the tools application or when working on linking different tools. Similarly, expanding this dialogue can also provide a better understanding of a tool's intended design versus its inferred potential applications obtained from only reviewing modelling features, as seen in Section 4.2. regarding the typical modelling time-step used by some tools and the clarifications from tool developers, or in Section 4.6 regarding their policy-related applications. However, it is important to point out that surveying can only be fully effective if there is a common understanding of terminology and a clear framing of survey questions. As a case in point, a survey question like "How is energy demand modelled in the tool?" can be understood in many ways, such as in terms of energy carriers (e.g. a country's demand for oil) or in terms of end-uses (e.g. demand for energy from households). In turn, this could lead to potential misunderstandings on whether the demand is modelled endogenously or exogenously depending on how the respondent interprets demand in the first place.

Second, modelling tools rely on exogenous demand datasets. Yet, there is still a lack of accessible data for modellers to understand projected and uncertain changes in demand, and to model high spatial and temporal resolution systems. Where available, standard input datasets are relied upon in energy system models, irrespective of their research focus, representing the frontier of data availability. The modelling of cross-sectoral decarbonization will open new challenges, including the integration of sectors for which ever more data is required and the need to specify demand that is matched to the weather conditions influencing the increasing prevalence of variable renewable generation. For this, coupling with demand modelling tools is necessary, but nascent. In addition to issues of data availability, greater energy system complexity and reliance on non-dispatchable technologies exposes the inadequacy of exogenous demand. Instead, modelling tools must embrace elastic and endogenous demand to develop highly interconnected energy systems.

Third, when investigating many tools that can do different things in terms of modelling energy transitions, it becomes clear that it is impossible to build a tool that can do it all. Most of the tools have been developed to fulfil a specific task within a defined scope or according to specific user-needs. It might have received updates and an increased number of capabilities, but the underlying general architecture, technology, and terminology remains the same. We would argue that efforts should be targeted towards linking these different tools to each other, utilizing the many capabilities that are already present. Individual tool development is obviously still required and necessary, but there is a trade-off between the details and granularity of a model and computational resources. In line with this, future review efforts could also study in more detail model coupling exercises and identify more specifically which tools are coupled together, which specific typologies exist and the trade-offs of coupling approaches. For instance, this could be done by examining the coupling of energy system modelling tools with demand models, socio-technical energy transition models, etc.

Finally, the transparency and policy-relevant applications of energy system modelling tools should be put into a real-world perspective. For example, the complexity of linking modelling tools should not jeopardize the interpretability of the underlying modelling assumptions and outcomes, as this would detract modellers and output consumers (e.g. decision/policy-makers). In line with this, model development should be conducted in such a way that it leads to actionable research, and in which policy and decision support takes center stage. In this regard, further research could be conducted to identify how user-needs and policy-making processes mark the development of modelling tools actually used for decision-support, and which features these have and need.

In line with this, modelling interpretability goes beyond the access to open code and the perceived transparency that this provides. While open development and open source development is laudable and a recommended practice, the "out-of-the-box" usability of a tool also needs to be accounted for as an additional dimension of accessibility. Doing so could enhance the application of energy modelling tools and allow for a more active engagement with a wider multiplicity of actors that can actively contribute and enrich the energy policy debate by using modelling outcomes, while also validating the appropriateness of energy system modelling tools in the real-world arena.

CRediT authorship contribution statement

Miguel Chang: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Jakob Zink Thellufsen:** Conceptualization, Methodology, Writing - original draft, Supervision, Project administration. **Behnam Zakeri:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Bryn Pickering:** Conceptualization, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Stefan Pfenninger:** Conceptualization, Writing - review & editing. **Henrik Lund:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Poul Alberg Østergaard:** Writing - review & editing.

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.

Acknowledgements

We would like to thank the tool developers and users participating in the survey. We also thank David Connolly and other contributors in the work presented in [4], which served as initially inspiration and starting point for this study. This work received funding from the SENTINEL project of the European Union's Horizon 2020 research and innovation programme under grant agreement No 837089, and the RE-Invest project which is supported by the Innovation Fund Denmark under grant agreement No. 6154-00022B.

Appendix A. Survey questionnaire structure

1. General information
Name of the modelling tool
2. Modelling specifications
2.1. Modelling method
Simulation//Optimization//Equlibrium (specify)//Other (specify)
2.2. Purpose of the model's mathematical formulation
Investment cost minimization//Dispatch cost minimization//Electricity import/export minimization//Social welfare maximization//Fuel minimization//Multi-criteria analysis//Agent-based analysis//Other (specify)
2.3. User interface:
Graphical user interface//Web-based (online) user interface//Direct coding and programming//GUI with the possibility of coding if needed// Other (specify)
2.4. Accessibility of modelling tool:
Open source//Free (freeware)//Commercially (paid) licensed//Free under special conditions//Other (specify)
2.5. Additional modules or solvers needed to run the model
Yes/No
2.5.1. Based on the above, are the additional module/solver: (check all that apply)
Open source//Free (freeware)//Commercially (paid) licensed//Free under special conditions//Other (specify)
2.7. Possibility to add equations/sectors/technologies/add-ons or other details to the structure of the model
Yes//No//Specific parts (specify)
2.8. Derivative/branch-out versions based on the original modelling tool
Yes//No//Not known
3. Application
3.1. Previous case studies
(Specify)
3.2. Previous linkeages with other modelling tools
Yes, soft-linked (ie. linked using an external workflow and tools//Yes, hard-linked (ie . linked in the source code)//Yes, integrated (making a new merged model)//No//Not known
3.3. Main user-base
Academics//Government/public officials//NGOs//Private/commercial users//Not known//Others (specify)
3.4. Previous use for policy-making
Yes, directly (reference below)//Yes, indirectly referred in a relevant official document (reference below)//No//Not known
3.4.1. Policy-relevant reference
(Specify)
4. Modelling resolution
4.1. Geographical resolutions represented in the modelling tool (multiple choice)
Global//Regional//National//Local//Project-specific resolution//Other (specify)
4.2. Minimum level of granularity to represent a technology (multiple choice)
Aggregated values//Individual plant/component(s) inputs//Other (specify)
4.3. Typical scale of technology representation in national level modeling
(Specify)
4.4. Sectors represented in the model (multiple choice)
Electricity generation//Individual heating//District heating//Cooling// Transport//Industry//Biofuel production//Other (please specify)
4.5. Temporal resolution (multiple choice)
Hourly//Monthly//Seasonal time-slices//Yearly//Multi-year//Other (specify)
4.6. Time horizon of modeled outputs (multiple choice)
1-day//1-year//Multi-year (specify) //Other (specify)
5. Key inputs
5.1. Represention of demand
Static demand (no response to supply cost)//Elastic demand (responsive to supply cost)//Energy efficiency improvement cost curves//Demand is modeled endogenously//Others (specify)
5.2. Demand-side flexibility to integrate variable renewable energy
Yes, electricity and heat//Yes, only electricity//No//Other (specify)
5.3. Electricity generation technologies considered (multiple choice)
Power plants (Thermo electric)//CHP plants//Nuclear//Hydro power (dam)//Run-of-river hydro//Wind//Photovoltaic//Solar Thermal// Geothermal//Wave and/or Tidal//Other (specify) //Any (user-defined)
5.4. Heat supply technologies considered (multiple choice)
Heat pumps//Fuel-based boilers//Electric boilers//Solar thermal//CHP plants//Geothermal//Industrial excess heat//Other (specify) //Any (user defined)
5.4. Storage technologies considered (multiple choice)
Pumped hydroelectric energy storage //Battery electric storage// Compressed-air energy storage//Rockbed storage//Hydrogen production i. e. *electrolysis//Power to gas//Power to liuid//Power to heat (electric heat pump and heat storage)//Liquid & Gas fuel storage//Smart charging of electric vehicles//Other (specify) //Any (user-defined)*
5.5. Transport technologies and sub-sectors considered (multiple choice)
Internal combustion vehicles//Battery electric vehicles//Intelligent battery electric vehicles//Hybrid vehicles//Rail//Aviation//Other (specify) //Any (user-defined)
5.6. Representation of electricity transmission and bottlenecks in the grid
Yes, as a transshipment network//Yes, as a DC or AC load flow network//Yes, a point-to-pool network (no explicit bilateral trade)//No// Other (please specify)
6. Additional information
6.1. Overview of the modelling tool (developers' description)
(Specify)
6.2. Specific modelling focus on a technology or group of technologies listed in the previous sections (ie. if the modelling tool has more level of detail on a specific technology)
Yes (specify)/No
6.3. Public availability of tool's documentation
Yes (please provide source)/No
6.4. Format of modelling tool documentation
Documentation file available online//Documentation file published// Online documentation//Online documentation linked to the mathematical model//Other (specify)

Appendix B. Supplementary data – Survey inputs

The following is the supplementary data to this article: [208].

References

[1] IEA. World Energy Outlook 2018; 2018. https://doi.org/10.1787/weo-2018-en.

[2] Horschig T, Thrän D. Are decisions well supported for the energy transition? A review on modeling approaches for renewable energy policy evaluation. Energy Sustain Soc 2017;7. https://doi.org/10.1186/s13705-017-0107-2.

[3] Ellenbeck S, Lilliestam J. How modelers construct energy costs: Discursive elements in Energy System and Integrated Assessment Models. Energy Res Soc Sci 2019;47:69–77. https://doi.org/10.1016/j.erss.2018.08.021.

[4] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. https://doi.org/10.1016/j.apenergy.2009.09.026.

[5] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renew Sustain Energy Rev 2014;33:74–86. https://doi.org/10.1016/j.rser.2014.02.003.

[6] A review of modelling tools for energy and electricity systems with large shares of variable renewables.pdf n.d.

[7] Savvidis G, Siala K, Weissbart C, Schmidt L, Borggrefe F, Kumar S, et al. The gap between energy policy challenges and model capabilities. Energy Policy 2019;125:503–20. https://doi.org/10.1016/j.enpol.2018.10.033.

[8] Prina MG, Manzolini G, Moser D, Nastasi B, Sparber W. Classification and challenges of bottom-up energy system models - A review. Renew Sustain Energy Rev 2020;129:109917. https://doi.org/10.1016/j.rser.2020.109917.

[9] Grunwald A. Energy futures: Diversity and the need for assessment. Futur Evol Psychol 2011;43:820–30. https://doi.org/10.1016/j.futures.2011.05.024.

[10] Foley AM, Gallachóir BPÓ, Hur J, Baldick R, McKeogh EJ. A strategic review of electricity systems models. Energy 2010;35:4522–30. https://doi.org/10.1016/j.energy.2010.03.057.

[11] Després J, Hadjsaid N, Criqui P, Noirot I. Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. Energy 2015;80:486–95. https://doi.org/10.1016/j.energy.2014.12.005.

[12] Mahmud K, Town GE. A review of computer tools for modeling electric vehicle energy requirements and their impact on power distribution networks. Appl Energy 2016;172:337–59. https://doi.org/10.1016/j.apenergy.2016.03.100.

[13] Van Beeck NMJ. Classification of energy models. FEW Res Memo 1999.

[14] Jebaraj S, Iniyan S. A review of energy models. Renew Sustain Energy Rev 2006;10:281–311.

[15] Mougouei FR, Mortazavi MS. Effective approaches to energy planning and classification of energy systems models. Int J Energy Econ Policy 2017;7:127–31.

[16] Ridha E, Nolting L, Praktiknjo A. Complexity profiles: A large-scale review of energy system models in terms of complexity. Energy Strateg Rev 2020;30:100515. https://doi.org/10.1016/j.esr.2020.100515.

[17] Müller B, Gardumi F, Hülk L. Comprehensive representation of models for energy system analyses: Insights from the Energy Modelling Platform for Europe (EMP-E) 2017. Energy Strateg Rev 2018;21:82–7. https://doi.org/10.1016/j.esr.2018.03.006.

[18] Pilavachi PA, Dalamaga T, Rossetti di Valdalbero D, Guilmot JF. Ex-post evaluation of European energy models. Energy Policy 2008;36:1726–35.

[19] Unger T, Springfeldt PE, Ravn H, Niemi J, Fritz P, Rydén B, et al. Coordinated use of energy system models in energy and climate policy analysis - Lessons learned from the Nordic Energy Perspectives Project; 2010.

[20] Hall LMH, Buckley AR. A review of energy systems models in the UK: Prevalent usage and categorisation. Appl Energy 2016;169:607–28. https://doi.org/10.1016/j.apenergy.2016.02.044.

[21] Lopion P, Markewitz P, Robinius M, Stolten D. A review of current challenges and trends in energy systems modeling. Renew Sustain Energy Rev 2018;96:156–66. https://doi.org/10.1016/j.rser.2018.07.045.

[22] Bhattacharyya SC, Timilsina GR. A review of energy system models. Int J Energy Sect Manag 2010;4:494–518. https://doi.org/10.1108/17506221011092742.

[23] Musonye XS, Davíðsdóttir B, Kristjánsson R, Ásgeirsson EI, Stefánsson H. Integrated energy systems' modeling studies for sub-Saharan Africa: A scoping review. Renew Sustain Energy Rev 2020:128. https://doi.org/10.1016/j.rser.2020.109915.

[24] Markovic D, Cvetkovic D, Masic B. Survey of software tools for energy efficiency in a community. Renew Sustain Energy Rev 2011;15:4897–903. https://doi.org/10.1016/j.rser.2011.06.014.

[25] Keirstead J, Jennings M, Sivakumar A. A review of urban energy system models : Approaches, challenges and opportunities. Renew Sustain Energy Rev 2012;16:3847–66. https://doi.org/10.1016/j.rser.2012.02.047.

[26] Allegrini J, Orehounig K, Mavromatidis G, Ruesch F, Dorer V, Evins R. A review of modelling approaches and tools for the simulation of district-scale energy systems. Renew Sustain Energy Rev 2015;52:1391–404. https://doi.org/10.1016/j.rser.2015.07.123.

[27] Van Beuzekom I, Gibescu M, Slootweg JG. A review of multi-energy system planning and optimization tools for sustainable urban development. In: 2015 IEEE Eindhoven PowerTech, PowerTech 2015; 2015. p. 1–7. https://doi.org/10.1109/PTC.2015.7232360.

[28] Ferrari S, Zagarella F, Caputo P, Bonomolo M. Assessment of tools for urban energy planning. Energy 2019;176:544–51. https://doi.org/10.1016/j.energy.2019.04.054.

[29] Scheller F, Bruckner T. Energy system optimization at the municipal level: An analysis of modeling approaches and challenges. Renew Sustain Energy Rev 2019;105:444–61. https://doi.org/10.1016/j.rser.2019.02.005.

[30] Sinha S, Chandel SS. Review of recent trends in optimization techniques for solar photovoltaic-wind based hybrid energy systems. Renew Sustain Energy Rev 2015;50:755–69. https://doi.org/10.1016/j.rser.2015.05.040.

[31] Weinand JM, Scheller F, McKenna R. Reviewing energy system modelling of decentralized energy autonomy. Energy 2020;203:117817. https://doi.org/10.1016/j.energy.2020.117817.

[32] Lund H, Arler F, Østergaard PA, Hvelplund F, Connolly D, Mathiesen BV, et al. Simulation versus optimisation: Theoretical positions in energy system modelling. Energies 2017;10:1–17. https://doi.org/10.3390/en10070840.

[33] Crespo del Granado P, van Nieuwkoop RH, Kardakos EG, Schaffner C. Modelling the energy transition: A nexus of energy system and economic models. In: Energy Strateg Rev, 20; 2018. p. 229–35. https://doi.org/10.1016/j.esr.2018.03.004.

[34] Hirt LF, Schell G, Sahakian M, Trutnevyte E. A review of linking models and socio-technical transitions theories for energy and climate solutions. Environ Innov Soc Transitions 2020;35:162–79. https://doi.org/10.1016/j.eist.2020.03.002.

[35] Fattahi A, Sijm J, Faaij A. A systemic approach to analyze integrated energy system modeling tools, a review of national models. Renew Sustain Energy Rev 2020;133:110195. https://doi.org/10.1016/j.rser.2020.110195.

[36] Olsthoorn D, Haghighat F, Mirzaei PA. Integration of storage and renewable energy into district heating systems: A review of modelling and optimization. Sol Energy 2016;136:49–64. https://doi.org/10.1016/j.solener.2016.06.054.

[37] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.

[38] Thellufsen JZ, Lund H. Cross-border versus cross-sector interconnectivity in renewable energy systems. Energy 2017;124:492–501. https://doi.org/10.1016/j.energy.2017.02.112.

[39] Li FGN, Trutnevyte E, Strachan N. A review of socio-technical energy transition (STET) models. Technol Forecast Soc Change 2015;100:290–305. https://doi.org/10.1016/j.techfore.2015.07.017.

[40] Li FGN, Strachan N. Take me to your leader: Using socio-technical energy transitions (STET) modelling to explore the role of actors in decarbonisation pathways. Energy Res Soc Sci 2019;51:67–81. https://doi.org/10.1016/j.erss.2018.12.010.

[41] Trutnevyte E, Hirt LF, Bauer N, Cherp A, Hawkes A, Edelenbosch OY, et al. Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. One Earth 2019;1:423–33. https://doi.org/10.1016/j.oneear.2019.12.002.

[42] Bolwig S, Bazbauers G, Klitkou A, Lund PD, Blumberga A, Gravelsins A, et al. Review of modelling energy transitions pathways with application to energy system fl exibility. Renew Sustain Energy Rev 2019;101:440–52. https://doi.org/10.1016/j.rser.2018.11.019.

[43] Bolwig S, Folsland T, Klitkou A, Lund PD, Bergaentzlé C, Borch K, et al. Energy Research & Social Science Climate-friendly but socially rejected energy-transition pathways : The integration of techno-economic and socio-technical approaches in the Nordic-Baltic region. Energy Res Soc Sci 2020;67:101559. https://doi.org/10.1016/j.erss.2020.101559.

[44] Bazilian M, Rice A, Rotich J, Howells M, DeCarolis J, Macmillan S, et al. Open source software and crowdsourcing for energy analysis. Energy Policy 2012;49:149–53. https://doi.org/10.1016/j.enpol.2012.06.032.

[45] Pfenninger S, Hirth L, Schlecht I, Schmid E, Wiese F, Brown T, et al. Opening the black box of energy modelling: Strategies and lessons learned. Energy Strateg Rev 2017;19:63–71. https://doi.org/10.1016/j.esr.2017.12.002.

[46] Morrison R. Energy system modeling: Public transparency, scientific reproducibility, and open development. Energy Strateg Rev 2018;20:49–63. https://doi.org/10.1016/j.esr.2017.12.010.

[47] Oberle S, Elsland R. Are open access models able to assess today's energy scenarios? Energy Strateg Rev 2019;26:100396. https://doi.org/10.1016/j.esr.2019.100396.

[48] Groissböck M. Are open source energy system optimization tools mature enough for serious use? Renew Sustain Energy Rev 2019;102:234–48. https://doi.org/10.1016/j.rser.2018.11.020.

[49] openmod. Open Energy Modelling Initiative; 2020. https://openmod-initiative.org/[accessed February 23, 2020].

[50] REEEM Energy Systems Modelling Project. Role of Technologies in an Energy Efficient Economy – Model Based Analysis Policy Measures and Transformation Pathways to a Sustainable Energy System; 2018.

[51] MEDEAS. Modelling the Energy Development under Environmental and Socioeconomic Contraints;2018; n.d. http://www.medeas.eu/[accessed February 24, 2020].

[52] SET-nav. Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation 2018. http://www.set-nav.eu/[accessed February 24, 2020].

[53] REFLEX. Analysis of the European Energy System under the Aspects of Flexibility and Technological Progress 2018. http://reflex-project.eu/.

[54] openENTRANCE. Open Energy Transition Analyses for a low-Carbon Economy 2019. https://openentrance.eu/[accessed February 24, 2020].

[55] SENTINEL. Sustainable Energy Transitions Laboratory 2019. https://sentinel.energy/[accessed February 24, 2020].

[56] Klemm C, Vennemann P. Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches. Renew Sustain Energy Rev 2021;135:110206. https://doi.org/10.1016/j.rser.2020.110206.

[57] Lund H, Thellufsen JZ. EnergyPLAN - Advance Energy Systems Anaysis Computer Model (Version 15.1) 2020. https://doi.org/10.5281/zenodo.4001540.

[58] Ben Amer S, Gregg JS, Sperling K, Drysdale D. Too complicated and impractical? An exploratory study on the role of energy system models in municipal decision-making processes in Denmark. Energy Res Soc Sci 2020;70:101673. https://doi.org/10.1016/j.erss.2020.101673.

[59] Silvast A, Laes E, Abram S, Bombaerts G. What do energy modellers know? An ethnography of epistemic values and knowledge models. Energy Res Soc Sci 2020;66:101495. https://doi.org/10.1016/j.erss.2020.101495.
[60] Mundaca L, Neij L, Worrell E, McNeil M. Evaluating energy efficiency policies with energy-economy models. Annu Rev Environ Resour 2010;35:305–44. https://doi.org/10.1146/annurev-environ-052810-164840.
[61] Mendes G, Ioakimidis C, Ferrão P. On the planning and analysis of Integrated Community Energy Systems: A review and survey of available tools. Renew Sustain Energy Rev 2011;15:4836–54. https://doi.org/10.1016/j.rser.2011.07.067.
[62] Manfren M, Caputo P, Costa G. Paradigm shift in urban energy systems through distributed generation: Methods and models. Appl Energy 2011;88:1032–48. https://doi.org/10.1016/j.apenergy.2010.10.018.
[63] DeCarolis JF, Hunter K, Sreepathi S. The case for repeatable analysis with energy economy optimization models. Energy Econ 2012;34:1845–53. https://doi.org/10.1016/j.eneco.2012.07.004.
[64] Mirakyan A, De Guio R. Integrated energy planning in cities and territories: A review of methods and tools. Renew Sustain Energy Rev 2013;22:289–97. https://doi.org/10.1016/j.rser.2013.01.033.
[65] Huang Z, Yu H, Peng Z, Zhao M. Methods and tools for community energy planning: A review. Renew Sustain Energy Rev 2015;42:1335–48. https://doi.org/10.1016/j.rser.2014.11.042.
[66] Lund H, Arler F, Østergaard P, Hvelplund F, Connolly D, Mathiesen B, et al. Simulation versus Optimisation: Theoretical Positions in Energy System Modelling. Energies 2017;10:840. https://doi.org/10.3390/en10070840.
[67] Lyden A, Pepper R, Tuohy PG. A modelling tool selection process for planning of community scale energy systems including storage and demand side management. Sustain Cities Soc 2018;39:674–88. https://doi.org/10.1016/j.scs.2018.02.003.
[68] Abbasabadi N, Mehdi Ashayeri JK. Urban energy use modeling methods and tools: A review and an outlook. Build Environ 2019;161:106270. https://doi.org/10.1016/j.buildenv.2019.106270.
[69] Loulou R, Remme U, Anudia A, Lettila A, Goldstein G. Documentation for the TIMES Model - PART I; 2005.
[70] Yang C, Yeh S, Zakerinia S, Ramea K, McCollum D. Achieving California's 80% greenhouse gas reduction target in 2050: Technology, policy and scenario analysis using CA-TIMES energy economic systems model. Energy Policy 2015;77:118–30. https://doi.org/10.1016/j.enpol.2014.12.006.
[71] Shi J, Chen W, Yin X. Modelling building's decarbonization with application of China TIMES model. Appl Energy 2016;162:1303–12. https://doi.org/10.1016/j.apenergy.2015.06.056.
[72] Salvucci R, Gargiulo M, Karlsson K. The role of modal shift in decarbonising the Scandinavian transport sector: Applying substitution elasticities in TIMES-Nordic. Appl Energy 2019;253:113593. https://doi.org/10.1016/j.apenergy.2019.113593.
[73] Di Leo S, Caramuta P, Curci P, Cosmi C. Regression analysis for energy demand projection: An application to TIMES-Basilicata and TIMES-Italy energy models. Energy 2020;196:117058. https://doi.org/10.1016/j.energy.2020.117058.
[74] Nijs W, Simoes S, Sgobbi A, Ruiz-Castello P, Thiel C, Giannakidis G, et al. Improved Representation of the European Power Grid in Long Term Energy System Models: Case Study of JRC-EU-TIMES. In: Giannakidis G, Labriet M, Ó Gallachóir B, Tosato G, editors. Informing Energy Clim. Policies Using Energy Syst. Model. Insights from Scenar. Anal. Increasing Evid. Base, Cham: Springer International Publishing; 2015. p. 201–22. https://doi.org/10.1007/978-3-319-16540-0_12.
[75] Howells M, Rogner H, Strachan N, Heaps C, Huntington H, Kypreos S, et al. OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development. Energy Policy 2011;39:5850–70. https://doi.org/10.1016/j.enpol.2011.06.033.
[76] Löffler K, Hainsch K, Burandt T, Oei PY, Kemfert C. Von Hirschhausen C. Designing a model for the global energy system-GENeSYS-MOD: An application of the Open-Source Energy Modeling System (OSeMOSYS). Energies 2017;10. https://doi.org/10.3390/en10101468.
[77] Wiese F, Bramstoft R, Koduvere H, Pizarro Alonso A, Balyk O, Kirkerud JG, et al. Balmorel open source energy system model. Energy Strateg Rev 2018;20:26–34. https://doi.org/10.1016/j.esr.2018.01.003.
[78] Pfenninger S, Pickering B. Calliope: a multi-scale energy systems modelling framework. J Open Source Softw 2018;3:825. https://doi.org/10.21105/joss.00825.
[79] Energianalyse. COMPOSE n.d. http://www.energianalyse.dk/index.php/software [accessed September 17, 2020].
[80] Berkeley Lab. DER-CAM n.d. https://gridintegration.lbl.gov/der-cam [accessed September 17, 2020].
[81] Zerrahn A, Schill WP. Long-run power storage requirements for high shares of renewables: review and a new model. Renew Sustain Energy Rev 2017;79:1518–34. https://doi.org/10.1016/j.rser.2016.11.098.
[82] Quoilin S, Hidalgo Ganzalez I, Zucker A. Modelling Future EU Power Systems Under High Shares of Renewables The Dispa-SET 2.1 open-source model; 2017. https://doi.org/10.2760/25400.
[83] Sun N. Model-based investigation of the electricity market: unit commitment and power plant investments; 2013.
[84] Chappin EJL, de Vries LJ, Richstein JC, Bhagwat P, Iychettira K, Khan S. Simulating climate and energy policy with agent-based modelling: The Energy Modelling Laboratory (EMLab). Environ Model Softw 2017;96:421–31. https://doi.org/10.1016/j.envsoft.2017.07.009.
[85] Hirth L. The European electricity market model EMMA 2014:12.
[86] Skar C, Doorman GL, Pérez-Valdés GA, Tomasgard A. A multi-horizon stochastic programming model for the European power system; 2016.
[87] Zakeri B, Virasjoki V, Syri S, Connolly D, Mathiesen BV, Welsch M. Impact of Germany's energy transition on the Nordic power market – A market-based multi-region energy system model. Energy 2016;115:1640–62. https://doi.org/10.1016/j.energy.2016.07.083.
[88] Quintel Intelligence. Energy Transition Model n.d. https://docs.energytransitionmodel.com/main/intro/[accessed September 17, 2020].
[89] EMD International A/S. energyPRO n.d. https://www.emd.dk/energypro/support/tutorials-guides/[accessed September 17, 2020].
[90] Lugovoy O, Potashnikov V. energyRt n.d. https://energyrt.org/[accessed September 17, 2020].
[91] Limpens G, Moret S, Jeanmart H, Maréchal F. EnergyScope TD: A novel open-source model for regional energy systems. Appl Energy 2019;255:113729. https://doi.org/10.1016/j.apenergy.2019.113729.
[92] Fraunhofer ISI. Enertile n.d. https://www.enertile.eu/enertile-en/publication.php [accessed September 17, 2020].
[93] Fraunhofer ISE. ENTIGRIS n.d. https://www.ise.fraunhofer.de/en/business-areas/power-electronics-grids-and-smart-systems/energy-system-analysis/energy-system-models-at-fraunhofer-ise/entigris.html [accessed September 17, 2020].
[94] Heuberger CF. Electricity Systems Optimisation with capacity eXpansion and Endogenous technology Learning (ESO-XEL) 2017. https://doi.org/10.5281/zenodo.1048942.
[95] Despres J. Development of a dispatch model of the European power system for coupling with a long-term foresight energy model. Cah Rech EDDEN 2015;37.
[96] JRC - Smart Electricity Systems and Interoperability. EUPowerDispatch n.d. https://ses.jrc.ec.europa.eu/eupowerdispatch-model [accessed September 17, 2020].
[97] Peñate Vera S. GridCal n.d. https://gridcal.readthedocs.io/en/latest/# [accessed September 17, 2020].
[98] Homer Energy. Homer Grid n.d. https://www.homerenergy.com/products/grid/index.html [accessed July 19, 2020].
[99] Dufo López R. iHOGA n.d. https://ihoga.unizar.es/en/[accessed September 17, 2020].
[100] Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., et al. Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications; 2014.
[101] Kuhn P. Iteratives Modell zur Optimierung von Speicherausbau und -betrieb in einem Stromsystem mit zunehmend fluktuierender Erzeugung; 2012.
[102] Strbac G, Pudjianto D, Sansom R, Djapic P, Ameli H, Shah N, et al. Analysis of Alternative UK Heat Decarbonisation Pathways 2018:159.
[103] EEG. Invert-EELab n.d. https://www.invert.at/.
[104] Aune FR, Golombek R, Kittelsen SAC, Rosendahl KE. Liberalizing European Energy MarketsAn Economic Analysis. Cheltenham, UK: Edward Elgar Publishing; 2008.
[105] Osorio S, Pietzcker R, Tietjen O. Documentation of LIMES-EU - A long-term electricity system model for Europe 2020.
[106] Jacobson MZ, Delucchi MA, Cameron MA, Mathiesen BV. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. Renew Energy 2018;123:236–48. https://doi.org/10.1016/j.renene.2018.02.009.
[107] Jacobson MZ, Delucchi MA, Cameron MA, Coughlin SJ, Hay CA, Manogaran IP, et al. Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries. One Earth 2019;1:449–63. https://doi.org/10.1016/j.oneear.2019.12.003.
[108] Van Den Bergh K, Bruninx K, Delarue E, D'haeseleer W. LUSYM: a Unit Commitment Model formulated as a Mixed-Integer Linear Program 2016.
[109] Maon GmbH. Maon n.d. https://cloud.maon.eu/handbook [accessed September 17, 2020].
[110] Huppmann D, Gidden M, Fricko O, Kolp P, Orthofer C, Pimmer M, et al. The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. Environ Model Softw 2019;112:143–56. https://doi.org/10.1016/j.envsoft.2018.11.012.
[111] Energy Information Administration. The National Energy Modeling System: An Overview 2018; 2019.
[112] EPRI. OpenDSS n.d. https://sourceforge.net/projects/electricdss/[accessed July 17, 2020].
[113] FFG. OptEnGrid n.d. https://projekte.ffg.at/projekt/1822013 [accessed September 17, 2020].
[114] Després J, Keramidas K, Schmitz A, Kitous A, Schade B, Diaz Vasquez A, et al. POLES-JRC model documentation. Publications Office of the European Union; 2018. https://doi.org/10.2760/814959.
[115] Mantzos L, Wiesenthal T. POTEnCIA model description: Version 0.9. vol. JRC100638; 2016. https://doi.org/10.2791/416465.
[116] E3MLab. Primes Model version 2018: detailed model description 2018.
[117] PSR. SDDP User Mannual Version 16.0 2019.
[118] Capellán-Pérez I, De Blas I, Nieto J, De Castro C, Miguel LJ, Carpintero Ó, et al. MEDEAS: A new modeling framework integrating global biophysical and socioeconomic constraints. Energy Environ Sci 2020;13:986–1017. https://doi.org/10.1039/c9ee02627d.
[119] Brown T, Hörsch J, Schlachtberger D. PyPSA Python for power system analysis. J Open Res Softw 2018;6. https://doi.org/10.5334/jors.188.
[120] Energistyrelsen. RamsesR 2018:1–38.

[121] Cohen S, Becker J, Bielen D, Brown M, Cole W, Eurek K, et al. Regional Energy Deployment System (ReEDS) Model Documentation: Version 2018. Natl Renew Energy Lab 2019. https://doi.org/NREL/TP-6A20-67067.
[122] Aboumahboub T, Auer C, Bauer N, Baumstark L, Bertram C, Bi S, et al. REMIND - REgional Model of INvestments and Development - Version 2.1.0 2020.
[123] Energinet. SIFRE: Simulation of Flexible and Renewable Energy sources 2015: 1–34.
[124] Blair N, Diorio N, Freeman J, Gilman P, Janzou S, Neises TW, et al. System Advisor Model (SAM) General Description (Version 2017.9.5) 2018.
[125] TUHH. TransiEnt Library n.d. https://www.tuhh.de/transient-ee/en/news.html [accessed September 17, 2020].
[126] Leaver JD, Gillingham KT, Leaver LHT. Assessment of primary impacts of a hydrogen economy in New Zealand using UniSyD. Int J Hydrogen Energy 2009; 34:2855–65.
[127] Mayer J, Bachner G, Steininger KW. Macroeconomic implications of switching to process-emission-free iron and steel production in Europe. J Clean Prod 2019; 210:1517–33. https://doi.org/10.1016/j.jclepro.2018.11.118.
[128] RFF-CMCC-EIEE. WITCH Model n.d. https://www.witchmodel.org/documentation/[accessed September 17, 2020].
[129] NEP. Coordinated use of Energy system models in Energy and Climate policy analysis; 2010.
[130] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33. https://doi.org/10.1016/j.apenergy.2015.05.086.
[131] Poncelet K, Delarue E, Six D, Duerinck J, D'haeseleer W. Impact of the level of temporal and operational detail in energy-system planning models. Appl Energy 2016;162:631–43. https://doi.org/10.1016/j.apenergy.2015.10.100.
[132] Deane JP, Drayton G, Ó Gallachóir BP. The impact of sub-hourly modelling in power systems with significant levels of renewable generation. Appl Energy 2014; 113:152–8. https://doi.org/10.1016/j.apenergy.2013.07.027.
[133] Pfenninger S. Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability. Appl Energy 2017;197:1–13. https://doi.org/10.1016/j.apenergy.2017.03.051.
[134] McCallum P, Jenkins DP, Peacock AD, Patidar S, Andoni M, Flynn D, et al. A multi-sectoral approach to modelling community energy demand of the built environment. Energy Policy 2019;132:865–75. https://doi.org/10.1016/j.enpol.2019.06.041.
[135] Keppo I, Strubegger M. Short term decisions for long term problems - The effect of foresight on model based energy systems analysis. Energy 2010;35:2033–42. https://doi.org/10.1016/j.energy.2010.01.019.
[136] Prina MG, Lionetti M, Manzolini G, Sparber W, Moser D. Transition pathways optimization methodology through EnergyPLAN software for long-term energy planning. Appl Energy 2019:356–68. https://doi.org/10.1016/j.apenergy.2018.10.099.
[137] Capros P, De Vita A, Tasios N, Siskos P, Kannavou M, Petropoulos A, et al. EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050. European Commission; 2016.
[138] Capros P, Kannavou M, Evangelopoulou S, Petropoulos A, Siskos P, Tasios N, et al. Outlook of the EU energy system up to 2050: The case of scenarios prepared for European Commission ' s " clean energy for all Europeans " package using the PRIMES model. Energy Strateg Rev 2018;22:255–63. https://doi.org/10.1016/j.esr.2018.06.009.
[139] Capros P, Zazias G, Evangelopoulou S, Kannavou M, Fotiou T, Siskos P, et al. Energy-system modelling of the EU strategy towards climate-neutrality ☆. Energy Policy 2019;134:110960. https://doi.org/10.1016/j.enpol.2019.110960.
[140] Solé J, Samsó R, García-Ladona E, García-Olivares A, Ballabrera-Poy J, Madurell T, et al. Modelling the renewable transition: Scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model. Renew Sustain Energy Rev 2020;132:37–49. https://doi.org/10.1016/j.rser.2020.110105.
[141] Bacekovic I, Østergaard PA. Local smart energy systems and cross-system integration. Energy 2018. https://doi.org/10.1016/j.energy.2018.03.098.
[142] Thellufsen JZ, Lund H, Sorknæs P, Østergaard PA, Chang M, Drysdale D, et al. Smart energy cities in a 100% renewable energy context. Renew Sustain Energy Rev 2020;129. https://doi.org/10.1016/j.rser.2020.109922.
[143] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's Energy Vision 2050. Copenhagen: Aalborg University; 2015.
[144] Paardekooper S, Lund RS, Mathiesen BV, Chang M, Petersen UR, Grundahl L, et al. Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps; 2018.
[145] Hansen K, Mathiesen BV, Skov IR. Full energy system transition towards 100% renewable energy in Germany in 2050. Renew Sustain Energy Rev 2019;102: 1–13. https://doi.org/10.1016/J.RSER.2018.11.038.
[146] Paardekooper S, Lund H, Chang M, Nielsen S, Moreno D, Thellufsen JZ. Heat Roadmap Chile: A national district heating plan for air pollution decontamination and decarbonisation. J Clean Prod 2020;272.
[147] Dominković DF, Bačeković I, Ćosić B, Krajačić G, Pukšec T, Duić N, et al. Zero carbon energy system of South East Europe in 2050. Appl Energy 2016;184: 1517–28. https://doi.org/10.1016/j.apenergy.2016.03.046.
[148] Dominković DF, Dobravec V, Jiang Y, Nielsen PS, Krajačić G. Modelling smart energy systems in tropical regions. Energy 2018;155:592–609. https://doi.org/10.1016/j.energy.2018.05.007.
[149] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53.
[150] Robinson JB. Energy backcasting A proposed method of policy analysis. Energy Policy 1982;10:337–44. https://doi.org/10.1016/0301-4215(82)90048-9.
[151] Dreborg KH. Essence of backcasting. Futures 1996;28:813–28. https://doi.org/10.1016/S0016-3287(96)00044-4.
[152] Höjer M, Mattsson L-G. Determinism and backcasting in future studies. Futures 2000;32:613–34. https://doi.org/10.1016/S0016-3287(00)00012-4.
[153] Paehlke R. Backcasting as a policy tool: The role of values. Crit Policy Stud 2012; 6:337–48. https://doi.org/10.1080/19460171.2012.704975.
[154] Thellufsen JZ, Paardekooper S, Chang M, Lund H. Benefits to single country modelling: Comparing 14 interconnected individual country models to a single 14-country model. In: 5th Int. Conf. Smart Energy Syst. 4th Gener. Dist. Heating, Electrif. Electrofuels Energy Effic. - Langelin. Pavillonen, Copenhagen, Denmark, Copenhagen, Denmark; 2019. p. 244.
[155] Thellufsen JZ, Chang M. Modelling an individual country within the context of the surrounding energy systems – the importance of detail. Proc. 2nd LA SDEWES Conf.. 2020.
[156] Østergaard PA, Andersen AN. Booster heat pumps and central heat pumps in district heating. Appl Energy 2016;184:1374–88. https://doi.org/10.1016/j.apenergy.2016.02.144.
[157] Ben Amer-Allam S, Münster M, Petrović S. Scenarios for sustainable heat supply and heat savings in municipalities - The case of HelsingØr, Denmark. Energy 2017;137:1252–63. https://doi.org/10.1016/j.energy.2017.06.091.
[158] Østergaard PA, Jantzen J, Marczinkowski HM, Kristensen M. Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems. Renew Energy 2019;139:904–14. https://doi.org/10.1016/j.renene.2019.02.140.
[159] Pavičević M, Mangipinto A, Nijs W, Lombardi F, Kavvadias K, Jiménez Navarro JP, et al. The potential of sector coupling in future European energy systems: Soft linking between the Dispa-SET and JRC-EU-TIMES models. Appl Energy 2020;267:115100. https://doi.org/10.1016/j.apenergy.2020.115100.
[160] Connolly D. Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries. Energy 2017;139:580–93. https://doi.org/10.1016/j.energy.2017.07.037.
[161] Mathiesen BV, Lund H, Connolly D, Wenzel H, Ostergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. https://doi.org/10.1016/j.apenergy.2015.01.075.
[162] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. Energy 2018;160:720–39. https://doi.org/10.1016/j.energy.2018.06.222.
[163] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80. https://doi.org/10.1016/j.energy.2019.03.092.
[164] Darby SJ. Demand response and smart technology in theory and practice: Customer experiences and system actors. Energy Policy 2020;143:111573. https://doi.org/10.1016/j.enpol.2020.111573.
[165] Anjo J, Neves D, Silva C, Shivakumar A, Howells M. Modeling the long-term impact of demand response in energy planning: The Portuguese electric system case study. Energy 2018;165:456–68. https://doi.org/10.1016/j.energy.2018.09.091.
[166] Child M, Breyer C. Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050. Renew Sustain Energy Rev 2016;66:517–36. https://doi.org/10.1016/j.rser.2016.07.001.
[167] Schröder M, Abdin Z, Mérida W. Optimization of distributed energy resources for electric vehicle charging and fuel cell vehicle refueling. Appl Energy 2020;277: 115562. https://doi.org/10.1016/j.apenergy.2020.115562.
[168] Neves D, Pina A, Silva CA. Demand response modeling: A comparison between tools. Appl Energy 2015;146:288–97. https://doi.org/10.1016/j.apenergy.2015.02.057.
[169] O'Connell N, Pinson P, Madsen H, O'Malley M. Benefits and challenges of electrical demand response: A critical review. Renew Sustain Energy Rev 2014; 39:686–99. https://doi.org/10.1016/j.rser.2014.07.098.
[170] ENTSO-E. ENTSO-E Transparency Platform n.d. https://transparency.entsoe.eu/[accessed October 3, 2018].
[171] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission extension in a cost-optimised, highly renewable European energy system 2018.
[172] Schlott M, Kies A, Brown T, Schramm S, Greiner M. The impact of climate change on a cost-optimal highly renewable European electricity network. Appl Energy 2018;230:1645–59. https://doi.org/10.1016/j.apenergy.2018.09.084.
[173] Zappa W, Junginger M, van den Broek M. Is a 100% renewable European power system feasible by 2050? Appl Energy 2019;233–234:1027–50. https://doi.org/10.1016/j.apenergy.2018.08.109.
[174] Lombardi F, Pickering B, Colombo E, Pfenninger S. Policy Decision Support for Renewables Deployment through Spatially Explicit Practically Optimal Alternatives. Joule 2020;4:2185–207. https://doi.org/10.1016/j.joule.2020.08.002.
[175] Díaz Redondo P, van Vliet O. Modelling the Energy Future of Switzerland after the Phase Out of Nuclear Power Plants. Energy Procedia 2015;76:49–58. https://doi.org/10.1016/j.egypro.2015.07.843.
[176] Hilbers AP, Brayshaw DJ, Gandy A. Importance subsampling: improving power system planning under climate-based uncertainty. Appl Energy 2019;251:113114. https://doi.org/10.1016/j.apenergy.2019.04.110.

[177] Pfenninger S, Keirstead J. Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. Appl Energy 2015;152:83–93. https://doi.org/10.1016/j.apenergy.2015.04.102.
[178] Lombardi F, Rocco MV, Colombo E. A multi-layer energy modelling methodology to assess the impact of heat-electricity integration strategies: The case of the residential cooking sector in Italy. Energy 2019;170:1249–60. https://doi.org/10.1016/j.energy.2019.01.004.
[179] Möller C, Kuhnke K, Reckzügel M, Pfisterer H-J, Rosenberger S. Energy storage potential in the Northern German region Osnabrück-Steinfurt. In: 2016 Int. Energy Sustain. Conf.; 2016. p. 1–7. https://doi.org/10.1109/IESC.2016.7569497.
[180] Hörsch J, Hofmann F, Schlachtberger D, Brown T. PyPSA-Eur: An open optimisation model of the European transmission system. Energy Strateg Rev 2018;22:207–15. https://doi.org/10.1016/j.esr.2018.08.012.
[181] Kiviluoma J, Meibom P. Methodology for modelling plug-in electric vehicles in the power system and cost estimates for a system with either smart or dumb electric vehicles. Energy 2011;36:1758–67. https://doi.org/10.1016/j.energy.2010.12.053.
[182] U.S. Energy Information Administration. International Energy Outlook 2016. Washington, DC; 2016.
[183] Child M, Nordling A, Breyer C. Scenarios for a sustainable energy system in the Åland Islands in 2030. Energy Convers Manag 2017;137:49–60. https://doi.org/10.1016/j.enconman.2017.01.039.
[184] Østergaard PA, Andersen FM, Kwon PS. Energy systems scenario modelling and long term forecasting of hourly electricity Demand. Int J Sustain Energy Plan Manag 2015;7:99–116. https://doi.org/10.5278/ijsepm.2015.7.8.
[185] Kwon PS, Østergaard P. Assessment and evaluation of flexible demand in a Danish future energy scenario. Appl Energy 2014;134:309–20. https://doi.org/10.1016/j.apenergy.2014.08.044.
[186] Bossmann T, Staffell I. The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. Energy 2015;90:1317–33. https://doi.org/10.1016/j.energy.2015.06.082.
[187] Riva F, Gardumi F, Tognollo A, Colombo E. Soft-linking energy demand and optimisation models for local long-term electricity planning: An application to rural India. Energy 2019;166:32–46. https://doi.org/10.1016/j.energy.2018.10.067.
[188] Nijs W, Gonzalez H, Paardekooper S. JRC-EU-TIMES and EnergyPLAN comparison - Deliverable 6.3: Methodology report for comparing the scenarios between JRC-EUTIMES and EnergyPLAN; 2018.
[189] Krook-Riekkola A, Berg C, Ahlgren EO, Söderholm P. Challenges in top-down and bottom-up soft-linking: Lessons from linking a Swedish energy system model with a CGE model. Energy 2017;141:803–17. https://doi.org/10.1016/j.energy.2017.09.107.
[190] Andersen KS, Termansen LB, Gargiulo M, Gallachóirc ÓBP. Bridging the gap using energy services: Demonstrating a novel framework for soft linking top-down and bottom-up models. Energy 2019:277–93. https://doi.org/10.1016/j.energy.2018.11.153.
[191] Helgesen PI, Lind A, Ivanova O, Tomasgard A. Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport. Energy 2018;156:196–212. https://doi.org/10.1016/j.energy.2018.05.005.
[192] Deane JP, Chiodi A, Gargiulo M, Gallachóir BPÓ. Soft-linking of a power systems model to an energy systems model. Energy 2012;42:303–12. https://doi.org/10.1016/j.energy.2012.03.052.
[193] Nijs W, González IH, Paardekooper S. JRC-EU-TIMES and EnergyPLAN comparison Deliverable 6.3: Methodology report for comparing the JRC-EU-TIMES and EnergyPLAN scenarios; 2018.
[194] Thellufsen JZ, Nielsen S, Lund H. Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland. J Clean Prod 2019;214:377–88. https://doi.org/10.1016/j.jclepro.2018.12.303.
[195] Sadri A, Ardehali MM, Amirnekooei K. General procedure for long-term energy-environmental planning for transportation sector of developing countries with limited data based on LEAP (long-range energy alternative planning) and EnergyPLAN. Energy n.d. https://doi.org/https://doi.org/10.1016/j.energy.2014.09.067.
[196] Strachan N, Balta-Ozkan N, Joffe D, McGeevor K, Hughes N. Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. Int J Hydrogen Energy 2009;34:642–57. https://doi.org/10.1016/j.ijhydene.2008.10.083.
[197] Blanco H, Nijs W, Ruf J, Faaij A. Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization. Appl Energy 2018;232:323–40. https://doi.org/10.1016/j.apenergy.2018.08.027.
[198] Novosel T, Perkovi L, Ban M, Keko H, Puk T, Kraja G. Agent based modelling and energy planning e Utilization of MATSim for transport energy demand modelling 2015;92:466–75. https://doi.org/10.1016/j.energy.2015.05.091.
[199] Pfenninger S, DeCarolis J, Hirth L, Quoilin S, Staffell I. The importance of open data and software: Is energy research lagging behind? Energy Policy 2017;101:211–5. https://doi.org/10.1016/j.enpol.2016.11.046.
[200] Cao KK, Cebulla F, Gómez Vilchez JJ, Mousavi B, Prehofer S. Raising awareness in model-based energy scenario studies—a transparency checklist. Energy Sustain Soc 2016;6. https://doi.org/10.1186/s13705-016-0090-z.
[201] Pianosi F, Sarrazin F, Wagener T. How successfully is open-source research software adopted? Results and implications of surveying the users of a sensitivity analysis toolbox. Environ Model Softw 2020;124:104579. https://doi.org/10.1016/j.envsoft.2019.104579.
[202] Carrillo AL, Martinez S, Falgueras J, Scott-Brown KC. A reflective characterisation of occasional user. Comput Human Behav 2017;70:74–89. https://doi.org/10.1016/j.chb.2016.12.027.
[203] Savidis A, Stephanidis C. Unified user interface design: Designing universally accessible interactions. Interact Comput 2004;16:243–70. https://doi.org/10.1016/j.intcom.2003.12.003.
[204] Koppelaar RHEM, Keirstead J, Shah N, Woods J. A review of policy analysis purpose and capabilities of electricity system models. Renew Sustain Energy Rev 2016;59:1531–44. https://doi.org/10.1016/j.rser.2016.01.090.
[205] European Commission. In-depth analysis in support of the Commission Communication COM(2018) 773 A Clean Planet for all. Brussels: 2018.
[206] Mathiesen B V., Lund H, Hansen K, Ridjan I, Djørup SR, Nielsen S, et al. IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark. Dep Dev Planning, Aalborg Un 2015:156 pp. https://doi.org/ISBN: 978-87-91404-78-8.
[207] Lund H, Thellufsen JZ, Østergaard PA, Nielsen S, Sperling K, Djørup SR, et al. Smart Energy Aalborg; 2019.
[208] Chang M, Thellufsen J, Zakeri B, Lund H. Survey of energy system modelling tools - Results. Mendeley Data 2021;V1. https://doi.org/10.17632/6s59gbxh6p.1.