Energy Strategy Reviews 38 (2021) 100737

Contents lists available at ScienceDirect

Energy Strategy Reviews

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

Flexibility options and their representation in open energy modelling tools

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ARTICLE INFO

Dataset link: https://github.com/rl-institut/OpFEl

Keywords:
Flexibility
Flexibility options
Energy systems modelling
Renewable energy integration

ABSTRACT

To reach climate targets, future energy systems must rely heavily on variable renewable energy sources (VRES) such as wind and photovoltaic (PV). As the share of VRES increases, the topics of flexibility and the smart interplay of different flexibility options grow in importance. One way to analyse flexibility options and enhance the design of future energy systems is to use energy system modelling tools. Although a wide range of openly accessible models exist, there is no clear evaluation of how flexibility is represented in these tools. To bridge this gap, this paper extracts the key factors of flexibility representation and introduces a new classification for flexibility and influencing factors. To evaluate the current modelling landscape, a survey was sent to developers of open energy modelling tools and analysed with the newly introduced Open ESM Flexibility Evaluation Tool (OpFEl), an open source evaluation algorithm to assess the representation of different flexibility options in the tools. The results show a wide range of different tools covering most aspects of flexibility. A trend towards including sector coupling elements is visible. However, storage and network type flexibility, as well as aspects touching system operations, are still underrepresented in current models and should be included in more detail. No single model covers all categories of flexibility options to a high degree, but a combination of different models through soft coupling could serve as the basis for a holistic flexibility assessment. This, in turn, would allow for a detailed evaluation of energy systems based on VRES.

1. Introduction

The decarbonisation of power supply systems is crucial for tackling climate change. For this reason, the international community has committed to ambitious goals for expanding renewable energy technologies within the Paris Agreement [1]. To achieve these goals, variable renewable energy sources (VRES) such as wind and photovoltaics (PV) must play a substantial role in the supply of electric energy in most countries [2].

The complexity of the energy supply system increases as the share of VRES grows. This increase in complexity is mainly due to three technological characteristics of VRES: variability, uncertainty and local distribution [3].

In conventional power systems, large-scale fossil-fuelled power plants provide dispatchable electricity to consumers, following a one-directional power flow from higher voltage levels to the distribution grid. By introducing VRES, uncertainty is added to the supply side, due to their varying output nature. In addition, we observe a much higher granularity of power plants following the introduction of small-scale decentralised VRES power plants. This leads not only to an increased challenge in controlling and operating the power plant fleet but also to bi-directional power flows in the grid. To keep the system stable and reliable, we must therefore add and use a broad range of flexibility options to balance supply and demand both geographically and temporally. In conclusion, flexibility is critical for designing and operating up to 100% renewable energy (RE) systems. It is therefore essential for the planning and operation of future power systems to consider and study different flexibility options [2].

Since energy systems are highly complex, decision-makers rely heavily on the predictions of energy system models to find cost-optimal and sustainable future supply scenarios [4]. This affects different stakeholder groups from portfolio planners and power plant operators to grid operators and policymakers. The incorporation of flexibility into energy systems modelling is therefore a prerequisite for the proper modelling and simulation of high share RE systems. This can be achieved by accounting for operational constraints of supply-side technologies and adding new flexibility options such as strengthened grid networks, storage units and demand-side management (DSM) to existing models.

However, there is no one-size-fits-all solution for including flexibility options in energy system models. Different research questions call for distinct modelling approaches. The evaluation of transient stability,

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https://doi.org/10.1016/j.esr.2021.100737
Received 17 August 2021; Received in revised form 4 October 2021; Accepted 13 October 2021
Available online 15 November 2021

for example, needs a tool with a high temporal resolution in the sub-second range and a realistic representation of the grid assets. Assessing investment decisions and long-term energy planning require a much lower temporal resolution because these models simulate years or even decades of the behaviour of future energy systems. In general, energy system modelling must strike a delicate balance between great technical detail and sufficient abstraction to make problems computable [4]. To achieve this, researchers and modellers have created a wide range of energy modelling tools covering various aspects and characteristics of energy systems.

A detailed overview of the existing modelling landscape is required when selecting the appropriate model to answer specific research questions. Various reviews and classifications have been introduced to provide such an overview [5–7]. However, there has not yet been an analysis of energy system models focusing specifically on flexibility representation. As the focus shifts towards high share VRES energy systems, it is crucial to understand the capabilities of existing energy system models (ESMs). Such understanding allows researchers to select appropriate energy system models for a specific representation of flexibility options and to identify aspects that are missing in existing models. In order to fill this research gap, we address the following open questions: What flexibility options exist, and how can they be categorised? How are the different dimensions and types of flexibility represented in open energy modelling tools? What recommendations can be derived for future implementation of flexibility in open energy models?

In this study, we conduct a literature review to identify the key technologies and properties for modelling flexibility. Based on this review, we introduce a classification of flexibility in power systems and factors that influence the available flexibility. In the second step, we present a questionnaire that was sent out to identify the representation of these technologies and properties in current open energy system models. The results are examined for shortcomings and room for improvement in the representation of flexibility in the tools surveyed.

The paper is structured as follows: Section 2 summarises the existing literature on model overviews and classifications of flexibility. It also introduces a new classification of flexibility. Section 3 describes the methodology we use to obtain the representation of flexibility and gives an overview on the models considered in the survey. Section 4 presents the results, Section 5 the discussion and Section 6 the interpretation of the results.

2. Background to flexibility options and energy system models

Flexibility is the ability of a power system to adapt its operation to either foreseen or unforeseen changes in energy system behaviour, e.g. changes in network configuration, generation, or load according to local climate conditions, user needs, or network outage [8,9]. The underlying principle is that supply and demand have to be balanced to allow for stable system operation. Many different options can enhance the flexibility of power systems so that high shares of VRES can be integrated. Lund et al. provide an extensive overview of such measures in [10]. To capture the representation of these options in modelling tools, it is necessary to identify all flexibility options and classify them into distinct categories.

A number of approaches exist to classify flexibility options. Table 1 summarises the classification schemes found in existing literature. All sources mention some variation of supply- and demand-side flexibility, storage and flexibility provided by the grid or its components. Most sources also mention sector coupling (SC) as another flexibility option. Aggregation concepts such as smart grids or exchange with neighbouring grid zones are mentioned as a possibility to increase the utilisation of available sources. The influence of the operating strategy and forecast accuracy are mentioned less frequently. All of the papers examined also specify the market as a possibility to enhance power

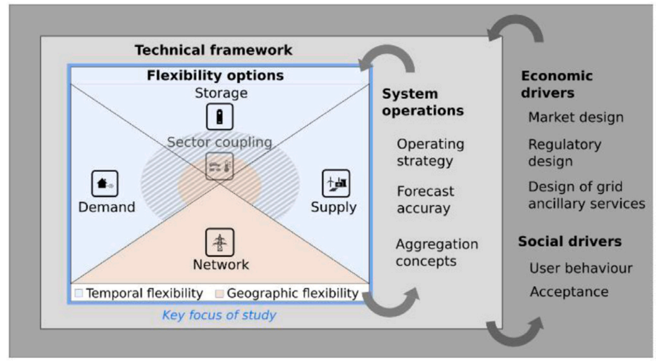

Fig. 1. Classification of flexibility in energy systems.

system flexibility. Other recurring factors are the design of ancillary services (AS) and regulatory design, such as grid codes.

The literature analysed provides a detailed overview of the different technical flexibility options. However, only one source introduces a hierarchy, putting the different types of options into relation with each other [16]. This interplay does not include all options, however. We therefore introduce a new classification scheme in an attempt to merge the above-mentioned approaches, relating technical flexibility and their operation with economic and social drivers and adding *temporal* and *geographical dimensions*. Fig. 1 visualises the proposed classification. Temporal flexibility is the ability to alter the power input or output in time. This can be achieved by increasing or decreasing power generation or demand. Geographic flexibility is the ability to match supply and demand from different locations.

We call the technologies available in a power system, forming the basis of flexibility and therefore focus of the following investigations, *flexibility options*. These are further subdivided into five *flexibility categories*: supply side, demand side, storage, network and sector coupling. Flexibility options are restricted by technical constraints within their operation. We call these constraints *operational characteristics*. Operational characteristics related to most of the flexibility options are efficiency, ramping, response and recovery time. Research questions addressing flexibility options and their optimal combination include: Will future power systems have sufficient flexibility to incorporate 100% renewable energy supply? What is the optimal mix of flexibility options in a highly decentralised future energy system? Which storage technologies are necessary to ensure system stability?

Traditionally, temporal flexibility has been provided by generation units. Supply-side flexibility options include fossil- or nuclear-based thermal generation or dispatchable renewable energy sources (RES). VRES can also provide temporal flexibility, e.g. by being controlled in curtailed operation and ramped up during peak demand or curtailed even further. Operational characteristics on the flexibility of generation units include minimum and maximum output, ramping constraints and minimum up and down time.

Another way to provide temporal flexibility is to include the demand side. This can be achieved using different mechanisms, such as the direct control of loads by the grid operator. Price incentives used to shift loads to periods of high power production are another possibility. Direct control has already been used in the case of industrial loads. Although price incentives and other control mechanisms for including households and the service sector have not been used widely, they have become an increasingly prominent topic of discussion in research [18]. The available flexibility of demand can be characterised by the maximum deferrable load, shifting time and recovery time after activation.

A third flexibility option – storage units – have the ability to shift load or supply over time. They can act as both supply and demand, being able to draw power from the grid, save it over time and feed it back

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Table 1
Overview of flexibility classifications.

Source	Network	Supply	Demand	Storage	SC	Operations	Aggregation	Forecasting	Regulations	Market	AS	Interplay
[10]	x	x	x	x	x	o	o	o	(o)	x	x	(o)
[11]	x	x	x	x		x	(x)	x	(x)	x	x	(o)
[12]	o	x	x	x	(x)	o	(x)			o	o	
[13]	x	x	x	x	o	x	o		x	x	x	
[14]	(x)	x	x	x			x			x		
[15]	x	x	x	x	o	o	x	o	o	x	o	
[16]	x	x	x	x	x	x	o	(o)	o	x	(o)	x
[17]	x	x	x	x	x		x	(o)		x	(o)	

x - defined as own category; o - no own category, but mentioned in text; (x/o) - only partly mentioned.

later. The most commonly used power storage systems are pumped hydro storage (PHS). However, there are other storage technologies at different maturity levels, such as compressed air energy storage (CAES), flywheels, capacitors and a variety of battery technologies. The flexibility of storage units is influenced by their capacity, state-of-charge, self-discharge, efficiency and ageing.

Geographical flexibility is mainly provided by the network, i.e. transmission and distribution grids. Measures to increase geographical flexibility include grid extensions, interconnection to other power systems and dynamic reconfiguration by switches. Limiting factors include the capacity of lines and transformers, as well as the current grid configuration.

Sector coupling introduces new technologies into the power system. These technologies represent a link to other energy sectors such as heat and transport. Connecting different sectors opens the possibility to use other energy storage and transport units. Viewing all flexibility options from a power system perspective, sector coupling elements may act like supply, demand and storage units. Power-to-X technologies and electric vehicles (EVs) can serve as both supply and demand technologies. Not only do sector coupling elements behave like more than one type of flexibility, they also connect the temporal and geographic dimension. Fuels produced by power-to-X, for example, can be moved to other places before being converted back to power. The flexibility of sector coupling elements is dependent on the demand, infrastructure and flexibility of the connected sector; and it is restricted by operational characteristics of the transforming technology.

As stated in [19], technologies are not the only factors that influence energy systems. We therefore put the introduced technical flexibility options and their operation into relation with economic and social drivers. For the later analysis of the models, however, we focus on flexibility options as such as the basis of power system flexibility. Therefore, both system operations and economic and social drivers are considered only marginally in the further analysis. Nevertheless, they are briefly outlined below.

System operations do not include flexibility options as such, but describe the interplay and operations of the different players and technologies. It comprises how flexibility options are operated, which has a strong impact on the available flexibility. For example, the same battery storage can provide up and down regulation if operated at around 50% of its capacity, whereas it can only provide up regulation when kept at full charging level to increase supply security. These aspects include unit commitment or reserve procurement as well as improving the forecast quality of supply and demand as a measure to decrease the need for flexibility and increase flexibility supply [10]. Another concept attributed to system operations and able to make flexibility options available to the system are smart grids. This concept includes the intelligent monitoring, protection and optimisation of grid resources at all voltage levels [20]. It poses an alternative to conventional central grid planning with focus on grid reinforcement by expanding on distributed resources [21] and including storage and demand response. New aggregation concepts such as virtual power plants (VPPs), microgrids and energy cells also fall into this category. VPPs and microgrids both enable the inclusion of distributed energy resourcess (DERs) [22]. Microgrids often allow an operation in islanded mode and include the grid and its components in a limited geographical area. They furthermore utilise hardware innovations such as smart inverters or switches [22]. VPPs on the contrary can include components in a large geographical area and combine these providing access to wholesale markets for smaller units. They depend more on smart metering and information and communication technology and already find application in the current system [22]. The idea of energy cells or so called system-of-systems approach allows for a complexity reduction to reduce the operation of the system to a manageable problem size in times of increasing complexity [23].

Questions relevant to system operations include: How does bidding behaviour influence reserves? How much additional flexibility can aggregators provide? What is the optimal size of independently operating energy cells in a connected cellular system?

Overlaying drivers that influence system operations and therefore the availability of flexibility are *economic* and *social* ones. Economic drivers cover the system design, including the market, AS and regulations. Measures to create greater flexibility through economic drivers include shortening the trading and reserve procurement time horizons [14], location-specific pricing, integrating electricity markets [10], designing additional regulation reserves and flexible ramping products [13]. Research questions associated with this economic drivers include: What are the optimal procurement time horizons? Is it necessary to create an additional market for flexibility? Do we need different ancillary services in a system based on renewable energy?

Social drivers become increasingly important through the deployment of DERs as assets of private persons are added to the mix. User behaviour and acceptance therefore influence the amount of available flexibility. Social barriers for the deployment of flexibility are mainly behavioural aspects such as imperfect information, credibility and trust, bounded rationality, social inertia and personal values other than economic maximisation [23]. Research questions addressing social drivers are: How do user preferences influence the available flexibility of EVs? Which incentive structures are the most promising to increase user participation and acceptance in local flexibility markets?

Energy system modelling is a valuable tool for answering some of these questions. It was found that the optimal tool depends heavily on the specific research questions and the objectives required to answer them [24,25]. It is therefore crucial to specifically assess the representation of flexibility options in models in order to evaluate their suitability to answer questions concerning power system flexibility.

Several papers and other sources provide an overview of the existing modelling landscape in energy system modelling [4,7,24–30]. Rinkjøb et al. for example, give a good overview of 75 models, general model characteristics, and technological and economic parameters, including the modelled markets [28]. Although they do not mention specific models, Deng and Lv evaluate the changes in model formulation owing to the incorporation of renewables [31]. They highlight the growing importance of short-term system operation, transmission constraints, storage units and demand-side response in the models. The authors of [32] focus on social aspects in energy system models and frameworks and find that these factors are mainly included through exogenous assumptions or in the discussion of results. They state that approaches

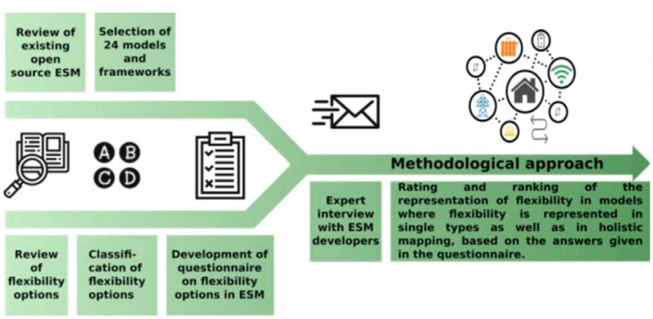


Fig. 2. Methodological approach.

exist such as agent-based modelling which allow for a better representation of social factors and behavioural aspects but there is still room for improvement within the examined models. Many of the energy system models and frameworks are under continuous development and evolve as new questions and energy policy challenges arise. Review papers can therefore only give a snapshot of the modelling landscape at the time of the study. To deliver continuous and up-to-date information on different modelling tools, the Open Energy Platform provides factsheets on 132 models and frameworks used for energy system modelling [33]. The online list provided by the openmod initiative, specifying 50 open source models and frameworks, has a similar purpose [34].

Considering the representation of flexibility in different models, single aspects were found to be missing [29] or posing a major challenge for energy system modelling [28,31]. To the best of our knowledge, however, there has not yet been a systematic analysis of energy system models for the purpose of understanding their representation of flexibility options, which is why we address this in our study.

3. Research settings and method

The methodological approach of this study, shown in Fig. 2, is divided into three main parts. The first part involved selecting the models under analysis. In the second part, we developed a questionnaire to evaluate the representation of flexibility options in energy system modelling, based on the classification introduced in Section 2. In the third part, we evaluated the models under examination to assess the representation of flexibility in the single categories and from a holistic perspective.

3.1. Model selection

Various open energy system modelling tools and frameworks exist, as described in the previous section. In the context of this study, we made a final selection of 24 models and frameworks.[1]

In the literature, balancing uncertainty and transparency is mentioned as one of the major challenges in energy systems modelling [4], and authors have suggested learning from the open source community. Later, the importance of opening up energy system models to increase the transparency and quality of research was stressed [35]. In recent model development, there has been a recognisable trend towards open source and open access in energy system modelling [7,36] and the maturity of open source energy models has been demonstrated [30]. For these reasons, our study focuses on open source modelling tools.

We preselected models based on the ESM review specified in Table 1, the Open Energy Platform [33] and the openmod initiative [34]. These sources were combined with a review of the classification of flexibility types, which was described in further detail in Section 2.

To reach out to a broad audience of open source model users and developers, we presented the research goal and questionnaire at a workshop hosted by the openmod initiative, and sent an appropriate request to model developers in the openmod forum and via its mailing list. The final selection of models was then made by the developers who responded to the request and were willing to complete the questionnaire. In addition, the developers of models that were interesting in terms of flexibility options were contacted directly and asked to complete the questionnaire (e.g. region4FLEX).

Finally, we collected data from 24 models (including six frameworks). The majority of these models classify themselves as ESMs, while the others are called electricity or power system models. Rinkjøb mentions in [28] that, as a rule, energy models were not actively used before the 2010s. This is also reflected in our model selection, given that 19 of the 24 models were published after 2010. The oldest models - Balmorel, EnergyPlan and OSeMOsys - were developed in the early 2000s. This shows that holistic energy system modelling is relatively new and in constant evolution. We selected both widely used models and niche models. To identify how widely the models have been used, we determined the number of citations of their first scientific reference. Models such as Times, OSeMOsys, EMMA, EnergyPlan, Pandapower and PyPsa yield more than 100 citations, while GridCal, Xeona or OMEGAlpes are cited only a few times.

Table C.4 contains a list of all the models and frameworks surveyed, a brief description of the models and the modelling language on which they are based. The overview shows that more than half of the models considered are based on the general-purpose programming language Python and about a quarter on the algebraic modelling language GAMS.

3.2. Questionnaire with classification of flexibility

As mentioned in Section 2, flexibility is becoming crucial when it comes to planning and designing of the future energy supply structures. In this context, it is important not only to focus on a few flexibility options, but also to consider different social and economic drivers and options with regard to supply, demand, storage, sector coupling, and the network (see all drivers and options in Fig. 1). We call the integrated assessment of these different categories a holistic approach. To pursue this holistic approach, we derived the following evaluation categories: general characteristics, supply, network, storage, demand, and sector coupling. These categories provided the structure of our questionnaire (set out in full in Appendix B).

The first section of the questionnaire was dedicated to the general part which covers general model characteristics, such as temporal and geographic scope and aspects regarding social and economic drivers. The second part of the questionnaire focused on the technical operational characteristics of several flexibility options, such as efficiency, ramping rate, response and recovery time. In the third part of the questionnaire, we asked about other specifications concerning flexibility options that are connected to a specific category such as whether or not a minimum load is implemented in conventional power plants. The fourth and final part of the questionnaire focused on the representation of specific technologies in an effort to determine whether the model is general enough such that these technologies can be represented or whether the model already has its own specific representation. All the specific supply-side, demand-side, storage and network-related technologies were listed in this section.

Developers of open energy system models[2] were sent the questionnaire and asked to complete it. The flexibility options surveyed are discussed in more detail in the next subsection, where we evaluated the single categories and combined them to create a holistic flexibility approach.

[1] From now on in this paper, we denote models and frameworks together as models, since the differentiation between a model and a framework is of no importance for the examination of flexibility options.

[2] The questionnaire for IRENA FlexTool was completed by the authors because the developers did not respond to our request.

Table 2
Model evaluation overview.

Flexibility category	Content		Rating
General	Geographic scope, temporal scope, temporal resolution, probabilistic behaviour, social factors		All possibilities equally weighted or yes \ no
	Decision making		Descending from decision-/agent-based to perfect foresight
Supply	Technologies	Conventional, dispatchable RES, VRES, fuel cells	Predefined 1 \ possible 0.5
	Detailed characteristics	Technology specifications, operational characteristics, discrete expansion	All possibilities equally weighted
Demand	Technologies	Household, industry, service	Predefined 1 \ possible 0.5
	Detailed characteristics	Technology specifications, operational characteristics, price elasticity	All possibilities equally weighted
Network	Technologies	Grid types, topology	Predefined 1 \ possible 0.5
	Detailed characteristics	Grid representation, import \export, ancillary services	Mainly individual rating (see Table D.5 in Appendix)
Storage	Technologies	Long-term, medium-term, short-term	Predefined 1 \ possible 0.5
	Detailed characteristics	Technology specifications, operational characteristics, storage implementation	Mostly yes \ -no, sometimes individual rating (e.g. ageing)
Sector Coupling	Technologies	Supply technology, demand technology, storage technology	Predefined 1 \ possible 0.5
	Detailed characteristics	Technology specifications, operational characteristics, sector representation	Individual rating for technology specifications and sector representation

3.3. Model evaluation

The methodology applied in this paper aims to provide an initial evaluation to simplify the choice of an appropriate open energy model. It assesses the level of modelling detail for each flexibility category, and outlines the suitability of the models for modelling energy or power systems using a holistic approach. This was realised by rating the models, as summarised in Table 2. For each answer in the questionnaire, a specific rating was given depending on its importance in the representation of flexibility.

The first part of the evaluation focused on general parameters such as the spatial and temporal scope, the temporal resolution, the decision-making process implemented and the representation of probabilistic behaviour and social factors.

The second part surveyed the technical parameters concerning several flexibility options. The operational characteristics that were relevant for all flexibility categories included efficiency, ramping, the response time and the recovery time after activation. The parameters relevant to the network were grid representation and the modelling of the import and export of energy. Another part of the evaluation addressed technology-specific parameters that influence flexibility. The parameters describing conventional power plants were minimum load and discrete power plant capacity expansion as well as those concerning variable renewable energies such as curtailed operation. Furthermore, the demand side was evaluated in terms of the implementation of maximum deferrable load, shifting time and price elasticity. Finally, this part also questioned whether and how storage, its ageing and self-discharge are implemented.

There are different types of ratings as shown in Table 2. Some parameters, such as temporal and geographic scope, are rated without any hierarchy, meaning that every ticked box counts as one point. Other factors, such as the representation of technology, are rated such that one option is preferable to another, resulting in a higher rating. As an example, predefined technologies score a whole point, whereas the possibility to implement that technology earns only half a point. Some parameters, such as decision-making, are evaluated by means of more complex functions. All detailed ratings can be found in Table D.5. To render the models comparable, the detailed ratings were added together by

$$rating_{model} = \frac{\sum_{i\in\mathbb{N}}^{n} rating_{model,i}}{n},$$

where n is the number of parameters.

4. Results

The following section presents the results of the analysis. First, Section 4.1 provides insights into the outcomes with regard to the general model characteristics. Second, Section 4.2 gives an overview of the representation of the individual flexibility categories and the coverage of their technical characteristics. Finally, Section 4.3 presents a holistic assessment of the models.

4.1. General model characteristics

Although general model characteristics are not considered to be flexibility options, they influence the representation of those options nonetheless. In this research paper, as mentioned above, the general model characteristics under evaluation are spatial and temporal scopes, temporal resolution, decision-making, social factors and probabilistic aspects.

Fig. 3 shows how many models cover each spatial and temporal scope and resolution. The left plot shows that most models cover all spatial scopes. In approximately half of all models examined, a local, regional or international scope is usually used. It is striking that the national scope is usually used in almost 80 % of the models.

Other spatial scopes are possible or predefined by the model in nearly 50 % of cases. These scopes are based on the power grid levels, for example, or the area of a medium-voltage grid. Some of the models also allow for a continental or an arbitrary scope.

The centre plot shows how many models cover each temporal scope. A period between days and years can be simulated in all the models under examination. This scenario period is usually used in more than 90 % of the models. Fewer models are able to simulate short-time scales for periods of less than a few days. Approximately 25 % of the models allow for the application in another temporal scope. In most of these models, the input data determine the temporal scope.

The right plot illustrates how many models cover each temporal resolution. Hourly resolution is the most common resolution in approximately 80 % of the models making it the most widely used resolution. Resolutions larger or smaller than one hour are usually used by around

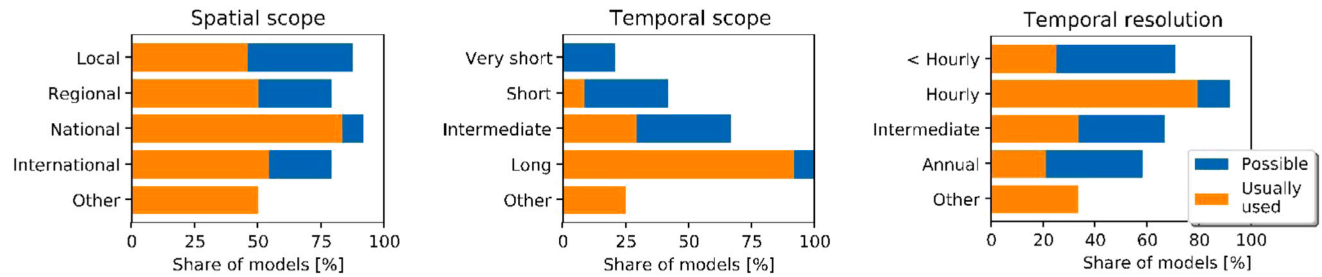


Fig. 3. Representation of geographical scope (left), temporal scope (centre) and temporal resolution(right).

30 % of the models. In addition, a resolution of more than one hour or less than one hour is possible in a further 30 % of models.

Regarding decision-making processes, 80 % of the models can make decisions according to perfect foresight. Other decision-making processes such as the rolling horizon and the agent-based process are represented less frequently, in approximately 35 % and 15 % of the models. Detailed information is depicted in the Appendix in Fig. E.11.

A probabilistic behaviour is implemented in less than 25 % of the models under investigation. Those models that are able to represent probabilistic behaviour often use Monte Carlo analysis, as well as other methods. Detailed information is depicted in the Appendix in Fig. E.11.

Just over 20 % of the models include social factors. These factors refer mainly to economic parameters, such as taxes and costs, or user preferences. The questionnaire did not ask which social factors are mapped in which way and to what extent. Nevertheless, the results reveal that social factors are not implemented in most models and are therefore underrepresented.

4.2. *Flexibility categories*

Fig. 4 illustrates how well, based on our defined parameters and level of potential detail, each flexibility category is represented within the models under examination. The figure reveals that, on average, the flexibility of sector coupling is the category for which most models score in many of the questioned aspects. The majority of models reach a level of representation exceeding 65 %. Considering that sector coupling is a relatively new field, this appears remarkable. In the supply category, approximately half of the models achieve a representation of more than 60 %. On average, demand and storage are equally well represented. More than half of the models achieve a degree of representation of more than 50 % in each category. However, both two categories have a wide range of representation. Furthermore, the results show that networks tend to be represented less well than the other categories, which may be because networks are often represented in a simplified way. Sections 4.2.1 to 4.2.5 below provide a detailed assessment of the flexibility categories. In these subsections, with the exception of the network representing non-temporal flexibility, operational characteristics comprise four elements: efficiency, ramping, response time and recovery time. The detailed operational characteristics are listed in Table D.5. The reader should be aware that the level of fulfilment for all of these categories is also dependent on the type and level of questioned aspects. Hence, the comparison between categories for a specific model only has informative value.

4.2.1. *Supply*

Fig. 5 gives insights into the representation of the supply side. Most models are able to represent the majority of supply-side technologies. However, there are differences in the level of representation in these technologies. Conventional technologies, such as fossil fuel-based generation and nuclear power, and dispatchable renewable supply technologies, such as bioenergy and hydro power (reservoir and run-of-river), can be implemented in 90 % to 100 % of the models under examination, and are predefined in roughly half of them. Variable PV,

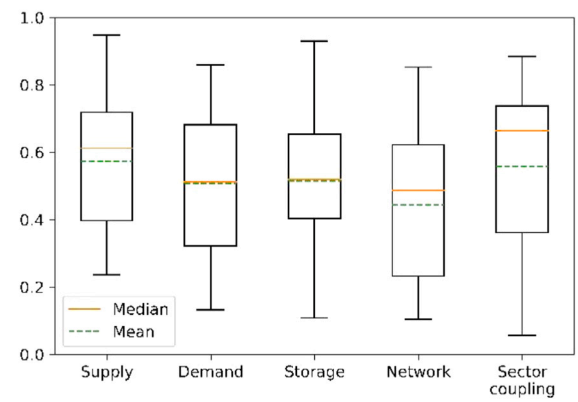


Fig. 4. Representation of flexibility categories.

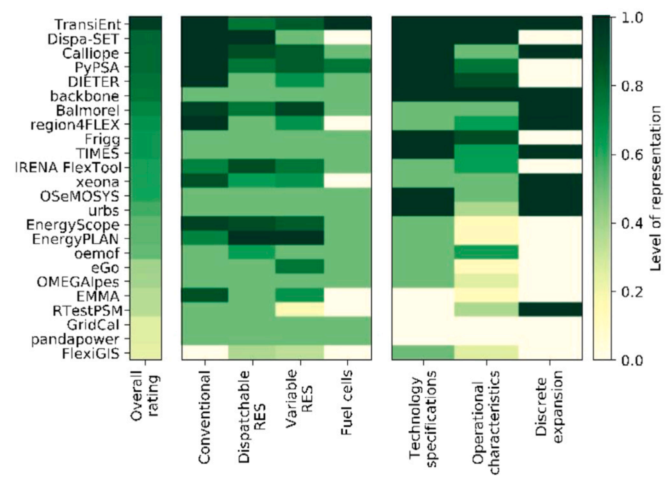


Fig. 5. Representation of supply side technologies (left) and other specifications (right).

and onshore and offshore wind technologies can also be implemented in almost all the models and are predefined in nearly 60 % of them. Geothermal, concentrated solar power, fuel cell technologies, and wave and tidal power are not as well represented in the models. While in the majority of models it is possible to implement these technologies, less than a fifth of them have predefined classes. Only EnergyPlan models dispatchable and variable renewable energy sources with the highest degree of representation with respect to the considered aspects.

Technology specifications comprise the minimum load of conventional power plants and curtailed operation as a specification of VRES. The minimum load is implemented in almost 80 % of the models. Curtailed operation is possible in nearly 50 % of them. Fewer than 40 % of the models enable a discrete power plant expansion.

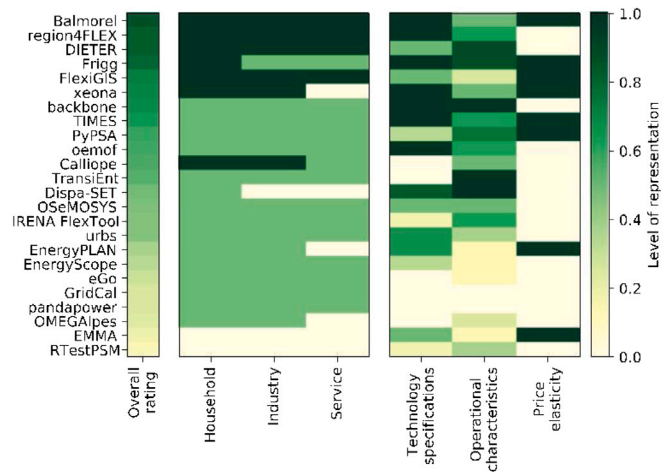


Fig. 6. Representation of demand side technologies (left) and other specifications (right).

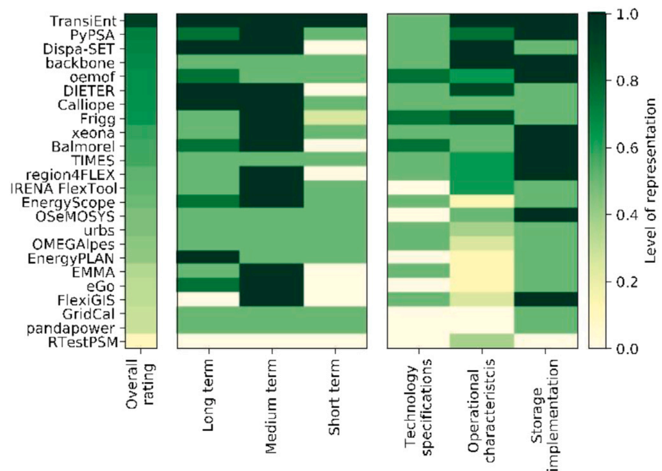


Fig. 7. Representation of storage technologies (left) and other specifications (right).

The five models with the highest degree of representation (TransiEnt, Dispa-SET, Calliope, PyPSA, DIETER) are strong in conventional generation technologies and technology specifications compared to all the other models. In particular, with regard to technology specifications, all five models represent ramping, minimum load, and curtailed operation of RES. However, not only conventional energy sources have predefined classes in these models; commonly used RES such as bioenergy, hydro energy, photovoltaic and wind energy also show high levels of representation.

4.2.2. Demand

Fig. 6 provides an overview of the representation of the demand side. Although 70 to 85 % of the models are able to represent individual load sectors such as households, services and industry, only around a quarter of them have predefined classes of the load sectors under examination. Households tend to be best represented, followed by the industrial sector and then the service sector.

Technology specifications include the possibility to determine a maximum deferrable load (MDL). This deferrable load can either be defined according to the time of day when the load can be shifted (time-dependent) or according to different load types with regard to technologies or load sectors, such as households, industry and the service sector (type-dependent). A deferrable load has the highest degree of representation if it can be mapped in both a time-dependent and type-dependent manner. More than 40 % of the models are able to define both time-dependent and type-dependent MDL. Around 15 % of the models can only map a time-dependent change of MDL; no MDL is implemented in further 15 % of the models.

All five models that score the highest in the area of demand based on our evaluation (Balmorel, region4FLEX, DIETER, Frigg, FlexiGIS) are able to represent time-dependent and type-dependent deferrable loads. This is an essential requirement for representing flexible loads in a renewable energy system. In addition, these five models have predefined classes or methods for household loads. The service and industry sectors are also predefined in four of the five models. Also, all five models can map the efficiency of demand technologies. However, other operational characteristics, such as ramping, response time and recovery time, are implemented in only three of the five models. These operational properties are represented by only three models at the highest complexity level. These three models (backbone, TransiEnt, Dispa-SET) are not among the five highest-rated models in this category.

4.2.3. Storage

Fig. 7 illustrates the representation of storage technologies and their characteristics in the various models. Among the storage technologies examined, capacitors and flywheels are considered to be short-term storage units. Batteries are categorised under medium-term storage technologies, whereas PHS and CAES are classified as long-term storage technologies.

Batteries tend to be best represented among all storage technologies related to the power sector, followed by PHS and CAES. Capacitors and flywheels are represented less frequently than the other technologies; only TransiEnt has predefined classes for them.

Technology specifications in storage technologies comprise cycle and calendrical ageing, and self-discharge. Almost 80 % of the models do not cover storage ageing, while more than 15 % take calendrical ageing into account. Only TIMES has implemented cycle ageing. Nearly 70 % of the models consider self-discharge over time.

Storage specifications describe how complex storage units are implemented. Storage units can either be modelled in a simplified static way or dynamically, e.g. considering a temperature-dependent efficiency or a seasonally varying storage capacity. Concerning these storage specifications, the results show that nearly 55 % of the models represent storage units with a fixed/simplified model, whereas more than 40 % are able to model storage units dynamically, e.g. with regard to efficiency dependent on temperature or seasonally varying storage capacity. One model has not implemented any storage technologies.

Among the five highest-rated models (TransiEnt,PyPSA, Dispa-SET, backbone, oemof) in the category of storage, only TransiEnt has predefined classes or methods for all storage technologies under consideration. Long-term and medium-term storage technologies can be implemented in the other four models. Among the five models, short-term storage technologies are represented the worst. Furthermore, neither calendrical nor cycle ageing is implemented in four of the five models. Calendrical ageing is only specified in oemof.

4.2.4. Network

Fig. 8 illustrates how network-related technologies are mapped in the models under examination. Among the grid types, distribution grids are represented worse than transmission grids. Around 45 % of the models contain predefined transmission grids. Approximately 25 % of the models feature predefined classes or methods for distribution grids.

Grid topology includes properties such as automated network extension and the use of switches. The results reveal that grid extension is implemented in almost 35 % of the models. Switches are represented the least.

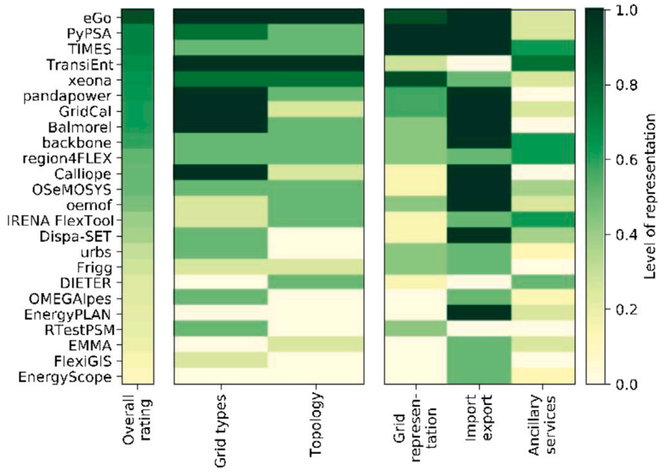


Fig. 8. Representation of network side technologies (left) and other specifications (right).

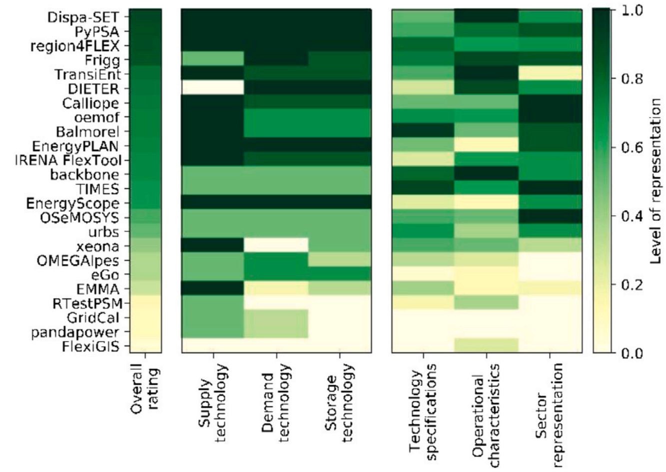


Fig. 9. Representation of sector coupling technologies (left) and other specifications (right).

Grid representation refers to the method by which networks are represented electrically. Networks can be represented by a net transfer capacity or by power flow in alternating current (AC) networks (AC power flow) or as a direct current (DC) power flow approximation. DC power flow and transfer capacity can be used in less than 60 % and 45 % of the models, respectively. AC power flow is only represented in less than 40 % of the models.

Almost 55 % of the models enable the modelling of the import and export of power using a simplified method. Furthermore, the representation of import and export is flow-based in 45 % of the models. Approximately 10 % of these models facilitate the modelling of import and export using a simplified or a flow-based method. Less than 10 % of the models do not include import/export modelling. Just under 20 % of the models are based on other import/export methods; these refer, for instance, to representation by means of cost functions.

Ancillary services such as spinning reserve, balancing energy, sheddable loads, feed-in management, and curtailment of variable renewable energy technologies are represented in 20 % to 45 % of the models. In contrast, re-dispatch and power factor correction are represented in less than 20 % of them. All models still have room for improvement regarding ancillary services, e.g. none of them consider black start capability.

TransiEnt has the largest variety of ancillary services (spinning reserve, balancing energy, sheddable loads, feed-in management, power factor correction, and curtailment). The five highest-rated models achieve a significant degree of representation because most of them cover both distribution and transmission grids, and are able to represent both AC and DC power flow.

4.2.5. Sector coupling

Sector coupling is a cross-sectional issue in relation to the other categories. Fig. 9 shows that sector coupling is generally well represented, particularly given that it is a relatively new area, especially when it comes to representing sector coupling supply, demand, and storage technologies.

Sector-coupled supply includes only combined heat and power (CHP) because it is capable of producing both heat and electricity. While fuel cells are also capable of using waste heat, their primary goal is to generate electricity. As such, they have already been discussed in Section 4.2.1. Most models are capable of representing CHP. This corresponds to the previous conclusion that supply-side technologies are generally well represented.

Demand-side technologies include power-to-gas, heat pumps, and EV. Despite the fact that these are relatively new technologies, a considerable number of models are capable of representing them. In particular, the three best-rated models can represent sector-coupled demand at the highest level of complexity, as defined in the evaluation scheme employed.

Sector coupling storage technologies include fuels, heat storage, and vehicle-to-grid (V2G). A large number of models are able to represent one or more of these storage technologies.

Sector representation refers to how well heat and transport sectors are represented in terms of exogenous aggregated demand or endogenous disaggregated choices for demand or technologies. The results reveal that the heat sector is better covered than the mobility sector, which is neglected in almost 60 % of the models. In contrast, around 40 % of the models do not cover the heat sector.

Technology specifications include how technologies are implemented. These specifications, corresponding to those mentioned above under supply, demand and storage, include discrete expansion, curtailment for supply technologies, ageing for storage technologies and other specifications. These specifications do not reach the degree of representation that the technologies themselves achieve. Furthermore, no model meets the highest degree of representation in this area.

Among the five highest-scoring models in the sector coupling domain, Dispa-SET, PyPSA andregion4FLEX feature the highest level of modelling details in representing sector coupling technologies. EnergyPlan and EnergyScope also achieve the highest level of modelling details in sector coupling technologies.

4.3. Holistic approach

As mentioned in Section 2, flexibility is becoming crucial when it comes to planning and designing future energy supply structures. In this context, it is important not only to focus on a few flexibility options, but also to consider different options of supply, demand, storage, sector coupling, and network. The following section shows the extent to which the models surveyed models represent a holistic approach of flexibility.

Fig. 10 provides an overview of the ranking of the models under examination in the relevant categories, as defined in our evaluation scheme. Many models are powerful in individual categories but perform only moderately in others. TansiEnt, for instance, appears to be the most potent model. This model has a very high degree of representation with regard to supply and storage, while many other models perform better when it comes to demand. EMMA, for instance, achieves a high level of representation in the demand category compared to other categories. The same applies to eGo, pandapower and GridCal, which exhibit an above-average performance in the network, but fare less well in the

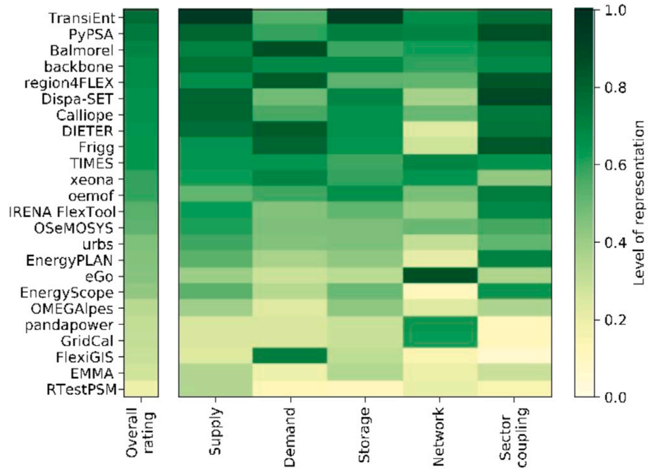


Fig. 10. Holistic representation of all flexibility categories.

Table 3
Representation of holistic approach within models with more than 70% of representation in any category.

Model	Supply	Demand	Storage	Network	Sector coupling
TransiEnt	95 %		93 %		77 %
Dispa-Set	80 %				82 %
Calliope	79 %				74 %
PyPSA	79 %		71 %		85 %
DIETER	76 %	82 %			
backbone	75 %				
Balmorel	71 %	86 %			70 %
region4FLEX		82 %			84 %
Frigg		80 %			84 %
FlexiGIS		71 %			
eGo				85 %	
oemof					70 %
EnergyPLAN					70 %

other categories. In the field of sector coupling, some models consider a wide range of sector coupling aspects. Other models, on the other hand, focus specifically on the electricity sector and only rarely consider elements related to the heating and transport sector. Many models map individual categories very well. Among the models that achieve a high degree of representation in a certain category, the representation is often over 80%.

The results summarised in the previous section also show that many operational characteristics are not well represented. This may be because many models use perfect foresight, and therefore several operational parameters, such as ramp rate or response time, are neglected. Since the economic and social drivers were not specifically part of the questionnaire, it is difficult to draw conclusions on this aspects. It appears however, that models such as EMMA and Balmorel address economic drivers, given that they are market models. Economic aspects are implicitly included in other models via price structures or investment decisions.

However, the results also reveal that a wide range of models exists that are strong in specific areas and weaker in others, depending on the focus of the model. When selecting a model to answer a specific research question, the strengths and weaknesses of each model should be considered.

The question remains as to the extent to which the models feature a holistic approach to flexibility options. To this end, a threshold value was chosen that is slightly above the highest median of the individual categories. The sector coupling category exhibits the highest median (almost 70 %). For this reason, all models with a representation above 70 % in a particular category were examined and depicted in Table 3. Models that were unable to achieve more than 70 % representation in any category were excluded from the representation. This fact should not cause users to assume that these models are generally less convenient to use. These models probably focus on aspects that were not explicitly included in the questionnaire, meaning that they may address research questions that do not focus on flexibility. The following conclusions are therefore closely connected to the aspects of the questionnaire and the evaluation criteria.

Table 3 shows that sector coupling appears to be exceptionally well covered based on our evaluation criteria. Ten models achieve a representation level of 70% or more. The comparatively large number of models may suggest that the open energy community is consciously promoting the relatively new topic of sector coupling. Note that this conclusion is drawn from a power sector perspective. Detailed aspects of the mobility and heat sector are not the subject of this examination. A specific evaluation of heat and mobility sector aspects may therefore lead to other conclusions. In contrast, there are only two models in the storage category and only one in the network category with a representation exceeding 70%.

To address specific research questions regarding one individual category, there is probably at least one appropriate model. However, a holistic approach, which shows flexibility across all categories considered with a high degree of representation, cannot be deduced from the results. Three models (TransiEnt, PyPSA, Balmorel) cover three of the five categories with a high degree of representation. Not one model achieves a high degree of representation in four or the five categories.

To answer specific research questions with a holistic approach of flexibility, different models can be combined to ensure broad coverage of the categories. Thus, it would be possible to use mainly one model with a comprehensive range covering almost all categories. In addition, one or two models could be used that are strong in the specific categories covered inadequately by the other model. One example of coupled models is eGo, which uses PyPSA to perform load flow calculations.

Moreover, many models will be expanded in the future by components that also affect flexibility. eGo, for example, will be upgraded with controlled charging for electric vehicles. The representation of power-to-X and the transport sector is likely to be improved in Balmorel. oemof will address the heat sector more comprehensively by optimising and simulating district heating and absorption heat pumps.

Regarding grid aspects, it is likely that TransiEnt will integrate a module that allows the investigation of voltage stability. Furthermore, a complete AC/DC simulation with additional components and harmonic analysis will be implemented in GridCal. Power flow calculations in pandapower will be extended to allow the consideration of asymmetric grid situations.

Demand response will be enabled by model coupling in Frigg, and automated model coupling will be implemented in Dispa-SET. Furthermore, FlexiGIS will integrate socio-economic aspects and an urban policy perspective.

The results suggest that many categories are mapped very well by individual models. However, a holistic approach to flexibility across all categories appears to be inadequately represented as yet. It may be advantageous to couple several models in this context. Moreover, flexibility aspects will be added to many models in the future.

5. Discussion and limitations

Our analysis revealed different levels of representation of technical flexibility options among the models surveyed. In this section, we critically reflect on our findings and discuss the limitations of this study.

First, the questionnaire itself contained certain biases due to the survey designers' understanding and interpretation of flexibility and modelling tools. We strove to minimise this bias by scanning the existing literature for model parameters and cross-checking the questionnaire with modelling experts before distributing it. To counteract deviations that may occur nevertheless due to different interpretations of the survey questions, we checked all of the completed questionnaires for consistency, and enquired and discussed matters with the developers if answers were unclear or suggested that the respondent may have had a different understanding of specific questions. With our methodology, we follow the line of argumentation of [36], where the authors recommend a dialogue with model developers for model overviews and validation purposes. The approach is also in line with [24] who sent a survey to model developers and [28] who validated their outcomes with the developers of most of the investigated models. A case study to evaluate how well our results reflect the actual modelling capabilities would be a valuable extension of our work.

Second, the scope of the questionnaire is limited. As stated in the background section, flexibility is a broad field covering numerous aspects and dimensions. It is quite a challenge to cover all aspects and dimensions in detail, while ensuring that the questionnaire does not become too long, affecting the response rate. To this end, the primary focus of this study was narrowed down to the technical representation of flexibility options in the models under examination, focusing on the power sector. Some aspects of system operations are covered by the decision-making process and probabilistic aspects. The social drivers are touched by behavioural and social aspects. A more detailed examination of the system operations and the economic and social drivers would be interesting, but exceeds the scope of this work and is left to further research.

Finally, in spite of all attempts to reach out to a wide variety of open source models, it was not possible to capture all existing models. However, a sufficient quantity and variety of models enabling a good overview was ensured by disseminating the questionnaire via the website and mailing list of the OPENMOD INITIATIVES and reaching out to specific interesting models by sending additional emails. While the models surveyed do not therefore necessarily represent a perfect sample of the global open source ESM landscape, the results identify specific trends nonetheless.

We discuss these trends and the reasons for different levels of representation in ESMs along the five flexibility options. We are aware that the level of representation obtained is highly dependent on the parameters chosen and their weighting. In this study, they were chosen such that flexibility options could ideally be represented holistically. However, some parameters may not be of interest to several questions on the topic of flexibility, while others may weigh more heavily than represented in the current evaluation. We therefore provide an open source version of the algorithm,[3] which enables users to adjust the weighting as required and provides the level of representation of all models. The tool is intended to help scientists choose the right tool for their specific research question.

In this study, sector coupling exhibited the highest rate of representation in all ESMs surveyed. This is quite surprising because the flexibility of sector coupling is a relatively new approach [36,37]. However, it must be noted that our study only examined sector coupling technologies from the perspective of the power system. The detailed evaluation of the representation of sector-specific aspects, such as their transport structure, was therefore excluded. As a result, all statements on the level of representation apply only to sector coupling technologies in power systems. Among these, many ESMs already include sector-coupling technologies such as PtG and heat pump (HP). These technologies enable electricity to be converted to different gas types and then used for heating, transport, industrial processes or reconversion to electricity. The existing literature shows an emerging trend in the investigation of cross-sectoral synergies [36], which explains the detailed mapping of sector coupling technologies. Since these technologies are an important long-term storage solution for high-share RE systems, they are included in many ESMs. This is also underlined by studies on high-level or 100 % RE that demonstrate the importance of PtG [37–39]. Nonetheless, a proper representation of the heat and transport sector in ESMs was often found to be missing. As such, there is room for improvement when it comes to comprehensively simulating sector-coupled flexibility [29], including behavioural aspects [40,41] and demand-side management in other sectors than electricity [29].

Supply-side and demand-side flexibility options have the second and third highest representation. Providing flexibility via different supply technologies is the most established form of flexibility in power systems. As a result, almost all models include conventional and RE as flexibility options, but have limitations with regard to the operational constraints of these options, even though it is possible to implement most constraints in the most common temporal scope of hourly increments. Other studies also found that certain operational aspects were underrepresented [29,30]. Demand-side flexibility, such as shifting the load of household appliances, the service sector and industrial loads, is enabled in most ESMs. The flexibility potential lies – as is the case with supply – within the range of hourly timesteps.

We observed a limited representation of storage flexibility options in the ESMs surveyed. While primarily medium-term and long-term storage options such as batteries and pumped hydro storage are included in almost all models, short-term storage such as capacitors and flywheels is missing in most cases. This result suggests that modelling the short-term storage behaviour and ageing of battery systems is a complex field and beyond the scope of most ESMs that look at long-term scenarios. In [42], for instance, PyPSA is used to compare battery storage and long-term storage technologies for a year on a European scale. A transient short-term energy system simulation in TransiEnt using batteries and a natural gas grid as storage units is described in [43]. A broader overview of energy storage in long-term system models is provided in [44].

In general, networks are not broadly covered as a flexibility option in any of the models aside from eGo. Modelling networks and the geographical flexibility associated with them requires a very detailed set of data and simulations. For this reason, most ESMs exclude this dimension and neglect geographical flexibility, with the exception of comparing different regions connected via transmission grids [37,45]. Detailed analysis at the medium- and low-voltage grid level has traditionally been conducted for grid integration studies [46] or for improving grid operations [47], applying commercial software such as PowerFactory [48] or Sincal [49].

The emerging field of including distribution grids in larger-scale energy system models has been shown to alter the results of long-term scenarios significantly [50]. In a recent study on the capabilities of energy system models, however, the representation of distribution grids was also found to be a possible field of improvement [29].

In summary, the results reveal the background of most models — they were designed to provide decision support for medium-term to long-term energy planning.

6. Conclusion

The importance of flexibility in the design of future energy systems is growing. Finding the appropriate flexibility option for planners and operators of power systems is crucial to provide reliable and cost-effective power, especially in high share VRES systems.

As the first result of our work, we introduced a new framework that captures the different characteristics of flexibility options. First, we distinguished between the geographical and temporal dimension.

[3] Open ESM Flexibility Evaluation Tool: https://github.com/rl-institut/OpFEl.

We then introduced aspects of system operation and presented economic and social drivers, which influence the utilisation of technical flexibility. Finally, we presented five different technological flexibility categories: network, supply, demand, storage and sector coupling and their operational characteristics. This framework can be used to describe, develop and improve flexibility options. We have applied the framework to assess the representation of flexibility options in ESM in an effort to support future energy modelling tasks by finding the most appropriate tool for the question at hand as well as identifying future research and development needs for new tools.

The results show that the geographical dimension is adequately represented among the models analysed, generally covering all geographical scopes from local to international. With regard to the temporal dimension, most models focus on long-term assessments and planning using hourly increments as simulation time steps. As shorter timescales become increasingly relevant as the share of VRES, we suggest placing greater emphasis on shorter timescales in future model development.

We further analysed the technical flexibility categories — supply, demand, storage, network and sector-coupling, including their operational characteristics. All technical flexibility options are well represented in at least one of the models. Based on our analysis and assessment criteria, we recommend to apply TransiEnt for modelling supply-side and storage flexibility, while Balmorel scores the highest for demand-side flexibility. We found that eGo represents network flexibility most comprehensively. However, network-type flexibility in particular is still covered in limited detail in most models. Dispa-SET exhibits the highest representation of sector-coupling features for power system flexibility. Most models still cover storage and network-type flexibility in limited detail. Thus, this needs to be prioritised in the process of refining and improving models. Another possibility to overcome certain weaknesses of individual models is to facilitate a soft coupling of different models. This would allow for a holistic evaluation of flexibility and energy systems based on VRES.

Flexibility depends not only on technical parameters of flexibility options, but also on the system operations. Aspects addressing system operation parameters are generally represented less strongly than those covering technical parameters. Most models use perfect foresight as the basis for investment and dispatch decisions and did not include probabilistic and behavioural aspects. Perfect foresight is appropriate for managing foreseen changes in either supply or demand, but less so for unforeseen changes. We therefore recommend using probabilistic approaches and including behavioural aspects to ensure that system operation flexibility tackling unforeseeable changes can also be assessed.

In summary, the open energy modelling landscape provides a broad set of solutions for modelling flexibility options in power systems. The appropriate selection depends on the research task at hand. Having said that, most questions can be addressed using existing models. Our open source version of the evaluation algorithm may help scientists find the appropriate models for their specific research purposes. Future work in model development should focus on coupling models and increasing the temporal resolution.

CRediT authorship contribution statement

Anya Heider: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualisation, Project administration. **Ricardo Reibsch:** Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualisation, Funding acquisition. **Philipp Blechinger:** Conceptualisation, Methodology, Validation, Writing – original draft, Writing - review & editing. **Avia Linke:** Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft, Writing – review & editing, Visualisation. **Gabriela Hug:** Conceptualisation, 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.

Data availability

The Open ESM Flexibility Evaluation Tool and supplementary materials related to this article can be found at https://github.com/rl-institut/OpFEl

Acknowledgments

We would like to thank all the ESM developers who completed our questionnaire and were willing to answer our subsequent questions. Without their support, this study would not have been possible. Furthermore, we would like to thank the Reiner Lemoine Foundation for its support, primarily through the creation of the PhD Graduate School. We acknowledge support by the German Research Foundation and the Open Access Publication Fund of TU Berlin.

Appendix A. List of abbrevations

AC alternating current
AS ancillary services
CAES compressed air energy storage
CCGT combined cycle gas turbine
CHP combined heat and power
DC direct current
DER distributed energy resources
DSM demand-side management
ESM energy system model
EV electric vehicle
LP linear programming
MDL maximum deferrable load
OCGT open-cycle gas turbine
PHS pumped hydro storage
PF power flow
PEMFC proton exchange membrane fuel cell
PV photovoltaic
RE renewable energy
RES renewable energy sources
RTestPSM Renewable test power system models
SC sector coupling
SOFC solid oxide fuel cell
VRES variable renewable energy sources
V2G vehicle-to-grid
VPP virtual power plant
HP heat pump

Appendix B. Questionnaire on flexibility options in open energy models

Survey on "Empirical research on flexibility options in open energy models"

The aim of this survey is to investigate the characteristics of energy system models. This includes the current status of implementation as well as future planned implementations. The focus lies on flexibility options, how they are implemented in the model and which technologies or parameters might be underrepresented in the modelling landscape.

The results of the survey will be evaluated and summarized in a review paper. The review paper is intended to help modelers select a suitable model for their respective research question. Furthermore it is planned to publish the collected information on the open energy platform to make it permanently accessible.

Your response will be treated confidentially and the results are used for academic reasons only.

You may reserve your right to anonymity if you wish to do so. In case you provide us with your details, only Anya Heider and Ricardo Reibsch (researchers at the RLS_Graduate_School on energy system transition of the Reiner-Lemoine-Stiftung) will see your response.

The completion of the survey takes about 30 min.

We know that not all the questions might be relevant for your specific model as we evaluate a variety of models with different focuses. If you are not sure about the answers or think they might need further explanation, please feel free to comment on the respective question. It will help us to better understand the models.

Thank you very much for your participation!

Part 0: Basic Information

Name:
Contact details (email):
Model / framework name:
Version:
Last updated:
Date:

Part 1: Model

This section raises information on the model itself and does not specifically focus on flexibility.

1.1 Which **spatial scope** is ***possible*** to be mapped with the model? What scopes it the model ***usually used*** for? *Multiple selections possible,* *NUTS = Nomenclature of Territorial Units for Statistics*		
Possible	*Usually used*	
☐	☐	local (NUTS3)
☐	☐	regional (NUTS1 - NUTS2)
☐	☐	national
☐	☐	international
☐	☐	other:

1.2 Which **temporal scope** can be mapped with the model? *Multiple selections possible*		
Possible	*Usually used*	
☐	☐	very short duration (<sec)
☐	☐	short duration (sec – 15 min)
☐	☐	intermediate duration (15 min - days)
☐	☐	long duration (days - years)
☐	☐	other:

1.3 Which **temporal resolution** can be mapped with the model? *Multiple selections possible*		
Possible	*Usually used*	
☐	☐	<hourly
☐	☐	hourly
☐	☐	intermediate
☐	☐	annual
☐	☐	other:

1.4 How is the **decision making process** implemented? *Multiple selections possible*	
☐	perfect foresight
☐	myopic foresight (rolling horizon)
☐	decision-/agent-based
☐	other:
☐	none

1.5 How is the **heat sector** represented? *Multiple selections possible*	
☐	excluded
☐	exogenous aggregated heat demand
☐	endogenous disaggregated choices regarding demand
☐	endogenous disaggregated choices regarding technology
☐	other:

1.6 How is the **transport sector** represented? *Multiple selections possible*	
☐	excluded
☐	exogenous aggregated transport demand
☐	endogenous disaggregated choices regarding demand
☐	endogenous disaggregated choices regarding mode, technology
☐	other:

1.7 Is a representation of **probabilistic behavior** implemented?	
☐ Yes	☐ No
Explanation *(optional)*:	

1.8 Is a representation of **social factors** or **behavioral aspects** implemented? *e.g. consideration of social justice, sufficiency, behavior of different actors etc.*	
☐ Yes	☐ No
Explanation *(optional)*:	

1.9 How are **grid ancillary services** represented? *Multiple selections possible*	
frequency measures ☐ spinning reserve ☐ balancing energy ☐ sheddable loads	voltage compensation ☐ power factor correction ☐ curtailment
Operational management ☐ feed-in management ☐ redispatch	☐ Reconstruction of supply / black start
Explanation *(optional)*:	

1.10 Are **new features** planned for the near future?	
☐ Yes	☐ No
If yes, which ones and when:	

1.11 Is it possible for the user to **implement new features**?	
☐ Yes	☐ No
Explanation *(optional)*:	

Part 2: Technologies

This section covers technical parameters that are applicable to several flexibility options.

All flexibility options (supply, demand, storage)

2.1 How is the **efficiency** of a flexibility option implemented? *e.g. efficiency dependent on power output or temperature*	
☐ by a fixed value	☐ by a function
☐ other:	
Explanation *(optional)*:	

2.2 Is the **ramping** of flexibility options implemented? *e.g. conventional power plants (short term to intermediate), demand (short term), storage (very short term)*	
☐ Yes	☐ No
Explanation *(optional)*:	

2.3 Is the **response time** of a flexibility option implemented? *e.g. conventional power plants, storages, demand, power electronics*	
☐ Yes	☐ No
Explanation *(optional)*:	

2.4 Is a **recovery time after activation** implemented? *e.g. conventional power plants, demand*	
☐ Yes	☐ No
Explanation *(optional)*:	

2.5 If **operational constraints** (ramping, response time) are implemented, when were they introduced?	
Year:	

Network

2.6 Is a **grid representation** implemented? *Multiple selections possible*	
☐ none	☐ transfer capacity
☐ AC power flow	☐ DC power flow
☐ interconnectors	
Explanation *(optional)*:	

2.7 Are **import and export** modelled?	
☐ simplified	☐ flow based
☐ none	☐ other:
Explanation *(optional)*:	

Part 3: Further specifications on flexibility options

This section evaluates technology specific parameters influencing the available flexibility.

Conventional power plants

3.1 Is a **minimum load** in conventional power plants implemented?	
☐ Yes	☐ No
Explanation *(optional)*:	

3.2 Is a **discrete power plant capacity expansion** in conventional power plants implemented?	
☐ Yes	☐ No
Explanation *(optional)*:	

Demand

3.3 How is the **maximum deferrable load** implemented? *Multiple selections possible*
☐ fixed value
☐ time-dependent
☐ type-dependent
☐ time- and type-dependent
☐ none
☐ other:

3.4 Is a **shifting time** implemented?	
☐ Yes	☐ No
Explanation *(optional)*:	

3.5 Is a **price elasticity** implemented?	
☐ Yes	☐ No
Explanation *(optional)*:	

Storage

3.6 How are **storages** implemented?	
☐ fixed (simplified static model)	☐ dynamic (e.g. efficiency dependent on temperature, seasonally varying storage capacity etc.)
☐ none	
Explanation *(optional)*:	

3.7 How is **aging** implemented? *Multiple selections possible*	
☐ cycle aging	☐ calendrical aging
☐ none	
Explanation *(optional)*:	

3.8 Is a **discharge over time / self-discharge** implemented?	
☐ Yes	☐ No
Explanation *(optional)*:	

Variable renewable energies

3.9 Is a **curtailed operation** in order to serve grid ancillary services implemented?	
☐ Yes	☐ No
Explanation *(optional)*:	

Part 4: Technology representation

This section focuses on the representation of specific technologies, if it is possible to represent them or a own representation already exists in the model.

4.1 Is it ***possible*** to represent the following **supply side technologies**? If yes, are they ***predefined*** within the model (e.g. as own class or template)? *Multiple selections possible*					
Fossil thermal generation					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Hard coal	☐	☐	CCGT
☐	☐	Lignite	☐	☐	OCGT
☐	☐	Oil	☐	☐	CHP
☐	☐	Natural gas	☐	☐	other:
Dispatchable renewable generation					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Bioenergy	☐	☐	Geothermal energy
☐	☐	Hydropower with reservoir	☐	☐	Concentrated solar power
☐	☐	other:			
Variable renewable generation					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Photovoltaic	☐	☐	Run-of-River hydro
☐	☐	Wind onshore	☐	☐	Wave power
☐	☐	Wind offshore	☐	☐	Tidal power
☐	☐	other:			
Other generation					
possible	*predefined*		*possible*	*predefined*	
☐	☐	PEM-FC	☐	☐	Nuclear
☐	☐	SOFC	☐	☐	other:
Comments *(optional)*:					

4.2 Is it ***possible*** to represent the following **demand side technologies**? If yes, are they ***predefined*** within the model (e.g. as own class or template)? *Multiple selections possible*					
Demand response					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Households	☐	☐	Industrial Loads
☐	☐	Service Sector	☐	☐	other:
Sector coupling					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Power-to-Gas	☐	☐	Heat pumps
☐	☐	Power-to-Hydrogen	☐	☐	Electric vehicles
☐	☐	other:			
Comments *(optional)*:					

4.3 Is it ***possible*** to represent the following **storage technologies**? If yes, are they ***predefined*** within the model (e.g. as own class or template)? *Multiple selections possible*					
Electricity-to-Electricity					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Pumped hydro storage (PHS)	☐	☐	Batteries
☐	☐	Compressed air energy storage (CAES)	☐	☐	(Super-) Capacitors
☐	☐	Flywheels	☐	☐	other:
Energy system integration					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Fuels (e.g. Hydrogen)	☐	☐	Heat storages
☐	☐	Vehicle-to-grid	☐	☐	others:
Comments *(optional)*:					

4.4 Is it ***possible*** to represent the following **network related technologies**? If yes, are they ***predefined*** within the model (e.g. as own class or template)? *Multiple selections possible*					
Grid type					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Distribution grids	☐	☐	Transmission grids
Grid operation					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Smart grids	☐	☐	Microgrids
☐	☐	other:			
Grid topology					
possible	*predefined*		*possible*	*predefined*	
☐	☐	Interconnectors	☐	☐	Network extension
☐	☐	Switches	☐	☐	other:
Comments *(optional)*:					

Appendix C. Overview of models under consideration

Table C.4
Overview of models under consideration.

Name	Model; framework	Modelling language	Short description
BACKBONE	f	GAMS	BACKBONE is an adaptable energy systems modelling framework. It is an optimisation framework, based on mixed-integer programming [51].
BALMOREL	m	GAMS	BALMOREL is a partial equilibrium model for optimising and analysing energy systems focusing on the international electricity and combined heat and power sector [52].
CALLIOPE	f	Python	CALLIOPE is an energy systems modelling framework with a high temporal and spatial resolution. The framework is based on scale-agnostic formulation [53].
DIETER	m	GAMS	DIETER stands for *dispatch and investment evaluation tool with endogenous renewables*. The model was developed to study the role of storage and further flexibility options. It identifies cost-minimising combinations of power production, demand-side-management and storage capacities, taking into consideration reserve and wholesale markets [54].
DISPA-SET	m	GAMS & Python	DISPA-SET is an optimisation model for unit-commitment and dispatch. It focuses on flexibility and balancing problems [55].
EGO	m	Python	EGO stands for *electricity grid optimisation*. The model is an intersection for the high- and medium voltage layer. It is used to simulate grid and storage development costs for all voltage layers. The two tools ETRAGO and EDISGO, parts of the EGO project, focus on the simulation of transmission and distribution grids, respectively [56].
EMMA	m	GAMS	EMMA stands for *European electricity market model*. It is a partial equilibrium optimisation model, which models prices, capacities, output, profits and deal flows in the electricity market [57].
ENERGYPLAN	m	Delphi & Pascal	ENERGYPLAN is a model for the design of energy planning strategies. It simulates the operation of national energy systems and is based on economic and technical analyses of different implementations of energy systems and investments [58].
ENERGYSCOPE	m	GLPK & GLPSOL	ENERGYSCOPE is a linear optimisation model for planning urban and regional energy systems for the purpose of optimising investment and operating strategies [59].
FLEXIGIS	m	Python	FLEXIGIS stands for *Flexibilisation in Geographic Information Systems*. It is a modelling platform for energy systems and flexibility options in urban areas. FLEXIGIS uses geo-referenced urban energy infrastructure for simulating local electricity consumption, power generation and the distribution to decentralised storage in urban settings [60].
FRIGG	m	Python	FRIGG is the soft-linking of frameworks to model demand flexibility through a set of differential equations and a dynamic price-making algorithm to minimise system costs. The physical side of the energy system can be modelled by well-established frameworks such as TIMES, BALMOREL or CALLIOPE. The model uses data from these frameworks, generates hourly prices and simulates the demand side. The flexibility of the demand side can be implemented by calculating energy system equilibria by returning a changed demand level to the energy system model [61].
GRIDCAL	m	Python	GRIDCAL is an optimisation tool for modelling transmission as well as distribution grids. It allows an extension by building or reusing parts of other models[62].
IRENA FLEXTOOL	m	GLPK	IRENA FLEXTOOL stands for *International Renewable Energy Agency Flexibility Tool*. It is a detailed tool for analysing the flexibility of energy systems and their optimal costs, including innovative technologies that provide new flexibility options [63].
OEMOF	f	Python	OEMOF stands for *open energy modelling framework*. It is a modular open source framework for cross-sectoral, multiregional and time-step-flexible energy system modelling, based on a linear optimisation library [64].
OMEGALPES	m	Python	OMEGALPES stands for *Generation of Optimisation Models As Linear Programming for Energy Systems*. It is an energy systems modelling tool for linear optimisation. OMEGALPES is based on the linear programming (LP) modeller PuLP, which is written in Python [65].
OSEMOSYS	f	GLPK & Python	OSEMOSYS stands for *Open Source Energy modelling System*. The framework enables powerful energy systems analysis and prototyping of new energy model formulations focusing on medium and long-term time scopes. It is based on linear optimisation [66].
PANDAPOWER	m	Python	PANDAPOWER is a simulation tool for the detailed modelling of power systems. The tool, based on the Python data analysis library pandas and the power system analysis toolbox PYPOWER is a simple network calculation program [67].
PYPSA	m	Python	PYPSA stands for *Python for Power System Analysis*. It is a simulation and optimisation toolbox for energy systems, especially for modelling long time-series and large-scale networks [68].
REGION4FLEX	m	Python	REGION4FLEX is an optimisation model for load shifting potentials in the German high voltage network, which includes the electricity and heat sector [69].

(*continued on next page*)

Table C.4 (*continued*).

Name	Model; framework	Modelling language	Short description
Renewable test power system models (RTestPSM)	m	Python	The test case renewable power system models were developed in the *Calliope* framework and are an easy way to approach energy system modelling. The models, which can be run in different optimisation modes, provide generation and transmission expansion planning, economic dispatch and unit commitment-type power system models [70].
TIMES	f	GAMS	TIMES stands for *The Integrated MARKAL-EFOM System*. TIMES is a energy system model generator that combines a technical engineering approach with an economic approach on energy modelling. It is based on linear programming [71].
TransiEnt	m	Modelica	TransiEnt is a dynamic system simulation model library that simulates integrated energy networks in different scenarios with a high share of renewable energies. Simulations are based on differential algebraic equations [72].
urbs	f	Python	urbs is an optimisation model generator for capacity expansion planning and unit commitment for distributed energy systems. It is based on linear programming, and focuses on the optimisation of storage sizing and use [73].
xeona	m	UML & C++	xeona stands for *extensible entity-oriented optimisation-based network-mediated analysis*. xeona is an object-oriented simulation environment designed to facilitate sustainability policies taking into account uncertainties. The model combines multi-agent simulation with high-resolution system optimisation modelling [74].

Appendix D. Overview of models and their evaluation

Table D.5
Model rating methodology.

Category	Specification	Rating
General	Geographic scope	Local (NUTS3); used, local (NUTS3) /possible, regional; used, regional; possible, national; used, national; possible, international; used, international; possible
	Temporal scope	Very short; used, very short; possible, short; used, short; possible, intermediate; used, intermediate; possible, long; used, long; possible
	Temporal resolution	<Hourly; used, <hourly; possible, hourly used; hourly; possible, intermediate; used, intermediate; possible, annual; used, annual; possible
	Probability	Yes: 1; no: 0
	Decision making	Perfect foresight & rolling horizon; myopic foresight & decision-/agent based = 1; rolling horizon; myopic foresight & decision-; agent based = 0.8, perfect foresight & rolling horizon; myopic foresight **or** perfect foresight & decision-; agent based = 0.6, rolling horizon; myopic foresight **or** decision-; agent based = 0.4, perfect foresight = 0.2, else = 0
	Social factors	Yes: 1; no: 0
Characteristics	Efficiency	Function: 1; fixed value: 0.5; ∈ operational characteristics
	Ramping	Yes: 1; no: 0; ∈ operational characteristics
	Response time	Yes: 1; no: 0; ∈ operational characteristics
	Recovery time	Yes: 1; no: 0; ∈ operational characteristics

(*continued on next page*)

Table D.5 (*continued*).

Category	Specification	Rating
Network	Distribution grid	Defined: 1; possible: 0.5
	Transmission grid	Defined: 1; possible: 0.5
	Network extensions	Defined: 1; possible: 0.5
	Switches	Defined: 1; possible: 0.5
	Grid representation	AC power flow (PF) & DC PF & inter-connectors & transfer capacity = 1; AC PF & DC PF & inter-connectors = 0.86; AC PF & DC PF & transfer capacity = 0.71; AC PF & DC PF = 0.57; AC PF & transfer capacity **or** DC PF & transfer capacity = 0.43; AC PF **or** DC PF = 0.28; else: 0
	Grid ancillary services	Spinning reverse, balancing energy, sheddable loads, feed-in management, redispatch, power factor corrections, curtailment, black start
	Import	Flow based: 1; simplified: 0.5
Supply	Coal	defined: 1; possible: 0.5
	Lignite	defined: 1; possible: 0.5
	Oil	defined: 1; possible: 0.5
	Natural gas	defined: 1; possible: 0.5
	CHP	defined: 1; possible: 0.5
	Combined cycle gas turbine (CCGT)	defined: 1; possible: 0.5
	Open-cycle gas turbine (OCGT)	defined: 1; possible: 0.5
	Bio energy	defined: 1; possible: 0.5
	Hydro reservoirs	defined: 1; possible: 0.5
	Geothermal energy	defined: 1; possible: 0.5
	Concentrated solar power	defined: 1; possible: 0.5
	PV	defined: 1; possible: 0.5
	Wind onshore	defined: 1; possible: 0.5
	Wind offshore	defined: 1; possible: 0.5
	River hydro	defined: 1; possible: 0.5
	Wave power	defined: 1; possible: 0.5
	Tidal power	defined: 1; possible: 0.5
	Proton exchange membrane fuel cell (PEMFC)	defined: 1; possible: 0.5
	Solid oxide fuel cell (SOFC)	defined: 1; possible: 0.5
	Nuclear	defined: 1; possible: 0.5
	Curtailed operation	yes: 1; no: 0; $\in$ Technology Specifications
	Minimum load	yes: 1; no: 0; $\in$ Technology Specifications
	Discrete capacity expansion	yes: 1; no: 0
Demand	Households	Defined: 1; possible: 0.5
	Industrial load	Defined: 1; possible: 0.5
	Service sector	Defined: 1; possible: 0.5
	Maximum deferrable load	Time- & type dependent =1; Type dependent **or** time dependent = $\frac{2}{3}$; Fixed value = $\frac{1}{3}$; $\in$ technology specifications
	Shifting time	Yes: 1; no: 0; $\in$ technology specifications
	Price elasticity	Yes: 1; no: 0
Storage	Batteries	Defined: 1; possible: 0.5
	Storage implementation	Dynamic: 1; static: 0.5
	Ageing	Cycle ageing; calendrical ageing; $\in$ technology specifications
	Self-discharge	Yes: 1; no: 0; $\in$ technology specifications
	PHS	Defined: 1; possible: 0.5
	CAES	Defined: 1; possible: 0.5
	Capacitors	Defined: 1; possible: 0.5
	Flywheels	Defined: 1; possible: 0.5

(*continued on next page*)

Table D.5 (*continued*).

Category	Specification	Rating
Sector coupling	Power-to-gas	Defined: 1; possible: 0.5
	Power-to-hydrogen	Defined: 1; possible: 0.5
	Heat pumps	Defined: 1; possible: 0.5
	Electric vehicles	Defined: 1; possible: 0.5
	Synthetic fuels	Defined: 1; possible: 0.5
	Heat storage	Defined: 1; possible: 0.5
	Vehicle-to-grid	Defined: 1; possible: 0.5
	Heat sector	Endogenous disaggregated technology & endogenous disaggregated demand = 1; Endogenous disaggregated technology **or** endogenous disaggregated demand = $\frac{2}{3}$; Exogenous aggregated demand = $\frac{1}{3}$; Heat sector excluded or not specified = 0
	Transport sector	Endogenous disaggregated technology & endogenous disaggregated demand = 1; Endogenous disaggregated technology **or** endogenous disaggregated demand = $\frac{2}{3}$; Exogenous aggregated demand = $\frac{1}{3}$; Transport sector excluded or not specified = 0
	Sector coupling demand	If power-to-gas **or** power-to-hydrogen **or** heat pumps **or** electric vehicles was ticked as defined **or** possible: Shifting time: yes = $\frac{1}{3}$; Price elasticity: yes = $\frac{1}{3}$; Rating of maximum deferrable load derived by 3; $\in$ technology specifications
	Sector coupling supply	If CHP was ticked as defined **or** possible: Minimum load: yes = 0.5; Discrete power expansion: yes = 0.5; $\in$ technology specifications
	Sector coupling storage	If synthetic fuels **or** heat storage **or** vehicle-to-grid was ticked as defined **or** possible: Self-discharge: yes = $\frac{1}{3}$; Cycle ageing: yes = $\frac{1}{6}$; Calendrical ageing: yes = $\frac{1}{6}$; Storage implementation: dynamic = $\frac{1}{3}$; Storage implementation: fixed; static = $\frac{1}{6}$; $\in$ technology specifications

Appendix E. Figures of single flexibility categories

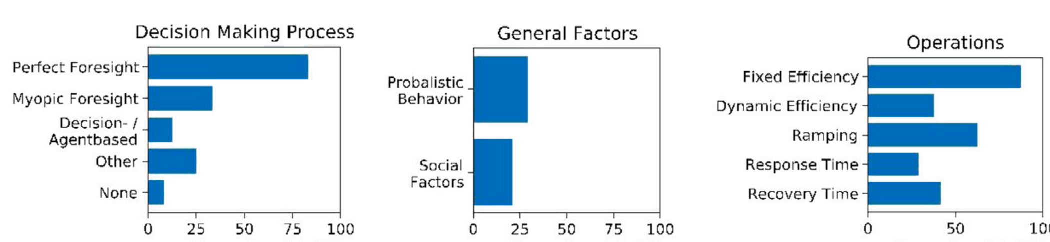
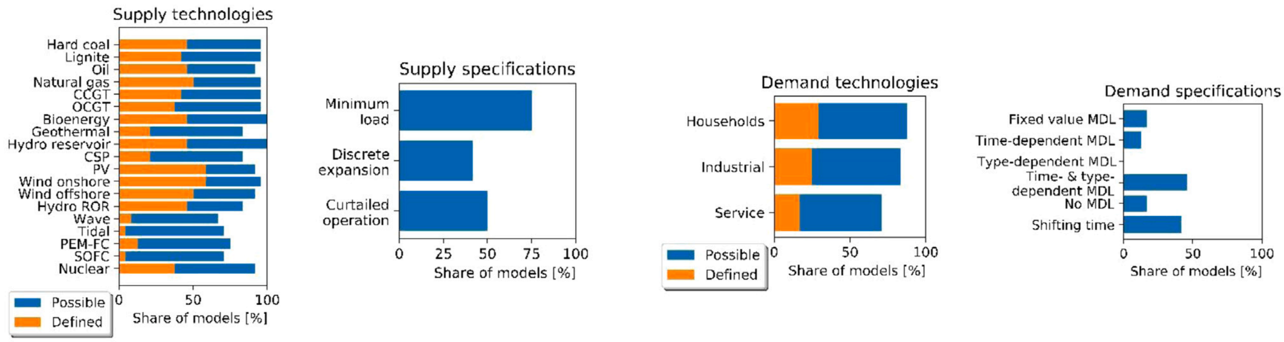


Fig. E.11. Representation of decision-making processes (left), probabilistic behaviour and social factors (middle) and operational characteristics (right).



(a) Supply-side technologies (left) and specifications (right)   (b) Demand-side technologies (left) and specifications (right)

Fig. E.12. Supply-side technologies (left) and specifications (right).

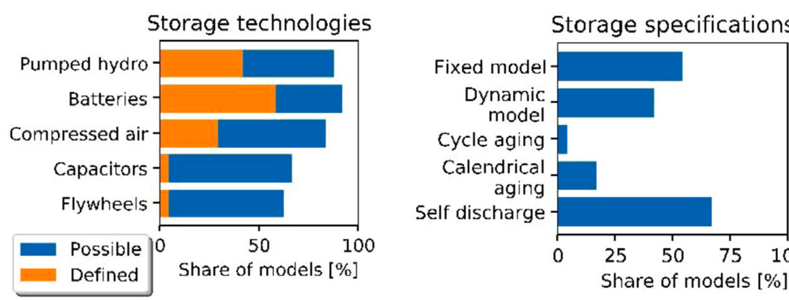


Fig. E.13. Representation of storage technologies (left) and specifications (right).

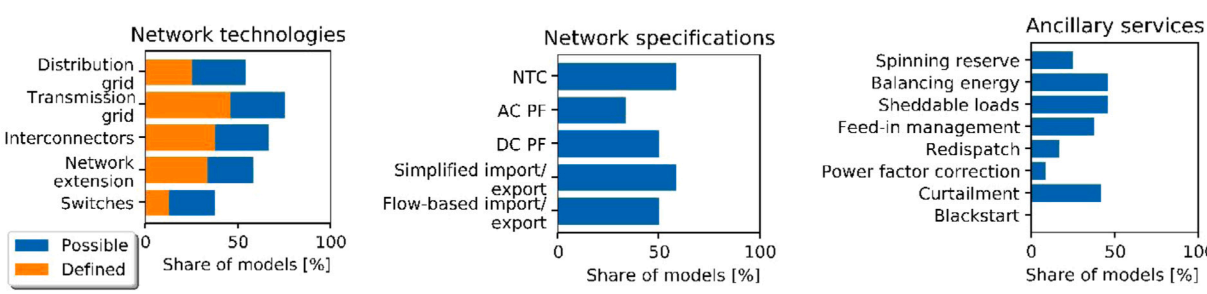


Fig. E.14. Representation of network technologies (left), specifications (middle) and ancillary services (right).

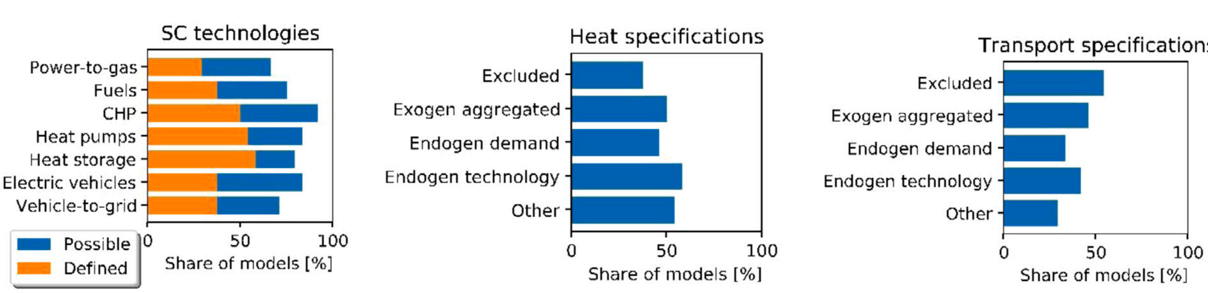


Fig. E.15. Representation of sector coupling technologies (left), heat (middle) and transport sectors (right).

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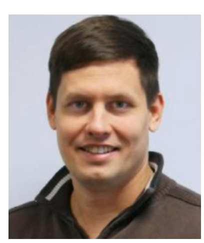

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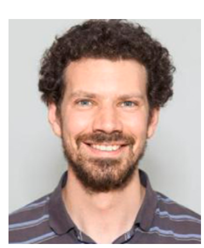

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