

# Analysis of electricity market models for future power systems

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**Abstract**—Electricity market models play a crucial role in addressing various research questions related to future electricity supply systems. As the energy transition progresses, the electricity market must evolve to incorporate renewable energy and demand-side flexibility while ensuring adequate investment incentives for reliable capacity. The design of electricity market models for future electricity markets requires a multifaceted approach that considers temporal, spatial, methodological, technical, and integrative criteria. A comprehensive review of 30 existing models identifies opportunities for advancement, particularly in the area of simulating the future electricity market. The analysis of these models indicates areas where improvements can be made in terms of realistic modeling. These areas include the modeling of human behavior, enhanced spatial resolution, representation of multiple electricity markets, and improved uncertainty modeling.

**Index Terms**—electricity market modeling, renewable power system, literature review

## I. INTRODUCTION

As part of the European Green Deal, the EU Commission has defined the objective of achieving climate neutrality by 2050. A major aspect on the way to achieve this goal is the decarbonization of the energy system, in particular the electricity supply system. Renewable energy sources are increasingly replacing fossil fuel power plants, making electricity generation more dependent on the variability of renewable energy sources such as wind and solar. Consequently, generation becomes more susceptible to supply fluctuations and less adaptable to fluctuations in demand. In contrast, the emergence of new consumer categories, such as electric vehicles and heat pumps, has introduced a degree of flexibility in consumption patterns. A key challenge lies in the integration of these novel technologies into the electricity market, necessitating adaptations to ensure its future resilience.

The aim of electricity market models is to create simulations that accurately reflect future market scenarios. These models illustrate price fluctuations resulting from auctioning and bidding processes, offering a framework for analyzing short-term as well as long-term questions. These questions encompass business-related, macroeconomic, and regulatory issues [1]. Electricity market

models are also used to generate input data for load flow calculations. It is important to note that electricity market models are inherently uncertain. Achieving a high degree of accuracy in the modeling of the electricity markets is imperative for decision-making processes to be founded on solid grounds. The incorporation of dynamic elements, such as the emergence of new market participants or shifts in regulatory frameworks, is essential to ensure the relevance and accuracy of the model. This raises the question of what requirements must be imposed on an electricity market model to adequately reflect the future electricity market.

This paper proposes a set of requirements for future electricity market models. These requirements are derived for a realistic modeling of the electricity markets. No consideration was given to which criteria ensure a particularly high level of complexity and, consequently, should be simplified in terms of calculability. Subsequently, a data set of 30 current electricity market models was examined to determine their fulfillment of the developed requirements. The findings indicate areas that could be developed to improve future models.

## II. REQUIREMENTS OF FUTURE ELECTRICITY MARKET MODELS

To model the electricity market, multiple factors must be considered, such as the feed-in of power plants, cross-border electricity flows, and demand patterns [2]. Those input data and frameworks change over time. One significant change is the upcoming energy transition, which will lead to a restructuring of the electricity market. Ideally, electricity market models should appropriately account for these changes. Furthermore, simulations should run quickly without requiring too much computing capacity. In reality, not all requirements can be met perfectly and a trade-off must be found.

This section analyzes the requirements that electricity market models must meet in order to adapt to future electricity markets. The analysis is conducted with the aim of modeling as close to reality as possible, while neglecting potential constraints. There are multiple requirements for electricity market models that will be relevant in

future. Here, they were structured into five categories to provide a comprehensive overview: Temporal, spatial, methodological, technical, and integrative requirements. Table I shows the requirements along with a short description and the ideal configuration to achieve the most realistic outcome. In Section III, they are used as criteria for the following analysis.

TABLE I  
REQUIREMENTS FOR FUTURE ELECTRICITY MARKET MODELS

Requirements	Description
Temporal Requirements	
Time Coupling	Representation of time-coupling flexibility options; Ideal: Detailed consideration
Temporal resolution	Time steps considered in the data used and simulation; Ideal: 15 min time intervals
Spatial Requirements	
Market Coupling	Representation of international electricity trading; Ideal: Flow-based market coupling
Spatial Resolution	Level of spatial aggregation of data; Ideal: Highly detailed data
Methodological Requirements	
Modeling Methodology	The methodology underlying the model; Ideal: Depends on the application
Human Behavior	Integration of human behavior into market activities; Ideal: Complex agent-based modeling
Uncertainties	Consideration or omission of uncertainties; Ideal: Consideration, method depends on application
Technical Requirements	
Technical Restrictions	Consideration or neglect of technical restrictions for market participants; Ideal: Detailed consideration
Integrative Requirements	
Electricity Markets	Consideration of different electricity markets; Ideal: Mapping of all markets and interactions
Multi-Sector Analysis	Representation of sector coupling; Ideal: Mapping of all sectors and interactions

### A. Temporal Requirements

1) *Time Coupling*: To reduce fluctuations in renewable energy generation, time-coupling flexibility options are highly relevant in future energy systems. Flexibility

options compensate for unpredictable variations in electricity generation and consumption. One of them is the bringing forward or the postponement of generation or consumption, called time-coupling [3]. The curtailment of power plants, energy storage, and demand-side options enable such temporal shifts. These time-coupling effects require detailed consideration in electricity market models.

2) *Temporal resolution*: The temporal resolution describes how detailed the time steps in the models are. The resolution is selected according to the market with the shortest-term electricity products and therefore corresponds to the scope of markets that are analyzed. Time intervals for the resolution can be for example daily, hourly, or quarter-hourly. If the intraday market is considered, which trades the shortest-term energy products, the temporal resolution would be set to quarter-hourly [4]. Which electricity markets need to be mapped in order to model the future electricity market as realistically as possible, is discussed in Subsection II-E. Anticipating this, it is becoming increasingly relevant to model short-term trading markets, since short-term electricity trading is used to adapt to unpredictable changes in energy supply or consumption [1]. Therefore, the ideal temporal resolution for future electricity market models corresponds to 15 min intervals.

### B. Spatial Requirements

1) *Market Coupling*: Market coupling refers to cross-border electricity trading and serves as a spatial flexibility option. At the European level, market coupling is well established, whereas different market coupling mechanisms are applied [5]. The flow-based market coupling mechanism has been proven to be the most effective [6] and the EU intends to implement it as the dominant method [7]. As flexibility options are expected to become increasingly important, it is crucial to integrate market coupling in future electricity market models. To achieve the most realistic model, it is recommended to incorporate flow-based market coupling, considering all relevant parameters.

2) *Spatial Resolution*: The spatial resolution describes the degree to which the spatial distribution of market participants is taken into account in data sets. In future energy systems, factors like solar radiation or wind speeds will increasingly determine the distribution of power plants. Furthermore, future energy systems are expected to become more decentralized, featuring small-level power plants spread over large areas [8]. Currently, electricity trading does not depend on local distributions within one market area. However, localization signals, which could reduce the increasing grid load due to the peak production of renewable energy generation, are discussed [9]. Therefore, the spatial distribution of

production, consumption and flexibility options should be considered using detailed data in terms of spatial resolution for realistic modeling.

### C. Methodological Requirements

1) *Modeling Methodology*: For modeling future electricity markets, there are different underlying methodological strategies. They can be created by disaggregating higher-level market structures into individual components (top-down) or by aggregating in the opposite direction (bottom-up) [10]. A combination is also possible by building on superordinate market structures and incorporating relevant details [11]. Top-down models are usually more suitable for analyzing sectors and their interactions, while bottom-up models focus on technical and economic details [11]. It is advantageous to deploy bottom-up modeling, as future energy systems will be more decentralized and contain multiple small-level components. However, the suitability of the underlying methodology depends on the individual application.

2) *Human Behavior*: Market dynamics are based on individual human behavior and strategic decisions. In contrast, it is often assumed that all market decisions are made rationally. Also, depending on the methodology, the market modeling is conducted from a central perspective [12]. Although human behavior can never be fully estimated in electricity market models, there are attempts to get as close as possible. Especially agent-based models are considered to have great potential to simulate more realistic market dynamics [13]. These models simulate the behavior of market actors with individual decision-making and learning strategies. They also take into account interactions between actors and include social aspects into market behavior [12].

3) *Uncertainties*: Although the objective of electricity market models is to simulate realistically, outputs of the models cannot be seen as fixed forecasts. Even with the most complex data and best integrated algorithms, there are uncertainties that can influence the market results. For example, fluctuations in electricity demand, unpredictable variations in electricity supply, or price fluctuations of externally coupled markets influence the electricity market [1]. Models can either assume that all input parameters are predefined (deterministic) or take uncertainties into account [1]. This can be realized using various methods. Stochastic programming assigns probability distributions to uncertain variables [1]. Another method is the scenario analysis, which compares multiple possible outcome scenarios. The suitable method depends on the particular application of the model and therefore cannot be determined in general terms.

### D. Technical Requirements

The bidding processes on the electricity market are not only defined by financial interests, but also by technical

constraints. Technical restrictions of market participants, especially power plants, include, among others, minimal up- and down-times, time for maintenance, minimum generation and load gradients [10]. For modeling the electricity market realistically, it is essential to take such restrictions into account.

### E. Integrative Requirements

1) *Electricity Markets*: As mentioned before, the electricity market consists of multiple markets, including the spot market, the futures market and the balancing market [5]. When deciding on which electricity market is essential for market models, it is important to understand their functions. The spot market is seen as a price signal to other markets [14]. It is further divided in the day-ahead market and the intraday market. Often, the intraday market is neglected in market models. However, the trading volume on the intraday market is growing, since it is used for short-term compensation [1], [15], [16]. The futures market is important for long-term market transactions, which are expected to increase due to hedging against fluctuating prices [17], [18]. The balancing market is necessary for system stability and the security of supply. It is expected to require more balancing energy in a future system with a growing share of renewable electricity production. Therefore, depending on the application, modeling all markets and interactions is ideal for a realistic simulation.

2) *Multi-Sector Analysis*: Sector-coupling is considered as another flexibility option. At a surplus of energy, electrical energy can be converted into heat, for example. Next to the heat sector, the hydrogen sector, the gas sector, the industrial sector, and the transportation sector are relevant in a carbon-free energy system [8]. Coupling technologies are, for example, electric vehicles, heat pumps, and electrolyzers. The coupling of different sectors causes interdependencies and can influence electricity prices. For a realistic electricity market model, it is important to represent all coupled sectors including their interactions and dependencies.

## III. CURRENT MARKET MODELS

A large number of electricity market models are currently employed. The subsequent section analyzes the degree to which the requirements developed in this work has been implemented in existing models. Initially, an evaluation scheme is presented that facilitates a comparison between different electricity market models with regard to the requirements. Thereafter, 30 currently utilized electricity market models are presented. Subsequently, the models will be evaluated using the evaluation scheme, and overall trends will be derived.

### A. Evaluation Scheme

The objective of the evaluation scheme is to facilitate a comparative analysis of various electricity market models based on the established criteria. Wherever possible, the criteria are discretized on a scale of one to five, with a higher value indicating greater accuracy of the respective aspect. The value "one" thus signifies a rudimentary or non-existent consideration of an aspect, while the value "five" denotes the ideal characteristics with respect to future requirements. A comprehensive description of the discretized values can be found in Table III in the Appendix A. It is imperative to underscore that this evaluation does not imply a judgment of the models as either superior or inferior. Instead, the implementation of the criteria, which relate exclusively to realistic modeling, is the sole aspect evaluated. It is acknowledged that a comprehensive evaluation necessitates the incorporation of additional criteria.

For certain criteria, a discretization is not feasible, as their optimal expression is contingent upon the specific use case. Consequently, a characterization is employed to describe the models. This approach is adopted for the criteria *Modeling Methodology* and *Uncertainties*.

The technical criterion *Technical Restrictions* will not be further analyzed in the following evaluation. This is due to the fact that for some models, it is challenging to comprehend the precise modeling as the source code is not always available. Consequently, a fair assessment of this criterion is not possible for all models.

### B. Overview over selected models

In total, 30 distinct electricity market models are examined in this paper. An overview of the models and the sources consulted can be found in Table II in the Appendix A. The models were selected based on the criteria currency and variety. The final set of models encompasses exclusively those that underwent at least one update subsequent to 2014 and have been published after 2018. To ensure a comprehensive coverage of a wide range of use cases, the analysis incorporates diverse model methodologies and time periods.

Prior to the evaluation of the discretized criteria in the subsequent subsection, the characterized criteria will be presented. Figure 1 illustrates the variety of methodologies and the handling of uncertainty. It is evident that bottom-up models with a deterministic approach to uncertainty handling are predominantly utilized.

### C. Evaluation of current models

In the following, the evaluation of the models is performed. An overview of the discretized values of each criterion for each model can be found in the Appendix A in Table IV. Based on this, an average value for each

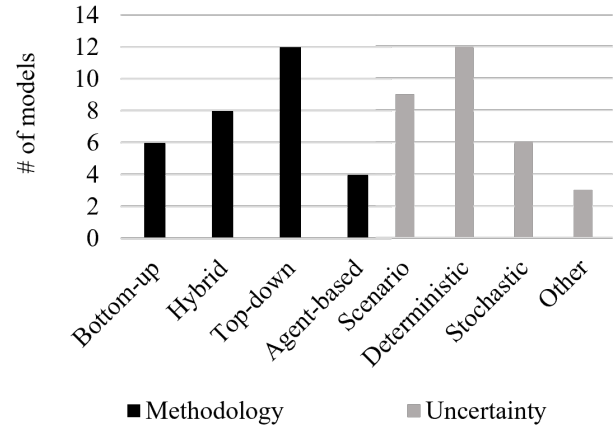


Fig. 1. Categorization of modeling methodologies and uncertainties

discretized criterion can be calculated over all models. The resulting values can be observed in Figure 2.

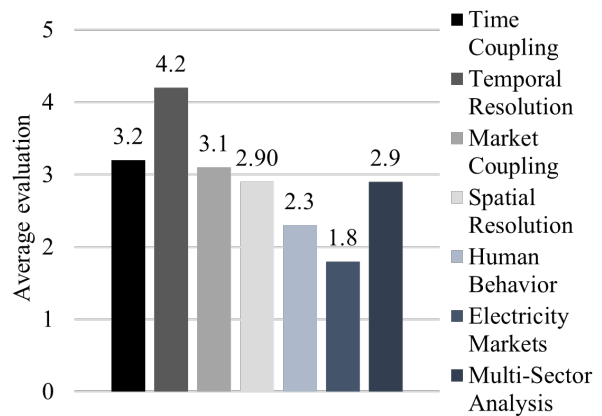


Fig. 2. Average rating over the criteria

These average values can be regarded as a preliminary indication of which factors should be given particular consideration in the development of future electricity market models. A detailed analysis of each criterion is carried out in the following.

1) *Time Coupling*: Given the increasing prevalence of storage technologies, the management of time coupling will become increasingly significant. The majority of models currently incorporates a range of representation of time coupling, with an average value of 3.2 across the models. Since time coupling is a primary driver of complexity, a trade-off between accuracy and processing time must be addressed, a subject that will not be explored further in this work.

2) *Temporal Resolution*: Temporal resolution is defined as the number of steps that are simulated individually. The majority of the models examined exhibit a temporal resolution of one hour or less and therefore

have a discretized value of *five*. As can be seen in Figure 2, the mean value is 4.2. This finding provides a solid foundation for the further development of the models, as a realistic simulation of renewable energy sources depend on an accurate representation of the time segments.

3) *Market Coupling*: An increased market coupling in Europe should lead to an improvement in overall welfare. However, the average value of 3.1 may be somewhat deceptive due to the substantial variability observed across the models examined. It is noteworthy that a mere four models encompass a comprehensive simulation of international trade, attaining a value of *five*. Consequently, it can be posited that future enhancements to the modeling of market coupling are warranted.

4) *Spatial Resolution*: Spatial resolution is defined as the degree of spatial granularity with which market participants are represented. In numerous models, the geographical areas are segmented into expansive divisions. The majority of models exhibit minimal or no spatial granularity resulting in an average value of 2.9. This indicates a possible oversight of local variations. To date, the necessity of regionalization in electricity market models for the European market is only necessary on a high level. However, the prospect of incorporating local incentives into the electricity market requires the enhancement of spatial granularity in future.

5) *Human Behavior*: The depiction of human behavior describes the degree to which individual strategic behavior of market participants is modeled. Most models do not depict human behavior or do so only in a static manner, leading to an average value of 2.3. This can be explained by the structure of conventional models, which were conceptualized within the paradigm of a centralized market. However, a discernible trend is emerging towards agent-based market models that are capable of depicting complex human interactions. This development aligns with the trend toward decentralization in the energy market, signifying a shift towards more realistic modeling. However, it is important to acknowledge the limitations of current models in fully capturing strategic behavior, which can impede the interpretation and reproducibility of results.

6) *Electricity Markets*: The criterion electricity markets describes the extent to which different electricity markets are integrated in the models. As illustrated in Figure 3, the majority of the models do not directly model bidding in electricity markets, rather, they depict market behavior through the representation of supply and demand. Approximately half of the models consider the intraday market. However, only a few models incorporate the balancing capacity market, and none the futures market.

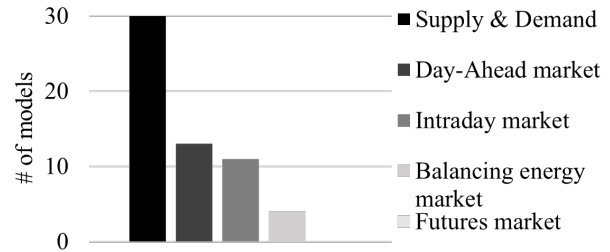


Fig. 3. Frequency of modeling of the individual electricity markets

The fact that the futures market is not modeled can be attributed to the nature of the market. The contracts on the futures market are often fixed for long periods of time and are used to hedge prices against the spot market. As prices are set on the spot market and prices on the futures market are linked to it, the relevance of modeling the futures market is considered to be low. Because of the increasing penetration of renewable energies, the short-term intraday market as well as the balancing capacity market will become more important and should be considered in future models.

7) *Multi-Sector Analysis*: The sectors or coupling mechanisms  $CO_2$ , heat, transportation, fuels, and gas resp. hydrogen were considered. On average, around three of these are considered in one model (average value of 2.9). It can be seen that the heat sector and fuels are considered frequently. The depiction of the gas and hydrogen market and the respective coupling technologies Power-to-Gas and Power-to-Hydrogen can be improved further in the future.

#### IV. CONCLUSION

A changing electricity market leads to new challenges for electricity market models. Therefore, the requirements for electricity market models change in future. This paper derived requirements for future models including temporal, spatial, methodological, technical and integrative criteria. A data set of 30 currently used electricity market models were analyzed regarding the fulfillment of the derived requirements. It can be concluded that future modelers ought to prioritize the incorporation of human behavior, enhanced spatial resolution, consideration of electricity markets, and the integration of uncertainty modeling as these elements have been identified as areas of improvement. While this work focuses only on the criterion of a realistic modeling, future work should also take different criteria, especially the complexity of the models, into account.

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APPENDIX

A. Overview of electricity market models

TABLE II  
OVERVIEW OF ELECTRICITY MARKET MODELS

	<b>Full name</b>	<b>Developer</b>	<b>Sources</b>
<i>AMIRIS</i>	Agent-based Market Model for the Investigation of Renewable and Integrated Energy Systems	-	[12]
<i>Belmorel</i>	A Model for Analyses of the Electricity and CHP markets in the Baltic Sea Region	Elkraft System	[19]
<i>DESTinEE</i>	Demand for Energy Services, Supply and Transmission in Europe	Imperial College London	[20]
<i>DIETER</i>	Dispatch and Investment Evaluation Tool with Endogenous Renewables	German Institute for Economic Reserach, Berlin	[20]–[23]
<i>Dispa-SET 2.0</i>	Unit Commitment and Power Dispatch Model	Institute for Energy and Transport, Joint Research Centre	[20], [24]
<i>E2M2s</i>	European Electricity Market Model	Institute of Energy Economics and Rational Energy Use (IER), University of Stuttgart	[20], [25]
<i>ELMOD</i>	Spatial Optimization Model of the Electricity Sector	DIW Berlin	[20], [21], [23], [26]
<i>Eltramod</i>	Electricity Transshipment Model	Chair of Business Management, esp. Energy Economics, TU Dresden	[20], [23], [26], [27]
<i>EMCAS</i>	Electricity Market Complex Adaptive System	Argonne National Laboratory	[19], [20], [28], [29]
<i>EMLab</i>	Energy Modeling Laboratory	TU Delft	[20], [30]
<i>EMMA</i>	European Electricity Market Model	Potsdam Institute for Climate Impact Research / Neon Neue Energieökonomik	[20], [23], [31]–[33]
<i>EMPIRE</i>	European Model for Power System Investment with Renewable Energy	Norwegian University of Science and Technology	[20], [34]
<i>EULR</i>	European Lagrangian Relaxation Model	RWTH Aachen University	[35]
<i>GENESYS</i>	Genetic Optimization of a European Energy Supply System	RWTH Aachen University	[20], [23], [36]
<i>IKARUS</i>	-	Institute of Energy Research at Research Centre Jülich	[19], [20], [37], [38]
<i>LIBEMOD</i>	Liberalization Model for the European Energy Markets	CREE Frisch Centre	[20], [39]
<i>LIMES-EU</i>	Long-term Investment Model for the Electricity Sector of Europe	Potsdam Institute for Climate Impact Research	[20], [40], [41]
<i>MARKAL / TIMES</i>	Market Allocation Model / The Integrated MARKAL-EFOM System	Energy Technology Systems Analysis Program, International Energy Agency	[19], [20], [23], [42]
<i>METIS</i>	Modeling the European Power System	Directorate-General for Energy of the European Commission	[20], [37], [43], [44]
<i>MultiMod</i>	Multiscale Modeling	German Institute for Economic Research, Berlin	[20], [21], [45]
<i>OSeMOSYS</i>	Open Source Energy Modeling System	KTH Royal Institute of Technology	[20], [23], [37]
<i>PERSEUS</i>	Program Package for Emission Reduction Strategies in Energy Use and Supply	Institute for Industrial Production, Karlsruhe Institute of Technology (KIT)	[19], [20], [42], [46], [47]
<i>POLES</i>	Prospective Outlook on Long-term Energy Systems	EDDEN laboratory, University of Grenoble-CNRS	[20], [37], [48]
<i>PRIMES</i>	Price-Induced Market Equilibrium System	Energy-Economy-Environment Modeling Laboratory (E3MLab), National Technical University of Athens	[19], [20], [37], [42], [49]–[52]
<i>Prognos</i>	-	-	[53]
<i>PyPSA</i>	Python for Power System Analysis	Frankfurt Institute for Advanced Studies	[20], [23], [54]
<i>REMix</i>	Renewable Energy Mix	Institute of Engineering Thermodynamics, German Aerospace Centre	[20], [37], [55]
<i>REMod-D</i>	Renewable Energy Model - Deutschland	Institute of Engineering Thermodynamics, German Aerospace Centre	[20], [25], [56]
<i>stELMOD</i>	Stochastic ELMOD	German Institute for Economic Research, Berlin	[20], [21], [23]
<i>urbs</i>	-	Chair of Renewable and Sustainable Energy Systems, Technical University of Munich	[20], [23]

## B. Discretization of criteria

TABLE III  
DISCRETIZATION OF CRITERIA

Criteria	1	2	3	4	5
<i>Time Coupling</i>	None	One type of storage	Multiple, but simplified storage technologies	Consideration of storage capacities through PtX	Full modelling of long-term storage systems
<i>Temporal Resolution</i>	More than one year	Yearly	Multiple time-slices per year	Multiple time-slices per day	Hourly and above
<i>Market Coupling</i>	None	Limited	Cross-border network utilization	Simplified consideration	Realistic consideration
<i>Spatial Resolution</i>	None	National level	Regional level	City level	Geoinformationssystem-based data
<i>Human Behavior</i>	none	Demand statistics	Strategic bidding and/or profit optimization	Agent-based modelling	Complex agent-based analysis
<i>Electricity Markets</i>	Static consideration of supply and demand	One market (typically day-ahead market)	Two markets (typically +intraday market)	Three markets (typically +balancing market)	Four markets (typically +derivatives market)
<i>Multi-Sector Analysis</i>	One sector	Two sectors	Three sectors	Four sectors	All relevant sectors

## C. Overview of electricity market models

TABLE IV  
DISCRETIZED VALUES OF ELECTRICITY MARKET MODELS

	Time Coupling	Temporal Resolution	Market Coupling	Spatial Resolution	Human Behavior	Electricity Markets	Multi-Sector Analysis
<i>AMIRIS</i>	3	5	4	2	5	2	1
<i>Belmorel</i>	3	5	2	3	1	3	3
<i>DESTinEE</i>	1	5	4	2	1	3	1
<i>DIETER</i>	3	5	2	2	3	3	1
<i>Dispa-SET 2.0</i>	3	5	?	3	1	1	3
<i>E2M2s</i>	4	5	?	4	1	1	2
<i>ELMOD</i>	2	5	4	4	1	3	2
<i>Eltramod</i>	2	5	5	2	1	3	1
<i>EMCAS</i>	4	5	1	4	5	3	2
<i>EMLab</i>	3	2	5	3	5	3	1
<i>EMMA</i>	3	5	4	2	1	3	2
<i>EMPIRE</i>	3	5	3	2	2	1	1
<i>EULR</i>	5	5	4	2	3	2	4
<i>GENESYS</i>	3	5	5	2	1	1	3
<i>IKARUS</i>	4	1	1	2	2	1	5
<i>LIBEMOD</i>	2	4	4	2	3	1	4
<i>LIMES-EU</i>	4	3	3	3	3	1	5
<i>MARKAL/TIMES</i>	4	5	1	3	2	1	5
<i>METIS</i>	1	5	5	5	3	3	2
<i>MultiMod</i>	3	1	3	1	4	3	4
<i>OSeMOSYS</i>	4	4	1	3	2	1	5
<i>PERSEUS</i>	5	3	1	4	2	1	3
<i>POLES</i>	4	2	2	3	2	1	2
<i>PRIMES</i>	4	1	4	3	5	1	4
<i>Prognos</i>	2	5	3	4	4	1	4
<i>PyPSA</i>	3	5	3	4	1	1	4
<i>REMix</i>	4	5	3	5	2	1	3
<i>REMod-D</i>	4	5	1	2	1	1	3
<i>stELMOD</i>	2	5	4	4	1	4	2
<i>urbs</i>	3	5	4	3	2	1	4