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# An agent-based modelling framework for the simulation of large-scale consumer participation in electricity market ecosystems

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## Abstract

The role of consumers as price-sensitive participants in electricity markets is considered essential to ensure efficient and secure operations of electricity systems. Yet the uncertain or unknown consequences of active market participation remain a large barrier for active consumer-side market participation. Simulations are a powerful tool to reduce this uncertainty by giving consumers an insight on the potential benefits and costs of market participation. However, the simulation setup must be adapted to each market context and each consumer market participation strategy. To simplify the simulation development process and improve the comparability of simulation results, this paper proposes a modular yet systematic electricity market modelling framework. The framework applies object-oriented programming concepts for business ecosystem modelling presented in previous works to develop an agent-based model of a consumer-centric electricity market ecosystem. The market ecosystem is represented by a multitude of interacting submarkets with their own logic. Within submarkets, context-independent and context-dependent elements are distinguished to provide model abstraction which can be adapted to different contexts. This framework is illustrated by applying it to three different submarkets in the Western Danish electricity market context: the Nordpool day-ahead market, the Nordpool intraday market, and the Frequency Containment Reserve market. The submarket role abstractions allow to benefit from the commonalities between the analysed submarkets during model implementation, while the role parametrisations allow to quickly adapt the roles to each market context. The implementation of the modelling framework in the Nordic context highlights the benefits of a modular approach in a liberalised and unbundled market context.

**Keywords:** Agent-based model, Object-oriented programming, Electricity market ecosystem, Consumer flexibility, Market participation strategy, Model framework

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## Introduction

In a liberalised market context, the role of system planning, scheduling and operations has been progressively decentralised, passing from a monopolistic system operator to a multitude of generation side and consumption side market participants, coordinated by market prices (Joskow 2022; Li et al. 2016). In a mature market with fair competition, market prices should therefore accurately reflect system needs, both for short-term operations and long-term investments (Roques and Finon 2017). Such market-driven system operations rely on price-responsive flexible demand, where consumers adapt their consumption based on how much they are willing to pay for power supply (Ma et al. 2017a, 2018a). Yet until now, consumers largely remain passive market participants, not willing to adjust their consumption to system needs (Leinauer et al. 2022). Indeed, behavioural factors such as risk-willingness and innovation culture play an important role in implementing consumption-side flexibility (Alcázar-Ortega et al. 2015; Ma and Jørgensen 2018). Meanwhile, with the planned phase-out of dispatchable fossil-fuel power plants in many countries, demand-side participation in electricity markets is increasingly encouraged to improve the flexibility in the system (Billanes et al. 2018). This demand-side flexibility allows to avoid expensive reserve resources and helps increase the integration of renewables in the grid (Cecati et al. 2011).

To encourage consumer-side market participation, various electricity market models have been developed over the years to simulate potential benefits of market participation. In the context of market restructuring and role decentralisation brought by market liberalisation, agent-based modelling (ABM) has emerged as a popular modelling tool for electricity markets. Agent-based modelling (ABM) simulations are a type of simulation where autonomous agents can evolve in a predefined environment to pursue their own strategy while following basic preestablished rules (Ringler et al. 2016). Agents only access information from the environment in which they evolve through interactions with other agents (Wang and Paranjape 2017), and have limited knowledge of the overall state of the system (Baum et al. 2017). ABM simulations are therefore suited to represent decision making processes in electricity markets which are decentralised with incomplete information availability (Christensen et al. 2019).

Modelling approaches focusing on participant's specific preferences and properties are particularly relevant for consumers, as operational risk-averseness, revenue uncertainty and reluctance to change have been identified as some of the key barriers for the uptake of consumer-side market participation (Leinauer et al. 2022; Alcázar-Ortega et al. 2015; Olsthoorn et al. 2015; Værbak et al. 2019). The specific success criteria of each consumer could result in different market participation strategies, depending on how well the market can satisfy these criteria (Fatras et al. 2022b). A particular challenge for consumers is to navigate the complexity of liberalised electricity markets, which are often composed of a series of interacting submarkets, each providing different services to the grid at different time resolutions, over different timespans, and with different participation requirements (Fatras et al. 2022b; Ma et al. 2019a). The properties and interactions between submarkets are also very context dependent. Overall, the diversity of submarkets on the market side and the differences in success criteria on the consumer side make it difficult for consumers to adopt systematic methods to easily evaluate market participation suitability. Evaluation tools must therefore be modular, in order to easily adapt the evaluation

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to different large-scale consumer types and market contexts, yet systematic, to streamline the evaluation process and improve the comparability of results.

To address this challenge, the following work aims to develop a systematic, modular and consumer-centric ABM framework to simulate consumer-side participation in electricity markets. Due to the large diversity of consumer types and behaviours, this study will only focus on large-scale electricity consumers, who are able to directly participate in the electricity market without market intermediaries. Large-scale consumers were identified to face the lowest implementation barriers due to preliminary experience with demand-side management, availability of ICT infrastructure, loads scheduled ahead of consumption time, less reliance on third-parties, and a more rational logic influenced to a greater extent by price signals (Shoreh et al. 2016; Samad and Kiliccote 2012; O'Connell et al. 2014).

The approach is considered consumer centric as it represents the electricity market from a consumer perspective, as an ecosystem of interacting submarkets in which the consumer can participate. The approach is systematic, as it identifies core context-independent building blocks which provide the modelling blueprint, and it is modular, as it allows these building blocks to be assembled differently depending on the market context. The modular and systematic approach are based on object-oriented programming concepts, which are implemented through the Java-based Anylogic software. In this study, the developed framework is tested in the Western Danish electricity market (DK1) context by conceptually modelling consumer participation in three different submarkets: the day-ahead market, the intraday market, and the frequency containment reserve (FCR) market (Ma et al. 2016). These three submarkets have been chosen due to their differences in market properties, to test the modularity of the presented approach.

The presented modelling framework will facilitate and help standardise the development of simulations to evaluate consumer-side market participation suitability. The consumer-centric approach should increase consumers' understanding and confidence in model results by providing tailor-made solutions, while the modular approach should increase the comparability of results between different large-scale consumers, business models, and market contexts, which allows to evaluate the relative performance of obtained results.

The rest of this paper will first provide some background on the use of ABM in electricity markets. Then the general framework of the model is presented, with a step-by-step guide for model implementation. The developed framework is then applied to different submarkets in the Danish market context, and finally a discussion and conclusion provide further insights on the presented approach.

## Background

### Impact of liberalisation on market structure

Electricity market liberalisation, a process started in the 90 s in many countries throughout the world, was implemented to improve the efficiency of system operations and investment by promoting fair competition (Wilson 2002). Competition was put in place by breaking down the monopoly of system operators: vertical unbundling was implemented to separate roles along the supply chain from generation to consumption, and horizontal unbundling was implemented to increase the number of actors within each

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step of the supply chain (which were suited to competition) (Joskow 2022). This unbundling process has led to a multiplication of actors within the electricity market and has transferred the responsibility of electricity system operations and investment from a centralised entity to competing actors cleared in the electricity market. As an electricity system has multiple requirements to fulfil, different market types, referred to here as submarkets according to the definition in Lopes (2018a), Stoft (2002), constitute the electricity market. Each of these submarkets represents a value chain which a large-scale consumer can decide to participate in or not. Efficient planning, scheduling and operations of the electricity system depend on active participation in each of these submarket types, and efficient coordination between the submarkets. Submarket interactions are what is referred to as market architecture in Lopes (2018a); Stoft (2002). Examples of submarket types found in the literature, without being exhaustive, are given in Table 1.

Each of these submarket types can consist of multiple submarkets, depending on the specific architecture of the electricity market. The overall system created by the different submarkets, the market participants, and the interactions between and amongst participants and submarkets is here referred to as an electricity market ecosystem. The market ecosystem is an extension of the business ecosystem concept presented in Ma (2019), where a business ecosystem is defined as a large number of interconnected participants depending on each other for mutual effectiveness and survival (Ma 2019; Iansiti and Levien 2002). In a market ecosystem, submarkets are represented as individual and interconnected entities in the system, despite not having an independent strategy or behaviour in the system. Such ecosystems reflect the complexity of liberalised markets, where access to market information depends on time, interactions, and the overall architecture of the market.

### Existing models

Several ABM models focusing on electricity markets have emerged in recent years as a subbranch of agent-based computational economics. Some established electricity market ABM models in the literature are AMES (Agent-Based Modelling of Electricity Systems) for the bidding of generating companies (GenCos) in wholesale markets, used in Ref. Kiran et al. (2019) and El-Adaway et al. (2020); MASCEM (Multi-Agent Simulator

**Table 1** Submarket types found in liberalised electricity market contexts

| Submarket type | Description |
| --- | --- |
| Wholesale submarkets | Direct electricity trading between generators and consumers, or between market intermediaries on either side, depending on the consumer's size and preferences |
| Retail submarkets | Contracts between the consumer and a market intermediary which purchases electricity in wholesale submarkets on behalf of the consumer |
| Ancillary Service submarkets | System balancing services provided by market participants and coordinated by the system operator during operation times to ensure overall balance between demand and supply at all times |
| Congestion submarkets | Load adjustment services provided by market participants to avoid congestions in the grid |
| New capacity investment submarkets | Investment in additional power generation capacity, usually over longer timescales |
| Decarbonisation submarkets | Submarkets to encourage the consumption of low-carbon power |

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of Competitive Electricity Markets) (Pinto et al. 2014), designed to test the participation of market players in different markets and different contexts, used in Ref. Praça et al. (2019) and Pinto and Vale (2019); and PowerACE, designed to model the impact of renewable energy generators on electricity markets, used in Ref. Klein et al. (2019) and Fraunholz et al. (2021). Among these models, only MASCEM potentially allows to include consumer-side participants. Other existing models are MATREM (Multi-Agent Trading in Electricity Markets), which models generation-side and consumer-side participants bidding into exchange-based markets and bilateral contracts (Lopes 2018b), and more case-specific models, such as Ref. Etukudor et al. (2020),which focuses on local peer-to-peer markets with automated negotiation frameworks, or Ref. Zhang et al. (2019), which presents a novel two-stage trading mechanism for direct market participation of large-scale consumers.

A typical application of such models is to aggregate market participants' bids and model their impact on market clearing, to provide a deeper understanding of the impact of market participation on market outcomes (Kühnlenz et al. 2018). This is referred to here as a market-centric approach, as results are particularly useful for market regulators implementing market regulation changes to improve market participation. Market-centric models typically need to use small-scale case studies, such as the IEEE 30-bus system in Shafie-Khah and Catalão (2014), to keep the number of agents to a reasonable level. On the other side, other implementations of ABM focus on the demand response strategies with electricity market prices already provided, either as forecasts such as in Algarvio et al. (2016), scenarios in Golmohamadi et al. (2019), or historical data such as in Zheng et al. (2020). This is referred to here as a consumer-centric approach, as the impact of the consumer's actions on the overall market is considered less important. However, Ref. Shinde et al. (2021) notes that very few electricity market ABMs explicitly include the trading mechanisms and market rules during model setup, which makes it difficult to adapt the models to different submarket types or market contexts. In Ref. Shinde et al. (2021) demonstrates the importance of differences in submarket trading mechanisms by implementing an ABM approach in a continuous intraday market context. In this case, trading agents cannot implement established bid optimisation strategies developed for centrally cleared exchange markets and must instead implement heuristic learning strategies to adapt to continuously cleared bids with imperfect information about competitors' bids.

### Electricity market ABM ontology

In Santos et al. (2016b), Santos et al. underline the importance of making electricity market ABM interoperable, in order to facilitate information exchange between models and compare different energy systems. Model interoperability requires a common ontology. Ontology is here understood based on the definition of Maedche and Staab as "a formal, explicit specification of a shared conceptualization" (Maedche and Staab 2001). Early attempts to create electricity market ontologies include ELMO, where a layered ontology based on geographical applicability range is applied in the Greek electricity market (Alexopoulos et al. 2009). Underlining that this ontology has not been generalised to other European electricity markets, and that it has not been developed specifically for ABM implementation, Ref. Santos et al. (2016a) proposes its own electricity market

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ontology (EMO), applied to the MASCEM electricity market ABM. EMO uses an upper-level ontology common to all markets, from which market specific applications can be extended. EMO has since been extended and implemented in the EPEX market in Ref. Santos et al. (2017a), the Iberian market in Ref. Santos et al. (2018), and the Nordpool market in Ref. Santos et al. (2017b) The AiD-EM ontology is a more low-level ontology extending the EMO, developed to standardise the communication of market participants with electricity market models when implementing market participation strategies (Santos et al. 2021). The AiD-EM ontology therefore focuses more on the participant logic than the market operator logic. The Tools Control Center application ontology presented in Teixeira et al. (2020) pushes the decision support tool concept further by using semantics to allow co-simulation between heterogeneous simulation tools.

However, such approaches require a common agreement between models on the upper-level ontology, which can be hard to achieve in practice, and could lock future market designs into the framework of the upper-level ontology (Ma et al. 2019b). Moreover, each market context requires its specific lower-level ontology based on the upper-level ontology, which limits the reusability of the developed models. In Ma et al. (2019b), Ma et al. conclude a review on existing ontologies for electricity market ABM with the need for more clarity in the ABM design methodology to ensure reproducibility. Moreover, despite existing electricity market ontologies, Lopes underlines in Lopes (2018a) the heterogeneity in description and representation of electricity markets software agents, and criticises the lack of framework for model results comparability.

### Specificity of the presented approach

The diversity of electricity market ABM approaches presented above has created the need for increased standardisation to allow interoperability and comparability of model results. While extensive work has been done on describing market agents and their communication protocol in a standardised way, the modelling of the submarkets which these agents interact with lacks consistency and remains too context specific. Moreover, the modelling design steps are usually omitted, providing a description of the model components without explaining how they can be assembled into a model. This makes reusability and comparability of models in different market contexts difficult. The modelling framework outlined in this paper complements the existing work by proposing a systematic yet modular consumer-centric modelling approach of electricity markets. More specifically, the main contributions are the following:

- An application of object-oriented programming concepts to electricity market architecture modelling by identifying commonalities and differences in electricity market ecosystems and representing market participants' interaction with such ecosystems.
- A systematic model conceptualisation through context-independent market roles, role parametrisation, and predefined functions. The use of such building blocks simplifies model development and improves comparability of results in different market contexts.
- A consumer-centric representation of electricity markets as an ecosystem of interacting submarkets which the consumer can choose to participate in. Each submarket

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has easily adaptable context-dependent parameters, which allows tailor-made solutions for consumers adapted to a specific electricity market ecosystem.

This one-to-many (consumer-to-submarkets) bidding approach taken in this study is a reversal of the many-to-one (consumers-to-market) bidding approach implemented in traditional agent-based models of electricity markets, as is summarised in Fig. 1. The focus is not on the impact of market participation strategies on market prices, as the many-to-one approach would do, but rather on which submarkets to participate in based on available submarket information.

**Model framework.**

The following framework follows the business ecosystem modelling process first presented in Ma (2019), which consists of three parts. Part I-"Business Ecosystem Architecture Development" and Part III-"Ecosystem simulation and reconfiguration" have both been applied to energy ecosystems with multiple cases, e.g., electric vehicle home charging (Ma et al. 2021; Værbak et al. 2021), smart buildings (Ma et al. 2017b, 2017c), and microgrids (Ma et al. 2019a, 2018b). There the focus has been on the impact of distributed loads on the grid. In this paper, the work developed in Ma et al. (2021) and (Værbak et al. 2021) is adapted to the electricity market ecosystem context, more specifically from the point of view of a single large-scale consumer.

**Model boundaries**

Reference Ma (2019) uses the concept of Minimum Viable Ecosystem (MVE) to choose the ecosystem boundaries and identify the relevant stakeholders in the model accordingly. Ref. Værbak et al (2019) defines the MVE as "a completed ecosystem with minimum elements (actors, roles, and interactions), [which] still can serve the identified ecosystem boundary". The MVE therefore focuses on modelling the minimal amount of actors and interactions required for a stakeholder to obtain added value from a proposed business model. This is relevant when modelling electricity markets at a national or international scale, which are large business ecosystems involving many actors and which cannot be modelled in their entirety, both due to limited information access and limited computational capacity. The inaccuracies from the MVE simplification are compensated by data inputs from exogenous components. Exogenous components cannot be changed by simulation results, and therefore make the model less flexible for scenario
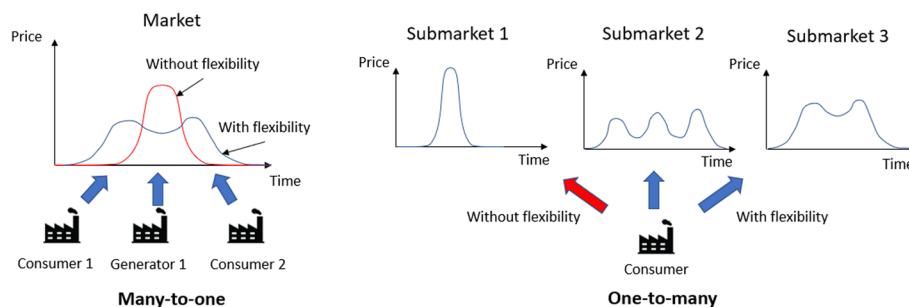


**Fig. 1** Electricity market ABM modelling approaches

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exploration. The simpler the MVE, the more extensive and accurate the external database must be to compensate for the model's shortcomings.

In this study, actors and interactions included in the MVE are chosen based on the perspective of a single large-scale consumer participating in the electricity market. Market bids of generators and other consumers are not explicitly modelled. For this reason, market prices dependent on centralised clearing cannot be explicitly modelled, and historical prices and forecasts are used instead. This makes the consumer a price taker, as its actions do not influence clearing prices. This is acceptable if the consumer represents a negligible share of market transaction volumes. The reliance on historical data also implies that model results can only show what could have been gained from market participation in the past but cannot predict how much will be saved in the future. Historical market data could be replaced with market price forecasts based on future system assumptions to explore future scenarios, but this is not the focus of this study. In the following model, market price data is provided by a separate agent representing exogenous components.

Physical system properties such as network congestion, frequency stability and system imbalance are not modelled directly either. Instead, they are implicitly included in the data input from short-term balancing markets, whose market prices should reflect the physical state of the system. System operators in charge of grid operations, such as the Transmission System Operator (TSO) and Distribution System Operator (DSO), are therefore only included in the model for their roles as information provider to the market or as market operators for short-term balancing services. Data metering and administration roles are not included either.

Finally, market intermediaries such as retailers, aggregators, and independent balancing responsible parties (BRP) are also excluded from the model. Many large-scale consumers have the advantage of having large enough loads to directly participate in electricity markets without load aggregation (Fatras et al. 2022b; Samad and Kiliccote 2012; Howard et al. 2020). The modelled large-scale consumer is therefore assumed to be its own BRP. This avoids the reliance on third parties interfering in load scheduling, which was identified as an adoption barrier (Leinauer et al. 2022; Alcázar-Ortega et al. 2015), and allows to evaluate the benefits of direct market participation compared to traditional passive participation through retail contracts. As noted previously, market liberalisation has led to a large diversity of submarkets. The choice of submarkets to include in the model will depend on the evaluated consumer value chain, and on participation feasibility from a technical and regulatory point of view (Fatras et al. 2022b). As this is not the focus of this study, submarkets included in the case study will only be selected based on their suitability to illustrate the framework.

### Model components

The presented modelling framework makes a distinction between context independent and context dependent model components. Certain actions must be executed in any market context to achieve the required electricity services. Examples of such actions are customer billing, market bidding, or bid clearing. Such context-independent actions are assigned to roles, which are responsibilities to be fulfilled by actors in the ecosystem, as defined in Ma et al. (2021) and ENTSO-E (2019). However, how these roles are

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implemented depends on which actors these roles are assigned to, and which other actors in the model they are influenced by. The context-dependent actors which roles are assigned to are defined as agents. This study therefore relies on the hypothesis that any electricity market can be modelled as a combination of context-independent roles which are adapted to a specific market context to create an overall market ecosystem.

The application of agents and roles in this work is based on the object-oriented programming (OOP) framework for agent-based modelling of energy business ecosystems presented in Værbak et al. (2021). The OOP approach couples data and methods together into objects (Liang 2018), making use of the abstraction provided by methods to implement them in different contexts. In this study, the methods are provided by predefined roles, the data is provided by the market context, and their combination creates the modelled electricity market ecosystem. The model framework in Værbak et al. (2021) and in this study are developed in Anylogic, a Java-based software with agent-based modelling features (Cenani 2021). OOP concepts in this section will therefore be referred to using Java programming language.

### Roles

Roles correspond to Java Interfaces, which are abstract Classes providing a blueprint of the actions which that role fulfils. This blueprint defines the input format, output format, and methods corresponding to that role, while leaving the methods empty. The method body, referred to as logic, is only defined once the role is implemented by a specific agent. This basic context-independent definition of the methods which a role must fulfil relates to the OOP concept of abstraction. Abstraction simplifies the description of an object to its most defining characteristics, without giving details on the implementation of each characteristic. This role abstraction ensures consistency in model development by using the same methods, while providing modularity by adapting methods to the given context.

To provide further consistency in model development, the roles used in this framework are based to the largest extent possible on the Harmonised Electricity Market Role Model (HRM), developed by the European Network of Transmission System Operators-Electricity (ENTSO-E) to improve information exchange and comparability between different countries (ENTSO-E 2019). Since the HRM focuses on the wholesale and retail markets, its ontology is expanded here to fit the broader ecosystem of interacting submarkets presented in this study. Additionally, a role can include subroles, implying that an agent adopting that role also must implement the methods defined in these subroles. This follows the concept of inheritance in Java, where an interface (a role) "extends" another interface (a subrole). To keep track of the role which an interface is associated with, interfaces are referred to as *I_Role*, in line with the approach in Værbak et al. (2021), where "*Role*" is the name of the role which the interface is associated with. The relevant HRM roles and their corresponding adaptation to the consumer-centric approach in this study are summarised in Table 2.

To provide further consistency to role implementation, role parameters are defined as attributes in abstract classes of each role, which must be given a value upon role implementation. Examples of role parameters could be the scheduling frequency or the scheduling time resolution for a Scheduling Agent role. For agents responsible for market

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**Table 2** Roles in electricity market MVE

| ENTSO-E HRM role name | Adapted framework role name | Description |
|---|---|---|
| Party administrator | Market regulator | Establishes and enforces market rules to follow. Additionally, the market regulator can play an active role during market operations by ensuring that market participants respect market rules |
| Data Provider | Data Provider | Provides endogenous and / or exogenous data to market participants who have data access rights |
| Imbalance settlement responsible | Imbalance settlement responsible | Financially settles the grid imbalance costs which the grid operator incurred due to market participants' real-time operational divergences from schedules cleared in the market |
| Consumer | Consumer | Consumes electricity and pays bills accordingly. Has operational requirements which constrain the flexibility in market participation |
| Energy trader | Energy trader | Bids load volumes and prices in the electricity market, based on price forecasts and operational constraints given by the Consumer |
| Balance responsible party | Balance responsible party | Pays the imbalance costs caused by differences between scheduled and dispatched consumer loads |
| Scheduling agent | Scheduling agent | Sets the consumer's schedule based on loads cleared in the market |
| Market operator | Divided into subroles | See section "Modelling submarkets" |

operations, these parameters are fixed and set by the Market Regulator role, as will be detailed in the section "Modelling submarkets".

### Agents

Agents in an ecosystem correspond to Java objects, which are instances of Classes. The Classes define how the object should behave once it is instantiated in the model. An agent implements roles by providing context-depending logic to the empty interface methods. Multiple roles can be assigned to an agent, and conversely, multiple agents can be assigned the same role (Værbak et al. 2021). While classes in "strict" OOP only act upon request, agents in Anylogic are dynamic, with internal delays and scheduled events (Borshchev 2013). This provides the agents a certain level of autonomy representing independent decision making in a market context.

Here a distinction must be made between passive and active agents. Active agents have one or multiple success criteria they aim to fulfil, which will influence how the role is implemented to satisfy these criteria. For example, financial savings are a success criterion of an agent fulfilling the role of market bidder. The importance of this criteria will influence how much it is willing to bid in a given submarket at a given time. Active agents can adjust the logic of the roles based on how well the role outputs satisfy the agent's success criteria. This adjustment process as the agent interacts with its environment is generally called agent "learning".

On the other side, passive agents' role implementation is not influenced by the agent's strategy, and only depends on context-specific rules and properties. However, passive

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roles are not static in themselves, as their set of predetermined rules can be changed by an active agent, such as for example a market regulator. Changing such operation rules can influence the interaction dynamics between roles. For example, changing the bidding deadline of a specific submarket can cause participants to increase bidding in that submarket at the cost of other submarkets, as the changed bidding deadline is better aligned with participants' operational requirements.

Following the Java OOP principle of encapsulation, methods and attributes implemented in agents are defined as either public or private. Private methods and attributes can only be accessed by the agent itself and represent information and decision logic only accessible to the agent. Public methods and attributes are visible and accessible to other agents and will be used in agent interactions, as will be explained next. This distinction between roles and agents is summarised in Fig. 2.

### Interactions

An agent-based model relies on exchange of information between modelled agents to achieve an overall system behaviour. In the consumer-centric electricity market context, interactions occur between the consumer and the submarkets, but also between submarkets, and with the regulator and data-providers. As mentioned in the previous section, roles are differently distributed among agents depending on the market context. This implies that the information received by agents depends on the roles they are assigned to. On the other hand, the information received and emitted by roles only depends on the methods they must implement, which are context-independent. While the data type remains the same for a given role, the market context will determine whom this data is sent to, at what time, with what frequency, and in what format. For this reason, interactions in this model are again divided into context-independent and context-dependent components.

Context-independent components are based on communication between roles instead of agents, as implemented in Værbak et al. (2021). Such communication depends on methods defined in each role's interface, where the method declaration parameters specify the type of interface which can access that method. These context-independent communication methods are called flow methods, as they allow an exchange of flows between agents. Flows can be of different nature, representing exchange of information, data, monetary value, goods, or intangible value, as defined in Ma et al. (2021). In this study, data flows represent exogenous data, while information flows represent endogenous data. Role-based communication ensures role consistency in different market contexts, avoids to redefine the communication protocol for each agent adopting a new role,
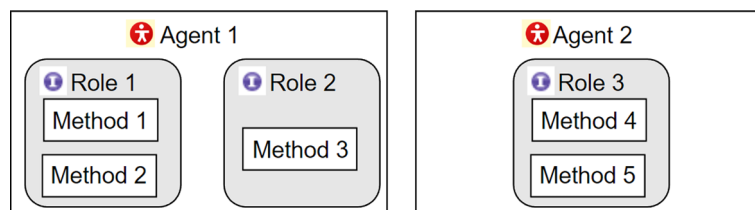


**Fig. 2** Relationship between agents and roles

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and prevents agents from accessing information which their roles don't allow them to (Værbak et al. 2021). Flow methods are set as public to be able to call each other, but can only be called by roles with appropriate data access rights.

Context-dependent components adapt the role communications to the agents which each role is assigned to. In this study, this is done through methods called connection methods, which specify the address which flow methods must refer to when calling each other. When a role is assigned to another agent, only the agent mentioned in the connection method must be changed to adapt the model. Connection methods belong to the agent and are therefore defined as private. Connection methods are defined as either passive or active, depending on which role first gets in contact with the other role to start an interaction. In a hierarchical information flow structure, roles sending messages to a larger information aggregator are assigned active connections, while the information aggregator is set as passive. In case no hierarchy is defined, connections are set as passive or active randomly.

### *Model implementation*

The actions of market participants included in the model are governed by a series of methods of different types. Role methods used to fulfil the role's purpose are defined as characteristic methods and are set as private, as they represent an agent's internal logic. Moreover, when implemented in an active agent, characteristic methods can call methods which are specific to the agent which the role is assigned to. Such agent-specific methods are set as private and defined as strategy methods, as they define the strategy implemented by the agent to achieve its success criteria. Together, the characteristic and strategy methods represent the internal methods of the agent. These internal methods are called by Anylogic Event functions, which are activated either cyclically at the specified time and frequency defined by the role's parameter values, or conditionally after receipt of a trigger message, depending on the role's characteristic functions.

These internal methods are complemented by agent interactions, each defined by the combination of a public flow method and a private connection method. These interactions methods are also called by Anylogic Event functions. Interactions methods are only called by Event functions in one of the two roles involved in the interaction, to avoid interaction redundancy. By convention, the role with the active connection method is also the one implementing the Event function to call the flow method. Role interactions within the same agent still use flow methods, but no connection methods, as all information is shared within the agent. Agents concentrating many roles therefore have a significant advantage in terms of informatic access, which can be used to study the impact of information access on market power. The different components of an agent implemented in the ecosystem are summarised in Table 3.

### Modelling submarkets

The model components outlined above are very general and can be applied in different domains. The following section presents in more detail how this framework is implemented in an electricity market model.

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**Table 3** Summary of agent structure

| | Context independent (defined by role) | Context dependent (defined by agent) |
|---|---|---|
| Attributes | – Role parameter definition (private): define in the role abstract class the characteristic attributes belonging to the role | – Role parameter values (based on market regulator or user input)<br>– Received input data |
| Internal methods | – Characteristic methods definition (private): define in the role interface the main actions expected to be fulfilled by the role, with appropriate input and output formats in the method definition | – Characteristic methods implementation: define how the role actions are executed<br>– Event functions: define when and how often characteristic methods are called based on role parameters<br>– Strategy methods (private, active agents only): methods which influence how the characteristic functions are implemented |
| Interaction methods | – Flow methods definition (public): define in the role interface what is exchanged (goods, data, information, financial flows,…) with which role | – Connection methods (private): provide the address for flow method communications by indicating the agent which a role belongs to<br>– Event functions: define when and how often flow methods are called based on role parameters |

### Submarkets as agents

Submarkets in an electricity market ecosystem are designed to fulfil a specific set of roles to ensure satisfactory system operations. Each submarket is therefore considered as an agent which implements a set of roles. This is an extension of the ENTSO-E HRM, which considers Market Operator as a role without distinguishing between submarket types, and without specifying the actions to fulfil by the market operator. Submarket agents are passive agents, whose logic is determined by an external agent which these submarkets are assigned to. Submarkets are therefore usually subagents of a larger agent in the electricity market ecosystem, which itself can be passive or active. External agents such as market regulators can also have an influence on the submarket logic.

The roles assigned to a submarket depend on the submarket type. While submarket designs vary for each market context, certain submarket types are repeatedly found in different market contexts, as mentioned in the Background section on market liberalisation. As the case study presented in this work will focus on demand-response, the roles assigned to submarket types focusing on short-term operations are shown in more detail in Fig. 3.

The diagrams in Fig. 3 represent generic submarket types, without applying them to a specific market context. The roles assigned to each market type do not change much with context, as the market types are defined by these roles. The same applies for the roles which each submarket interacts with. An exception is the Data Provider role, which depends on the boundaries of the MVE and the internal logic of the submarkets. The Data Provider role could in some cases be internalised by submarkets. An example is a submarket cleared bilaterally instead of through an exchange, in which case external market price data is not available for the internal bid clearing logic. Figure 3 also shows that some subroles are common to all submarkets, such as Billing. This role requires a service quantity (energy or load in this case) and a service price (which can for example be fixed or per unit quantity), irrespective of the context.
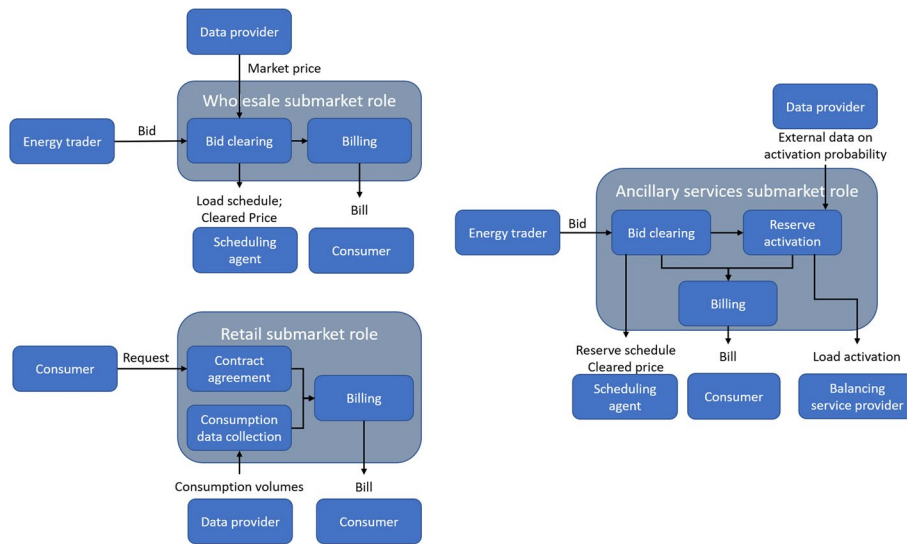
**Fig. 3** Roles assigned to different submarket types

However, the time at which this information is provided and how the bill is calculated will depend on the specific rules of the submarket.

### Submarket role standardisation

To further simplify the implementation of submarket agents in a given context, submarket method implementations for each role can be chosen from a predefined and standardised set of options. This assumption is based on the fact that individual components of market designs are often chosen from a limited set of real-life implementations. For example, market bidding mechanisms can be classified into bilateral and exchange-based market architecture, while market pricing mechanisms can be divided into pay-as-bid, pay-as-clear, or other existing auction mechanisms (Stoft 2002). Each of these market mechanisms is characterised by a specific algorithm. These algorithms correspond to predefined methods, which are stored in a class named *F_Role*, according to the submarket role's name. The predefined method chosen within *F_Role* depends on the market context and is determined by the role parameters assigned to the role once it is implemented in an agent.

Role parameters are also used to implement the empty methods in a submarket's interface *I_Role.* For example, (Fatras et al. 2022b) describes different ancillary service submarkets in the Danish market context using four bidding parameters (bid resolution, bid frequency, bid deadline, minimum bid size) and five activation parameters (activation speed, activation symmetry, response duration, automatic activation, information exchange frequency). These parameters are needed to respectively implement the "Bid clearing" and "Reserve activation" roles shown for the ancillary service submarket in Fig. 3. Parameters are used both in characteristic methods, to determine how submarkets operate, but also in flow methods and Event functions, to determine how often, at what time, and in what format information is exchanged.

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Role parameters are therefore both used to select the predefined methods in *F_Role* and to implement the empty methods in *I_Role.* Such role parameters are part of the role's "blueprint", but their value is context dependent. Unfortunately, Java interfaces do not allow to define empty attributes whose value can be assigned once the interface is implemented in an agent. Therefore, the method parameters cannot be defined in *I_Role*. Instead, a class named *P_Role* is defined for each role, where all relevant role parameters are defined. *P_Role* classes are implemented along with *I_Role* interfaces and *F_Role* classes when a role is implemented in an agent. The relationship between the different classes and interfaces assigned to a submarket agent is summarised in Fig. 4.

This definition of role interfaces and classes provides a structure when instantiating submarkets in a specific context. In a purely market-driven context, the agent implementing the submarket agent is passive: market outputs only depend on market rules, defined by an external and neutral Market Regulator role, and market inputs, provided by external market participants. Nonetheless, the outcome of passive submarkets can be influenced by indirect intervention of external stakeholders with vested interests in the submarket outcomes, as underlined in Fatras et al. (2022a). This level of indirect intervention depends on how many and which external agents the submarket is connected to. Alternatively, direct market intervention is possible in a context of incomplete market unbundling, where the market operator implementing a specific submarket can use it to its advantage to fulfil socio-political, economic, environmental or other success criteria.

**Step-by-step model setup**

The above sections have described the different parts constituting the model and the object-oriented approach behind it. This final section of the model framework will explicitly summarise how to combine these different elements in a methodical way, to set up a model for a specific market context. The steps are summarised in the flowchart in Fig. 5.

*Step 1: Defining the electricity market ecosystem*

*1.1:* Identify submarkets where the consumer could participate from a technical and regulatory perspective. This requires a good understanding of the consumer's flexibility, operational constraints, and risk-willingness. Simultaneously, it requires an analysis of the different electricity submarkets within an ecosystem, to determine
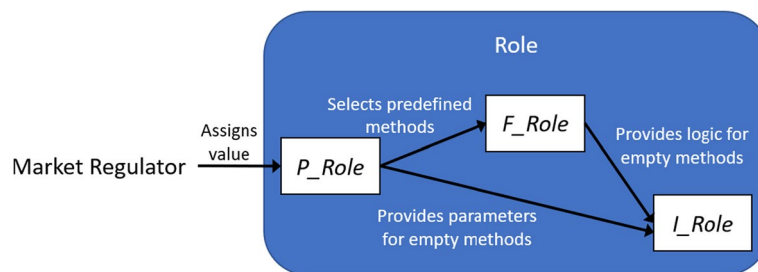


**Fig. 4**  Submarket role classes and interfaces interactions
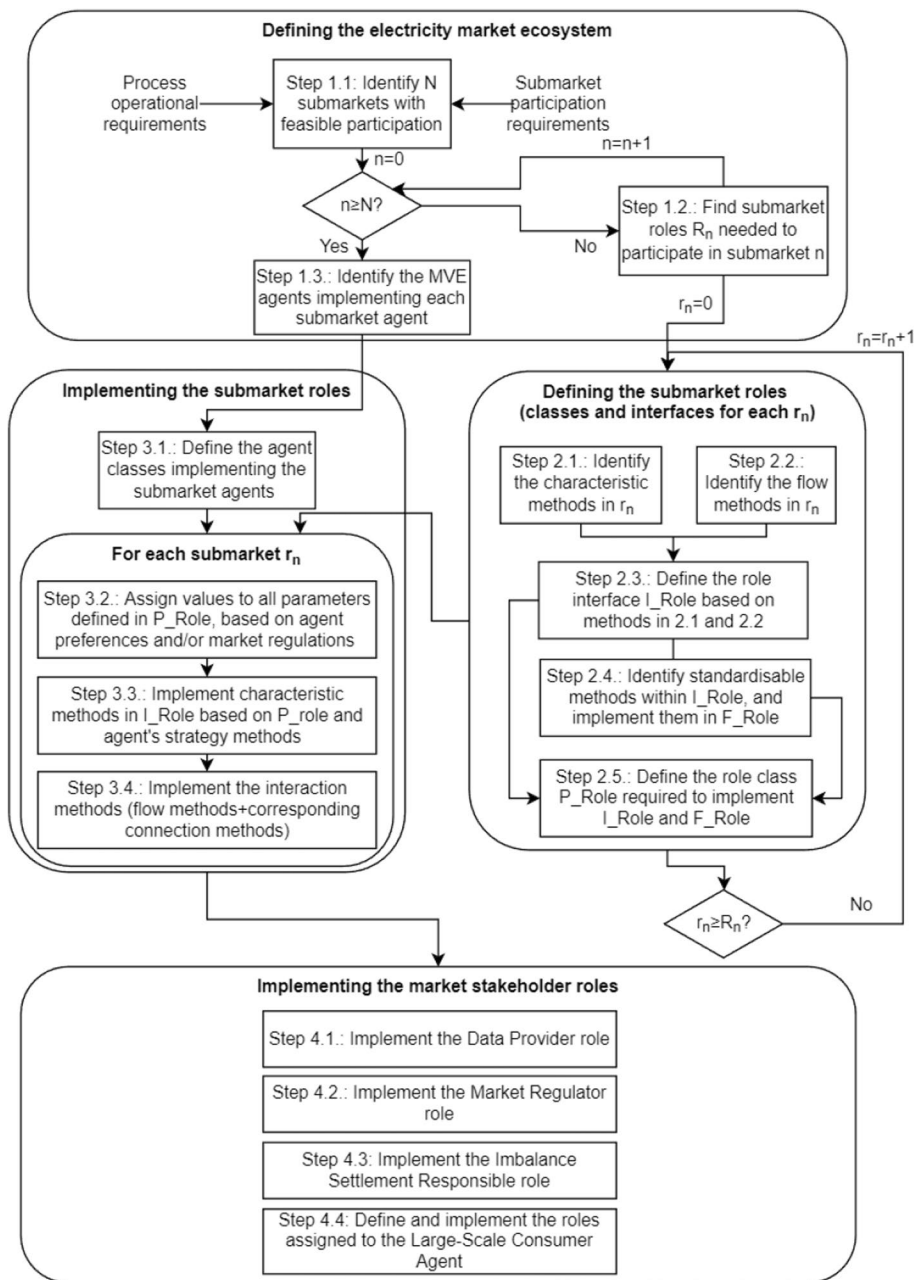
**Fig. 5** Flowchart of modelling setup steps

which market regulations would fit best with the consumer's properties. Such an approach is presented in Fatras et al. (2022b), but is not the focus of this study.

***1.2.:*** For the chosen submarkets, identify the key roles required to link the consumer to the submarkets. To remain within the scope of an MVE, only roles necessary for direct market participation should be included for a large-scale consumer. Roles representing inputs from exogenous factors must be included, to compensate for the model boundaries.

***1.3.:*** Identify the MVE agents associated with each submarket agent.

### Step 2: Defining the submarket roles

The modelling steps outlined in step 2 assume the interfaces and classes belonging to a submarket role have not been defined yet. In case *I_Role*, *F_Role* and *P_Role* are already defined, step 2 can be ignored.

For each submarket role:

**2.1.:** Identify the characteristic methods which must be fulfilled (without implementing them).

**2.2.:** Identify the role interactions required to fulfil the characteristic methods. Define flow methods accordingly (without implementing them). A market ecosystem map can be generated based on all the identified role interactions.

**2.3.:** Define the role interface *I_Role* based on the identified characteristic methods and flow methods.

**2.4.:** Within the characteristic methods in *I_Role*, identify the methods which can be standardised through predefined methods and implement these predefined methods. These methods are stored in the role class *F_Role*.

**2.5.:** Identify the role parameters required to implement both the predefined characteristic methods, the empty characteristic methods, and the flow methods, and store them in the role class *P_Role*. At this stage, role parameters are defined without being assigned specific values.

### Step 3: Implementing the submarket roles

**3.1.:** Define the agent classes which the submarket roles belong to, including the agent's success criteria and strategy methods to implement the submarket roles. The role interfaces are implemented within these classes.

For each submarket role:

**3.2.:** Assign values to the method parameters in all *P_Role* classes associated to the agent. In case the submarket is operated by a passive agent, parameter values are defined in the Market Regulator role (defined in the next section) and sent to each role through interaction methods.

**3.3.:** Implement the empty characteristic methods from *I_Role*, taking into account the success criteria of the agent to which they belong and parameters values assigned in P_Role.

**3.4.:** Implement the flow methods within the role and the corresponding connection methods to allow role interactions with the correct agents.

### Step 4: Implementing the market stakeholder roles

Active and passive market stakeholders interacting with the submarkets in the MVE are defined and implemented in this last step.

**4.1.:** Implement the Data Provider role with its corresponding agent based on available market data. Flow and connection methods are implemented based on the endogenous and exogenous inputs which the methods in the market ecosystem need.

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***4.2.:*** Implement the Market Regulator role with its corresponding agent. Method parameters identified in *P_Role* for each role must be defined here as well, as the Market Regulator will initialise all roles at the simulation start by communicating the adequate parameter values.

***4.3.:*** Implement the Imbalance Settlement Responsible role, if relevant. This concerns markets where participants directly bid in the submarkets and operate on a self-dispatch basis.

***4.4.:*** Define and implement the roles assigned to the Large-Scale Consumer agent. The agent must be assigned all roles required by the market ecosystem to ensure market participation. Role implementations must take into account the specific strategy of the large-scale consumer agent, based on the consumer's strategy and success criteria. As this is not the main focus of this study, this is not covered in more detail here.

## Case study

The case study focuses on implementing the Western Denmark market ecosystem (DK1 synchronous area). The following section applies the presented framework to this context. The model framework is implemented for a large-scale consumer located in the DK1 synchronous area (Western Denmark), which is part of the Nordic electricity market. The Nordic electricity market is at an advanced stage of liberalisation, and therefore consists of a large range of submarkets which the consumer can bid in. As mentioned in the introduction, pre-modelling market screening steps should be applied to select the most relevant submarkets for a specific large-scale consumer. As this study does not specify a particular large-scale consumer type, submarkets are instead chosen based on their ability to illustrate the modularity of the developed approach. Therefore, this study focuses on the Nordpool Spot day-ahead market, the Nordpool Elbas intraday market, and the Frequency Containment Reserve (FCR) market.

The day-ahead market allows producers and consumers to plan operation schedules a day in advance, based on cleared price–volume bids. The volumes traded on the day-ahead market represent 80% of the region's electricity consumption (Agency et al. 2018). The day-ahead market is an exchange market cleared by the market operator Nordpool. Bids are submitted at noon for all 24 h of the next day, at an hourly resolution, and are cleared centrally at uniform price based on merit order (Energinet 2007). The day-ahead market operates on a self-dispatch basis, meaning that market participants are responsible for following the schedules cleared in the market. Deviations from the cleared schedule at dispatch time must be paid back to the Imbalance Settlement Responsible, which in Denmark is a role taken up by the national Transmission System Operator (TSO) Energinet.

The intraday market allows producers and consumers to adjust their operational schedules cleared in the day-ahead market by offering to buy or sell energy at a self-determined price (pay-as-bid price). Schedule adjustments can be required due to unexpected outages, changed production and consumption forecasts, or can be motivated by opportunistic market arbitrage. The intraday market is cleared on the Elbas exchange operated by Nordpool but consists of bilateral bid matching. Bidding and clearing occur

continuously from day-ahead market clearing at 14:00 on the previous day up to one hour before consumption (Energinet 2007). Volumes traded on the intraday market are also taken into account when settling imbalances to pay to the Imbalance Settlement Responsible.

The FCR market is a primary reserve market to provide frequency stabilisation services to the grid. Market participants who clear bids agree to provide capacity to the TSO, which can activate this capacity by ramping energy production or consumption either up or down, depending on system needs. The TSO, which is the market operator for the FCR market, therefore also has a Reserve Activation role (a more general term for the Load Frequency Control Operator role defined in the ENTSO-E HRM). DK1 is part of the larger FCR cooperation spanning across western Europe, where TSOs pool the reserve bids in an exchange and clear them at uniform price based on merit order. Bids are sent to at 8:00 AM on the previous day for the next day, in four-hour blocks, and cleared at 8:30AM (Energinet 2022).

The analysed submarkets are thereby cleared sequentially, and market participants know clearing volumes and prices of upstream submarkets by the time they participate in the next submarket. However, uncertainty arises when participation strategies rely on coordinated bidding, where bidding in one submarket considers possible future prices in downstream submarkets. The time sequence (and thereby the information sequence) of the different submarkets is summarised in Fig. 6.

## Results

The step-by-step model setup outlined in the model framework is here applied to the Danish market ecosystem presented in the Case Study.

### Defining the Danish electricity market ecosystem

The roles and agents of the MVE corresponding to a large-scale consumer participating in the Danish day-ahead, intraday, and FCR submarkets are shown in Fig. 7, using the modified ENTSO-E HRM terminology.

The TSO agent has only been included for its role as FCR market operator and imbalance settlement responsible but is not acting as system operator in the MVE. On the consumer side, all the market intermediary roles, such as energy trader, scheduling agent,
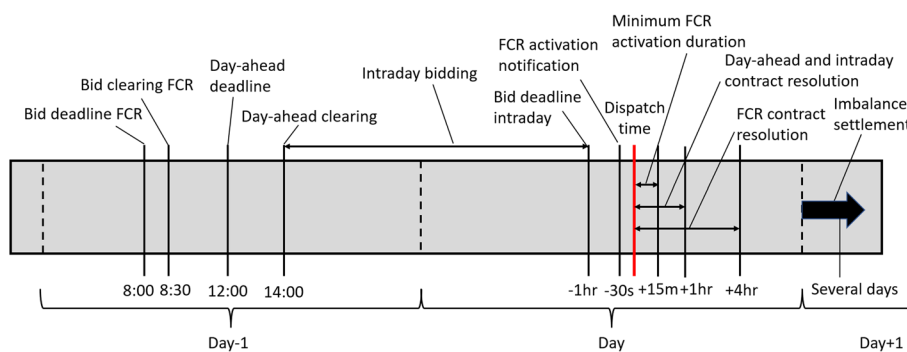


**Fig. 6** Submarket participation timeline

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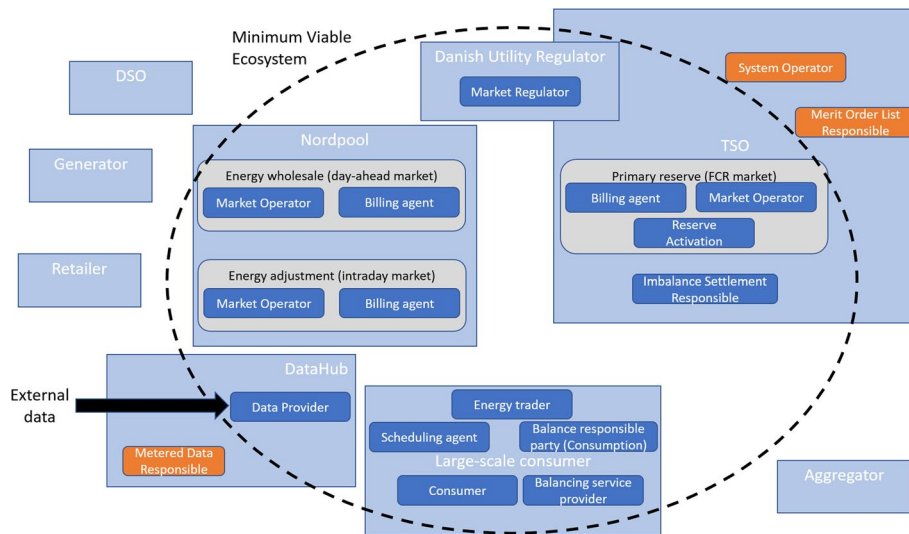


**Fig. 7** Agents and roles in the electricity market model MVE
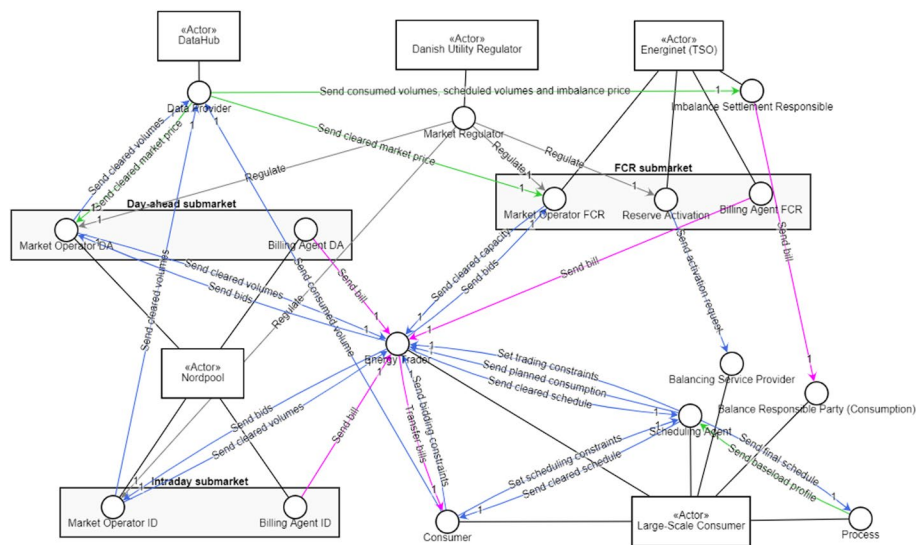


**Fig. 8** Ecosystem map of modelled electricity market

and balance responsible party, have been assigned to the large-scale consumer. The roles and agents identified in Fig. 7 are explained in more detailed in the next sections.

**Defining the submarket roles**

An ecosystem map is shown in Fig. 8 to illustrate the role interactions based on which the flow methods are defined for the different submarket roles. The roles are shown as circles, agents as rectangles, and interactions are coloured coded, following the convention outlined in Ma et al. (2021). Submarket interactions are done indirectly via the Data Provider, which sends information on clearing market prices at specific

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times and frequencies. In sequential submarkets, the prices in one submarket are thereby influenced by prices in submarkets cleared ahead.

Based on the submarket descriptions in the previous sections and the ecosystem interactions shown in Fig. 8, the characteristic methods, flow methods, and role parameters are derived for the roles taken by the three analysed submarkets. The role abstraction principle is used to implement the same role to different submarkets.

### Market operator

In Fig. 9, the interfaces and classes of the Market Operator role are shown using modified UML class diagrams. Events and connection methods are shown using simple method definitions. The parameters in the *P_Role* class are based on the market bidding parameters for short-term markets identified in Fatras et al. (2022b) and the market bidding mechanism types identified in Fatras et al. (2022a). The predefined bidding logic and clearing logic are also based on the market bidding mechanism classification given in Fatras et al. (2022a).

### Billing agent

In Fig. 10, the interfaces and classes belonging to the Billing Agent role are shown using modified UML class diagrams. Events and connection methods belonging to the agent are shown using simple method definitions. The parameters in the *P_Role* class are based on the market settlement parameters found in the literature (Energinet 2019; NordPool: NordPool Settlement 2022). The billing logic translates the cleared bids received from the market operator into costs linked to every Energy Trader.

### Reserve activation

In Fig. 11, the interfaces and classes belonging to the Reserve Activation role are shown using modified UML class diagrams. Events and connection methods are
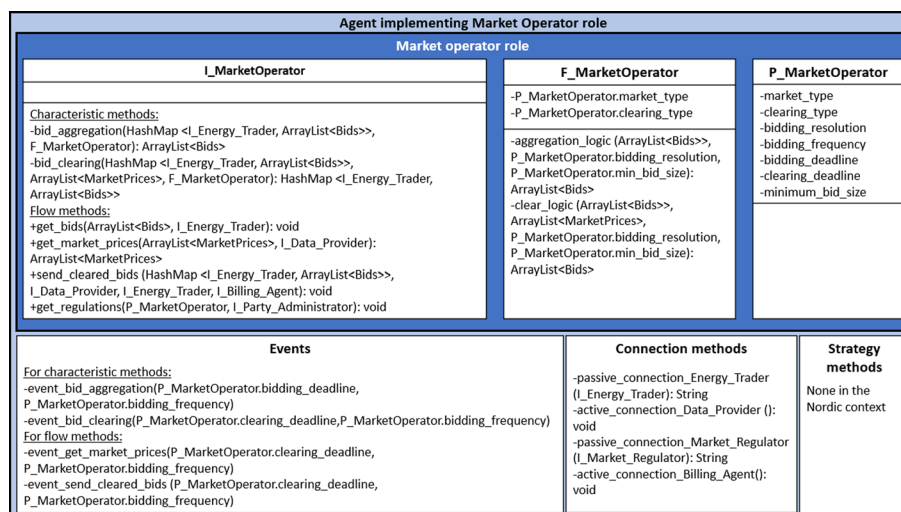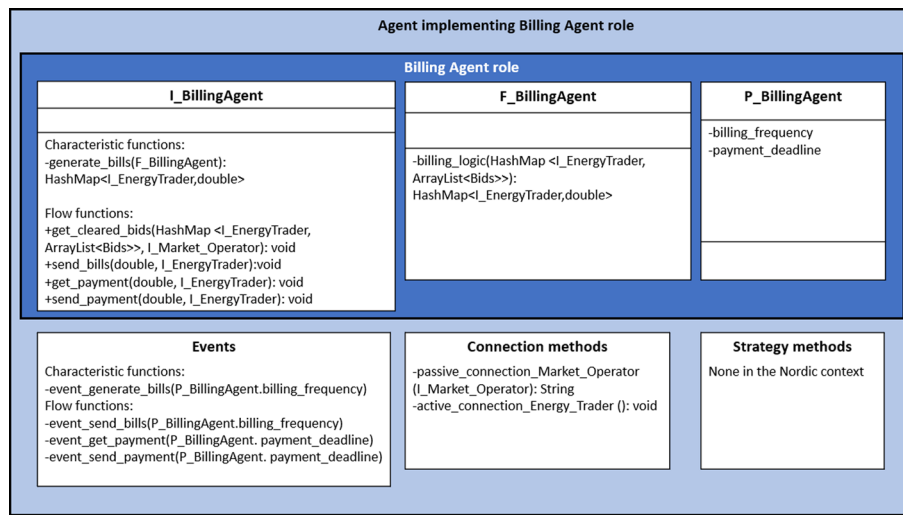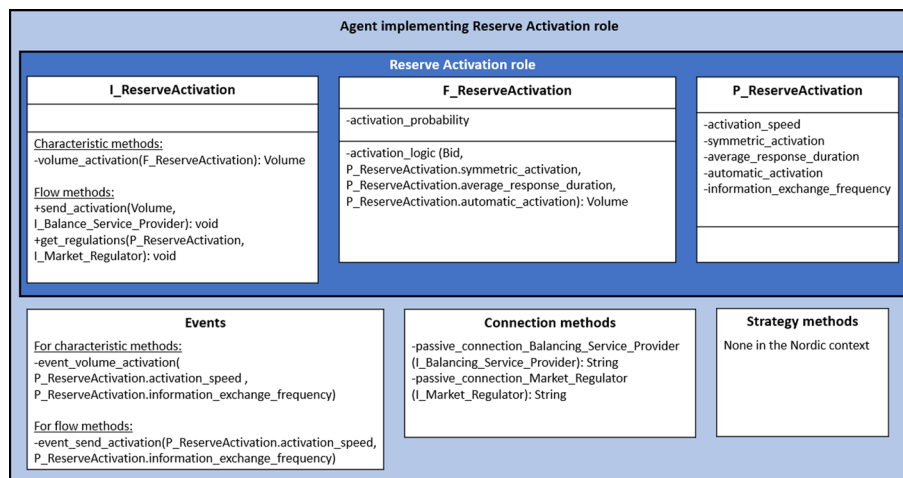


**Fig. 9** Interfaces, classes and methods for Market Operator role implementation

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**Fig. 10** Interfaces, classes and methods for Billing Agent role implementation



**Fig. 11** Interfaces, classes and methods for Reserve Activation role implementation

shown using simple method definitions. The parameters in the *P_Role* class are based on the market operational parameters for short-term markets identified in Fatras et al. (2022b). The reserve activation logic is assumed to be probabilistic based on historical data of capacity reserve activation.

The logic of the F_Role methods is not explicitly described in the above figures, in line with the abstraction level of this paper.

### Implementing the submarket roles

The applicability of the approach to different submarket contexts is shown below by providing the *P_Role* parameter values required to set up the role methods and the Agent names required to set up the connection methods. Table 4 shows the implementation the Market Operator role in the three studied submarkets. Table 5

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**Table 4** Market Operator role implementation for different submarkets (data from Fatras et al. 2022b; Energinet Regulation A 2007))

|  | Parameters and agents for role implementation | Day-ahead submarket | Intraday submarket | FCR submarket |
|---|---|---|---|---|
| P_Role parameters | Market_type | Exchange | Bilateral | Exchange |
|  | Clearing_type | Uniform Price | Pay-as-Bid | Uniform Price |
|  | Bidding_resolution | 1 h | 1 h | 4 h |
|  | Bidding_frequency | 24 h | 1 h | 24 h |
|  | Bidding_deadline | 12:00 @ Day-1 | Hour-1 | 08:00 @ Day-1 |
|  | Clearing_deadline | 13:00 @ Day-1 | Cleared at the same time as bids | 08:30 @ Day-1 |
|  | Minimum_bid_size | 0.1 MW | 0.1 MW | 1 MW |
| Agents | Connect_Energy_Trader | Large-Scale Consumer | Large-Scale Consumer | Large-Scale Consumer |
|  | Connect_Data_Provider | DataHub | Self | DataHub |
|  | Connect_Market_Regulator | Danish Utility Regulatory | Danish Utility Regulatory | Danish Utility Regulatory |

**Table 5** Billing Agent role implementation for different submarkets (data from Energinet (2019); NordPool: NordPool Settlement 2022))

|  | Parameters and agents for role implementation | Day-ahead submarket | Intraday submarket | FCR submarket |
|---|---|---|---|---|
| P_Role parameters | Billing_frequency | Daily | Daily | Weekly |
|  | Payment_deadline | D + 1 @ 11:00 | D + 1 @ 11:00 | No information found. Set to Monday at 12:00 |
| Agents | Connect_Market_Operator | Self | Self | Self |
|  | Connect_Energy_Trader | Large-Scale Consumer | Large-Scale Consumer | Large-Scale Consumer |

shows the implementation of the Billing Agent role in the three studied submarkets. Table 6 shows the implementation of the Reserve Activation role in the FCR market.

### Implementing the market stakeholder roles

This section provides more detail on the roles identified in Fig. 7 which are part of the MVE but do not belong to a submarket. The characteristic functions associated with these roles are not detailed here, as they are not the focus of this study.

#### *Data provider*

In the Danish context, the Data Provider role is implemented by the open data platform DataHub, which provides market participants access to consumption, market price, and other market operations data, depending on participants' information access rights. The role logic only consists of flow methods to receive and send data

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**Table 6** Reserve activation role implementation for FCR submarket (data from Fatras et al. 2022b; Energinet 2019))

|  | Parameters and agents for role implementation | FCR submarket |
|---|---|---|
| P_Role parameters | Activation_speed | 30 s |
|  | Symmetric_activation | Yes |
|  | Average_response_duration | 15 min |
|  | Automatic_activation | Yes |
|  | Information_exchange_frequency | 1 s |
| Agents | Connect_Balancing_Service_Provider | Large-Scale Consumer |
|  | Connect_Market_Regulator | Danish Utility Regulator |

and information. The Data Provider must therefore have a validation protocol to ensure data can only be accessed by allowed agents. As DataHub is a data platform, it behaves as a passive agent, without a personal strategy.

### Market regulator

The Market Regulator role is assigned to the Danish Utility Regulator (DUR) agent in the unbundled Danish electricity market context. This agent is mainly active at simulation start through an initialisation Event which calls the flow methods sending the role parameter values to the different submarkets in the ecosystem. Since the DUR is an independent agent without vested interests in market participation, the Market Regulator does not interfere in market operations, except to penalise market participants not respecting market regulations. As the aim of this simulation is to test the impact of given market regulations on market participation, regulations are considered "static", and the Danish Utility Regulator is considered a passive agent.

### Imbalance settlement responsible

The Imbalance Settlement Responsible role is taken up by Energinet, the Danish Transmission System Operator. Bid volumes cleared by the consumer in the day-ahead and intraday market are added up and compared to the volumes at dispatch time, received from the Data Provider, to calculate the imbalances caused by the consumer (Energinet 2008). Volumes activated in the FCR market are not considered, as they are too small. The load imbalances are billed to the Balance Responsible Party at regulating power prices, which are provided at an hourly resolution by the Data Provider. In this model, the TSO implementing this role is considered a passive agent.

### Large-scale consumer roles

In the consumer-centric electricity market MVE, the large-scale consumer takes on both the roles of electricity consumers and market intermediaries, as its size, equipment, and risk-willingness are considered acceptable to bid directly into submarkets. Following the ENTSO-E terminology, the large-scale consumer is a Consumer, Energy Trader, Balance Responsible Party and Scheduling Agent. Since the large-scale consumer is also providing frequency stabilisation services to the grid through participation in the FCR market, it is also a Balancing Service Provider. In terms of interactions

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with other agents, the Energy Trader will be the main source of interaction with Market Operators to offer and clear bids. The Consumer and Balance Responsible Party will mainly receive financial flows as bills for the charged or provided services. Finally, the Balancing Service Provider receives activation requests from the Reserve Activation role. Many interactions also occur between these roles, which depend on the internal strategy of the consumer, which is an active agent.

## Discussion

### Balancing consistency and modularity

The application of the Market Operator and Billing Agent roles to the three submarkets have shown that the implementation process for different submarkets is streamlined by the abstraction and parametrisation provided by the presented framework. This present paper complements previous studies on electricity market ontologies by decomposing markets into their different submarkets, and in turn describing these submarkets by the different roles they must fulfil. The electricity market is described as an aggregation of standardised building blocks, creating an ecosystem influenced by the context in which this market is implemented. The distinction between context-independent and context-dependent elements of the market structure is thereby underlined, showing electricity markets present commonalities and variabilities. While the EMO presented in Refs. Santos et al. (2016a) and the ENTSO-E HRM in ENTSO-E (2019) standardise the different actors and their interactions within a market, the presented work standardises the different submarket types and their interactions within a market.

However, the strong context-dependency of electricity market ecosystems prevents from having a completely automated model setup approach. For empty methods in role interfaces, the logic remains to be defined by the model developer. Predefined methods considerably reduce the modelling workload, as the method logic is chosen from a limited set of predefined options. Such predefined methods are a programmatic implementation of the market property categories identified in previous studies such as in Refs. Fatras et al. (2022a), (2022b). This comes at the cost of model accuracy, as the predefined options cannot always perfectly reflect a given market context. When choosing methods to predefine in *F_Role*, a trade-off must be found between consistency and modularity.

Assuming context-independent flow methods for role interactions also improves model setup consistency, at the cost of implementation rigidity. For example, the Market Operator role assumes interactions with a Data Provider role to obtain market price information. However, in the case of the intraday market, prices are cleared on a pay-as-bid basis, implying no central clearing price data is available. In this model, this was solved by making the intraday Market Operator get market price data from itself. The systematic role definition therefore introduces some redundant modelling steps. Nonetheless, this allows large-scale consumers to quickly test different business models, where agents take up different roles. In particular, this allows large-scale consumers to test direct market participation strategies, without passing through market intermediaries such as in Refs. Golmohamadi et al. (2019); Nehrir et al. (2018). This provides a greater sense of ownership and control of demand response solutions, which was identified as a critical element for demand-side market participation (Leinauer et al. 2022; Alcázar-Ortega et al. 2015).

### Reliance on data

The simplification of the electricity market ecosystem to its Minimum Viable Ecosystem creates a significant reliance on input data to compensate for the exogenous factors not considered in the model. This is particularly important for submarkets with centralised clearing, as the price depends on market participants not included in the MVE. Therefore, market participation suitability can only be evaluated based on historical market prices, or on potential future market price forecasts, but cannot consider the impact of consumer strategy on market prices. This is a drawback of the price-taker consumer-centric MVE approach compared to ABM models where market prices are calculated endogenously based on provided agent bids, such as in Refs. Algarvio et al. (2016); Rylatt et al. (2018); Steber et al. (2018).

As the boundaries of the model are expanded, more parts of the energy market could be directly modelled. This implies less dependence on fixed external data and allows to test more hypotheses by analysing the dynamics of the system. However, this comes at the cost of increased uncertainty, since assumptions must be taken in the model, which might make scenario results deviate from reality. For consumers hesitant to participate in electricity markets, a fine balance must therefore be found between giving new insights from scenario exploration and staying within plausible scenarios supported by real-life data.

### Conclusion

The presented agent-based modelling approach proposes a framework and step-by-step methodology to model electricity markets in a flexible, yet consistent and simple way. The model is set up from a consumer's perspective by only including stakeholders directly interacting with the consumer in a Minimum Viable Ecosystem. The use of object-oriented programming concepts allows to differentiate between reusable context-independent elements and context-specific stakeholder logic and agent interactions. The specificity of the market context is also provided by the data input to the model, which compensates for the simplifications taken during model setup. In general, the model framework aims to find a balance between consistency and accuracy, to provide consumers with simple yet insightful modelling tools for market participation evaluation.

The implementation of this framework in the Danish context has shown that different submarket types could be quickly modelled while only changing the values of a few parameters. The proposed approach can then be adapted to other market contexts around the world, as long as they have undergone some level of market unbundling, where system operations depend on the interactions between multiple stakeholders and submarkets. The submarket modelling would then change based on the assigned agent, the assigned market regulations, and the stakeholders allowed to interact with that submarket. Of particular interest when comparing different market contexts is the impact of market architecture on information access, and the influence of agents' market power on the submarket outputs.

In general, the presented approach complements existing studies on electricity market ABM by standardising the modelling of submarkets within the market, using object-oriented programming concepts of abstraction, encapsulation and inheritance to easily adapt the model to different market structures in unbundled market

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contexts. Modelling setup steps are also outlined to provide a design methodology for the electricity market model. This improves the comparability of results in different market contexts, which is important to avoid generalisations based on too context-specific results.

The implementation of the model framework in this study has mainly focused on the overall model architecture and how to set up an electricity market ecosystem as an agent-based model. Future work will have to describe in more detail the logic of the consumer's roles when participating in this market ecosystem, with specific market participation strategies based on personal success criteria. A multi-criteria decision-making approach could be taken to consider the non-financial aspect of large-scale energy consumers' decision making process.

**Abbreviations**

| | |
|---|---|
| ABM | Agent-based modelling |
| DK1 | Western Denmark synchronous area |
| FCR | Frequency containment reserves |
| MVE | Minimum viable ecosystem |
| TSO | Transmission system operator |
| OOP | Object-Oriented Programming |
| HRM | Harmonised Electricity Market Role Model |
| ENTSO-E | European Network of Transmission System Operators-Electricity |
| DUR | Danish Utility regulator |

## Declarations

**Ethics approval and consent to participate**
Not applicable.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare that they have no competing interests.

**References**
Alcázar-Ortega M, Calpe C, Theisen T, Carbonell-Carretero JF (2015) Methodology for the identification, evaluation and prioritization of market handicaps which prevent the implementation of Demand Response: application to European electricity markets. Energy Policy 86:529–543

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Alexopoulos P, Kafentzis K, Zoumas C (2009) ELMO: An Interoperability Ontology for the Electricity Market. ICE-B2009. p. 15–20

Algarvio H, Couto A, Lopes F, Estanqueiro A, Holttinen H, Santana J (2016) Agent-based simulation of day-ahead energy markets: impact of forecast uncertainty and market closing time on energy prices. 2016 27th International Workshop on Database and Expert Systems Applications (DEXA): IEEE; p. 166–70

Baum G, Lopez S, Olsina F, Blanco G, Rehtanz C (2017) Agent-based learning model for assessing strategic generation investments in electricity markets. 2017 IEEE Manchester PowerTech. Manchester, UK; pp. 1–6

Billanes JD, Ma Z, Jørgensen BN (2018) The Bright Green Hospitals case studies of hospitals' energy efficiency and flexibility in Philippines. 2018 8th International Conference on Power and Energy Systems (ICPES); p. 190–5

Borshchev A (2013) The big book of simulation modeling: multimethod modeling with AnyLogic 6. AnyLogic North America

Cecati C, Citro C, Siano P (2011) Combined operations of renewable energy systems and responsive demand in a smart grid. IEEE Trans Sustain Energy 2(4):468–476

Cenani Ş (2021) Emergence and complexity in agent-based modeling: review of state-of-the-art research. J Comput Design 2(2):1–24

Christensen K, Ma Z, Værbak M, Demazeau Y, Jørgensen BN (2019) Agent-based decision making for adoption of smart energy solutions. IV International Congress of Research in Sciences and Humanities Science and Humanities International Research Conference (SHIRCON 2019). Lima, Peru: IEEE

Danish Energy Agency (2018) European experiences on power markets facilitating efficient integration of renewable energy. Danish Energy Agency

El-Adaway IH, Sims C, Eid MS, Liu Y, Ali GG (2020) Preliminary attempt toward better understanding the impact of distributed energy generation: an agent-based computational economics approach. J Infrastruct Syst 26(1):04020002

Energinet (2007) Regulation A: principles for the electricity market 2007.

Energinet D (2008) Regulation C2—the balancing market and balance settlement. Doc no. 2008

Energinet (2022) Ancillary services to be delivered in Denmark—Tender conditions

ENTSO-E (2019) The Harmonised Electricity Market Role Model

Etukudor C, Couraud B, Robu V, Früh W-G, Flynn D, Okereke C (2020) Automated negotiation for peer-to-peer electricity trading in local energy markets. Energies 13(4):920

Fatras N, Ma Z, Duan H, Jørgensen BN (2022a) A systematic review of electricity market liberalisation and its alignment with industrial consumer participation: a comparison between the Nordics and China. Renew Sustain Energy Rev. 167

Fatras N, Ma Z, Jørgensen BN (2022b) Process-to-market matrix mapping: a multi-criteria evaluation framework for industrial processes' electricity market participation feasibility. Appl Energy. 313

Fraunholz C, Kraft E, Keles D, Fichtner W (2021) Advanced price forecasting in agent-based electricity market simulation. Appl Energy 290:116688

Golmohamadi H, Keypour R, Bak-Jensen B, Pillai JR (2019) A multi-agent based optimization of residential and industrial demand response aggregators. Int J Electr Power Energy Syst 107:472–485

Howard D, Ma Z, Engvang J, Hagenau M, Jørgensen K, Olesen J, et al (2020) Optimization of energy flexibility in cooling process for brewery fermentation with multi-agent simulation. 6th IEEJ International Workshop on Sensing, Actuation, Motion Control, and Optimization. Shibaura Institute of Technology, Tokyo, Japan

Iansiti M, Levien R (2002) The new operational dynamics of business ecosystems: Implications for policy, operations and technology strategy. Citeseer

Joskow PL (2022) From hierarchies to markets and partially back again in electricity: responding to decarbonization and security of supply goals. J Inst Econ 18(2):313–329

Kiran P, Chandrakala KV, Nambiar T (2019) Agent based locational marginal pricing and its impact on market clearing price in a deregulated electricity market. J Electr Syst 15(3):405–416

Klein M, Frey UJ, Reeg M (2019) Models within models–agent-based modelling and simulation in energy systems analysis. J Artif Soc Soc Simul 22(4)

Kühnlenz F, Nardelli PH, Karhinen S, Svento R (2018) Implementing flexible demand: real-time price vs market integration. Energy 149:550–565

Leinauer C, Schott P, Fridgen G, Keller R, Ollig P, Weibelzahl M (2022) Obstacles to demand response: why industrial companies do not adapt their power consumption to volatile power generation. Energy Policy 165:112876

Li Q, Ma Z, Jørgensen BN (2016) Discussion on China's power sector reforms and where to next? 2016 13th International Conference on the European Energy Market (EEM): IEEE; p. 1–5

Liang YD (2018) Introduction to Java programming and data structures. Pearson Education

Lopes F (2018a) Electricity markets and intelligent agents Part I: market architecture and structure. Electricity markets with increasing levels of renewable generation: structure, operation, agent-based simulation, and emerging designs. Springer; p. 23–48

Lopes F (2018b). MATREM: an agent-based simulation tool for electricity markets. Electricity markets with increasing levels of renewable generation: structure, operation, agent-based simulation, and emerging designs. Springer; p. 189–225

Ma Z (2019) Business ecosystem modelling—the hybrid of system modeling and ecological modeling: an application of the smart grid. Energy Inform 2(1):35

Ma Z, Jørgensen BN (2018) A discussion of building automation and stakeholder engagement for the readiness of energy flexible buildings. Energy Inform 1(1):54. https://doi.org/10.1186/s42162-018-0061-z

Ma Z, Prljaca Z, Jørgensen BN (2016) The international electricity market infrastructure-insight from the nordic electricity market. 2016 13th International Conference on the European Energy Market (EEM). Porto, Portugal: IEEE; p. 1–5

Ma Z, Friis HTA, Mostrup CG, Jørgensen BN (2017a) Energy flexibility potential of industrial processes in the regulating power market. Proceedings of the 6th International Conference on Smart Cities and Green ICT Systems. Porto, Portugal: SCITEPRESS - Science and Technology Publications, Lda; p. 109–15

Fatras *et al. Energy Informatics* 2022, **5**(Suppl 4):47

Page 29 of 30

Ma Z, Billanes JD, Kjærgaard MB, Jørgensen BN (2017b). Energy flexibility in retail buildings: from a business ecosystem perspective. 2017b 14th International Conference on the European Energy Market (EEM). Dresden, Germany: IEEE; p. 1–6

Ma Z, Billanes JD, Jørgensen BN (2017c) A business ecosystem driven market analysis: the bright green building market potential. The 1st Annual International Conference of the IEEE Technology and Engineering Management Society. Santa Clara, California USA: IEEE

Ma Z, Jørgensen BN (2018a) Energy flexibility of the commercial greenhouse growers, the potential and benefits of participating in the electricity market. IEEE PES Innovative Smart Grid Technologies North America (ISGT North America 2018a). Washington, DC, USA: IEEE

Ma Z, Santos AQ, Gamborg F, Nielsen JF, Johannesen JM, Jensen MDH, et al. (2018b) Solutions for remote island microgrids: discussion and analysis of Indonesia's remote island energy system. The International Conference on Innovative Smart Grid Technologies (IEEE PES ISGT Asia 2018b). Singapore: IEEE

Ma Z, Broe M, Fischer A, Sørensen TB, Frederiksen MV, Jørgensen BN (2019a). Ecosystem thinking: creating microgrid solutions for reliable power supply in India's power system. 2019a 1st Global Power, Energy and Communication Conference (GPECOM). p. 392–7

Ma Z, Schultz MJ, Christensen K, Værbak M, Demazeau Y, Jørgensen BN (2019b) The application of ontologies in multi-agent systems in the energy sector: a scoping review. Energies 12(16):3200

Ma Z, Christensen K, Jørgensen BN (2021) Business ecosystem architecture development: a case study of Electric Vehicle home charging. Energy Inform

Maedche A, Staab S (2001) Ontology learning for the semantic web. IEEE Intell Syst 16(2):72–79

Nehrir H, Dehghanpour K, Sheppard J, Kelly N (2018). Agent-based modeling of retail electrical energy markets with demand response. IEEE Trans Smart Grid

NordPool: NordPool Settlement. https://www.nordpoolgroup.com/en/trading/Clearing/Settlement/. 2022. Accessed 29 Jun 2022

O'Connell N, Pinson P, Madsen H, O'Malley M (2014) Benefits and challenges of electrical demand response: a critical review. Renew Sustain Energy Rev 39:686–699

Olsthoorn M, Schleich J, Klobasa M (2015) Barriers to electricity load shift in companies: a survey-based exploration of the end-user perspective. Energy Policy 76:32–42

Pinto T, Vale Z (2019) AID-EM: adaptive decision support for electricity markets negotiations. Proceedings of the twenty-eighth international joint conference on artificial intelligence demos: IJCAI; p. 6563–5

Pinto T, Vale Z, Sousa TM, Praça I, Santos G, Morais H (2014) Adaptive learning in agents behaviour: a framework for electricity markets simulation. Integr Comput-Aided Eng 21(4):399–415

Praça I, Ramos S, Andrade R, da Silva AS, Sica ET (2019) Analysis and simulation of local energy markets. 2019 16th International Conference on the European Energy Market (EEM): IEEE; p. 1–5

Ringler P, Keles D, Fichtner W (2016) Agent-based modelling and simulation of smart electricity grids and markets—a literature review. Renew Sustain Energy Rev 57:205–215

Roques F, Finon D (2017) Adapting electricity markets to decarbonisation and security of supply objectives: toward a hybrid regime? Energy Policy 105:584–596

Rylatt M, Gammon R, Boait P, Varga L, Allen P, Savill M, et al (2013) CASCADE: an agent based framework for modeling the dynamics of smart electricity systems. Emergence: Complexity and Organization. 15(2)

Samad T, Kiliccote S (2012) Smart grid technologies and applications for the industrial sector. Comput Chem Eng 47:76–84

Santos G, Pinto T, Vale Z, Praça I, Morais H (2016a) Electricity markets ontology to support MASCEM's simulations. International Conference on Practical Applications of Agents and Multi-Agent Systems: Springer; p. 393–404

Santos G, Pinto T, Zita V, Praça I, Morais H (2016b) Enabling communications in heterogeneous multi-agent systems: electricity markets ontology. ADCAIJ Adv Distrib Comput Artif Intell J 5(2):15–42.

Santos G, Pinto T, Praça I, Vale Z (2017a) EPEX ontology: enhancing agent-based electricity market simulation. 2017a 19th International Conference on Intelligent System Application to Power Systems (ISAP): IEEE; p. 1–6

Santos G, Pinto T, Praça I, Vale Z (2017b) Nord pool ontology to enhance electricity markets simulation in MASCEM. EPIA Conference on Artificial Intelligence: Springer; p. 283–94

Santos G, Pinto T, Praça I, Vale Z (2018) Iberian electricity market ontology to enable smart grid market simulation. Energy Inform 1(1):1–14

Santos G, Pinto T, Vale Z (2021) Ontologies to enable interoperability of multi-agent electricity markets simulation and decision support. Electronics 10(11):1270

Shafie-Khah M, Catalão JP (2014) A stochastic multi-layer agent-based model to study electricity market participants behavior. IEEE Trans Power Syst 30(2):867–881

Shinde P, Kouveliotis-Lysikatos I, Amelin M (2021) Analysing trading trends in continuous intraday electricity markets. 2021 56th International Universities Power Engineering Conference (UPEC): IEEE; p. 1–6

Shoreh MH, Siano P, Shafie-khah M, Loia V, Catalão JP (2016) A survey of industrial applications of Demand Response. Electric Power Syst Res 141:31–49

Steber D, Hübler J, Pruckner M (2018) A comprehensive electricity market model using simulation and optimization techniques. 2018 Winter Simulation Conference (WSC): IEEE; p. 2095–106

Stoft S (2002) Power system economics: designing markets for electricity. IEEE press

Teixeira B, Santos G, Pinto T, Vale Z, Corchado JM (2020) Application ontology for multi-agent and web-services' co-simulation in power and energy systems. IEEE Access 8:81129–81141

Værbak M, Ma Z, Christensen K, Demazeau Y, Jørgensen BN (2019) Agent-based modelling of demand-side flexibility adoption in reservoir pumping. 2019 IEEE Sciences and Humanities International Research Conference (SHIRCON). p. 1–4

Værbak M, Ma Z, Demazeau Y, Jørgensen BN (2021) A generic agent-based framework for modeling business ecosystems: a case study of electric vehicle home charging. Energy Informatics 4(2):1–26

Fatras *et al. Energy Informatics* 2022, **5**(Suppl 4):47

Page 30 of 30

Wang Z, Paranjape R (2017) Optimal residential demand response for multiple heterogeneous homes with real-time price prediction in a multiagent framework. IEEE Trans Smart Grid 8(3):1173–1184

Wilson R (2002) Architecture of power markets. Econometrica 70(4):1299–1340

Zhang J, Zheng Y, Yao M, Wang H, Hu Z (2019) An agent-based two-stage trading model for direct electricity procurement of large consumers. Sustainability 11(18):5031

Zheng Y, Yu H, Shao Z, Jian L (2020) Day-ahead bidding strategy for electric vehicle aggregator enabling multiple agent modes in uncertain electricity markets. Appl Energy 280:115977

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