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# Agent-based modelling and simulation of smart electricity grids and markets – A literature review

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ABSTRACT

The realisation of the smart grids and markets vision constitutes a substantial transition of electricity systems affecting multiple stakeholders and creating various technical, social, economic, political, and environmental challenges. These need to be considered adequately in decision support tools for agents in electricity systems. Agent-based modelling and simulation as a flexible and rich modelling framework can serve as a testbed for analysing new paradigms in the field of smart grids, such as demand response, distributed generation, distribution grid modelling, and efficient market integration. While so far wholesale electricity markets have been the focus of agent-based modelling and simulation, this paper provides a detailed review of literature using such techniques for analysing smart grids from a systems perspective. For that purpose, a general classification of applying agent-based modelling and simulation techniques to electricity systems is provided. The literature review of specifically using agent-based modelling and simulation for analysing smart grids shows that, although being still a limited field of research, quite different applications are identified with the number of contributions having increased in recent years. Agent-based modelling and simulation can deliver specific insights in how different agents in a smart grid would interact and which effects would occur on a global level. Thereby, the approach can deliver valuable input for decision processes of stakeholders and policy making. Future research could feature more focused analyses of storage systems, local market concepts, interactions with centralised markets, and the role of intermediaries.



**Contents**



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## 1. Introduction

Electricity systems in developed countries are subject to a substantial transition process towards smart grids and markets.[1] Various factors are driving this process including environmental concerns and corresponding policies supporting renewable energy sources (RES), concerns of security of supply including aspects of self-sufficiency, efforts to increase system efficiency, deregulation as well as considerable technological advancements. Consequently, electricity systems, in particular on the level of distribution networks, will need to cope with an increasing diffusion of distributed and fluctuating generation (e.g. [2]). An intelligent control of such generation units and consumers, either directly or indirectly, is proposed in order to tackle emerging challenges. This requires a technological upgrade of electricity systems as well as a rethinking of stakeholders, like consumers, generators, grid operators, market operators, and regulators. The transition towards smart grids is of high relevance and involves different technical, social, economic, political, and environmental dimensions.

New operating paradigms in smart grids require innovative or adapted methods for studying electricity systems in order to provide adequate decision support. Traditional computational methods for analysing electricity systems (e.g. [3–5]), such as large-scale, centralised optimisation models, are, to some extent, based on obsolete assumptions and may fail to deliver suitable support. Thus, the changing environment in electricity systems alters the requirements for power system modelling tools, a situation comparable to the process of deregulation in previous decades (e.g. [6]).

Agent-based modelling and simulation (ABMS) has been proposed by many researchers as a suitable modelling approach for complex, socio-technical problems [7] and qualified as a scientific instrument [8]. Particularly, agent-based simulation techniques have been applied to study electricity systems and markets and gained respective recognition [3]. To date, the strong focus of ABMS techniques in the field of electricity systems has been on wholesale electricity markets [9–13]. In line with that, agent models concentrated so far mostly on large generation companies, typically considered to behave rational or at most boundedly rational in the sense of having incomplete information [14].

Though recently, researchers have started to use ABMS tools as well to analyse decentralised structures in electricity systems. Being a growing field of research and application, this paper attempts to provide a review of models based on ABMS to study explicitly smart electricity grids and markets. To the best of the authors' knowledge this is the first kind of such a review. This paper's contribution to the ABMS-related research field is threefold. First, a general classification of applying ABMS techniques to electricity systems is given. Second and central to this paper, an overview of applying ABMS models to smart grids and markets is provided. Thereby, relevant literature is presented and compared according to smart grid issues. References to related research fields and applications are given. Third, new avenues of research using ABMS for studying smart grids are proposed.

This paper is structured as follows: Section 2 introduces the concept of ABMS in more detail, argues how the technique can be used to analyse electricity systems, and provides a typology of agent-based research of electricity systems. Literature specifically studying smart grids using ABMS techniques is reviewed in Section 3. In Section 4, the presented literature is discussed with respect to research trends, similarities, and gaps. Section 5 summarises and concludes the paper.

## 2. Agent-based modelling and simulation techniques for systems analysis

### 2.1. Economic studies of complex adaptive systems

Complex adaptive systems (CAS) feature by definition heterogeneous, interacting and adaptive units as well as emergent properties. Adaptive behaviour of entities can be interpreted in different ways ranging from simply reacting to environmental conditions, to directing actions in order to achieve defined or evolving goals, to actively exerting control over the environment [15,16]. Individual behaviours and interactions between entities lead to effects on the aggregated level of the total system, a phenomenon called “emergence” [8].

In order to study real-world CAS adequate computational models are necessary. ABMS has been suggested by many researchers as a suitable modelling technique. According to [8], the approach can feature concepts of heterogeneity, autonomy, explicit space, local interactions, bounded rationality, and non-equilibrium dynamics. In certain cases, ABMS can be more appropriate than other modelling approaches because the latter might face difficulties in detecting and describing direct, functional, analytical relationships between agents and the total system behaviour. In contrast, ABMS allows autonomous, heterogeneous agents to interact according to specific rules and lets the macro-level evolve indirectly and bottom-up. This is what Epstein [8] calls “generative social science”. Similarly, Tesfatsion [15] refers to a “culture-dish approach”.

More generally, ABMS can be subsumed under the generic terms of “multi-agent systems” (MAS) or “agent-based computing” which simply describe various computational instruments following an agent-based approach (e.g. [17]).[2] MAS comprise also the domain of (distributed) artificial intelligence and agent-based control systems which aim to design autonomous (software) agents and implement them in real-world cases (in the sense of designing and configuring systems in practice). In contrast, ABMS specifically deals with the computational representation of CAS within their boundaries following at least one of the four research objectives defined below (in the sense of analysing systems). When studying economically motivated relationships and processes the research strand is also known as agent-based computational economics (ACE) [15,21,22].[3]

ABMS and ACE can be applied to pursue different research objectives (e.g. [15]). By definition, ABMS aims at understanding interactions within and the emergence of a given CAS. This research objective is explorative and descriptive. Second, disposing of a suitable agent-based model, researchers can also use it as an experimental laboratory in order to test in a normative way how

[1] “Smart grid” is typically used as a very generic term. Various definitions exist in academic literature and in practice one of them defining a “smart grid” as an “electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies. A smart grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies […]” [1]. According to this definition, the term “smart grid” is not limited to technological aspects of electricity grids, but is also to be seen in conjunction with market-oriented solutions in the sense of “smart markets”. In this paper, the term “smart grid” is used accordingly without further elaborating on nuances.

[2] The definition and differentiation between ABMS and MAS is not fully consistent in the literature. References can be found using the terms to explicitly stress differences (e.g. [18]), in a rather hierarchical manner (e.g. [19] and in this paper), and synonymously (e.g. [20]), respectively.

[3] In this paper, the terms “agent-based modelling and simulation” or ABMS and “agent-based computational economics” or ACE are used interchangeably if not stated otherwise.

the simulated CAS behaves under certain conditions. Thereby, policies, institutions, shocks, and other definable scenarios can be tested with regard to their effects on the behaviour of agents and system. Computational models can replace expensive and impracticable real-world experiments. A third research objective can be qualitative insight as well as theory generation and verification, i.e. the systematic analysis of economic systems and conditions under which regular patterns do emerge or not. ABMS can, thereby, help to disprove theories by means of empirical falsifiability. Fourth, on-going research using ABMS should continuously improve its methodological foundations. In order to consistently use ABMS, the model needs to feature sound approaches for the implementation, calibration as well as verification, validation, interpretation, and visualisation of results.

### 2.2. Key concepts of agent-based computational economics

Given that the ABMS approach is rather a framework than one definite methodology for analysing real-world systems, there is traditionally neither a universally valid definition nor modus operandi. Nevertheless, a basic procedure and key concepts featured in most ABMS models can be identified.

The following steps are common in most ABMS (e.g. [23]). Based on a well-defined research question, the modelling exercise starts by constructing an economy with its initial population of agents and institutional framework. Agents are to be defined, amongst others, by their initial state, relationships with other agents, decision rules, and learning behaviour. Following the generative, culture-dish philosophy the subsequent evolution of the economy happens without the intervention of the modeller. All agent actions are solely based on the initially defined attributes as well as the on-going, autonomous decisions. The latter, in turn, can be influenced by previous decisions, interactions with other agents or institutions, and respective learning effects. The aggregation of individual agent decisions leads to an emergent system behaviour. Analysing results, ideally, includes back-testing and validation.

While central to the ABMS approach, a common definition of agents is not available in the literature and in the developed agent-based models.[4] A very basic definition of agents is, for instance, given by [25] postulating the following properties: autonomy, social ability, reactivity, and pro-activeness. Naturally, there is a continuum between active, decision-making, adaptive, learning agents and more or less passive agents. Similarly, the background, motives, objectives, and functions of the agents can be quite diverse. There are economic agents (e.g. consumers, producers, and intermediaries in electricity systems) as well as institutional and environmental agents (e.g. market operators, regulator, and weather in electricity systems). Heterogeneity of agents can originate from many distinctive features, be they part of the social, cultural, biological or another domain.

Each agent exhibits a certain behavioural model which can, likewise, range between a complex, multi-criteria optimisation model and a simple set of fixed rules. Agent models can be intended to reflect the ability of certain agents to learn from past experiences and to adapt correspondingly. Suitable approaches can be found, for instance, in the field of machine learning. All these individual models could be subjected to a verification process, e.g. by using methods from social sciences. Given the flexibility to equip each agent with its own behavioural model, ACE research allows to consider aspects contradicting the theory of completely competitive markets. Thus, ABMS researchers might consider facets such as asymmetric information, uncertainty, strategic interaction, learning, social norms, transaction costs, and externalities (e.g. [15]).

### 2.3. Electricity systems as complex adaptive systems

Electricity systems can be considered as CAS [26] or systems-of-systems [27,28] with autonomous agents and emergent behaviour. ABMS has been widely used to study electricity systems integrated in an economic, technical, and social context. In particular, the dynamics of the smart grids transition require adaptable modelling approaches in order to deliver adequate decision support.

In order to link upstream electricity generation with downstream consumption, the electricity supply chain involves physical transmission and distribution via electricity grids as well as retail activities. Furthermore, electricity systems are interlinked with multiple other commodity markets and are essentially integrated in daily business and social life. Different economic, physical, informational, and social layers are of interest when designing and operating electricity systems. Within and between these layers, a multitude of heterogeneous entities make individual decisions and interact via different markets, bilateral contracts, and other institutional frameworks. Major stakeholders include consumers, producers, intermediaries, market operators, grid operators, and regulatory bodies, all of which face different types of decision problems and environmental conditions (e.g. available information, competitive situation, stakeholder involvement).

Many developed electricity systems have experienced a strong growth of distributed generation in recent years. The diffusion of local storage systems and electric vehicles might become another important factor in the future. Smart structures in the form of automated agents, grids, and markets are expected to support integrating these new structures in the electricity system in order to guarantee security of supply while complying with additional economic and environmental objectives at the same time.

These current developments stress the heterogeneity of electricity systems, the importance of bi-directional interactions as well as feedback loops between agents and institutions, and the social context of electricity supply. ABMS can be a suitable tool to analyse smart grids with respect to the research objectives defined above.[5] The suitability is underpinned given the general ability of ABMS to describe systems in transition, such as it is the case for the smart grids vision (e.g. [14,29]).

### 2.4. Agent-based modelling and simulation of electricity systems

The multi-agent approach has been widely applied to study electricity systems and markets and gained respective recognition [3]. Apart from ACE for electricity systems in the sense of this paper, other applications of MAS approaches focus on technological aspects or information processing between agents or describe agent-based control systems. The focus of this paper is eventually on reviewing literature using ACE in order to analyse aspects of smart electricity grids. This research strand is classified and delimited from other MAS approaches for electricity systems in the following section. Fig. 1 shows the main classification scheme of ABMS as MAS and the different research streams of ACE applied to electricity systems.

[4] For instance, [24] discuss the lack of a shared notion for the agent concept across ABMS and related research.

[5] In a broader sense, multi-agent approaches can also act as an enabler and solution to successfully implementing smart grid structures in electricity systems. Agent-based control strategies can be used for automation of decentralised processes, e.g. in virtual power plants or demand response control units.

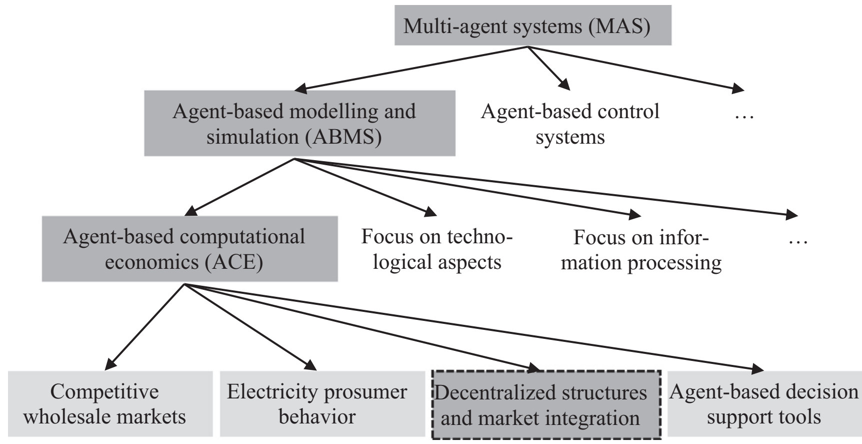


**Fig. 1.** Classification of MAS approaches (focus of review shaded).

The typology of ACE research in this paper follows the electricity supply chain and market structure, respectively, and is categorised in four streams:

A. *Competitive wholesale markets*: The study of competitive wholesale electricity markets has been the centre of several large-scale ABMS models which usually feature a centralised market clearing mechanism. The focus of such research is on market and auction design as well as on bidding strategies of large traders (e.g. conventional generators). Aspects of distributed generation and demand response are often not considered explicitly. An extensive discussion of ABMS models for wholesale electricity markets can be found in existing literature review papers [9–13].
B. *Electricity prosumer behaviour*: Electricity generators and consumers as single entities are the main explanandum in the second group. Literature is classified in this group when it is strongly focused on the detailed modelling of electricity consumption behaviour and generation on a low level of aggregation, i.e. for single agents or agent types. Also indirect effects, for instance the diffusion of smart meter technologies among electricity consumers (e.g. [30]), are to be seen as part of this group. Market integration (e.g. via direct participation or intermediaries) is not the focus of such models. Interaction between prosumers and markets is simulated in a rather static manner without bi-directional feedback and impact on other market participants. Exemplary applications can be found in [31–35].
C. *Decentralised structures and market integration*: The study of changing paradigms in electricity systems with regard to smart grids and markets using ABMS models is the focus of this literature review. Research of this type attempts to answer questions related to the integration of demand response and distributed generation in local or centralised markets as well as other aspects of smart grids and smart markets, respectively (see Section 3).

The fourth stream termed “agent-based decision support tools” is not necessarily distinct with respect to the research object but rather concerning the interaction between model and model user. Various agent-based tools have been developed which explicitly are aimed at supporting the decision-making process of power market participants and at demonstrating processes within electricity systems to experts or third parties. In particular, agent-based participatory designs and “multi-player” architectures are to be subsumed under this category. [36] presents a version of the agent-based simulation model PowerACE for the German wholesale electricity market as an experimental laboratory in which real-world persons can adopt the role of market agents. [37–39] present simulators for electricity markets to be used for training purposes. [40] extends such approaches by opening the competitive simulation environment PowerTAC (Power Trading Agent Competition) to external researchers. In dedicated tournaments teams can compete against each other for the most profitable strategy.

The physical transmission and distribution of electricity is not assumed to be a distinct group of ABMS research. Although, grid operators can be seen as agents and grid conditions can influence other agents' behaviour depending on how such situations are signalled (e.g. within locational marginal pricing schemes), the representation of grids has not been a focus of ABMS so far (e.g. [11])[6], in particular not on the level of distribution grids. However, due to their increasing importance in smart grids, the latter are implicitly included in the research of decentralised structures and reviewed, where applicable, below.

Other agent-based modelling techniques in the field of electricity systems can have a strong or strict focus on technological and informational aspects, which is why such research is not classified as ACE. Examples can be found in [42–44].

Finally, in contrast to ABMS, other large domains of agent-based computing are aimed at directly designing intelligent agents with artificial intelligence (software) to be implemented in real-world systems (hardware) (e.g. [45]). Such agent-based systems can be employed in control, monitoring, and safety systems, in particular on a distributed level, which interact autonomously with other members of the system be they human or again automated devices. With the changing environment in the electricity system, the automation of decentralised processes is about to become more important than ever. Examples can be found in [46–50]. How the large-scale diffusion of automated devices will in turn affect the macroevolution of electricity systems is a key issue to be researched.[7]

## 3. Results from reviewing literature on using agent-based computational economics for simulating smart grids

This section provides the results of reviewing relevant literature focusing on new operating paradigms in smart grids using an

[6] One exception is, for instance, the AMES model for electricity systems using locational marginal pricing by solving a DC optimal power flow problem [41].

[7] As for the other ACE research streams which are beyond the scope of this paper, a comprehensive classification of such related work cannot be provided here but should illustrate the wide field of application of MAS alone in the electricity sector.

ACE approach. For the review relevant journals and conference proceedings have been analysed thoroughly in order to give a review as comprehensive as possible.[8]

The identified research tackles questions related to new operating paradigms in smart grids and markets such as demand response, distributed generation, intermediaries and their interactions with prosumers as well as local markets and their integration in centralised markets. The research contributions are classified according to their main focus. A summary of the findings as well as a discussion of similarities, differences, and potential deficits are provided in Section 4.

### 3.1. Holistic system analysis

First, studies are presented which adopt a holistic view on smart grid systems. [51] proposes a multi-agent architecture specifically designed to address decision-making in decentralised electricity markets. The research is motivated by the restructuring of the electricity supply industry with a higher degree of decentralisation and market orientation. The overarching model architecture is described in a loose way with the multi-agent simulation EMMAS (Electricity Market Multi-Agent System). The agent concept differentiates between basic (atomistic) and synthetic (combined) agents with the latter being a composition of different basic agents. A basic agent can be a consumer, generator, transmission system operator, distributor, market operator, wholesaler, retailer, or a regulator. The intelligence of the agents is described very generally and includes learning from past experiences or from a given expertise domain. The EMMAS includes a transport and distribution market model which is not further detailed in [51]. Although, there is no concrete definition of the system under consideration and no details about scale and aggregation level are given, the simulation model is, according to the authors, able to represent different systems in a flexible way. In a case study provided, a day-ahead wholesale market with wholesalers, generators, and the market operator is modelled.

[52–54] present a MAS for local electricity systems which is intended to study current challenges in electricity distribution networks due to an increasing penetration with fluctuating electricity feed-in from distributed RES. Based on specific agent models for simulating time series of electricity demand and generation, distribution networks with flexible loads and generation can be modelled. A load flow calculation is used to signal potential congestion and to adjust load or generation dynamically. [53] presents a module for simulating generation profiles of distributed units, such as wind and PV units, with a high spatial and temporal resolution. In [54], the model is used to generate interdependent load and generation profiles of the systems' agents. According to the authors, results from the MAS can be used by grid operators during their investment planning process. The model is not formally described and no details are given concerning the agents' behavioural assumptions.

A prototype agent-based model to examine the effects of individual behaviour and social learning on patterns of electricity use is presented in [14]. The contribution offers a holistic view on the electricity system considering technical aspects, human interaction, and framework policies. The paper is focused on the behaviour of households, which is why the transition of the electricity system into a smart grid is also described as a socio-technical and inter-disciplinary transition. The contribution remains widely conceptual, in which the ABMS approach and its foundation are comprehensively addressed. The overall issue is embedded into the concept of Multi-Level Perspective (e.g. [55]) allowing a systematic study of socio-technical transitions. Furthermore, the Energy Cultures framework serves as context for the agents of local electricity systems [56]. Different behaviour change theories (e.g. Theory of Planned Behaviour, Value-Belief-Norm) are presented which are essential for simulating individual behaviour and social learning. The proposed agent-based model includes different kinds of prosumer and aggregator agents, with the latter taking part in wholesale markets. The model differentiates three levels, namely demand–supply, markets, and power flow. The contribution lacks details about input data as well as a detailed definition of algorithms and behavioural models. In the course of the CASCADE research project, the model has been used for different research questions, e.g. how aggregators can contribute to flatten the demand profile of households with smart meters [57].

[58] presents a flexible power system modelling tool using an agent-based approach to simulate smart grid paradigms, such as demand response, energy storage, retail markets, electric vehicles, and new automated distribution systems. Advanced simulation tools for these new technologies and concepts are combined and applied within the electricity system simulation tool. An agent-based approach was chosen since traditional analysis tools fail to integrate the different and interacting levels of smart grids in one large-scale framework. Furthermore, classic modelling methods largely ignore learning effects and often provide only stylised results according to the authors. In order to analyse future electricity systems in an engineering-like way the model framework GridLAB-D was developed and also released as an open-source tool for the smart grid research community. Since its development the model was applied to various research questions, including an optimised operation of distribution grids, dynamic real-time pricing experiments, and the integration of renewable energy supported by demand response.

### 3.2. Demand response

The issue of demand response provided by different entities in smart grids, such as commercial buildings and electric vehicles, is addressed by the following research papers in detail. [59] examines how price-based demand response can improve efficiency and reliability of electricity systems. Demand response in the proposed model is provided by commercial buildings which are responsible for a considerable share of the total end-use electricity in the US. Unlike a static consideration of the buildings' load, the authors propose a new approach to integrate commercial buildings as autonomous and interacting agents in an ABMS framework. For that purpose, a physical building stock energy model is created and scaled up to the required aggregation level. Different types of buildings are simulated based on various input parameters. In order to understand the effects of demand response from commercial buildings, an agent-based model for an electricity market is introduced whose participants include generation companies, load-serving entities, commercial buildings aggregators, and an independent system operator. Based on an underlying physical transmission network, the independent system operator determines a locational marginal price. Generation companies can exploit market power and adjust their true marginal costs by a mark-up rate. Strategic bidding behaviour is modelled using the Roth–Erev reinforcement learning algorithm. Commercial buildings aggregators pool the load from all contracted buildings and procure the required electric energy on the market. If market prices exceed a certain threshold, commercial buildings aggregators can react by reducing electricity load, e.g. by turning off certain devices. How demand response impacts electricity prices is

[8] Given the novelty and dynamics of the field of application as well as the overlap between the different research streams the survey cannot be guaranteed to be complete. Nevertheless, the authors are confident to provide an extensive review of relevant literature on agent-based simulation methods of smart grids.

examined in different case studies with varying levels of competition.

Another aspect of future smart grids is the potential large-scale introduction of electric vehicles. The diffusion and use of electric vehicles are likely to change the electricity consumption behaviour of end-users but will also create additional challenges to the reliable operation of electric grids, particularly in distribution grids. At the same time, electric vehicles provide an interesting potential to control electricity load in an intelligent way given the significant options for load-shifting which could, for instance, also facilitate the integration of RES in electricity systems. [60] combines a stochastic model for mobility behaviour and a version of the agent-based simulation model PowerACE in order to study the effects of higher penetrations with electric vehicles and increasing electricity generation from RES on wholesale prices. Based on price signals the load of electric vehicles is dynamically controlled which allows balancing fluctuating RES feed-in. Furthermore, the authors note that the indirect control of distributed loads with dynamic prices can lead to so-called avalanche effects, if the individual loads are determined by using the same algorithm and information set and if there is no feedback loop in the scheduling algorithm (e.g. also [61]). This issue applies to other types of agents (e.g. distributed generation) as well and is therefore highly relevant for the operation of smart grids.

In [62] the PowerACE model is extended by an aggregator agent for electricity demand from electric vehicles. A diffusion model for electric vehicles and empirical data on mobility behaviour are used to estimate the total consumption of electric vehicles and their availability for charging in Germany. Based on the tariff structure of its customers, a smart charging manager as a new intermediary maximises its profits in the day-ahead market by exploiting the available load-shifting potential. Finally, the business model of the smart charging manager is analysed.[9]

[64], in turn, examines how demand response of households can form the basis of a business model for a new entrant in the electricity market. The business idea is focused on exploiting demand response potential of households through aggregators in order to reduce peak loads and use it as a balancing mechanism. For that purpose, a small-scale agent-based simulation consisting of households, a demand response aggregator, a utility, and an independent smart meter data manager is implemented. Households can be classified according to their willingness to adopt innovations, e.g. as early adopters. Based on simple rules and communication protocols households can provide demand reductions considering their adoption and flexibility. The authors provide results for several test cases with varying parameters. Finally, the demand response scheme is placed in a business context by determining an internal rate of return of avoided capital costs through peak load reductions.

### 3.3. Distributed generation

The emerging distributed supply structure is covered by the literature summarised in the following paragraphs. The focus of [65] is on how virtual power plants (VPP) are formed and operated in an electricity system. For that purpose, VPPs are introduced in an agent-based model and tested in studies for the Iberian electricity market. The analyses are based on the existing agent-based simulation model MASCEM. It can simulate several types of markets, including pool markets, bilateral contracts, balancing markets, and forward markets, and contains a representation of the transmission grid (e.g. [66]). VPPs are aggregators of mainly distributed generation units ("coalitions of agents"). The constituents of such VPPs cannot take part in the market directly for technical, institutional, or strategic reasons. On the one hand, VPPs are selling electric energy in the market as regular traders based on the contracted plants' characteristics. The objective is profit maximisation by adjusting generation and provision of reserve capacity. On the other hand, they internally manage their portfolio of contracted units. In the model, algorithms for forming and managing coalitions are proposed and tested in a case study. Implementation-wise, each coalition of agents forming one VPP is considered as an individual multi-agent system.

In general, given the innovations required for the development of smart grids, the study of business models for new energy services is of high relevance. [67] and [68] focus their research on the market-oriented integration of electricity generation from RES via new types of intermediaries exploiting different policies implemented in Germany. In order to achieve a reliable and economically efficient integration of RES into the electricity system and market, the support mechanisms in Germany are gradually adjusted from fixed feed-in tariffs to schemes incentivising a market-oriented production and feed-in, respectively. One of these adjustments, an optional market premium for direct marketing of electricity from RES on the power exchange, is the focus of the authors' analyses. In order to adequately set up and calibrate the agent-based simulation model, a comprehensive actor analysis is conducted by the authors. The AMIRIS model (Agent-based Model for the Integration of Renewables Into the Power System) focuses on the implementation of such new intermediaries for direct marketing of renewable electricity. Different types of intermediaries are modelled which offer plant owners corresponding remuneration options for their electricity, e.g. keep the fixed feed-in tariff or opt for the dynamic market premium. Depending on the expected profitability of the options, plant owners choose to close contracts with the intermediaries. The intermediaries' business models are, furthermore, complemented by an analysis of variable and fixed operating costs.

### 3.4. Other smart grids paradigms

Finally, other new paradigms in smart grids are summarised. The research focus is either on the exploitation of distributed potential for reserve energy, operation of distribution grids, or local markets. How an agent-based control system can be combined with simulation techniques is shown by [69]. Given the increasing relevance of distributed generation and the potential of demand response, a coordinated control of different units is targeted using an approach of "market-based control" of imbalances. According to the authors the proposed market-based optimisation yields the same results as a centralised optimisation assuming the availability of information and a competitive market. In the study, a software toolbox (PowerMatcher) is presented in order to optimally use the potential of electricity production and consumption of local agents. In a case study, the software is applied to control imbalance situations in a cluster of local units. This application is also used for developing a potential business model. The agent-based coordination of a "Distributed Balancing Service" is tested in a field experiment with five installations in the Netherlands and a business case analysis is conducted.

[70] proposes a preliminary approach for controlling an electrical distribution network based on a MAS. According to the authors, traditional centralised optimisation methods for load flow calculations are failing because of their static nature and low reactivity to new grid situations. In order to guarantee a safe

[9] The combination of modelling mobility behaviour and integration of electric vehicles in electricity markets using ABMS techniques can also be implemented with a different focus. For instance, [63] integrates the demand management of electric vehicles and an agent-based transportation simulation tool which allows a much more detailed consideration of the electric vehicles' availability for load management.

**Table 1**
Categorisation of reviewed literature according to smart grid themes.

| Reviewed literature | Demand response | Distributed generation | Intermediaries | Interaction with wholesale markets | Local markets | Grid modelling | Agent learning | Other | Technical implementation |
|---|---|---|---|---|---|---|---|---|---|
| [14] | (✓) | (✓) | (✓) | (✓) | | | (✓) | Conceptual model | Repast (Java) |
| [51] | | | | ✓ | | (✓) | (✓) | | Java, MySQL, KQML |
| [52–54] | ✓ | ✓ | | | | ✓ | | Generation forecasting of RES plants | JADE1 (Java) |
| [58] | ✓ | ✓ | (✓) | | | ✓ | | | GridLAB-D (C++/C/Java), MATLAB |
| [59] | ✓ | | (✓) | ✓ | | ✓ | ✓ | Demand response from commercial buildings | |
| [60] | ✓ | | (✓) | ✓ | | | | Demand response from electric vehicles | Java |
| [62] | ✓ | | ✓ | ✓ | | | | Demand response from electric vehicles | Java |
| [64] | ✓ | | ✓ | | | | | | |
| [65] | | ✓ | ✓ | ✓ | | | (✓) | | OAA2, Java |
| [67,68] | | ✓ | ✓ | ✓ | | | (✓) | | Repast Symphony (Java) |
| [69] | ✓ | ✓ | | (✓) | | | | Reduction of local imbalances | |
| [70] | | | | | | ✓ | (✓) | | Java |
| [71] | ✓ | | | | ✓ | | ✓ | Local reserve capacity market | MATLAB |
| [72] | | | | | | ✓ | | Energy storage | JADE1 (Java) |
| [73] | ✓ | | | | ✓ | | | Neighbourhood trading | Repast (Java) |

*Notes:* Research themes are considered to be covered if they are clearly focused and described in the reviewed literature. The check mark is put in parentheses if the theme is only indirectly covered or addressed but not elaborated in detail, e.g. because of its preliminary state of implementation; 1 Java Agent Development Framework; 2 Open Agent Architecture.

network operation on lower voltage levels new strategies of operation and control need to be developed. The authors propose an on-line and decentralised network control scheme to be simulated within a MAS. Based on a distribution grid model, different types of agents are introduced at each node ("Feeder", "Load", and "Neutral" agents). During the simulation the agents gather information and update their strategies in order to reach their objectives. In case of a mismatch between demand and supply within one zone or in case of network congestion, feeder agents are able to adjust the topology of their zone and to exchange loads with neighbouring zones. This allows an on-line optimisation of the network operation. Simple test cases show the validity of the feeder agent's strategies according to the authors. However, the proposed simulation model is described rather superficially, e.g. concerning the extent to which decisions are based on economic considerations.

[71] provides an example of a local market for reserve energy. The paper addresses the increasing relevance of ancillary services due to a higher electricity generation from fluctuating sources and how local agents can be integrated in markets for such services. Specifically, a new auction design for local reserve energy is proposed. The aim of the market is to provide additional flexibility to balance group responsible parties beyond simple accounting by incentivising regional trading of ancillary services. It is particularly worth mentioning that non-expert bidders, such as private households, are participating in the new market. Each bidder in the market tries to maximise its expected profits. Considered costs include fuel costs as well as opportunity costs arising from a trade-off between providing reserve energy and consuming electricity in order to satisfy the original needs. Since an analytical solution is not manageable, a specific bidder constellation is examined within an agent-based simulation model. An additional laboratory experiment to test the market design set up is planned.

The decentralised management of energy storage devices is the focus in [72]. With the help of an agent-based approach, the authors demonstrate how a decentralised negotiation algorithm can be used to efficiently optimise the operation of several storage units within a distribution network. The multi-agent system consists of several autonomous storage devices, other distributed energy resources, loads, and a distribution grid. The negotiation platform facilitates the exchange of services between the different decentralised units which, in turn, helps to improve the operation of the system. A case study illustrates that the agent-based coordination via the negotiation platform can reduce network losses. Although the research is not directly based on economic considerations, it shows the advantages of coordinating energy storage units in distribution systems in terms of network losses. However, the contribution is not very explicit about the negotiation algorithm implemented and how such autonomous energy storage units could behave in larger systems and, in particular, under market conditions.

[73] studies different types of consumers and their interactions with their neighbours in a smart grid environment. Simulated consumers can autonomously choose between using locally generated power, charging or discharging batteries, reducing their load, and exchanging energy with utilities or neighbours. Overall, the results show that consumers can reduce their electricity costs when dynamically adjusting their demand profile. The current version of the proposed model does not contain a grid representation. Challenges with respect to such local trading schemes, e.g. with respect to transaction costs, acceptance, or legal hurdles, are not explicitly addressed, which is why the presented study remains rather conceptual.

## 4. Discussion of current status of research and future issues

The literature reviewed in the previous section is summarised in Table 1 and classified according to relevant research themes relevant for smart grids. Different trends, similarities, and gaps can be identified from comparing the literature.

The overall picture of the reviewed literature shows that the research field of applying ACE techniques to analyse smart grids is still limited. Although different types of publications, i.e. not exclusively peer-reviewed journals, are analysed, the number of identified research papers is quite limited when compared to other research streams of ACE for electricity systems. For instance, [12] reviews 49 papers alone dealing with the modelling of wholesale electricity markets versus 19 in this paper in the context of smart grids. One reason is that smart grids as field of application has attracted attention only in recent years. Furthermore, difficulties exist in identifying relevant literature. On the one hand, there are well-known inconsistencies in defining ABMS and smart grid structures in electricity systems, which increases the risk of false negatives. On the other hand, the separation of ACE methods for smart grids from other types of MAS in this area is sometimes not fully unambiguous. Naturally, there is a strong overlap with agent-based control systems applied in smart grid environments. Such types of applications deal exactly with implementing automated devices in real-world systems in order to activate different kinds of intelligence in smart grids. Being only a small research area so far, the combination of ACE modelling techniques and smart grids-related research attracts at least more and more researchers as most of the reviewed literature was published in the last three years. Various recently completed and on-going research projects back this development.[10]

Although the research area is still limited, it can, at the same time, be considered to be quite diversified with respect to the research focuses. Except for the rather holistic approaches, e.g. in [14] and the GridLAB-D simulation platform [58], the contributions are quite focused on specific issues. The research issues include amongst others integrating demand response in local or wholesale markets, provision of system services by distributed units, and modelling distribution grids. Given the narrow focuses, interactions between different layers, e.g. with centralised wholesale electricity markets, are sometimes neglected. Thereby, a consistent and comprehensive evaluation of effects from smart grid structures is still difficult. Similarly, the concrete link to current market designs and implementation steps are missing, which is why some research papers remain rather academic (e.g. [64]). Issues of local acceptance are neither addressed explicitly.

When it comes to the different smart grids themes in isolation, it can be noted that demand response appears to be the best covered theme across the reviewed literature. Thereby, different sources of demand response (e.g. commercial buildings, electric vehicles) as well as different purposes (e.g. imbalance reduction, integration of RES) are addressed. Although electricity generation from RES is typically named in the research papers' motivation, distributed generation seems to attract somewhat less interest. Specifically, forms of distributed generation other than pure renewable systems, e.g. micro combined heat and power, are not analysed in much detail by any of the contributions. After all, the issue of aggregating distributed generation and consumers through dedicated intermediaries providing new services is addressed by several papers (e.g. [65,67]). The role of intermediaries in the future is highly relevant because for different

[10] Examples include the CASCADE project and its follow-up project AMEN lead by De Montfort University, the Agent.Netz project conducted by TU Dortmund University, University of Duisburg-Essen, and several industry partners, and the DEMO project conducted by Karlsruhe Institute of Technology.

reasons flexibility potentials cannot be directly exploited or stimulated in distribution networks by local agents. It is of particular interest, how sustainable business models either exploited by existing market players or by new entrants can be developed in order to foster market-oriented solutions.

Despite being considered as promising approaches to increase the flexibility of electricity systems, research gaps can be identified with respect to local markets as well as storage systems. The concept of local electricity markets is lacking a common definition but typically involves a more direct exchange of electricity between generation and consumption units within a limited area through regional marketplaces and the corresponding distribution network. Local markets should ideally provide simple interfaces, protocols, and low hurdles for qualification as well as participation, thereby reducing transaction costs for potential participants. On the one hand, local markets are expected to include a higher activation of demand entities, a better usage of distributed RES, an improved management of local grid congestions, and generally an increased local acceptance of electricity projects. On the other hand, local markets are by nature limited in size which can make them vulnerable to a lack of liquidity and abuse of market power. Moreover, the coordination and interaction with other markets and institutional frameworks need to be designed consistently. And despite being only a partial solution, the introduction of local markets would still be quite disruptive in most electricity markets. Consequently, the actual implementation would be challenging in terms of technology, information processing, and acceptance. In [71] a new local market for reserve energy is introduced which enables the balancing responsible party to directly exploit local potential for reducing reserve energy needs. The focus in [73] is on "neighbourhood electricity trading", a more radical approach allowing consumers to directly trade with other agents in close proximity. Similarly, literature with a focus on storage systems in smart grids is scarce. Only [72] analyses directly how an agent-based coordination of storage units can help to reduce network losses in distribution grids.

Finally, the reviewed literature struggles with well-known challenges of agent-based models concerning model description, calibration, verification, validation, and publication (e.g. [74]). No standard procedures exist to deal with these essential tasks, which is why they are handled quite differently across the reviewed literature. In several contributions model descriptions are rather sparse and not formalised which prevent the research contributions from being fully self-contained. This is also due to the fact that the concept of agents and of agent-based models is quite differently interpreted. Most models are implemented in Java or using Java-based modelling toolkits (e.g. RePast). The source code is only rarely published with exceptions provided partly in [71] and with the open-source tool GridLAB-D [58]. The calibration and validation of agent-based models and corresponding results are traditionally considered to be a grey area in ABMS research. Loose standards and procedures for simulations models in general and for agent-based model in specific have been published (e.g. [75]; [11] for an overview) and should, if practicable, be applied in order to increase the quality of the research and acceptance of the modelling technique.

## 5. Conclusions and outlook

The transition of electricity systems towards smart grids and markets is substantial and affects multiple stakeholders. The process creates various technical, social, economic, political, and environmental challenges which decision support tools for agents in electricity systems need to consider adequately. ABMS as a flexible modelling framework and rich empirical instrument [8] can be seen as a testbed for analysing innovative concepts and paradigms in the field of smart grids and markets, such as demand response, distributed generation, distribution grid modelling, and efficient market integration. The approach allows simulating in detail the behaviour of particular agents and observing an emergent development on system level by letting agents decide individually, interact, and learn. By integrating different disciplines, such as electrical engineering, economics, as well as other social sciences, and in combination with other modelling approaches, ABMS is a valuable approach to analyse opportunities and challenges in smart grids and markets.

Though, as in other fields of applications the approach itself faces various challenges and drawbacks if not addressed appropriately. General standards of ABMS-based research (e.g. model description, validation) need to be met in order to increase quality and acceptance of the research. Dealing predominantly with explorative research designs when addressing new issues in smart grids and markets, model calibration, verification, and validation are particularly demanding. Also, the flipside of the approach's flexibility is the risk of excessive complexity and spurious accuracy. All the more, harmonisation and consistency are essential in order to increase the comparability within the fields of ABMS-based research, with other approaches, and empirical observations.

In this paper, a general classification of applying ABMS techniques to electricity systems is given. Thereby, a differentiation is made between ACE focusing on the analysis of economic systems and agent-based control strategies aimed at designing real-world systems. Building on the classification, an overview of applying ACE models to electricity systems is provided. While so far the focus of ABMS-based research has been on wholesale electricity markets, in this paper the analysis of smart grids and markets is reviewed. For that purpose, material literature on using ABMS for relevant smart grid issues is presented and compared. Studying smart grids with ABMS models is a young and, therefore, still limited field of research. Nevertheless, quite different applications are identified and the number of contributions has increased in recent years given the high relevance of smart grid issues for the development of future electricity systems. In general, the reviewed literature shows that ABMS can deliver specific insights in how different agents in a smart grid would interact and which effects would occur on a global level.

With regard to practical implications, future research should include more prominently the analysis of local market concepts and storage systems. Concepts for local markets should also consider the wider system integration and acceptance of such active involvement schemes among initially unexperienced agents. Storage systems are particularly of interest given the flexibility potential to be provided by installations in smart grids. Overall, future works should as well consider in a more comprehensive way potential interactions with centralised markets and the role of intermediaries including an evaluation of their business models. Conceptually, research using ABMS techniques for smart grids and markets faces novel challenges concerning agent and model architecture. For instance, the approach requires in some cases a refocus from fully rational to rather boundedly rational and socially interacting decision makers. Furthermore, given the dynamics and novelty, data availability for smart grids is another key issue to be met by future research. In general, increasing the degree of multidisciplinarity in order to foster the integration of technical, social, economic, political, and environmental aspects could additionally improve future ABMS-based research of smart grids and markets. Thereby, ABMS can deliver valuable input for decision processes of stakeholders and policy making.

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