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A Framework for Agent-Based Simulations of Hybrid Energy Infrastructures

Christian Derksen[1], Cherif Branki[1] and Rainer Unland[1], *Fellow, IEEE*

[1]DAWIS, University of Duisburg-Essen, Essen, Germany

***Abstract*—In many countries, future energy supply, management, and consumption change completely compared to today's status. One reason is that sustainable energy production will rely on a large number of small and medium sized, de-centralized energy production units. The aim is to replace a small number of large power plants. The energy supply strategy change puts completely different demands on the energy grid as well as on the business models to run those energy grids efficiently and, especially, securely. The future energy grid will have to deal with an autonomous, communication-driven, highly diversified and dynamic, and continuously changing environment. Additionally, while today's energy grids are run as independent systems the interaction between different energy networks, like natural gas or district heat, will strongly increase in the future. Inspired by ideas and techniques like Mini-CHP (combined heat and power) or Power-to-Gas, it is expected that future energy networks have to be seen as an entire hybrid energy network, where quantities of energy and energy forms will be dynamically exchanged and substituted as required. As a consequence, a lot of expertise that was gained in the past is no longer valid. On the other hand, little experience exists when it comes to shaping and managing the future energy grid. Due to the nature of multi-agent based simulation this class of simulation tools is well-suited for the simulation of future energy networks. The main advantages are the autonomy of agents, their highly developed interaction skills, the inherent distributed/decentralized approach of control in such a system and the high flexibility in the execution of tasks.**

This article presents Agent.GUI, which can be seen as a simulation toolkit and framework for complex and diversified energy systems. Based on the well-known JADE platform, the toolkit provides a wealth of specific features tailored to the needs for simulation of hybrid energy networks.

***Index Terms*—Multi-Agent Systems, Agent-based Simulations, Smart Grids, Future Energy Networks, Hybrid Energy Networks.**

I. INTRODUCTION

THE ONGOING TRANSFORMATION of energy supply remains a major challenge of our time. Questions to be answered are how will our energy systems change, what abilities will be added and what rules will apply in order to allow our energy systems to operate with a higher number of renewable energy sources and in order to make it more sustainable and environment friendly. On the other hand availability and reliability must be ensured in a similar form. In particular, the extended use of more volatile energy producers, such as wind or photovoltaic, means a major challenge for the future energy supply. This requires for example techniques and business processes, that allow storage of wind-generated electricity, if it is not needed. But on the other hand also to satisfy energy demand, if wind energy is not available.. For this purpose several ideas for energy storages are currently discussed and developed, such as Power-to-Gas, where electricity is converted to hydrogen or methane, which can be fed into a gas network.

Even if the above scenario is an example, it illustrates that future energy networks need more and more bidirectional and planned consumption. Together with the current developments in the area of Smart Grids it can be expected that the future energy grid can be seen as hybrid, decentralized controlled and cooperating energy system.

With this paper we present an extension of our Agent.GUI framework and toolkit. It is meant to be an important building block for the challenging research area of future energy systems, by using the approach of Multi-Agent based Simulations (MABS) for hybrid energy networks and systems. Starting from a topological model of the underlying technical network as Multi-Agent system (MAS), our framework allows the modeling, implementation and configuration of different simulation setups that can be easily executed as a distributed simulation. Although they are represented differently in their usual graph-theoretical model, Agent.GUI now allows the modeling and simulation of electrical systems as well as the coupling of gas transportation networks and district heat systems. Because the paradigm of agents and MAS has already reached the scope of the energy sector, we see our Agent.GUI framework and toolkit as a promising tool for supporting the current developments in the energy sector.

This paper is structured as follows: The subsequent section focuses on Multi-Agent based simulations. Related work is presented in section III. Section IV will give a brief overview about the Agent.GUI framework and toolkit, while section V describes a modeling approach for Multi-Agent systems that are representing energy networks. The subsequent section VI discusses and outlines our work while section VII concludes this paper.

II. AGENT-BASED SIMULATIONS

This paper will rely on the definitions for agents and Multi-Agent system (MAS), as introduced by Wooldridge and Jennings [1]. Accordingly, an agent can be seen as an autonomous computational entity that is situated in some environment and that is capable of effective, autonomous interactions with this environment. Other properties and abilities that are usually assigned to intelligent agents are its social ability, a reactive or proactive behavior, and, if necessary, the capabilities to learn or to be mobile.

Depending on the concrete scenarios and its requirements, agents can be designed with different levels of complexity and sophistication. Agents are often defined as being reactive, deliberative or as being capable to learn (e.g. [2]).

If the overall system consists of a set of loosely coupled agents that are embedded in the same environment, a Multi-Agent System (MAS) is formed. Such systems can be composed in order to find faster and more diversified solutions that cannot be found by single, monolithic systems. For the practical problem solution the agents have to rely on communication, collaboration, negotiation, responsibility delegation, and trust. These subjects are also discussed in detail in the literature [3].

Changing the scope of agents and Multi-Agent systems from real problem-solving to virtual problem-describing tasks, leads to the area of Multi-Agent based Simulations (MABS). Here a specific scenario is modeled and conceptualized as MAS, wherein the involved active and (more or less) independent real world entities are mapped as agents that are embedded in an abstracted, shared and virtual environment.

Many authors describe the advantages of MABS (sometimes also called agent-based modeling - ABM) through the benefits that result from the conceptualization of a system as agency:

1. Provision of natural description of a real system,
2. Capture of emergent phenomena in a system,
3. Flexibility.

The first point was already mentioned above through the mapping of real world entities to individually behaving agents. Instead of an abstract statistical description, as for example for the traffic density on a road or a traffic jam, MABS are able to describe a model more naturally. Emergent behavior results from the interaction of individuals. Thus, examples can be found in real social groups as well as in social groups that are simulated by a MABS. Unlike a system that results from a strict mathematical modeling (e. g. with differential equations) with clear overall rules, a MABS may be able to capture group behaviors that are enriched with individual aspects for considerations and reasoning. Those can be differently motivated and reach different decisions for a single situation. MABS can be considered as a tool for simulations that are able to capture similar and nearly realistic aspects as conventional simulation frameworks, but with a more enriched and meaningful level of detail on the individual agent side.

The mentioned flexibility is achieved by the dynamic adaptation of a simulated situation. For such a MABS it is irrelevant how complex a simulation is, as long as the agents are able to couple themselves and interact with the given environment model that effects basically the overall complexity of a simulation. For example, a traffic simulation can have up to hundreds, thousands as well as 100000s of simulated cars. As additional degree of freedom the agents can be provided with a higher level of rationality or the ability to learn, which can change their reactions to occurring situations.

Introductions, descriptions and exemplary scenarios for Multi-Agent based simulation like the one described above, can be found, e. g., in [4], [5], [6], [8] and [8].

The foundation of each MABS is the modeling and abstraction of the real world scenario, which is basically the definition of a comprehensive environment model and of the agents that are situated in this environment.

In general, the implementation of a MABS can be very difficult, costly and time consuming. This basically depends on the question of how “real”, detailed or valid a simulation has to be and what kind of investigations will be performed with it. In order to give an illustration here, one could imagine an escape scenario of a cruise ship, where the ship, as environment, has to be modeled as well as the persons (agents) trying to escape. Particularly the physical aspects of movements on the virtual ship already have to be modeled with a high individuality of the simulated human beings (e. g. for children or elderly people).

The effort for implementing an agent-based simulation from the scratch can be seen as very complex and time consuming. As we described that already in [9] we refer here to our former description.

III. RELATED WORK

In this section we will concentrate on some aspects of the ongoing work in the area of smart grids or smart energy networks respectively. Herein we will consider aspects of simulations of smart energy networks and their topological representation. Furthermore we turn over to purely agent-based tools used in smart grids for different cases.

Technical simulations of energy networks are very common. They are used for short and middle term planning and dispatching as well as for long term studies and investment assessments. A full description and an in-depth survey of those software tools available here, would be however beyond the scope of this paper, since the list ranges from very general simulation toolkits like MATLAB and Simulink[1] to highly specialized and proprietary software tools.

In comparison to these standard software packages the introduction of agents and Multi-Agent systems in the energy domain is however relatively new. In recent years different approaches and efforts can be observed on the economic side as for example through the modeling and simulation of electricity markets [10], [11].

On the other hand side, inspired through the need of reliable coordination mechanisms that involve the expected high number of small, uncertain and more diversified energy producers, like photovoltaic, wind energy, electric vehicles or Mini CHP, much effort was spend to develop solutions for a more intelligent electrical power supply system that is commonly called Smart Grid. Here authors adapted ideas that are originally

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[1] http://www.mathworks.com/products/simulink/

originated from the area of distributed artificial intelligence (DAI) or MAS, as for example the ability of intelligent network components or participants to self-monitor, -diagnose, -organize, -configure or even -heal themselves in order to achieve a flexible, safe and reliable operation of the energy supply [12], [13], [14].

As mentioned above, the main driver for the currently very dynamic development of intelligent energy networks is the area of smart grids. Here a significant number of publications with different visions, proofs and small scale applications for distributed supply and demand side management have been presented and have shown the abilities of agents to support partly different ideas for Smart Grids. Examples can be found in micro grid control, electric vehicles, storage management, intelligent households and other [15], [16], 17], [18]. Here the common approach is to model the underlying (electrical) network topology as graph *G(V,E)*, where the vertices are representing single components or agents, as for example a power plant or a transformer. The connections between these components are modeled as edges, which corresponds generally to the three-phase wiring in power supply systems.

In this sense, the application of agents in district heating is also quite common and known as one point that has to be integrated in a Smart Grid; e. g. due Combined Heat and Power (CHP). Here slightly different approaches can be found for the modeling as MAS. That is on one hand side to model a CHP-plant as single entity that is part of the electrical network, while connections to heat customers are topologically neglected. A more detailed modeling was presented by Wernstedt [19], who concentrated on district heating systems, consisting of a holonic structure of different agents, like producer, redistributors and consumer agents, but without an integration of electrical networks. The underlying network and agent model is quite similar and applicable for electrical and heat networks, but it is not for the natural gas case, which we will describe in the following.

Compared to the efforts in the smart grids area, the number of research activities and publication that connect the potential abilities of intelligent agents with the transportation of natural gas is extremely rare. Only Pelletier et al [20] published in 2005 an agent-based approach for a gas market - scenario, where it was more generally described on how to model the underlying network topology of gas transportation systems and the involved market participants as MAS. Results, further improvements or publications on this interesting work could unfortunately not be found. The common topological model for gas networks in literature is also described as Graph *G(V,E)* consisting on vertices and edges. But differently to the graph model for electrical and heat transmission, edges representing the active or passive components, like compressor stations, vents, control valves and so on. Vertices are used to connect two or more components (edges) to each other or describing entries or exits of a gas transmission system [21], [22].

Multi-agent based simulations were used in many publications in order to show the applicability of agents for special tasks in the operation of smart grids as for example in [23], [24] and [25]. Here the compliance to the IEEE standard on the Foundation for Physical Agents (FIPA[2]) is often called in order to choose an appropriated agent platform. Such standardization allows interoperability over different agent platforms, by using the FIPA's Agent Communication Language (ACL). Taking into account the, in our view, justifiable demand for a standardized agent platform, then the number of freely available and supported agent platforms is low and reduces to two alternatives. Those are the agent platforms JADE[3] and ZEUS[4]. These platforms were extensively studied in many publications so that we refer to the work of Pipattanasomporn et al [23], who follows the same argumentation of standardization and who provide references for further reading. In contrast to that work, however, we already had chosen JADE extended by Agent.GUI as our agent platform and end user application, which we have described in parts in our previous publication [9].

A different approach for hardware-related simulations was discussed and described in [26]. Here the need of new simulation and testing tools that are applicable for the real time requirements of the future energy system were underlined and discussed. In contrast to those requirements, we would like to make clear, that we see our approach first of all more related to planning processes, which are in our opinion not subject of such real-time requirements. However, we see in this time difference, among others, an open and challenging research question, because it will determine how fast an energy network can be reconfigured.

To conclude this section we would like to point out that there are more open questions than solutions in the ongoing research and the current transformation of our energy supply. Comparing the types of energy networks to each other shows that there is a gap in the activities and the technical directions; in particular in the inclusion of agent technologies for natural gas transportation and district heat. With the expected higher interaction of these networks and a technology shift to a (more) decentralized or agent-driven energy supply, these must be included in the further developments.

Searching for a purely agent-based simulation toolkit, that provides compliance with the FIPA standards, shows that there is no ready and sophisticated tool available yet. However, on the other hand, it is quite obvious that the demands on new energy grids require sophisticated and extensive simulation studies in order to get a better understanding on how a future energy network may look like, not only on the physical level but also on the business level. The physical grid will look completely different due to the necessary two-way communication and due to the huge number of energy producers instead of the comparatively few large energy plants of today.

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[2] http://www.fipa.org

[3] http://jade.tilab.com/

[4] http://sourceforge.net/projects/zeusagent/

Business plans will be mainly driven by specific local needs and conditions, not least due to the less predictable behavior of some sustainable energy production systems. On the other hand, there is doubt that an energy system which will not be 100% reliable will end in a catastrophe for mankind which means that simulation studies need to be highly realistic and expressive. This, among others, will also mean that agent-based simulation studies may have to be able to manage 6 digit numbers of agents that interact with each other in a decentralized and intensive way.

In order to meet these challenges, we came to the conclusion that a complete new development of an agent framework and an agent-based simulation toolkit from scratch is not feasible. Instead we decided to extend JADE in several ways. Firstly, it is much more scalable and, thus, can deal with and manage very large agent communities. Secondly, a huge number of specific functionality for the simulation of energy girds has been integrated, which allows the expert to not only use Agent.GUI for the simulation of physical features and characteristics of energy networks but also for the simulation of its economic aspects and business models.

IV. AGENT.GUI: TOOL AND FRAMWEWORK

Agent.GUI[5] is a framework that extends the well known and widely used JADE agent platform. It provides thus the functionalities of JADE as well as additional features that allow a simplified execution of large scale MABS. Hereby Agent.GUI addresses the utilization of MAS and MABS for end users that are not involved in the paradigms of the agent technology. For this the framework provides a predefined graphical user interface (GUI), where users can configure and work on different environments and agent setups within so called agent projects. Up to now Agent.GUI provides two predefined environment models that can be used for simulation. One of these, the Graph or Network environment model, can be used for simulations of energy networks and will be introduced in the next section.

For the distributed execution of a Multi-Agent system Agent.GUI provides a background system that can be used in grids or in cloud computing; it supports the extension and balancing of a MAS platform over different machines in an automated manner. Various interfaces and a Plug-In mechanism allow the customization of the Agent.GUI end user application by developers. This can for example be used in order to integrate a new individual environment model or in order to customize the end user application. Additionally, external libraries can be added to the application during runtime. Agent.GUI was already introduced by us in [9].

V. MODELING ENERGY NETWORKS AS MAS

As implied in the related work section we believe that the simulation of intelligent energy networks needs to consider the different pure technical aspects as well as possible market mechanisms and rules. In a first step this leads to the necessity to deal with the physical properties of electrical networks, natural gas transmission systems and heat transfer. All these topics were extensively studied in there ancestral domains and have their inherent computational complexity, where the number of required physical parameters strongly differs depending on the domain. But consequently, the available knowledge, bundled into the appropriate formula and calculation methods, have either to be re-implemented or be used by appropriated libraries. We will come back to this point in the discussion of our future work, but we keep in mind that in every case a set of physical parameters is required.

Nevertheless, from the perspective of computer science everything has to start with the description of the physical network as graph, in which the intelligent components are embedded and where the overall network, in turn, builds the environment of a single network component. Depending on the domain we took the following considerations into account:

A. Electricity and District Heat

As described in the related work part, these two kinds of networks can be modeled as graph consisting of vertices and edges, while vertices are representing the active components. But it has to be considered that one single component, like a transformer, can be connected to several other components of the network. Additionally these connections can depend on different domains, as for example in the case of a CHP-plant, where gas is used for the generation of electrical power and heat. These observations result to a general modeling approach, where every vertex and every edge must be defined individually. Additionally, it has to be noted that a single connection has to transport detailed information about their current conditions. That is for example for the cabling between components, the phase voltages and the phase currents. In order to deal with such information, we have decided to generally integrate ontologies here, which allow a flexible handling of individual data models and different conditions.

B. Natural Gas

Natural gas is basically a multi-fuel mixture, which consists largely on methane, but it differs in the further chemical composition. The usage of different kinds of gas qualities, like for example with biogas, makes a detailed observation and a tracking of gas qualities indispensable, even in a simulation. For this we see the connections between components as uncritical as long that there are not more than two components involved. However, when branches are added, these branches have to be considered and modeled as a single component, by means single sub graphs. This has to be done in order to calculate or monitor resulting gas qualities at every entry or exit of a component.

Another important aspect is the question of predefined directions for edges. Starting from a stateless situation in the network, leads normally to undirected edges. This corresponds to the initial situation for pipelines and vents but not for the

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[5] http://www.agentgui.org

case of compressors, since they are usually built to work only in one direction. This generally requires two different kinds of edges, a directed and an undirected one.

From the above considerations the question remains, which of these graph components is now an agent, if this is not obvious, as for example for intelligent households, a compressor or a power plant? Does it make sense to model a pipe or a cable as an agent even if they are not representing really active or intelligent components?

We think so, because as soon as a component or device has to be observed in terms of reliability or compliance to constraints, tasks occur that should be also delegated to an agent, even if the tasks are simple. For a pipe this could be for example an independent monitoring for leaks.

To conclude this for simulations of intelligent energy networks, this result to a Multi-Agent system or environment model, which fully consists of agents, which is graph theoretically represented through a set of sub graphs and that is ontologically enriched with domain specific information. For this we see a formal description as follows:

Let $M = \{A, D, G, P, C, E\}$ be a Multi-Agent system where:

- $A=\{a_1,a_2, ...,a_i\}$ represents the set of agents that are equals to (partly) intelligent component in an energy network. The behaviors of the agents can so far not be formalized, because this will depend on the associated tasks and their implementation.
- $D=\{d_1,d_2, ...,d_i\}$ describes the domain in which an agent is embedded
- $G=\{g_1, g_2, ...,g_i\}$ is a set of sub graphs $g_i=a_i=(V,E)$ consisting on vertices and edges, which, taken together, define the total graph G. As constraint, in these sub graphs, at least one single vertex has to be included.
- $P=\{p_1,p_2,...p_3\}$ describes the set physical properties and constraints that have to be used for a single component.
- $CA=\{C_{1,},C_2,...,C_i\}$ represents a set off groups, collations or cluster that partition the set of sub graphs g_i or agents a_i in cooperating entities. Here we assume that all groups are disjoint, except of the connecting nodes between such clusters.
- $E=\{\varepsilon_1,\varepsilon_2,...,\varepsilon_i\}$ is the production or the consumption of energy or its equivalent over time, that will be produced or consumed by the agents a_i.

Since we present our integrated approach within our framework, we now shortly describe, the usage of Agent.GUI, in order to define and execute an energy network as MAS.

As earlier mentioned, the graph or network environment model is one of two predefined environment models, which can be chosen, within the applications project window. In order to define an energy network one needs to declare all involved domain types first, such as electricity, gas or district heat. It follows the definition of components that are to be specified by its name, their domain membership, the type of agent to be used and a graph prototype that defines the appearance of the component in the representation of the total graph. Further configurations can be done for ontology usage, imaging, coloring and other.

The most obvious and important graph prototypes are predefined and already integrated in our framework in order to assign a graph representation to a network component. Those are for example prototypes like a simple vertex, an undirected or a directed edge, as well as more complex elements like stars and rings. Additionally, these prototypes can be supplemented with own creations of graph prototypes.

While adding or removing a component to a model, the corresponding list of agents will be maintained automatically in order to define the agents that are to be started for a single simulation setup. In order to provide these agents with the needed initial information for their current state or with statistical information of energy usage, agents can be configured with different types of start arguments; these are in fact the start arguments for agents that are provided by JADE. Here Agent.GUI offers however a graphical user interfaces in order to configure the initial state of agents in the simulation setup by using specifiable classes out of ontologies. As example: A predefined base-ontology that comes with the framework allows configuring time series for energy consumption or xy-plots for characteristic compressor fields. Furthermore, by using a reflective access, Agent.GUI allows the usage of customized ontologies, which thus can be integrated as complex data model of simulated domain.

As conclusion, Figure 1. shows a simple example on how an agent-based simulation of a smart energy network with Agent.GUI can look like.

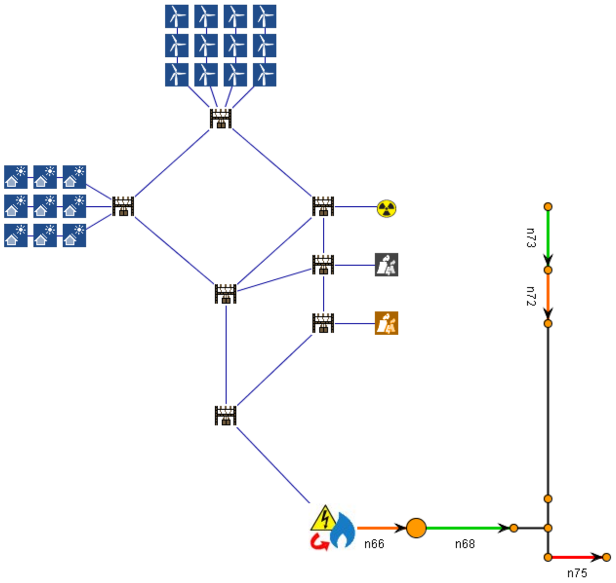

Fig. 1. Example for a hybrid energy network, modeled with Agent.GUI. It contains wind turbines, photovoltaic's, different plants (nuclear and coal), transformers, a Power-to-Gas unit in the bottom center and a simple gas network on the right side with entries, exits and one single compressor.

VI. DISCUSSION AND FUTURE WORK

The introduced modeling approach is the initial starting point of our own deepening in this challenging research area as well as the starting point for the further developments of the Agent.GUI framework and toolkit. Now, the integration of intelligent components (or agents) will be forced, where further open research questions are expected that has to be answered. The types of questions for simulations are very similar to the questions in the ongoing research for real Smart Grids, as for example in the question of re-implementing known calculation methods or not.

In our opinion this depends strongly on the ways in which energy networks are operated in the future. Here different ideas exist ranging from centralized controlled systems, over decentralized hierarchically systems to fully decentralized structures. Consequently, each of these types needs a different kind of sophistication for the involved agents. That corresponds to the communication between them, the used communication protocols, the self-awareness and the possible planning and collaboration strategies.

For a further centralized operation of energy networks, a re-implementation of calculation methods is simply not necessary, because the proven software tools can still be used or developed. This is changing as soon as a decentralized operation will be applied. Then calculation methods as for example the determination of gas parameters should be, somehow, possible on site, since the corresponding agent should be able to use such methods for its monitoring or its planning process. Then also questions occur with respect to emergence and trust, which will be essential for a decentralized organization of our future energy supply.

In addition, another interesting question is how future energy market will be organized and what rules have to be applied. Will the customer be able, for example, to change the electricity suppliers hourly or just for the single usage of their washing machine?

For these and all further questions, we consider the agent-based simulation as the most appropriate tool, because it allows us to iteratively learn and add intelligence to our energy networks, but without disturbing its current operation. Here MABS gives us the chance to reconstruct the complexity of the real world.

VII. CONCLUSION

In this article we introduced our framework Agent.GUI as a tool for Multi-Agent based simulations and have discussed its applicability to the current developments of future energy networks. For this, we have shown our approach to reflect and model components of hybrid energy networks as a Multi-Agent system. Furthermore we have shown how individual ontologies can be applied in order to enrich a component or the overall graph with the needed data models and physical parameters. After this we introduced the formal model of the resulting Multi-Agent system and have described the degree of freedom that our framework provides in order to translate a network model into an agent system and its necessary environment model.

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