Report from Dagstuhl Seminar 14181

Multi-agent Systems and their Role in Future Energy Grids

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14181 “Multi-agent systems and their role in future energy grids”. A number of recent events (e. g. Fukushima, Japan, and the largest blackout in history, India) have once again increased global attention on climate change and resource depletion. The evaluation of the feasibility of current approaches for future energy generation, distribution, transportation, and consumption has become an important requirement for most countries. There is a general consensus on the need for a fundamental transformation of future energy grids. The development of an information and communication technology (ICT) support infrastructure was identified as the key challenge in the design of an end-to-end smart grid. A multiagent system, with agents located at the edges and nodes of the grid and representing the interests of end-users, distributors, and providers, enables intelligent decisions to be made at each node in the electric power distribution network (grid). The seminar fostered discussions among experts from all relevant disciplines is to develop the foundation for the necessary interdisciplinary solution from engineering, computer science, and business management. The outcome was an understanding and identification of the requirements on the information systems for future smart grids.

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1 Executive Summary

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Due to the depletion of scarce resources for energy production and the problems associated with climate change, there is widespread interest in new approaches formanaging energy generation, distribution, transportation, and consumption. Overall we must find a way

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to combine the economics, physics, physical components, and governmental policies and regulations of energy systems, while satisfying the personal preferences of consumers. The goal is to create a global Smart Grid.

The main differences between the current and the envisioned future grid are the production ecosystem on one hand and the information exchange on the other. Current grids traditionally rely on a comparatively stable number of large power plants that produce a constant and predictable amount of power, as well as on smaller power plants that can be activated quickly if demand requires it. Power and information flow from the supply side to the demand side. This is reflected in the underlying business models, which are mainly dictated by the prices the few big producers can achieve on the global market and by the costs for transmitting the power through a distribution system usually owned by private companies. This will change as more and more renewable and distributed generation technologies spread to a household level.

The distinction between producer and consumer will become increasingly blurred as the flow of power as well as information among the resultant *prosumers* becomes bi-directional. The current grid operates at a high-voltage level suited for long distance delivery, while a prosumer-based network will be a more localized and low-voltage grid. Further, the increasing use of renewable sources will result in a less predictable generation pattern, a matter which in itself is raising a number of interesting challenges. In short, the new power grids will differ in magnitude and direction as well as in generation consistency, which will require a complete revision of the underlying business model as the currently predominant global (or, at least, national) market will be replaced by a number of local markets that will have to maintain the balance between supply and (individually generated) demand, i. e., market places for power generation as well as power consumption.

The development of an information and communication technology (ICT) support infrastructure will be the key challenge in the design of an end-to-end smart grid framework. This will require the capability to balance supply and demand and to handle complex operations. The efficient, real-time exchange of information and the coordinated decisions among many stake holders (consumers, distributors, transporters, and generators) have to be supported. This is not possible within the structure and practice of the current grid. Different levels of the grid (layout, control, ICT infrastructure, maintenance, failure handling, and business models), as well as the communication and cooperation among these levels, needs to be fully coordinated with all the other levels. To predict the emergent properties of the system under a range of different conditions and worst-case scenarios, extensive and effective simulation tools will be required. A solution to this large and very complex problem requires intelligent decisions to be made at each node in the electric power distribution network (grid), especially at the edges. To be manageable, the decisions must take advantage of locality constraints and end-user preferences. A multiagent system, with agents located at the edges and nodes of the grid and representing the interests of end-users, distributors, and providers, satisfies these requirements. It is thus the default system solution thatwas considered first and adopted at the Dagstuhl.

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3 Overview of Seminar Talks

The seminar featured an introductory talk by Fabrice Saffre, who outlined the issues in Demand-Side Management and contrasted them with the Demand-Response approach.

3.1 Demand-Side Management (DSM)

Fabrice Saffre (BT Research and Innovation – Ipswitch, UK)

The need for DSM arises as soon as:

1. The ratio between the supply of and demand for a resource fluctuates over time
2. The resource cannot be (efficiently) stockpiled for future use

We can find inspiration from biology based on the Lotka-Volterra predator-prey model, demonstrating how fluctuations between supply and demand are inevitable, but still must be controlled. The current approach to such control is the centrally orchestrated Demand Response model, favored by the power generation and distribution industry.

In contrast, DSM implies distributed choreography. It tries to shape the demand profile by providing incentives to consumers to time-shift their flexible loads away from periods during which resources are scarce. There are two problems with this:

1. It relies on the fiction that the average human is a rational being capable of identifying an optimal strategy
2. It disregards the "inconvenience cost" of doing things at unusual times

A solution to these problems is to employ intelligent agents to represent consumers, resulting in a multiagent system for control. Unlike humans, software agents can be built to specification, to predictably and reliably follow a set of algorithmic rules, and to not suffer the inconvenience of having a circadian rhythm. Putting agents in control of scheduling flexible loads (within the limits fixed by the owner) bears the promise of realising many more opportunities for DSM. The challenge is to define a set of rules that, when applied autonomously by each agent (based on information gathered through direct or indirect interaction with other agents), leads to the collective behavior of the entire population improving the match between supply and aggregated demand.

We postulate that game theory might not be the most suitable paradigm or source of inspiration. Moreover, market-based mechanisms, arguably game theory's most successful offsprings/relatives/application, might not offer the best solution either. Competition between selfish rational entities with unrestricted access to global, transparent information not only requires complex reasoning (with the associated risk of delays and computational overhead), it can lead to chronic inefficiency. This is because the social optimum often differs from the Nash equilibrium. We conclude that

1. Demand-Side Management could lead to massive waste reduction through better utilization of transient resources
2. A successful, widely applicable DSM solution could hold the key to "sustainability without austerity"
3. It is often assumed that DSM always means flattening the load profile, i. e., "shaving the peaks, filling the troughs"

4. Although it remains true in some cases (e. g., for bandwith), it is no longer necessarily so, especially in the energy sector where intermittent renewable sources (solar, wind, . . .) introduce variation on the supply side
5. Robust methods for incorporating dynamic targets and constraints on flexibility into DSM would be extremely valuable

3.2 Multiagent Systems Enabling the Smart Grid

Michael N. Huhns (University of South Carolina – Columbia, SC, US)

Energy allocation and distribution is a societal problem, which involves the management of scarce resources. Solving it requires a socio-technical system. The design of the system depends on verifying the following two hypotheses: (1) Participation: A sufficient number of people in a society can be motivated to participate either directly or indirectly via their intelligent software agents in the management of an essential and limited resource (electric power); (2) Stability: A system of interacting agents cooperating and competing for resources on behalf of a community of users will produce a controllable, stable, and prosocial allocation of resources.

Our approach relies on the following premises:

- Premise 1. Current pricing incentives are insufficient, because they are based on a history of past aggregate behavior and have little predictive value.
- Premise 2. The community of consumers exhibits rich social relationships and energy usage dependencies that can be handled better through peer-to-peer interactions rather than through centralized control.

3.3 Smart Grid Projects at University of Passau

Hermann de Meer (Universität Passau, DE)

Demand-Side Management (DSM) has been emerging as an important approach to mitigate volatile renewable power sources or other causes of demand and supply mismatches. We have developed the concepts of GreenSLAs (service level agreement) and GreenSDAs (supply demand agreement) as the basis of DSM schemes within the European projects ALL4Green and DC4Cities. While All4Green has been investigating peak shaving techniques within a demand response setting, DC4Cities has been more focused into following closely renewable energy sources as the pure basis of power supply within the confines of a smart city context. Both projects apply DSM in the context of existing automation frameworks of data centers (DC). DCs are large consumers of power while being relatively flexible in their power consumption profiles. Extensions of current grid operational conditions within the transition into the smart grid paradigm, introduce new dynamics and substantial risk potentials. To deal with such risks in a hybrid and multidisciplinary smart grid setting, has been the focus of the European HYRIM project.

3.4 Multiagent Systems Enabling the Smart Grid

Minjie Zhang (University of Wollongong, AU)

We briefly introduce two completed projects in agent-based modelling and simulation of power grid systems. In the first project, a Multi-Agent System (MAS) was proposed to automatically diagnose faults in a power grid network and to automatically execute emergency controls to prevent catastrophic failures of the network. A three-layer agent-based emergency control model was proposed to adaptively control the power grid system during its daily operations and emergencies, and an agent-based Q-learning approach was also proposed to restore the system automatically from faults and outages.

In the second project, MAS solutions were developed for managing a power distribution system by considering the renewable distributed generators. The proposed approaches employed the decentralized management to control distributed electric components in the distribution system adaptively for dynamically balancing power consumption and supply through using agent- based communication, decision-making, and cooperation. The MAS approaches required no dependency between agents and can be easily extended to any scale through using individual agents as "plug and operate" units.

4 Working Groups

The seminar participants self-organized into four working groups for discussions on physics-based models of energy grids so that they can be controlled, the control of such grids via agents, and the interactions among the agents and the humans and organizations they represent. The four groups were the following:

1. Multiagent systems for future energy grids, including dynamics and stability, robust / adaptive quality of service, self-organization, and emergent behavior
2. The smart grid as a network of networks
3. Market modelling, design, and simulation, including interaction with users, user behavior, and user privacy
4. Efficient scheduling, optimization, and control of energy and resources

4.1 Working Group 1: Multiagent Systems for Future Energy Grids

Wolfgang Renz (HAW – Hamburg, DE)

Joint work of Matthias Bürger, Michael N. Huhns, Christoph Mayer, and Peter Palensky

This working group focused on system dynamics: dynamics and stability, robustness, QoS, adaptivity, self organization and self*, and emergence. The basic question addressed was how to bridge the gap between a micro-model and macro-behavior using an empirical method based on data from sampling a parameter space to produce a roadmap for white-, gray-, and black-box models.

The recommendation is to create a stability testbed for complex energy systems. It would incorporate instability mechanisms in simplistic scenarios, with ideas on how to find them and offering collections of instability candidates. Its software architecture would be scalable and distributed. It would support plug-ins and interfaces among information-based and physics-based agents.

For an example of system dynamics, a households app switches on loads synchronously, thus causing higher prices. Consequently an industrial load switches off, which causes a reduced price. Households would profit from the lower prices at the expense of the industrial entity. This would recur when the industrial load is switched on again.

The identified features of a proposal for applied research are

- A starting situation where aggregation and brokerage are done asynchronously by humans and reaction times are measured in minutes
- A future situation where aggregation and brokerage are automated synchronously and reaction times are measured in seconds
- Example risks involve unstable power, price manipulation, distribution grid bottlenecks, and instabilities
- Objectives are to analyze risks, construct intelligent agents, and develop market rules, products, and demonstrations

4.2 Working Group 2: Network of Networks

Fabrice Saffre (BT Research and Innovation – Ipswitch, UK)

Joint work of Hanno Hildmann, Rainer Unland

We started from the realization that many of the problems encountered when trying to match energy supply and demand, particularly in the face of intermittent, unpredictable, and/or small renewable generating facilities (solar panels, wind turbines, etc.), emerged from the difficulty of untangling the intricate web of interdependencies among increasingly flexible and/or "intelligent" loads (such as the Internet of Things). A centralized method taking into account all constraints and uncertainties to identify an optimal schedule rapidly becomes intractable as the number of prosumers increases. In fact, depending on the level of flexibility in individual loads, the approach can start to break down beyond a mere handful of loads due to combinatorial effects.

From these considerations, we set off to create and test an experimental distributed management framework to try and address these questions. The first step in the chosen approach consists in forming expanding clusters of prosumers whose individual energy consumption/generation patterns are identified as compatible. At this stage, by "compatible" we simply mean that there exists a combined schedule (taking into account any available flexibility) for which the aggregated supply/demand profile is "flatter" for the cluster as a whole than it would be for its individual constituents.

Note that we prefer using the expression "cluster" rather than the more loaded term "coalition," because we deliberately avoid using market-based dynamics or methods inspired from game theory in favor of a simpler "mechanistic" approach in which prospective groups are formed through random aggregation. The newly formed cluster is then created or discarded based on compatibility, and the process is repeated until no more successful pairings are found.

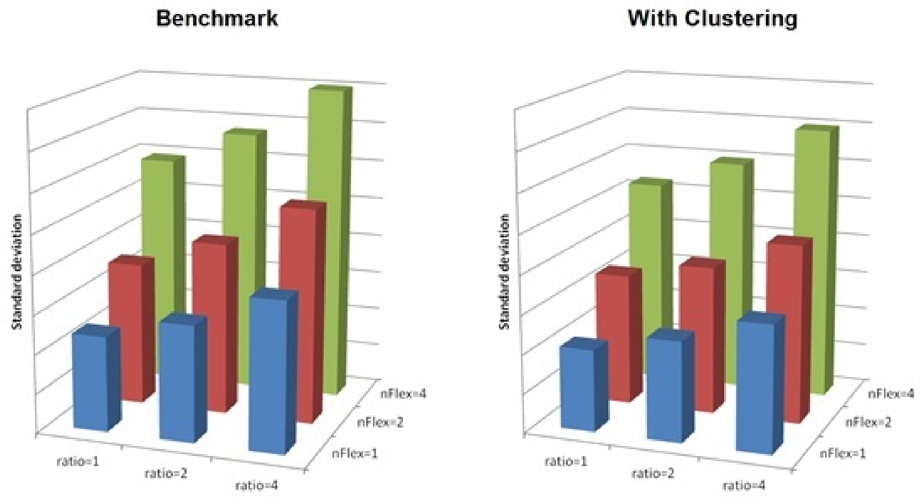


Figure 1 Early results.

Every so-formed cluster is considered a "meta-prosumer" and, in order to prevent a combinatorial explosion, its overall flexibility is restricted to a chosen target by "freezing" the schedule (execution time window) of some of the loads. Early results suggest that this heuristic approach can successfully flatten the aggregated profile (see Figure 1), approximating the optimal schedule at a minute fraction of the computational cost of an exhaustive search.

An additional challenge is found in the necessity to accommodate the limitations of the famously antiquated distribution grid, the topology of which severely constrains the amount of power that can "flow" from one node to another. Indeed, its "hierarchical" tree-like design is intended to provide adequate capacity for electricity to "cascade" from central generation facilities down to the end user, not to allow power generated at one leaf to be channelled to another, as a micro-grid scenario effectively requires.

Future work will involve taking such constraints into account when assessing the compatibility between members of a prospective cluster, as well as using realistically "peaky" 24-hour demand patterns. Both refinements are necessary in order to evaluate the potential of our prosumer clustering method in a practical deployment scenario.

4.3 Working Group 3: Market Modeling, Design, Simulation, and Interaction with Users, Including User Behavior and User Privacy

Gilbert Fridgen (University of Augsburg – Augsburg, DE)

Joint work of Sebastian Lehnhoff, Tobias Linnenberg, Tina Balke, Sonja Klingert, Costin Badica, Micha Kahlen, Michael Kaisers, and Wolfgang Ketter

In investigating markets, the group made the assumptions that there would be a local cooperative behind each feeder, it would work to maximize welfare but with individual constraints, it would have static and exclusive membership, it would operae as the sole trader on behalf of its members, and the agents of its members would behave cooperatively. The group outlined its objectives as

- Use PowerTAC and integrate it with a domain-specific simulator
- Provide high usability (for "normal" human users)
- Create a mixed-initiative system

It will be evaluated on use cases for training, analysis, and design. Its architecture will comprise a platform development / simulator made up of PowerTAC and other frameworks, a learning user interface agent, a preference elicitation tool (for single user preferences, such as "one is on holiday and won't need the energy and may thus provide it to its neighbor, who might need it for an EV"), and a scoping process. It would be useful in industry as training for traders, i. e., suppliers and aggregators, and as a micro-grid for energy cooperatives and local suppliers.

The open research questions are

- How to setup such an energy-cooperative?
  - how to align economic incentives?
  - how to setup a coordination scheme?
  - which communication mechanisms are needed?
- Is there a necessity for an infrastructure change, when we introduce energy cooperatives with agent-based control? (in terms of a "parallel network")
- How to build up agent-based cooperative business models for service-oriented providers? (in relation to getting them started)
- How to design, develop, and apply a decision support tool?

4.4 Working Group 4: Resource Efficient Scheduling, Optimization, and Control

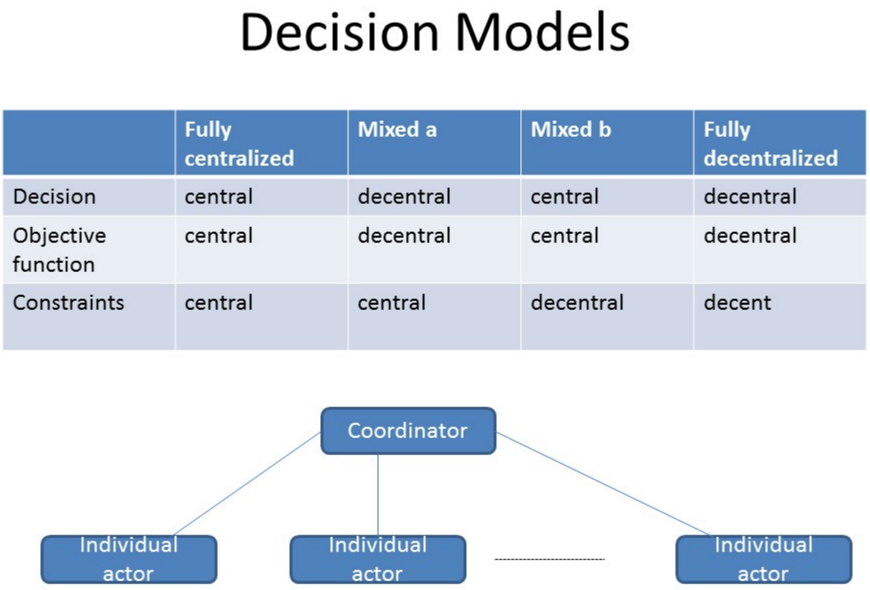
Marjan van den Akker (Utrecht University – Utrecht, NL)

Joint work of Christian Derksen, Ryszard Kowalczyk, Lars Mönch, Konstantina Valogianni, Eric van Heck, and Minjie Zhang

Utilizing resources efficiently requires different kinds of decisions to be made. These are shown in the Figures 2 and 3.

For agent-based distributed hierarchical decision making in future energy micro-grids, the group identified the following research questions:

1. How to balance supply-and-demand at different scales (e. g., planning vs. control)?
2. What are the decision making entities in different schemes? (e. g., local vs. global and makers vs. accountability)
3. What are the decision criteria? Global: cost/efficiency, QoS, CO2 … Local: min cost (energy, depreciation), satisfy needs (supply guarantee), …
4. How to align, via feedback and feed forward loops, capacity creation and utilization?
5. How to support/enable/facilitate the alignment (feedback and dynamic trade-offs/priorities) between the concerns of physical + economical + environmental + convenience/flexibility + regulatory … E.g., different objective functions and different constraints; minimum cost vs. maximum QoS; minimum cost + user flexibility as constraints



Decision Models

	Fully centralized	Mixed a	Mixed b	Fully decentralized
Decision	central	decentral	central	decentral
Objective function	central	decentral	central	decentral
Constraints	central	central	decentral	decent

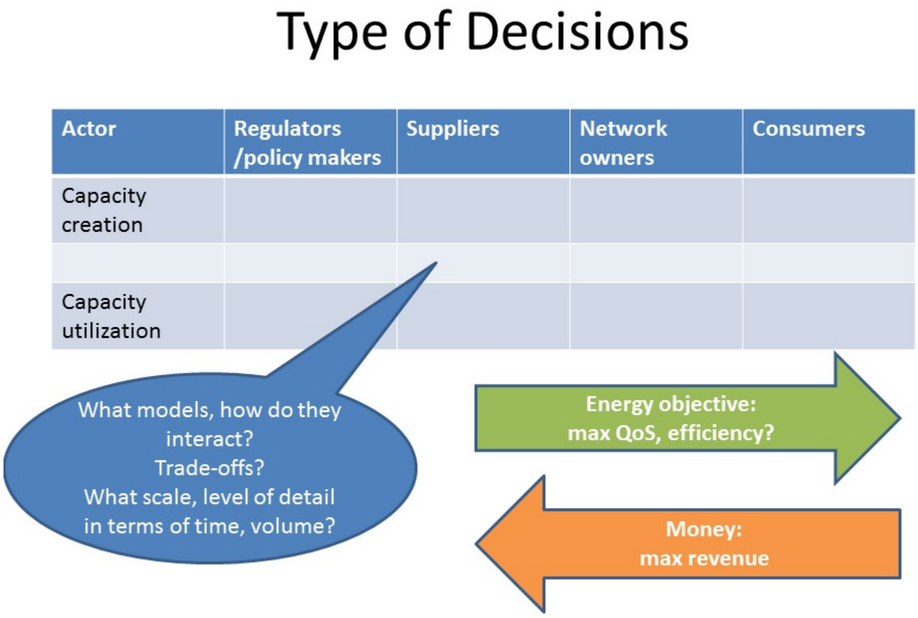
Coordinator

Individual actor

Individual actor

Individual actor

Figure 2 Decision models.



Type of Decisions

Actor	Regulators /policy makers	Suppliers	Network owners	Consumers
Capacity creation				
Capacity utilization				

What models, how do they interact?
Trade-offs?
What scale, level of detail in terms of time, volume?

Energy objective:
max QoS, efficiency?

Money:
max revenue

Figure 3 Type of decisions.

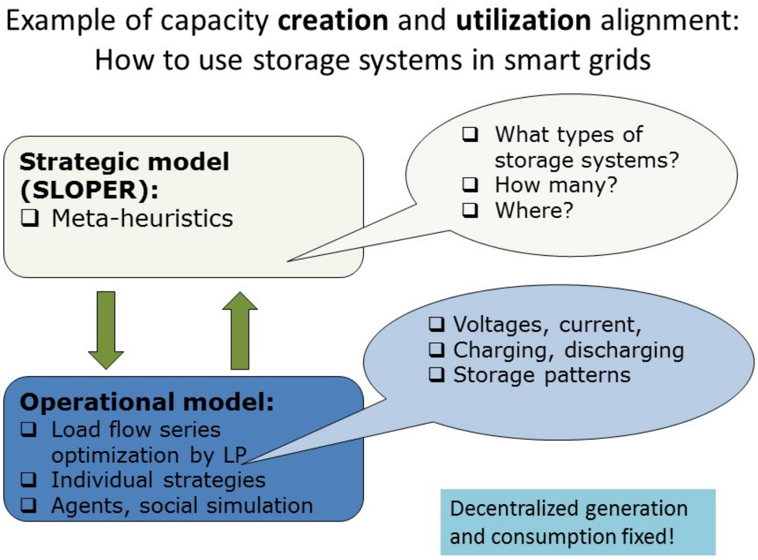


Figure 4 Example of capacity creation and utilization alignment.

The group recommended that the following project-staged approach would be effective. Start simple with a capacity utilization case, then extend with capacity creation, alignment cycle, etc. Specifically,

- DM Modeling (1, 2) (decision roles, decision types) considering different DM schemes (centralized, decentralized, mixed 1, mixed 2)
- Framework design (e. g., modularize/decompose into hierarchy (abstract level/layers/-modules?), decide on scheme for each layer, agent roles, interaction, communication, relationships/organization)
- Mechanism/techniques design (e. g., LP for centralized, auction for broker, meta-heuristics, machine learning, etc.)
- Evaluation (theoretical, experimental, etc.)
- Validation (case study, expert reviews, etc.)
- And then iterate . . .

5 Open Problems

Open problems were described throughout the previous sections, particularly in the working group summaries.

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