Schäuble, J.; Jochem, P.; Fichtner, W. (2016).

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Operations Research Proceedings 2014: Selected Papers of the Annual International Conference of the German Operations Research Society (GOR), RWTH Aachen University, Germany, September 2-5, 2014. Ed.: M. Lübbecke, 545-551, Springer, Cham.

doi:10.1007/978-3-319-28697-6_76

Impacts of Electricity Consumers' Unit Commitment on Low Voltage Networks

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Abstract Todays electricity consumer tend to become small businesses as they invest in their own decentralized electricity generation and stationary electricity storage as well as in information technology (IT) to connect and organize these new devices. Furthermore, the installed IT allows them at least technically to establish local markets. The variety of consumers and their characteristics implies numerous ways of how they optimize their individual unit commitment. This paper aims to analyze the impact of the individual consumers decisions on a future electricity demand and feed-in on low voltage network level. Therefore, in a first step the different unit commitment problems of the different small businesses have been modeled using linear programming (LP). In a second step these consumers are modeled as learning agents of a multi-agent system (MAS). The MAS comprises a local electricity market in which participants negotiate supply relationships. Finally, using scenarios with different input parameters the resulting impact is studied in detail. Amongst others, the simulations' results show major changes in electricity demand and feed-in for scenarios with high market penetration of storages.

1 Introduction

The design of a likewise sustainable, climate-friendly, safe, and efficient energy supply presents both current and future society with great challenges. In order to meet this requirement, the energy sector, driven by political, economical, and social decisions, is changing continuously. This evolution thereby affects all areas of energy supply, namely provision, transport, distribution and demand. Induced by expansion

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of decentralized electricity generation by renewable energy sources (RES), use of storage, new load characteristics such as electric vehicles [1], and market liberalization [2], as well as increased involvement of society on climate protection and market participation [3], the growing number and heterogeneity of actors and elements particularly increase the complexity of the electricity sector.

Apart from the implied problems, these developments offer great potential within a new design of a future power supply: More and more consumers will generate electricity (e.g. by using photovoltaic (PV) systems), and will apply storages [1, 4], therefore becoming in most hours less dependent on centralized conventional power generation. More frequently those electricity producing consumers will be situated in electricity networks which changed from a top-down to a bottom-up cell structure [3]. Moreover they might be organized in local markets [5] with simple access for individual actors using new IT appliances. These local systems offer an incentive to locally balance power supply and consumption, and hence reduce the degree of grid capacity utilization.

To estimate the potential of such a new design of a future power supply system, its elements and their impact on the system must be analyzed in detail. This paper therefore aims to examine individual households and their cost optimized scheduling of power consumption, generation, and storage, as well as the implications for the local system. Therefore, in a first step the different unit commitment problems of the above described households are described and modeled using LP. In a second step they are modeled as learning agents of a MAS although retaining their individual LP. Following a local electricity market in which participants negotiate supply relationships is integrated into the MAS. Finally, using different scenarios with several input parameters the resulting impacts are studied in detail.

2 Scheduling of Consumers' Generation, Demand, and Storage

With an increasing complexity of the households and their options of configuration, the demand for ways to optimize the scheduling of the system elements of the household rises. A connection to the electricity network (EN) and an electricity demand (ED) is thereby assumed for each household and each point in time t. The ED in this paper includes no load shifting potential (e.g. via delayed charging of electric vehicles). This paper focuses on three household configurations. Two of the configurations include an electric generation (EG), here a generation using PV is assumed exemplary. One of these configurations includes an electrical storage (ES). Figure 1 displays nodes and flows from source to sink ($F_{Source,Sink,t}$) in the last-mentioned household configurations. Whereat all nodes can function as sink. Moreover, nodes EN, EG, and ES equally can act as a source. Depending on their configuration the types of households are referred to as ND (Nodes EN and ED), NDG (Nodes EN, ED and EG), and NDGS (Nodes EN, ED, EG and ES).

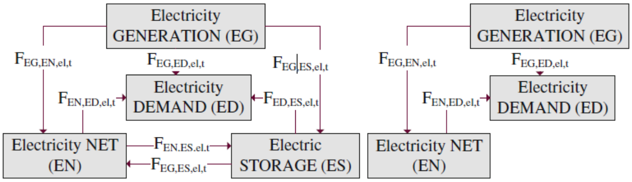

Fig. 1 Nodes and flows of the household configurations NDGS (*left*) and NDG (*right*)

Because households with the configuration NDG have to decide about the amount and the ratio of the feed-in ($F_{EG,EN\ ,t}$) and own consumption ($F_{EG,ED,t}$) for the points in time t ($0 < t \leq T$) with a positive activity level of EG ($X_{EG,t} > 0$) and an positive absolute value ED ($|D_t\ | > 0$) these households are modeled via LP. For the configuration NDGS the ows into the storage ($F_{EG,ES,t}$) from a positive own generation ($X_{EG} > 0$) have to be introduced into the above mentioned ratio. Moreover, decisions have to be taken on the level and the ratio of the feed-in ($F_{ES,EN\ ,t}$) and coverage of ED ($F_{ES,ED,t}$) respectively by the ES in points of times t with a positive state of charge of the ES ($X_{EG,t} > 0$). For the points in time when maximum charge of the ES level is not reached ($X_{ES,t} \leq L_{ES,t}$) additionally the decision on the amount of electricity to store from the EN ($F_{EN,ES,t}$) has to be taken. Table 1 lists relevant parameters and indices for the mathematical formulation of the model.

Objective function of the optimization problem of the household configuration NDG is the minimization of the system costs C_{NDG}

$$\min C_{NDG} \sum_{t \in T} F_{EN,ED,t} * p_t - F_{EG,EN,t} * r_{fi,t} - F_{EG,ED,t} * r_{OC,t} \tag{1}$$

Subject to (selection of constraints)

$$D_t = F_{EG,ED,t} + F_{EN,ED,t}\ , \forall t \in T \tag{2}$$

$$X_{EG * \propto_t * j_t} = F_{EG,ED,t} + F_{EG,EN,t}\ , \forall t \in T \tag{3}$$

(3)

Table 1 Description of selected model variables and parameters

$X_{ES,t}$	State of charge of the ES [kWh]
p_t	Electricity price in t [EUR/kWh]
$r_{fi,t}$	Price for feed-in electricity in t [EUR/kWh]
$r_{oc,t}$	Price for the own consumption in t [EUR/kWh]
D_t	ED of the household in t [kWh]
$\bar{X}_{EG}$	Maximal power of EG [kWp]
α_t	Capacity factor of the EG in t, $\alpha_t \in [0, 1]$
$\bar{L}_{ES,t}$	Storage capacity of the ES [kWh]
$\bar{X}_{ES}$	Maximal power of ES [kWp]
j_t	Length of the time step t [h]

where (2) ensures that the demand D_t is met for each t and (3) takes into account the electricity production of the PV system according to the capacity factor and installed capacity. For the optimization problem of the household conÞguration NDGS the objective function is the minimization of the system costs C_{NDGS}

$$min\ C_{NDGS} = C_{NDG} + \sum_{t \in T} \Big(F_{EN,ES,t} \cdot p_t - \frac{F_{ES,ED,t}}{F_{ES,ED,t} + F_{ES,EN,t}} \cdot F_{EG,ES,t} \cdot r_{fi,t} - \frac{F_{ES,EN,t}}{F_{ES,ED,t} + F_{ES,EN,t}} \cdot F_{EG,ES,t} \cdot r_{oc,t} \Big) \tag{4}$$

Subject to (in addition to constraints (2) and (3))

$$\bar{L}_{ES,t} \geq X_{ES,t-1} + F_{EG,ES,t} + F_{EN,ES,t}, \forall t \in T \tag{5}$$

$$\bar{X}_{ES,t} \cdot j_t \geq F_{ES,ED,t} + F_{ES,EN,t}, \forall t \in T \tag{6}$$

$$F_{ES,ED,t} + F_{ES,EN,t} + X_{ES,t} = F_{EG,ES,t} + F_{EN,ES,t} + X_{ES,t-1}, \forall t \in T \tag{7}$$

where (5) takes into account the maximal amount of energy that can be stored in the ES and (6) the maximal power of the ES. Equation (7) ensures balanced flows to and from the ES. Apart from the costs all variables are subject to the non-negativity constraint.

3 A Local Electricity System Modeled as Multi-agent System

To investigate the effects of the households actions on the local electricity system, the respective households are placed in a MAS as agents. The MAS is formed by the structuring low-voltage network, the agents (households, distribution system operator (DSO), and power supply company), and the environment (geographical and political system and market design). The modeled MAS is then implemented to run simulations with different input parameters.

The low voltage network is modeled in order to map the load flow between consumers and higher-level networks (medium voltage). In the model, the network can thus restrict the load flow and network bottlenecks and capacity requirements can be identified. The low voltage network is composed of the individual line sections (modeled as agents), the connection points of the generating and consuming agents, and their respective connections.

The environment describes the context in which the agents act. With the necessary IT installed agents can (at least technically) take action in a local market. Such a market is introduced into the model and modeled as regional spotmarket in which agents can negotiate their offers for sale or buy. The parameters, design and processes of this market are defined within this context. The environment also determines the geographical context and thereby has an influences on generation and demand of electricity (e.g. insolation and load characteristics).

The agents of the system represent different actors with different objectives (see Sect. 2). The characteristic of the agent population is determined within their context before ($t = 0$) each simulation run. Because no investment decisions are modelled the population of the agents does not change during simulation runtime. However, at each simulation step agents will readjust their decisions based on the newly gained information (e.g. update projections for electricity prices using precedent local spot market prices). Several agents have particular tasks such as the DSO which has to perform load flow calculations and the power supply company which operates as well as dispatches power plants and therefore provides the necessary operating reserve.

The implementation of the described MAS has been performed in Repast Simphony[1] which allows to include the optimization calculations of the respective agents. Anytime a recalibration of the unit commitment problems is necessary during a simulation run a connection to either GAMS[2] or Matlab[3] is established to recalculate the agents individual LP.

4 Input Parameters and Results

In this analysis the simulation runs are limited to one typical day (for reasons of simplicity) and do start with several agent population scenarios (different load characteristics and degree of technology diffusion) as initial points which are based on the energy system of the French island of Guadeloupe. Figure 2 shows the average costs of the power supply company for a typical weekday in October in different scenarios whereat A (08) serves as baseline as it denotes the situation at this day in 2008 without any local market transactions and ES diffusion. A (20,1) denotes a scenario with a low (5 %) and A(20,2) with a high (45 %) diffusion of ES in the house-holds (storage capacity and maximal power depend on household size). B(20,1) and B(20,2) show respective scenarios though with a higher number of household agents

1 Open source, Java-based simulation system, see http://repast.sourceforge.net/ [20.01.2015].
2 Modeling system for mathematical optimization, see http://www.gams.com/ [20.01.2015].
3 Numerical computation system, see http://www.mathworks.com/products/matlab/ [20.01.2015].

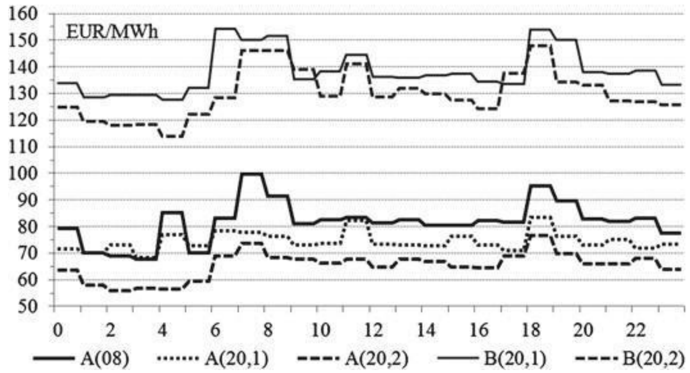

Fig. 2 Average costs of the system's power supply company during a typical weekday day for different scenarios

(which reflects the situation for a corresponding day in 2020) and thus a relatively higher electricity demand and peak load. The baseline A(08) shows price peaks in the morning and evening which are typical for the island. Those peaks are flattened and lowered for A(20,1) as well as A(20,2). For B(20,1) and B(20,2) price fluctuations are higher which is mainly due to the estimated power plant park in 2020 which comprises expensive peak power plants to handle higher demand. The diagramed prices in Fig. 2 demonstrate that, depending on the chosen environment and agent population, local electricity networks with high market penetration of ES and a local electricity market can lead to lower average costs for the power supply companies due to the balanced power consumption and generation. In the case of the island of Guadeloupe this additionally could help to avoid capacity bottlenecks in both grid and production which will most probably occur more frequently as power plant and grid expansion are not proportional to the increase in demand.

5 Conclusion

The applied bottom-up modeling process from individual customer to a local power network allows to integrate a multitude of details, but also reduces complexity where necessary. This made it possible to focus on the modeling of consumer with own PV electricity generation and storage and their actions on a local market. The com-posed multi agent system optimizes an overall cost minimizing objective for the local grid cell although agents do individually optimize their systems. Furthermore, simulations' results show major changes in electricity demand and feed-in for scenarios with high market penetration of storages. Nevertheless, simulation runs with present or pessimistic technology diffusion scenarios (such as A (08) and A(20,1) in Fig. 2) still show a high dependence of consumers and consequently grid cells on a connection to a greater power network to balance consumption and production.

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