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# Decentralized control of units in smart grids for the support of renewable energy supply

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ABSTRACT

Due to the significant environmental impact of power production from fossil fuels and nuclear fission, future energy systems will increasingly rely on distributed and renewable energy sources (RES). The electrical feed-in from photovoltaic (PV) systems and wind energy converters (WEC) varies greatly both over short and long time periods (from minutes to seasons), and (not only) by this effect the supply of electrical power from RES and the demand for electrical power are not per se matching. In addition, with a growing share of generation capacity especially in distribution grids, the top-down paradigm of electricity distribution is gradually replaced by a bottom-up power supply. This altogether leads to new problems regarding the safe and reliable operation of power grids. In order to address these challenges, the notion of Smart Grids has been introduced. The inherent flexibilities, i.e. the set of feasible power schedules, of distributed power units have to be controlled in order to support demand–supply matching as well as stable grid operation. Controllable power units are e.g. combined heat and power plants, power storage systems such as batteries, and flexible power consumers such as heat pumps. By controlling the flexibilities of these units we are particularly able to optimize the local utilization of RES feed-in in a given power grid by integrating both supply and demand management measures with special respect to the electrical infrastructure. In this context, decentralized systems, autonomous agents and the concept of self-organizing systems will become key elements of the ICT based control of power units. In this contribution, we first show how a decentralized load management system for battery charging/discharging of electrical vehicles (EVs) can increase the locally used share of supply from PV systems in a low voltage grid. For a reliable demand side management of large sets of appliances, dynamic clustering of these appliances into uniformly controlled appliance sets is necessary. We introduce a method for self-organized clustering for this purpose and show how control of such clusters can affect load peaks in distribution grids. Subsequently, we give a short overview on how we are going to expand the idea of self-organized clusters of units into creating a virtual control center for dynamic virtual power plants (DVPP) offering products at a power market. For an efficient organization of DVPPs, the flexibilities of units have to be represented in a compact and easy to use manner. We give an introduction how the problem of representing a set of possibly $10^{100}$ feasible schedules can be solved by a machine-learning approach. In summary, this article provides an overall impression how we use agent based control techniques and methods of self-organization to support the further integration of distributed and renewable energy sources into power grids and energy markets.



## Supply–demand-matching considering renewable energy sources

The 2013 IPCC report on climate change (IPCC, 2013) re-assessed expected trends in $CO_2$ concentration in the atmosphere, and alerted again significant effects on the surface and oceans' temperature of the planet. Following these results, it is inevitably necessary to reduce $CO_2$ emissions from human activities, especially from power production. The EU agreed on the goal to reduce domestic greenhouse gas emissions by 40% below the 1990 level by 2030. In order to reach this goal, the EU proposed an objective of increasing the share of renewable energy to at least 27% of the EU's energy consumption by 2030 (EU, 2014). In the year 2012, power production in Germany resulted in about 300 Mt of $CO_2$ emissions (UBA, 2013) particularly from coal fired power plants. Burkhardt et al. (2007) give an overview of specific $CO_2$ emissions (in g/kWh) for different types of power plants including the upstream chain and the end-of-life management. These emissions range from more than 1000 g/kWh $CO_2$ for power from brown coal fired power plants to 10…65 g/kWh for wind turbines. Hence future power supply systems will increasingly rely on distributed and renewable energy sources (RES) to reach the goal of $CO_2$ reduction — particularly if nuclear power is excluded. In 2030, between 50% (BMWi, 2010) and 67% (BMU, 2012) of the gross electricity demand of Germany are expected to be covered by electric feed-in from RES; in 2050, this share is expected to

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grow up to 85% (BMU, 2012). In the course of this politically driven evolution of the energy system, new challenges regarding the successful and sustainable integration of RES both into the power grid and into energy markets have to be addressed: As photovoltaic (PV) systems and wind energy converters (WEC) rely on solar radiation and wind force, respectively, their electrical feed-in may vary greatly and be unforeseen over small time periods (stochastic fluctuation of RES feed-in) as well as seasonal. (Not only) for this reason, the supply of electrical power from RES and the demand for electrical power are not per se matching, that is there are times of high electrical feed-in and low power demand, and vice versa. Even with today's comparatively low share of RES, these situations may yield negative electricity prices at the European Energy Exchange (EEX) (Wissing, 2012) due to the (short-term) surplus of power generation. Regarding the electrical infrastructure, the integration of RES increases the strain on power grid assets (e.g. power transformers) as today's power grids were historically designed for a top-down power transmission and distribution. With a growing share of generation capacity especially in distribution grids, the top-down paradigm is gradually replaced by a bottom-up power supply, leading to new problems regarding a safe and reliable operation of power grids (e.g. voltage control and power grid protection measures).

In order to address these challenges, the notion of Smart Grids has been introduced. The EU Commission Task Force for Smart Grids defines Smart Grids as "electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety" (EU ETP, 2010, p. 6). Integrating the behavior of a large set of distributed units, i.e. generators, power storage systems (e.g. batteries), and some types of power consumers is thus a key element of Smart Grids and a prerequisite for an optimized utilization of renewable energy supply. Taking the outlined challenges into account, our research goal is to optimize the (local) utilization of RES feed-in in a given power grid by intelligently integrating both supply and demand management measures with special respect to the electrical infrastructure. The main question regarding system design concerns the coordination concept of (distributed) power units: the possibilities range from centralized control systems, which gather and process all information in a central component, up to completely distributed systems, which solely rely on the self-organized interaction of local components (Negenborn, 2010). Due to the large amount of units, decentralized control, autonomous agents and the concept of self-organizing systems will become key elements in order to intelligently use the inherent flexibilities of distributed controllable generators, power storage systems and controllable power consumers.

In this article, we give examples of three different control methods for distributed units in a power grid. They illustrate in an increasing order different levels of decentralization. Thus, in the *Increasing local utilization of supply from PV systems using batteries of EVs* section of this article we show how a distributed load management system for battery charging/discharging of electrical vehicles (EVs) can increase the locally used share of supply from PV systems in a low voltage grid. Additionally, this load shifting method allows reducing the average load at the local transformer station significantly. The control strategy is decentralized insofar, as a scheduler of flexible units (batteries) in its low-voltage grid is provided at any grid connection point of low-voltage grids to medium-voltage grids.

Integration of large sets of small appliances into load management raises questions of predictable behavior of these devices as well as scaling problems for control algorithms. For a reliable demand side management of large sets of appliances clustering is necessary. In the *Self-organized clustering of small appliances for load balancing* section, we outline a self-organizing method of clustering appliances into so called virtual appliances. Although a scheduler for flexible loads is provided again at a grid connection point, scheduled units are clustered by a completely decentralized method.

The *Market-oriented dynamic virtual power plants* section of this article gives a short overview on how we are going to expand self-organized clusters of power units to a virtual control center for dynamic virtual power plants (dynamic VPPs) offering a product at an energy market. This virtual control center includes distributed methods for schedule optimization as well as rescheduling of units. Thus, we achieve an extensively decentralized control system for distributed units well beyond the control methods presented in the former sections.

A compact and efficiently manageable representation of flexibilities of units – sets of all operable schedules within a time frame – is a rather complex core problem of organizing VPPs. We will give an overview of an approach to represent flexibilities of units by support-vector decoders in the *Representation of large sets of feasible schedules* section. A shorter and lighter version of this article has been published in Sonnenschein et al. (2013).

## Increasing local utilization of supply from PV systems using batteries of EVs

In this section we show how a (central) control method for smart charging of electric vehicles (EVs) can increase the local usage of PV supply in a low voltage (LV) power grid. In this context, locality refers to the LV grid and its connection points for PV systems, households and EVs. Additionally, we show that grid constraints – i.e. the strain on local grid assets such as power transformers – can implicitly be taken into account by such a control method. As we already gave a thorough discussion of the control method and its implementation in Tröschel et al. (2011), we focus on the results of a simulation study.

A major challenge regarding smart charging of EVs is simultaneity. Consider the following thought experiment: In a small urban low-voltage (LV) grid comprising 70 (high-income) households, 20 battery electric vehicles (EVs) are located. The local power transformer has been laid-out for a maximum load of 200 kVA, which is quite comfortable regarding the households' yearly peak load of about 120 kW. Each EV has a maximum storage capacity of 30 kWh and a maximum charging power of 10 kW. The EVs are mostly used for commuting, that is on work-day evenings they are all returned more or less at the same time to their charging station. Uncontrolled charging – starting to charge an EV's battery as soon as it is connected to the charging station – can then result in a massive strain on the local power infrastructure: When all 20 EVs charge with high simultaneity, up to 200 kW charging power is needed in addition to the power demand of the 70 households. The resulting thermal strain of the transformer (designed for a load of max. 200 kVA) may lead to an increased aging or even damaging of this expensive asset.

With this worst-case scenario in mind, we developed a smart charging algorithm with two major design goals: 1) reduce the simultaneity of the charging process, and 2) maximize the local utilization of electric feed-in from PV systems. Thus, not only the strain on power grid assets should be reduced, but the EVs should also be charged with as much renewable energy as possible. The basic idea is as follows: We introduce a central management server at the substation level, such that the charging process in an LV grid is being managed by a single optimizing instance. As soon as the EV has connected to the charging station, four parameters are transmitted: The expected parking time (provided by the user), the current state of the battery, and a charging goal (e.g. 85%) with some flexibility (e.g. $\pm$15%). Both the charging goal and the flexibility are provided by the EV's user and may be subject to different (typically financial) incentives, e.g. given by the distribution system operator (DSO) in order to allow for a more flexible usage of the EVs' battery systems. The central server's objective is to generate plans in such a way that the sum of all plans approximate a given load curve – either predefined by the DSO in order to keep the LV grid's operation within feasible bounds or, in the case of a supply–demand-matching, a residual load threshold – while each individual plan reaches the charging goal within the parking time available. Thus, the EVs' users'