Supporting Renewable Power Supply through Distributed Coordination of Energy Resources

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Abstract. Renewable Energy Sources (RES) are considered a solution for a sustainable power supply. But integrating these decentralized power sources into the current power grid designed for a centralized power supply is a challenging task. We suggest distributed, agent-based and self-organized control algorithms for distributed units in a "Smart Grid" as a promising but challenging solution. Dynamical Virtual Power Plants (DVPP) are introduced as a first prototype of distributed controlled components of a Smart Grid. Tools and methods for a comprehensive evaluation of such new Smart Grid control methods in terms of technological indicators as well as sustainability indicators will be the next challenge in research and development for computer scientists in this domain.

Keywords: Renewable Energy, Distributed Control, Multi-Agent Systems, Virtual Power Plants

1 Motivation and Introduction

Since the work of Schellnhuber [1], research on the integration of renewable energy resources in power systems has proceeded from a sustainability perspective with the goal of reducing the usage of fossil energy resources. This goal refers mainly to environmental sustainability with both global and regional aspects along the whole chain of primary energy resource extraction (land-use and mining devastation, toxification due to mining processes) and energy usage (local pollution, greenhouse gas emissions). A transition path towards a reliable and sustainable future energy grid based on a significant share of decentralized renewable energy resources was defined in [2].

According to the 2013 IPCC report on climate change [3], it is absolutely necessary to reduce CO_2 emissions from all human activities to avoid global warming at a level that entails uncontrollable environmental impacts. A significant share of global CO_2 emissions can be explained by the combustion of fossil fuels for

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power production. Hence, it has become politically widely accepted in Europe, to reduce national shares of fossil fuels in power production significantly: The EU aims to generate 20% of its energy from renewable energy sources (RES) by 2020. In 2050, this share is meant to increase to 85% for the German electricity supply [4]. Such a politically driven evolution of the power system faces not only economical and societal challenges, but it must also address several technological challenges of ensuring a highly reliable power supply [5]:

- The fluctuating supply from such RES as photovoltaic systems or wind energy converters must be matched to the demand at all times. This requires rapidly controllable power plants such as gas turbines, storage systems, and demand side management.
- Power supply from RES is distributed in the grid; the power flow from large power plants on high voltage levels to consumers on low voltage levels, its current configuration, might become inverted. The grid infrastructure must be adapted to this new operational mode.
- To integrate a large set of small, rather unreliable power plants into the market, new market structures and new business models are needed.
- Distributed power plants, controllable loads and storage systems must also provide so-called ancillary services to contribute to voltage control and frequency control in the power grid.

1.1 Smart Grids

In order to address these challenges, new concepts for power grid operation – especially for the distribution grid – are needed; the notion of “Smart Grids” has been introduced for this purpose. The European Technology Platform (ETP) defines 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” [6]. An overall architecture of a Smart Grid is provided by the European version of the SGAM [7] – originally introduced by the NIST in 2009 – as a reference design (see Fig. 1) highlighting interoperability aspects. On the domain dimension in the SGAM, the energy conversion chain from bulk generation down to the customer premises is depicted, integrating the domain of distributed energy resources (DER) on the distribution level. The management systems for each level form the second dimension, emphasizing the different hardware, IT systems and actors involved from market down to field and process zone. The plane formed by these dimensions is combined with the different abstraction levels from the business level to the communication and component layer as an interoperability dimension. Information security in Smart Grids is an important part of the reference architecture [8], but it is a complicated topic of the subject of ongoing research. A state of the art overview of this topic can be found in [9].

Throughout this contribution we focus on the *function layer in the operation zone* of the SGAM, discussing *services to integrate Distributed Energy Resources (DER) into the power system.* The function layer is based on an information layer

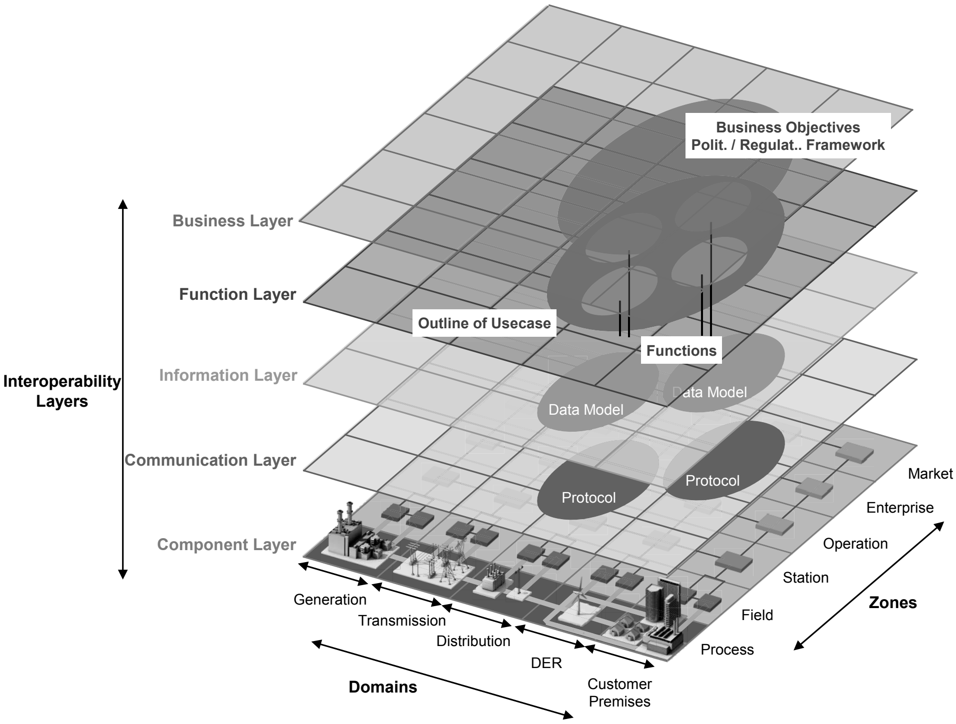

Fig. 1. Smart Grid Architectural Model (SGAM), Source: [7]

and a communication layer offering such information models and communication services as the CIM (Common Information Model) and the IEC61850 standard.

In the operation zone are located for example energy management systems, micro-grid management systems, electrical vehicle charging systems, and virtual power plants. From an ICT perspective, these services to integrate DER and RES into the power grid face several challenges [10]:

- Scalability: Integrate a huge amount of distributed power producers and consumers.
- Aggregation: Support aggregation forms such as virtual power plants.
- Restructuring: Allow transparent integration, segregation and substitution of new components in the ICT-based control system.
- Real time: Guarantee reaction within given time boundaries when using distributed components for system stability issues.
- Robustness: Disseminate critical system functions to redundant and distributed ICT components.

1.2 Virtual Power Plants

One of the most important approaches to efficiently integrate the large amount of DER and RES into the power grid's management system is to aggregate these resources. For this purpose, the concepts of *micro-grids* and *virtual power plants* (VPPs) are convenient. A comparison of both concepts can be found in [11]. Micrograds are physical parts of the power grid that are able to match demand and supply on their own – they can disconnect from the grid if necessary. VPPs were introduced in the late 1990s as a derivation of the *virtual utility* (VU) concept, which is defined as a "[. . .] flexible collaboration of independent, market-driven entities that provide efficient energy service demanded by consumers [. . .]." [12] In addition to this consumer-driven service definition, VPPs may have operational targets such as aggregating energy (commercial VPPs) or delivering system services (technical VPPs) [13]. But unlike microgrids, VPPs are not bound to physical parts of the grid – they are ICT-controlled aggregations of DER acting like large power plants in the market. A number of successful VPP realizations can be found in [14].

However, such VPPs usually focus on the long-term aggregation of generators (and sometimes storages and flexible consumers) only and are each still operated in a centralized manner. For an implementation of automatic restructuring, a more flexible concept is required. In the last years, a significant body of research has emerged on this topic. In this context, autonomous agents and the concept of self-organizing systems are key elements in order to intelligently use the inherent flexibilities of distributed generators, power storage systems and power consumers. For instance, [15] surveys the use of agent-based control methods for power engineering applications. Further exemplary applications can be found in [16–19] (also see the references therein). Finally, a research agenda in this context was proposed recently in [20].

This chapter focuses on the aspect of distributed control of distributed energy resources as an example of how advanced ICT methods can support an efficient, flexible integration of RES into the power grid. In section 2, we give a short introduction to the basics of distributed systems, multi-agent systems, and distributed optimization. The subsequent section introduces a vision of distributed control in power systems. This vision is the framework for our current research in Dynamic Virtual Power Plants (DVPP). In section 4, we discuss challenges in assessing sustainability indicators of such control methods by simulation studies.

2 Modeling of Distributed Systems in Computer Science

After the motivation of distributed control as a promising attempt to integrate RES into the power system, this section introduces the basic concepts of distributed, multi-agent based systems for readers not familiar with.

2.1 Coordination paradigms

The transformation of the electrical power system towards an integration of renewable energy resources requires a system model able to incorporate a huge number of independent and heterogeneous units, e.g. photovoltaic systems, wind energy plants and combined heat and power plants (CHP). Moreover, these system nodes are not reliable. For diverse reasons, these plants can be temporarily unavailable making demands on robustness and reconfiguration of failing or additional components. Modeling, simulation, and control of such complex systems has been a research topic in Computing Science since the advent of concurrent systems. The main question in the system's design concerns the coordination within the system: the possibilities range from centralized 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 [17].

These diverse system designs have different advantages and disadvantages which must be assessed in relation to the application case. Important evaluation criteria are fault tolerance, i.e. the system's fulfillment of its function even in the presence of faults, and performance, i.e. the system's need for resources (incl. time) to execute its task. Beside this, organizational and application-specific aspects have to be considered: in comparing centralized to distributed systems, important issues are whether sensitive information has to be exchanged and whether the organization of the system reflects the organization of the real world system and its needs. Furthermore, in the power grid domain, the geography has to be considered: power is generated at specific geographical locations and has to be transported via the power network. Hence, the locality of power production and consumption and of information processing has to be considered an important quality criterion.

The traditional power supply system can be seen as a *centralized system*: it consists of a small number of controllable power plants. A "control room" acts as a central component that knows the operational constraints of the plants and stipulates the plants' reactions when deviations from the original operating plans occur. The advantage of this organization is that the system's structure is very simple and easy to control. All information is collected at a central component and decisions can be based on complete knowledge about the system. The disadvantage is that all this (mutually sensitive) information has to be communicated, which creates a source of risk. Furthermore, as the system's goal usually is an optimal usage of its units, the search space of the underlying combinatorial optimality problem grows exponentially with the numbers of units. The amount of information that has to be processed in a single component is mainly responsible for the scalability of the system design. Hence, such a centralized solution is only possible in systems with a low number of units.

Compared to centralized systems, *decentralized systems* also own a central component, that contains all the information about the optimization objective function, but the central component does not have internal knowledge about the units' controllability, which reduces the potential risk of misusing information. In this paradigm, the central unit informs the local units about the objective aspired to. Each local unit determines its contribution to solving the delegated objective and communicates it to the central component. This reduces the combinatorial search space for the centralized component, but the question arises how the global system's objective can be broken down to complementary delegated goals. Here, the contribution of local, decentralized units can be seen as a partial solution. The number of messages that have to be sent increases if the diverse local solutions do not complement each other perfectly and further iterations are necessary.

The continuation of this idea leads to *hierarchical systems* in a tree topology, where each inner node acts as a central component for the units in its subtree. Hence, the communication effort is reduced, as information is only allowed between central components and a small number of assigned local components. Such a hierarchical approach suffers if an inner node of the tree fails. In case of a breakdown, the transmission of information to the root of the tree is disrupted and the unit cannot be incorporated in the optimization process. Besides, the problem of finding delegated but complementary goals for the subtrees causes the global optimum usually only to be approximated in an iterative process.

The hierarchical organization allows the system to reflect the main organization of the power network, which distributes power from the high voltage level to the low voltage level of customers. But for the future energy management it has to be taken into account, that photovoltaic systems and wind turbines feed electricity into the system at the low- and medium voltage level, respectively, such that a temporary reversal of the electrical power flow from top-down to bottom-up becomes possible. In addition, small CHPs, controllable loads and batteries of electrical vehicles are also located in the low and medium-voltage level of the power grid. Thus, approaches are researched that reverse the direction of control: PowerMatcher [21] is a well-known example of a hierarchical bottom-up control approach based on local auctions. It also allows local demand-supply matching in the power system. Of course, all general benefits and drawbacks of hierarchical control systems apply for this approach – static hierarchies in particular are not able to adopt structurally to significant changes in the system e.g. to significantly different behavior of RES and CHPs in the seasons of a year.

Distributed systems are decentralized systems that also allow the direct communication between local components, and *completely distributed systems* are additionally characterized by the absence of a central component. These systems are highly dynamic, as a failure of one node can be compensated for by other nodes. The operation of such a completely distributed system relies on the concept of self-organization, which is defined by Serugendo et al. [22] as a "mechanism or process enabling a system to change its organization without explicit external control." The direct communication also allows contracts between subsets of the systems and, hence, the forming of coalitions, which guarantee partial solutions. Solutions can be constructed bottom-up, starting with the contribution all components can deliver for solving the problem.

The desired characteristics scalability and robustness of distributed systems are gained in return for an increased effort in the coordination and control and in the engineering of dependable algorithms. In terms of the organizational structure, distributed systems reflect the requirements of Smart Grids best. Section 3 will introduce current approaches for the distributed control of dynamic virtual power plants.

2.2 Multi-Agent Systems and Self-Organization

In the previous section the renewable energy resources have been depicted as if their system components themselves were able to act, i.e. to communicate and to gather and process information. As the physical units usually lack such “intelligent” behavior, software components, so-called agents, adopt this task and act behalf of the physical unit. According to Wooldridge [23], such an (intelligent) *agent* is characterized by the following aspects:

- Autonomy: Each agent controls its inner state and is able to perform autonomous actions.
- Social ability: Agents observe their environment and are able to interact with other agents.
- Reactivity: Based on its perception of the environment and its own state, each agent can respond to changes in order to pursue its delegated (local) goal.
- Pro-activeness: Each agent can act in order to fulfill its goal.

A *Multi-Agent System* (MAS) is a distributed system, in which each agent has only incomplete information or capabilities for solving the problem, and the communication as well as the computation are asynchronous [24].

Due to the agents’ restricted view of the environment, the system’s state is distributed over all the agents, and the behavior of single agents is based on only partial knowledge of the system. But even if the global objective is not known to the agents, such systems can evolve in goal-oriented fashion and exhibit emergent properties that are not intrinsic to the agents’ behavior. The challenge of designing distributed systems is to model local agents who receive, process, and distribute as little information as possible, and to define their local goals so that the local behavior of all agents causes the system to converge to the aspired global goal, i.e. to design a ”‘self-organizing”’ system. Gershenson [25] describes this goal-oriented interaction of elements towards a global goal as a practical notion of self-organizing systems.

For the interaction of agents, diverse protocols have been established that rely on negotiations between agents [26]. The *contract net protocol* describes a self-organizing process that relies on collaborative agents (rather than competitive agents): An agent that decides that it will not achieve its local goal on its own, informs other agents about the subtasks which have to be achieved. These agents decide whether they are willing or able to solve such a subtask and answer with bids on the subtasks. After collecting these bids, the announcing agent chooses contract partners and informs the bidders of his decision. As the bidders themselves can also announce their subtasks and initiate sub-contracts, contract nets can evolve.

In addition, protocols for multi-agent systems have been developed that are based mainly on local decisions of agents regarding their controlled units. These agents interact by communicating their own decisions and their knowledge on the decisions of other agents in the systems. A reference to such a protocol is given at the end of the next subsection.

2.3 Distributed Algorithms

As mentioned before, the system's objective is a combinatorial optimization task, e.g. the minimization of the distance between energy production and usage over time. This optimization objective is the global goal of the system. In distributed MAS, the system's state is distributed over the agents who communicate via messages. The reaction of an agent as well as the transportation of messages needs time. Thus, several basic problems need to be solved. First, it is difficult to determine a consistent system's state, i.e. a snapshot of the system: If an agent is charged with collecting all information of all other agents, the delay time of messages causes the agents to answer the request at different times. Second, as the system evolves towards an optimization goal, the optimization process should stop when the goal is reached. The termination detection is quite difficult too: even if all agents have reached their local goals and are inactive, any pending message could trigger further activities. Thus, the distributed optimization has come to an end when there are neither active agents nor pending messages left.

These basic problems occur in many distributed systems – possible solutions have already been published, e.g. in [27]. Besides these basic algorithms, application-specific algorithms for the distributed optimization have to be developed that ensure the units' operational constraints and the system's convergence towards an optimum. An example of a combinatorial optimization heuristic for distributed agents can be found in [28].

3 Dynamic Virtual Power Plants

In section 1.2, the aggregation of distributed resources into VPPs was identified as an important approach to efficiently integrating large amounts of DER and RES into the power grid's management system. Traditional VPP concepts are usually based on a rather static set of aggregated units under centralized control. However, for an implementation along the transition path towards a reliable and sustainable future energy grid based on a significant share of decentralized RES, a more flexible approach is required. First, the difficulty of long-term forecasts for RES and their seasonal variation in power supply requires highly dynamic aggregation mechanisms that can adapt to changing behaviors, e. g. due to updated forecasts. A second source of variation is varying ambient conditions in the power system such as the current demand in a power market. Third, individual DER are usually owned by self-interested entities. Hence, an aggregation approach that leaves as much freedom of action as possible to the participants is a reasonable choice in this regard. In view of those three presumed properties, variability inside aggregations, variability at the ambient level, and self-interested entities, approaches for the aggregation and management of RES and DER that are based on self-organization principles are a viable option. As described in section 2, such approaches offer the needed dynamics and adaptivity for this case, while in turn requiring an increased effort in the coordination of the participating units at run-time, as well as increased preparatory engineering expenses to construct a dependable system. In the following, we give an example of such an approach and present the concept of dynamic virtual power plants (DVPP).

The DVPP concept is characterized by the use of self-organized control algorithms to integrate decentralized energy units into present active power markets as well as prospective markets for ancillary services. Active power schedules (henceforth referred to as *active power products*) and ancillary services (e. g. primary/secondary control reserve) can be offered on a market by a set of decentralized power producers, local storage systems and controllable loads after having been aggregated *dynamically* to coalitions. Aggregation takes place in a fully distributed and temporally flexible fashion, meaning that the organizational binding resulting from common product procurement is restricted to the provision of a provided product only and coalitions dissolve after their fulfillment. Compared to VPPs, which are constructed as a static set of units acting as an aggregated entity with predefined long-term goals, DVPPs are thus characterized by a large flexibility regarding the pool of aggregated units. Because of the distribution of both knowledge and control in the system, this flexibility leads to an ongoing adaptation to the system's environment, i. e. the current situation in the market.

A detailed description of the concept, including differentiation from related approaches, was given in [10]. It is important to notice that this concept provides only a vision of how DVPP can be integrated in the current energy market and system. Concrete implementations of this concept have to define the details regarding the use case considered. If for example voltage stability is considered as a system service to be delivered using active and reactive power, or frequency control using balancing energy, different constraints have to be taken into account along the whole process compared to the supply of active power. To illustrate the concept for non-experts in energy systems though, we pinpoint the general characteristics, omitting the details and dependencies needed for specific use cases. Figure 2 shows the conceptual steps involved in the formation and operation of DVPPs within a multi-agent setting (cf. section 2). In this setting, each energy resource is represented by a *unit agent*. Additionally, *market* and *grid agents* serve as communication interfaces for the respective services (e. g. product announcement by the market agent, and grid admissibility check of operation schedules by a grid agent). The visualized timeline (from top to bottom) depicts eight different steps:

Step 1 – Order book open for active power: Based on a prognosis for load and supply of uncontrollable consumers and renewable power plants, for a specific period of time in the future (e. g. next day 8 hours ahead), a market agent defines active power products and starts an auction for these products.

Step 2 – Coalition setup, bidding, matching: The published active power products are used as target functions for building coalitions of controllable

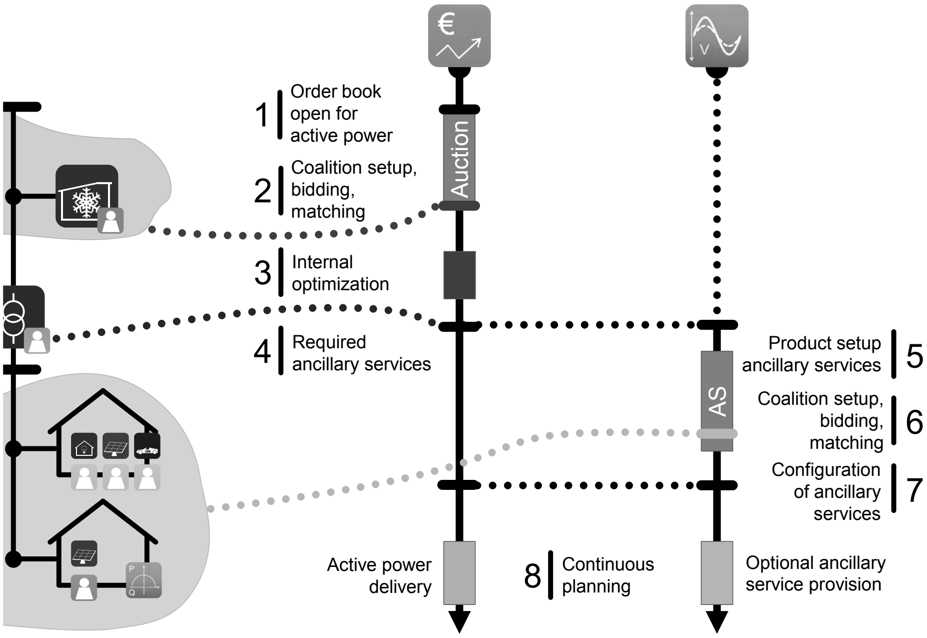

Fig. 2. Conceptual steps for formation and operation of dynamic virtual power plants.

loads, storage, and generators. The coalitions are formed in a self-organized process [29] through communication between agents based on the contract net protocol (cf. section 2). Subsequently, an elected representative agent for each coalition bids for products on the market. The bids of all coalitions are matched at the market, thus forming DVPPs out of successful coalitions. Moreover, the operation schedule of all energy resources in a DVPP is checked for local admissibility (in terms of feasible voltage levels and line loadings) by a grid agent behaving as a local arbitrator [30].

Step 3 – Internal optimization: After market matching, the schedule of all units in a DVPP is optimized with respect to the accepted product such that the overall benefit for the units of the coalition is maximized, while all constraints of controllable energy resources are still respected [28]. A required compact representation of feasible schedule sets is shown in [31].

Step 4 – Required ancillary services: A grid agent responsible for a grid section and thus for a successful product-coalition combination calculates the maximal needed amount of ancillary services within that particular section of the grid [30] and reports it to the market agent.

Step 5 – Product setup ancillary services: The needed ancillary services (e. g. short-term real-time changes in active or reactive power necessary for feasible operation) is divided into ancillary service products with local impact and effects. These products are then announced by the market agent.

Step 6 – Coalition setup, bidding, matching: Similar to step 2, DVPPs are formed with respect to the announced ancillary service products [32].

Step 7 – Configuration of ancillary services: After market matching for ancillary service products, the units within DVPPs have to be configured in order to react autonomously with stabilizing load changes (e. g. to frequency instabilities) for the respective contracted ancillary service product of the DVPP.

Step 8 – Continuous planning: Finally, all DVPPs enter the delivery phase, i. e. the period of time of the contracted products from step 1. Note that an energy resource may be part of both an active power DVPP and an ancillary service DVPP. Hence, a rescheduling in technical DVPPs delivering ancillary services as well as prognosis errors for RES or failures of units in DVPPs might affect the delivery of active power products. Therefore, an online adaptation mechanism is employed, that continuously evaluates reliability values and the operating status of each unit and is able to perform a reactive scheduling while respecting grid admissibility [33]. Rescheduling of active power delivery of a DVPP is based on a variation of the distributed optimization algorithm referenced in step 3.

DVPPs dissolve after product fulfillment (i. e. the end of the delivery phase), and the energy resources may participate in the next trading phase beginning with step 1 again. The approach uses distributed algorithms for formation and operation of dynamic virtual power plants throughout the whole process, thus meeting the requirements identified in Section 1.

4 Challenges in Assessing the Sustainability of Distributed Energy Resources Control

Dynamic virtual power plants as defined in the last section are considered to serve the goal of reducing fossil energy dependence by aggregating small distributed energy resources – both renewable generation and controllable loads – to virtual units with a reliable active power profile. With DVPP, flexibility in distribution grids should be used to reduce the overall consumption of fossil fuels, bring renewables to markets and deliver system stability services.

Simulation is a well-established means for evaluating distributed systems' behavior. Usually, in energy systems at least two systems are coupled: On the one hand, the energy system itself has to be simulated; on the other hand, the coordination system as an ICT-based system has to be co-simulated to evaluate the effect of the coordination system on the energy system's components. Up to now, very little work has been done to evaluate sustainability indicators of distributed coordination in energy systems. Assessments usually focus on single aspects of sustainability for specific applications, such as enlarged local usage of renewables in e-mobility [34] or CO_2 reduction gained by end-user decision support [35]. Some studies discuss sustainability on a broader scale, i. e. including provision and systemic effects as well (see e. g. [36] for an assessment regarding greenhouse gas emissions of ICT systems in general). In distributed coordination of energy resources, however, such an assessment is still missing. Therefore, we cannot compare the existing concepts (see Section 3) in terms of their sustainability characteristics.

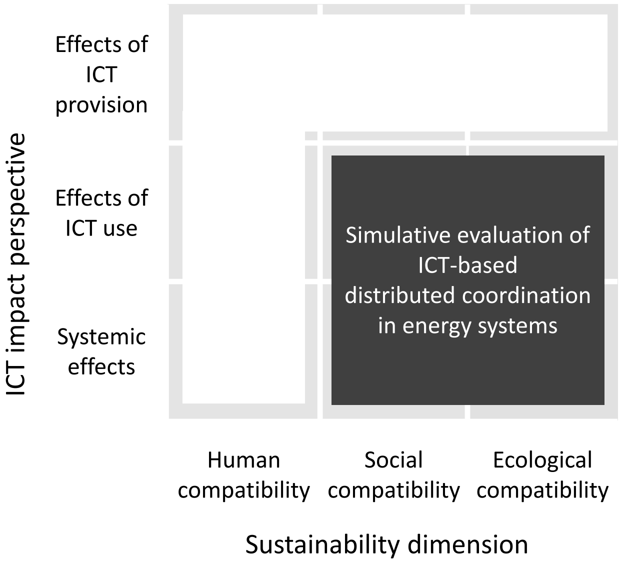

Fig. 3. Sustainability assessment for ICT-based distributed coordination in energy systems following the conceptual framework from [37] (reduced scope).

What is impeding the evaluation of the distributed coordination approaches with respect to the main motivational background, i. e. the sustainability performance on a broader scale? Distributed coordination systems can hardly be analyzed following an analytical approach, and experiments in the field cannot sufficiently show the system's behavior on a large scale. Therefore, an evaluation is performed based on simulations to analyze the distributed coordination system in terms of defined evaluation criteria. When sustainability indicators are taken into account in such a simulative evaluation, special requirements have to be fulfilled to answer the main question of whether the coordination scheme under evaluation really helps in reducing the fossil fuel share in energy delivery. In Figure 3, a classification of such a sustainability assessment is given following the integrated sustainability model as described in [37] (see Part I: "Introduction" in this book for an overview of this framework [38]). As can be seen, evaluating the substitution effect of ICT-based coordination in energy systems will only cover a small part of the plane formed by sustainability dimensions and ICT impact perspectives.

In the following, we elaborate some challenges in this context and suggest how the substitution effects of (distributed) coordination schemes for the integration of renewable energy resources can be evaluated for a sustainability assessment with such a reduced scope.

Effects on emissions and pollution: In coupled energy systems, a time resolution of less than one hour is needed for the simulation of the system to evaluate which kind of fossil fuel has been substituted in detail. In Germany, for example, the typical mid-time load peak has been covered by gas-driven power plants. On sunny days, this peak is cut off quite often by solar power. If the effect is compared to substituting coal-fired plants, quite a different emission reduction can be found. This can only be analyzed by taking into account both time resolution in supply and demand and the merit-order of conventional power plants. To analyze the effect of distributed coordination in energy systems, we therefore have to couple market information and power system information with a time resolution of 1 hour or below.

Effects on long-term substitution of fossil-fueled plants: Taking the example of solar power cutting the mid-day load peak, it can be seen that this has a relevant effect on the revenues generated with gas-fired power plants. To analyze the effects of distributed coordination in energy systems on the overall generation system, we therefore have to couple our simulation results with an analysis of the revenues and investments made in power plants.

Effects on power grid stability: A distributed coordination scheme in energy systems must not lead to violations of operational constraints in the power grid, as this would endanger system stability. Therefore, we have to analyze the effect of distributed coordination on the power grid itself using a power grid modeling and analysis tool and to take into account the results gained from this analysis within the coordination schemes.

Effects on electricity prices: Renewable energy resources have a remarkable effect on the electricity prices at the European energy exchange. This effect, known as the merit-order effect, is dependent on both the current prices for fossil-fueled power generation and the mid- to long-term investment in these power plants. Although the actual price reduction is still subject of discussion it is clear that a price reduction can be expected and has already been valuated on the energy exchanges as a consequence of renewable feed-in. It remains unclear though, when and to what extent these effects will appear on the consumer level – considering social compatibility, this is a highly relevant aspect.

In Figure 4, an overview of a hypothetical evaluation system is given that would be able to fulfill these requirements and deliver the needed indicators. As can be seen, even for a reduced scope of a sustainability assessment of distributed coordination in energy systems, these requirements cannot be met within a single simulation framework: We would have to couple market simulation, power plant simulation, investment analysis, distributed energy system simulation and ICT-based control. We do not show the circular references in such an evalua-

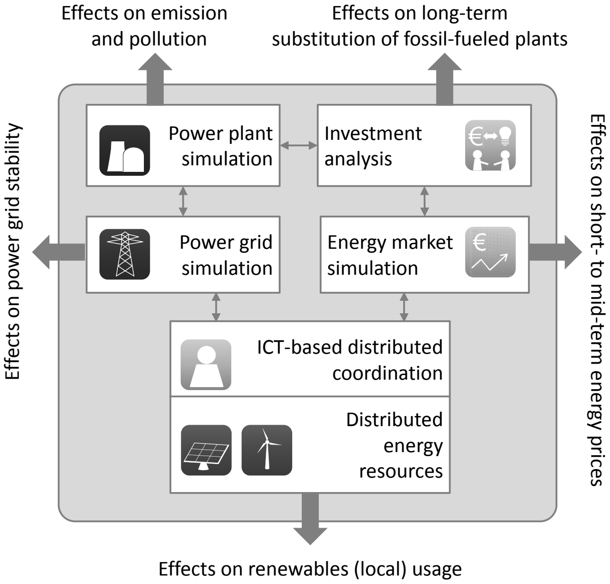

Fig. 4. Hypothetical sustainability evaluation system for distributed coordination in energy systems with the reduced sustainability scope as defined in Figure 3.

tion system that additionally hinder setting up such a sustainability assessment system for distributed control in energy systems.

What then is a way out of this trap of complexity? How can we analyze the sustainability of distributed coordination in complex systems like the electrical power system? We give some suggestions for a first approximation:

1. Define the sustainability indicators needed from each simulation framework for an integrated sustainability assessment.
2. Define a common scenario and parameter base for all simulation frameworks used. As the control scheme connects all layers by defining the operation scheme of energy units from different actors' perspectives, the parameter settings for all simulators have to be aligned. Although this sounds self-evident, this is one of the most demanding tasks in the process, as the different simulators work on different abstraction levels, and parameter settings for e. g. the market simulator seem to be independent of the power grid simulation.
3. Define input-output relations to reuse results from one simulator for the next, paying attention to the differences in time resolution and abstraction level of each simulator.
4. Ignore the circular references to separate the different simulators during runtime by flattening the simulation frameworks' runs to a sequence. The injected error can be mitigated by following an iterative approach. Define the minimum number of iterations, taking into account the different possibilities of sequencing the frameworks.

5 Discussion and Open Questions

Integration of large shares of renewable energy sources into the power grid is an essential task to reduce anthropogenic greenhouse gas emissions from the combustion of fossil fuels. This task requires a reorganization of the power grid not only by substituting e.g. fossil fired power plants by wind energy converters or photovoltaic systems, but it also demands for a substantial change in the operation mode of the power grid.

We have shown that distributed, self-organized control methods are an adequate choice to support integration of decentralized power supply into the grid operation – they are a promising research area. For the development of such control algorithms we propose Smart Grid algorithm engineering [39], a methodology integrating simulation-based evaluation of algorithms. Prototypical control methods for dynamic virtual power plants are a first result of applying this methodology.

Control algorithms in this application domain have to be evaluated with respect to several technologically motivated performance indicators, such as robustness, adaptivity, and scalability. Societal aspects such as privacy or data protection have to be integrated into the algorithms “by design”. We discussed issues that currently hinder the evaluation of these control approaches for their effects on the reduction of fossil fuel dependence, namely the needed integration of various simulation models, coupling Smart Grid simulation models, control algorithms, energy market simulation and investment analysis. To this end, we proposed some guidelines on how to reduce the complexity of the evaluation framework needed.

The development of ICT-based distributed coordination approaches in the energy sector has a large potential, but a detailed evaluation with respect to sustainability indicators remains an ambitious task where complex evaluation frameworks still need to be developed.

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