Energy Collectives: a Collaborative Approach to Future Consumer-Centric Electricity Markets

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I. Introduction

THE MASSIVE DEPLOYMENT of renewable energy generation capacities and the rise of more proactive energy consumers, e.g., households with solar panels and storage capabilities, challenge common practices across the energy sector. If appropriately accommodated, distributed generation and more flexible consumption could provide several technical, economical and societal benefits [1], [2]. Strands of literature exist to propose alternative paradigms to operations and control of such increasingly complex electric power systems, for instance, in centralized vs. decentralized manners, or in hierarchical control vs. market-based environments.

While system organization has rapidly evolved from an integrated hierarchical structure to a more decentralized model, electricity markets are still not up to date with the ongoing transformation of our economies towards more consumer-centric structures. Technological solutions exist to enable this type of decentralized and community-based management approaches, for instance on the cloud or using a blockchain, empowering consumers in the electricity markets while also benefiting utilities and grid operators [3], [4]. Following [5], consumer-centric markets may be organized as fully distributed peer-to-peer structures, but also most likely based on virtual communities of actors of the energy system with common interests, most likely financial, but not necessarily. Example resulting challenges include market organization [5], interaction with system operation [6], [7] and peer-to-peer negotiation mechanisms [8].

In this context, our aim is to introduce and analyse the market-based concept of *energy collectives* (i.e., a specific form of virtual energy community) as a flexible structure allowing for community-based operations in a market environment. After defining energy collectives and their operational framework in Section II, we describe in Section III a set of tools allowing to characterize and simulate how those may operate based on distributed optimization concepts. Subsequently, we use a number of test cases in Section IV to illustrate their functioning, as well as subsequent benefits. Section V gathers conclusions and perspectives regarding future works based on energy collectives.

II. Energy Collectives and their Operational Framework

An energy collective is defined as a community of actors of the power system that operates in a collaborative manner, optimizing usage of community resources while having a common agreement on how to interact with other energy collectives and the wholesale market, see Figure 1. Energy collectives are to be envisaged as a market construct and not related to a certain positioning on the electric power grid. In practice, this means that operation on a microgrid is only one possible configuration, but more generally such communities may be formed irrespective of grid connection and geographical location. Hence, an energy collective could be seen as special type of energy cooperative [9], with additional focus on market dynamics and operations similar to the case of virtual power plants [10] or of transactive energy services [11].

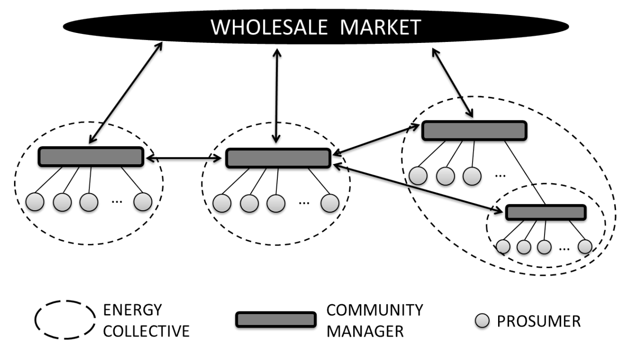

Fig. 1. Organization as an energy collective and interactions with the wholesale market and other collectives.

In a simplified setup, let us consider an energy collective composed by a set of generators, $j = 1, \dots, m$, for instance prosumers with extra solar power generation and micro-CHPs, and a set of consumers and prosumers needing additional electric energy, $i = 1, \dots, n$. For a given market time unit those are to find their optimal power generation (p_j) and consumption (c_i) levels, in view of their respective marginal utility functions, f_j^p and f_i^c. The optimal community dispatch is obtained as the solution of an exchange problem, i.e.,

$$\min_{\Gamma} \quad \sum_{j=1}^{m} f_j^p(p_j) - \sum_{i=1}^{n} f_i^c(c_i) - g(q_{\text{ext}}, \theta) \tag{1a}$$

$$\text{s.t.} \quad \sum_{i=1}^{n} c_i + q_{\text{ext}} - \sum_{j=1}^{m} p_j = 0 \tag{1b}$$

$$P_j^{\min} \leq p_j \leq P_j^{\max}, \quad j = 1, \dots, m \tag{1c}$$

$$C_i^{\min} \leq c_i \leq C_i^{\max}, \quad i = 1, \dots, n \tag{1d}$$

where $\Gamma = \{p_j, c_i\}_{j,i}$ is the set of $m+n$ decision variables and $q_{\text{ext}} = \sum_j p_j - \sum_i c_i$ is a continuous variable related to import and export (export is for q_{ext} positive). The function g models the common agreement on how the energy collective is to

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jointly handle its interaction with the outside world, based on a set of relevant parameters θ. In the most simple market-driven case, $g(q_{\text{ext}}, \theta) = \lambda_{\text{ext}} q_{\text{ext}}$ where λ_{ext} is the wholesale market price. In case the community wanted to be as autonomous as possible, one would naturally have $g(q_{\text{ext}}) = ||q_{\text{ext}}||_l$, with $l = 1, \ldots, \infty$.

As we consider that this problem is solved in a distributed fashion under the coordination of a (non-profit) community manager, different definitions for g are to impact the behaviour of its members, as well as their revenues and payments. This strongly links to existing work in literature focusing on congestion management of, e.g., telecommunication networks or electrical grids with charging of electric vehicles [12], where concepts such as proportional fairness and max-flow protocols are built upon. Note that our proposal is to be placed into perspective with related research that recently appeared in the power system literature, e.g., [13], [14].

III. Distributed Optimization Approach to the Operation of Energy Collectives

The nature of optimization problem (1), combined with the aim of all community members to individually accommodate their own sub-problem, readily suggests employing decomposition techniques to achieve opimiality in a distributed fashion. More precisely, the Alternating Direction Method of Multipliers (ADMM, [15]) is used here since allowing to explicitely define individual problems for each community member and supervise the exchange of information between community members and manager. Alternative decomposition approaches could be employed, with their advantages and caveats, as recently reviewed and compared in [16] for optimal power flow problems. Alternatively, consensus-based optimization approaches may allow for a full decentralized peer-to-peer orgnization, as for instance described in [8].

IV. Application and Case-studies

As a basis for illustration and discussion, we will use data for 300 prosumers, most of them equipped with solar power generation and controllable load, as well as 15 conventional generators of relatively small capacity (micro-CHPs). The data for solar power generation and electric load was originally collected from households in Australia [17] and shared as open data. As utility functions are undefined, we will make a proposal to make this dataset more general by building such utility functions, to be used in future consumer-centric market-related studies. The use of this dataset and our proposed generalization will allow others to readily reproduce our work and build on our findings.

In practice, this test case will first allow us to illustrate the functioning of the coordination mechanism for given market time units (i.e., under various conditions when it comes to solar power generation and load profiles). Then, revenues and payments will be analysed over longer periods. The impact of the definition of the interface function g will be thoroughly discussed, as well as its impact on the various types of actors forming the community.

V. Additional extensions

In the above, a simplified setup was described when introducing energy collectives and their functioning. In the full paper, these will be generalized to all possible actors, e.g., community storage, prosumers with residential storage, etc. Extensions to multi-period coordination while accounting for technical constraints (like, ramping for instance) will also be given. Furthermore, the possibility of trading among communities or of a Russian-doll setup, where some of the members of an energy collective are other energy collectives, as in Figure 1, will finally be discussed.

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