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Framework to manage multiple goals in community-based energy sharing network in smart grid

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ABSTRACT

Smart grid has opened up a new role of "prosumer" in an energy value network, transforming many conventional energy consumers into prosumers, who not only generate green energy but also share the surplus with utilities and other consumers. The concept of a goal-oriented prosumer community group (PCG) has emerged recently as an effective way to fulfill sustainable energy exchange. Such community-based energy sharing networks comprise multiple irreconcilable objectives such as demand constraints, cost constraints, and income maximization. In many cases, one goal may be achievable only at the expense of other goals. This necessitates the development of an effective framework to manage the multiple goals and reduce the gap with their achievement levels. Therefore, in this research paper, an effective framework is developed to negotiate among the multiple goals and thus to define optimal mutual goals for each PCG in a more sustainable manner using multiple-criteria goal programming techniques. Simulation results are presented to illustrate how the methods work in practical situations, where each of the objective measure is given a target value and the unwanted deviations from this set are minimized in an achievement function.

Introduction

The demand for energy in the world is continually rising. Worldwide energy consumption is expected to increase by 49% from 2007 to 2035 [1]. The majority of the current demand is met by nonrenewable energy sources such as coal, petroleum, and natural gas. However, the society is now faced with dwindling scarce nonrenewable energy resources resulting in electricity shortage and unpleasant climatic changes due to greenhouse gas emissions [20]. Thus, different solutions to combat the problem of energy shortage have emerged and one such solution would be allowing the energy users to generate the green energy and sell the surplus to the utilities [6], or even to the other consumers. This has introduced a new role of the "prosumer," that is an energy user who generates renewable energy in his/her domestic environment and either stores the surplus energy for future use or trades to interested energy customers in smart grid [2,20].

In current society, there are a considerable number of prosumers who produce renewable energy in their residential environment and share the surplus with the main utility grid [8,19]. However, as a single entity, such a prosumer (as an energy producer) is often excluded from the wholesale energy market due to their perceived inefficiency and unreliability. For example, in most cases, individual renewable generators, such as small scale solar systems and wind turbines, are too small to compete effectively in the market with large-scale power generators. Thus, they fail to produce and vend enough electricity to have a bargaining power in the competitive energy market, and thus will have to settle for a low price per kilowatt [10].

Moreover, a set of prosumers can be attached to a smart grid through dedicated technical infrastructure facilitating accumulated energy sharing between the groups of prosumers and the utility grid. Such prosumer groups are generally implemented through one of the two well-known technical infrastructures: virtual power plant (VPP) and micro-grid. A VPP is a group of domestic energy resources connected via a dedicated technical infrastructure with an aggregated capacity analogous to a usual power plant. On the other hand, the concept of a micro-grid has emerged in recent years as a localized grouping of distributed energy resources (DERs), which is somewhat similar to that of a VPP, but has some key differences. The micro-grids are smaller in size and concerned with a locality in operation, while the VPPs can vary from small to large sizes and follow the energy sharing on a large scale. One significant benefit of micro-grids over VPPs

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is the reduced transaction costs, as a result of fewer intermediary parties due to their localized operation. Compared to the individual prosumers' energy supply, such groups of prosumers can jointly provide a higher amount of energy and satisfy the energy buyers' demands with lesser effort.

However, several deficiencies are involved with prosumer groups that are formed through dedicated technical infrastructure (VPPs and micro-grid). The key deficiency is that this type of fixed architecture may result in inflexibility, which makes it complex to add or remove new members to the VPP/micro-grid. For instance, some prosumers may offer whatever amount of energy they can contribute, or prefer to contribute, leading to an unreliable energy supply to the energy buyers in the long term, ultimately resulting in negative morale toward the entire VPP or micro-grid-enabled prosumer group.

In order to address the aforementioned deficiency of prosumer groups in the form of VPP/micro-grid, as well as to promote sustainable social aspects with regard to the prosumer management in the long term, the concept of goal-oriented prosumer community groups (PCGs) has emerged in the society. Unlike a VPP and a micro-grid, the PCG virtually interconnects the prosumers and may not be necessarily connected technically. Furthermore, in the context of social perspective, the PCGs are formed with members having similar energy sharing preferences and interests and inspired to achieve a common goal. The concept of PCGs is a socio-technical improvement upon the existing literature on prosumer group paradigms built on VPPs and micro-grids. For example, the prosumer groups (existing in literature) are not goal oriented, as well as the prosumers have been merely interconnected via a technical infrastructure without taking their diverse energy sharing preferences and behaviors into account. Consequently, the lack of goal-oriented behavior reduces the reliability of energy supply to energy buyers in the long term. Moreover, the chances of possible disagreements among members are high in the existing prosumer groups because of their differing energy sharing interests and preferences.

Accordingly, the term "*goal-oriented prosumer community group*" is defined as a network of prosumers having relatively similar energy sharing behaviors and interests, which make an effort to pursue a mutual goal and jointly compete in the energy market [10]. One of the long-term benefits of PCGs is that they offer small players (prosumers) the negotiating power to be at par with big players (large scale energy providers such as utility grid) and eliminate the gap dividing them. Moreover, compared to individual prosumers, being part of a PCG can be seen as a big motivator for behavioral changes with regard to energy use, because the impact of a PCG's behavior can be more relevant and stronger than the impact of individual behavior. As a result, the PCGs can create a dynamic ecosystem of cooperating prosumers. This is particularly advantageous in remote areas that do not have abundant energy resources and incur huge costs as well as face difficulties in transporting energy to meet the energy needs of the users. In such situations, a strong interaction among the prosumers, consumers, and the utility grid will induce individuals to work together to more efficiently manage their electricity use. Such strategies are essential to act as incentives for the users to conserve energy, and later utilize it for their own benefit.

However, for the PCGs to emerge and be able to meaningfully interact with the smart grid infrastructure, several socio-technical challenges have to be addressed. The ways to tackle some of these challenges are considered to have been deployed as a core part of the smart grid [15,7,17]; some exist in other contexts (e.g., online communities) [4,11], while others still need to be developed. One of the key challenges that still need to be addressed is managing multiple goals in a community-based energy sharing network followed by allocating optimal mutual goals to PCGs. In literature, there are slightly similar research on optimized micro-grid operation techniques [3] (Erseghe et al., 2011) that aim in maximizing its goals by optimizing the production of the local distributed generators and power exchanges with the main distribution grid. However, in this research, our main aim is to optimize the prosumer community groups by negotiating among the diverse goals of prosumer community groups, thus reaching the optimal set of goals. The same goal management framework can be applied and further developed to manage diverse goals in Virtual power plants as well as the micro grids, which will intern optimize the energy generation and sharing.

The significance of addressing the aforesaid challenge can be described as follows. In general, the community-based energy sharing network encompasses different incompatible objectives such as meeting the group members' energy demand, meeting the external customers' (utility grid or consumer) demand, achieving higher income for the energy auctioned, reducing overall cost, etc. In many cases, one goal may be achievable only at the expense of another goal. For example, in order to reduce the overall cost associated with PCGs, the overhead of managing prosumers in PCGs can be reduced by reducing the number of active prosumer participations. However, reducing the number of participating prosumers will reduce the total energy production and sharing, while reducing the total income (feed-in tariff). Therefore, it is necessary to reach a favorable compromise among these multiple diverse goals with respect to the given constraints and priorities. Moreover, these goals are to be effectively broken down into customized mutual goals for different PCGs, where the prosumers of each PCG are inspired to achieve their respective mutual goals. Allocating optimized mutual goals to the PCGs inspires the members to achieve the set goal, and hence ensures a reliable energy supply to energy buyers in the long term.

Overall, the concept of PCGs is still in its infancy, and therefore the existing literature has very little to offer, either in investigating the related concepts or in resolving the aforementioned challenge, making our work novel within the smart grid research field.

Background

In this section, the existing literature on PCGs in the SG energy sharing process is briefly discussed.

PCGs have been emerged following the concept of the generic "community" that aggregates prosumers with similar energy sharing behaviors who may not be necessarily connected technically, but are connected logically and are inspired to achieve a mutually agreed upon goal. The concept of PCGs is an improvement upon the existing prosumer group paradigms built on VPPs and micro-grids [5]. In general, the prosumers are registered to community based energy sharing network and they receive the membership of different PCGs based on their energy contribution. The higher the membership level, the higher the amount of energy shared by a member and the greater the privileges and the more benefits the member gains [12]. The prosumers who are registered to the PCG are assumed to generate energy individually and any unused energy is virtually accumulated into the energy reserve. This unused energy is first used to fulfill the energy demand of local prosumers within the same PCG. Once the local demand is fulfilled, the surplus is sold in the energy market to external energy buyers such as other PCGs, consumers, or utility grids.

The existing literature of prosumer community groups has paid very little attention on addressing the challenges involved in PCGs [5,12,14]. Here, the scant amount of research on PCGs is discussed.

For instance, Karnouskos [5] investigates the different types of services required for the prosumer communities to operate, such as energy brokering, community behavioral simulation, energy information services, and real-time energy monitoring. Similarly,