Priority-Based Energy Sharing and Management Among Prosumers in Smart Grids

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I. INTRODUCTION

The ever-growing world population, irresistible modernization in lifestyle, state-of-the-art technical advancements, and the most coveted industrial growth significantly require to balance on a demand-supply gap in the energy sector [1]. The consumption of electric power is expected to rise by 49% in 2035 by taking the current demand into comparison [2]. The estimated energy mismatch can be fulfilled by increasing fossil fuel-based centralized generation [3]. However, the excessive use of these energy resources will add to the already elevated carbon emissions and asymmetrical economic depletion [4], [5]. To mitigate the negative impacts of these issues, the use of renewable energy resources (RERs) is an alternative at the microgrid or consumer level to benefit the people and to boost economic activity [6]. Besides, traditional grids may be transformed into smart grids (SGs) for managing such an immense paradigm shift in the energy sector [7]. Uncertainties and risks in the power supply and load control areas can be effectively managed through SGs [8]. Various demand-side management (DSM)-based schemes, such as load shifting, valley filling, peak clipping, load growth, and so on, are investigated in the literature to improve the system stability and effectively meet the energy demand to acquire a balanced load profile [7]. Moreover, the DSM allows users to freely participate in the power supply and management by using bi-directional

TABLE 1. ABBREVIATIONS.

| Abbreviation | Term                                      |
|--------------|-------------------------------------------|
| DER          | Distributed energy resource               |
| SG           | Smart grid                                |
| DSM          | Demand side management                    |
| BIP          | Binary integer programming                |
| ESS          | Energy storage system                     |
| RER          | Renewable energy resource                 |
| DLC          | Direct load control                       |
| PESM         | Prosumer-based energy sharing and management |
| MILP         | Mixed integer linear programming           |
| USD          | United States dollar                      |

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TABLE 2. A BRIEF SUMMARY OF RELATED WORK AND THE PROPOSED COMMUNITY MODEL.

| Research topics on prosumer communities | Modeling approach | References |
|----------------------------------------|-------------------|------------|
| Role of prosumer communities in future distribution grids | Game theory | [9] |
| Prosumer communities growth | Motivational theory | [10] |
| Bargaining power in future grids | Motivational theory | [11] |
| Community response to grids’ involvement for DLC | Survey | [12] |
| Operational complexity of future grids | Scheduling strategies | [13] |
| Prosumers classification and the most influential prosumer | Generation pattern | [14] |
| Energy trading with grid or community | Collaborative placement | [16] |
| Priority-based energy trading within community | Net-metering, peer-to-peer | [17] |

FIGURE 1. Role of prosumers.

communication channels to modify their energy patterns [18]. These active consumers are termed prosumers. The prosumer is an entity that produces and consumes energy simultaneously and shares surplus power to the grid or approachable adjacent consumers [19]. Figure 1 shows the role of prosumers. The subsidies by the government [20], green energy production, low installation cost, greater control, and competing power companies lead towards augmentation of prosumer communities [21].

A. RELATED WORK

Such far, there have been several studies on these prosumer communities. Table 2 summarizes the existing studies. In [9], a novel game theory-based model is investigated to analyze the role of prosumer communities for reliable energy sharing and management in the future distribution system. However, the proposed framework requires users’ participation. The prosumers’ participation is increased by using various motivational models [10], which result in providing more bargaining power to the groups with grid or nearby users [11]. In [12], the authors consider to estimate the community concerns in response to utility involvement in their habitual life. These communities will increase the operational complexity of the current distribution system due to discontinuous power supply, energy consumption pattern [13], and different incentives-based commerce among the communities. The energy consumption patterns of residential or commercial prosumers can significantly vary within a community. The residential prosumers have a less contribution in the energy market than the commercial prosumers [14]. In addition, the prosumer with a higher power-generation capacity can play a pivotal role within the community. The long-term and short-term power consumption behaviors of the prosumers can be assessed by using multiple assessment criteria [15]. In addition, scientific studies reveal that energy storage systems (ESSs) may be employed to reduce fluctuation impacts and prediction errors in resource utilization. These storage systems can be placed at the user’s end or shared with the community by its collaborative placement. According to [16], 50% savings can be achieved by using a collaborative approach based on the ESSs. Several trading systems such as net-metering and peer-to-peer trading are used for energy intake and supply amongst the communities. The energy trading with the grid is not preferred for the net-metering system due to constraints in power line capacity [17]. In this case, the communities also need to pay for transmission losses, unlike immense energy producers [22]. In [23], a load forecasting model is proposed for reshaping a load profile, which can finally lead to more sustainable and economic grid operations. The peer-to-peer trading system is considered for energy sharing and management without any priority criteria. Neagu et. al. in [24], encouraged the prosumers to share their surplus power with the Romanian grid using different smart peer-to-peer contracts for generating fiscal benefits. The prosumers are prioritized-based on their location, instantaneous power demand, and first-come-first-served criteria. In [25], the game-theoretic approach is used to 1) prioritize different energy stakeholders such as power deficient users, prosumers, and the grid; 2) model their interactions for energy trading. First, the surplus power held with the prosumers is used to meet the energy shortages. Next, the grid energy is also utilized to meet remaining power shortages in case of insufficient prosumers’ surplus power. Jiang et. al. in [26], investigated the optimization of energy interactions between prosumers and consumers employing
the social utility function and the Nash bargaining model. Min Qi et. al. in [27], studied the impact of different network constraints such as energy conservation, active power, charging, and discharging of storage systems due to the increasing number of prosumer communities for a distributed generation system. In this study, the standard IEEE-15 node system was employed to analyse the impact of the said constraints on prosumers trading with the grid. In [28], the game-theoretic approach and auction-based pricing strategy are used for prosumers energy trading based on an hour ahead and real-time price signal. The results maximize the social benefits with considerable improvement in energy transactions. In [29], the authors propose a cooperative prosumers-based energy sharing and management (PESM) approach within a prosumer community. It is observed that the energy shortage reduction is 44.13% at a very economic level with a cost of $3.35 in United States dollars (USD). In prior studies, several models are proposed to establish the prosumer community and estimate its impact on future grids. However, literature on the prosumers’ interaction within the community for energy trading, is lacking. Therefore, there is a need to develop a priority-based energy sharing and management model for prosumers’ community to maximize the users’ satisfaction without any conflict of interests.

B. CONTRIBUTION

In this paper, we propose a priority-based energy trading model that extends the prosumer-based model presented in [29] for energy sharing and management within a single community. Without loss of generality, the proposed model is still valid for energy trading among multiple communities. The contributions of this paper are summarized as follows:

- The proposed model is efficient and reliable. It employs an ESS and various newly introduced priority parameters such as renewable energy resources (RERs) and ESS capacities (kW), energy contribution for a day, and per-unit selling cost (USD) of surplus power for sharing with energy-deficient users. These priority criteria build trust for fair energy sharing without any conflict of interests.

- The objective of our proposed model is to maximize surplus power (kW) sharing with the energy-deficient users within a community at certain time slots with minimum cost. The cost of the surplus power, which is well-defined by all participants, is also considered simultaneously. We formulate the optimization problem and employ binary integer programming (BIP) to solve the problem with and without ESS scenarios.

- To investigate the interconnection of the demand-supply gap and the energy cost, we introduce a novel weight factor. Additionally, in the proposed model, the energy-deficient users have their own priorities under two different criteria, such as single-use and multiple-uses, based on their RERs and storage capacities (kW), per-unit selling cost (USD), and overall contribution within the community.

C. PAPER ORGANIZATION

The remainder of the paper is organized as follows: In Section II, the system model is presented while the problem formulation along with flowchart for a BIP-based solving method is presented in Section III. In Section IV, the results and discussion for a case study are provided. Finally, the conclusion remarks are drawn in Section V. For better readability, Table 1 presents the abbreviations used in this paper, while the mathematical notations used are listed in Table 3. The terms users and prosumers have been interchangeably used throughout this paper.

II. SYSTEM MODEL

In this section, we present the considered system model. Figure 2 shows the prosumer community participating into energy sharing. The prosumer community, \( P \), is the set of prosumers includes \( J \). The prosumers can use renewable energy resources to meet their energy demand along with the energy storage systems. The exploitation of environment-friendly RER will reduce the amount of carbon emissions and users’ grid dependency. However, the excessive use of these intermittent resources is not possible without the increased use of efficient, reliable, and dynamic ESS to improve grid stability [30]. According to Jean Ubertalli. et. al. [31], the ESS are also used to improve RER dispatchability while minimizing the energy curtailments. Different types of emerging generation technologies: 1) combined heat and power systems, 2) thermal energy systems, and 3) boilers can be integrated by using ESS. A communication network links the users with each other and with the local control center.
as well. A central utility grid manages power and communication flows in a slotted timeline $N \in \{1, 2, \ldots, 24\}$ hours. Some users in the system have surplus energy, while others may suffer from energy shortages at a certain time slot. In this system model, the main objective is to minimize the power cost by maximizing the use of surplus energy. Various optimization techniques, such as genetic algorithm, particle swarm optimization, binary integer programming (BIP), and mixed-integer programming (MIP), can be employed to formulate and solve the problem. Considering the decision variables and multiple objectives involved, we formulate our model using BIP to avoid complexity and make it practical for a real-world scenario. In the following section, we explain the formulation of the problem using BIP.

III. PROBLEM FORMULATION AND PROPOSED SOLUTION

In this section, we formulate the optimization problem for the above mentioned prosumer community model. Next we explain the work flow of the proposed BIP-based scheme to find the solution of the formulated problem.

A. PROBLEM FORMULATION

Let $P$ is the set of prosumers participating in the power-sharing scheme. Amid the prosumers, the users with surplus power, the amount of which is denoted as $P^+_j$, for the $j^{th}$ user at the $n^{th}$ time slot, are included in the set $J$, while the users with energy shortage, amount of which is denoted as $P^-_k$, for the $k^{th}$ user at the $n^{th}$ time slot, are included in the set $K$, such that $J + K \subset P$.

The research objective is to minimize the energy cost by maximizing the use of surplus power which is available at minimum cost in different timeslots of a day. The per unit surplus energy cost is assumed for different users. To avoid the conflict of interests for surplus power share among energy deficient users, different priority criteria are introduced. The optimization method is used: 1) to search for a suitable priority criterion for sharing surplus power within community, and 2) to share surplus power at minimum cost for highly prioritized power deficient user at first. Available power for any user is given by (1), while (2) and (3) represent the estimated amount of the surplus power, $P^+_j$, and the estimated amount of the power shortage, $P^-_k$, for the users $j$ and $k$ within prosumers’ community at the $n^{th}$ time slot.

$$P^+_j = \sum_{j=1}^{J} \sum_{n=1}^{24} (RP^+_j,n + GP^+_j,n + BP^+_j,n), \quad (1)$$

$$P^-_k = P^-_k, \quad \forall P^-_k < PD^-_k, \quad (2)$$

$$P^+_j = P^+_j - PD^+_j, \quad \forall P^-_j > PD^+_j, \quad (3)$$

where $P^+_j$ is the total available power (kW) supplied to the $j^{th}$ user at the $n^{th}$ time slot. The total power consists of the power generated by RER, $RP^+_j$, the power supplied by power grid, $GP^+_j$, and the stored power, $BP^+_j$. $PD^+_j$ and $PD^-_k$ denote the power consumed by the users having surplus power and power shortages, respectively. Note that the source of surplus power may be RER, ESS, or an expensive discontinuous grid supply due to many power curtailments. The source of surplus power is not considered in this paper. The cost is optimized by utilizing the surplus power of any user sharing it with other community members at a low per-unit price. The $\psi_{j,n}$, represents the total cost of surplus power for the $j^{th}$ user at the $n^{th}$ time slot, which is expressed as:

$$\psi_{j,n} = \sum_{j=1}^{J} \sum_{n=1}^{24} \psi_{j,n} Z_{j,n} \text{,}$$

as a result of the optimization problem using BIP.
where $Z_j$ denotes per-unit price in USD. The objectives of the optimization problem is given in the following:

$$\min \sum_{j=1}^{J} \sum_{n=1}^{24} \left( \alpha \Psi_{j,n} x_{j,n} - P_{j,n}^+ x_{j,n} \right), \quad (5)$$

$$\text{s.t.} \sum_{j=1}^{J} \sum_{n=1}^{24} P_{j,n}^+ x_{j,n} \leq \sum_{k=1}^{K} \sum_{n=1}^{24} P_{k,n}, \quad (6)$$

where $0 \leq \alpha \leq 1$, which is a weight factor and in (5), the objective function minimizes the total cost of energy while maximizing the use of surplus power. (6) shows that the summation of surplus power should be less than or equal to the summation of energy shortages for a time horizon to prioritize the power deficient users according to introduced priority criteria which will not be effective to meet objectives otherwise.

$$x_{j,n} = \begin{cases} 1, & \text{if the surplus power is available,} \\ 0, & \text{if the surplus power is unavailable.} \end{cases} \quad (7)$$

The weight factor $\alpha$ becomes zero if the power shortage needs to be minimized at any cost and becomes greater than zero if cost-saving is preferred. The higher value of $\alpha$ indicates the higher weight allocated to the cost minimization problem. In the case that there exist more than one power deficit users, a single criterion or multiple criteria are considered. In a single criterion, without ESS, the users are prioritized according to RER capacity. The user with higher RER capacity will get higher priority for surplus power share to meet the power shortages. By employing the ESS, the power deficit users get priorities based on ESS capacity. In some cases, the single criterion may not be enough to prioritize the power deficit users due to the same RER and ESS capacities. In such a case, multiple parameter-based criteria are used and

FIGURE 3. Flowchart for the BIP-based solving method.
therefore, the problem can be re-formulated into:

\[
\min \sum_{j=1}^{24} \sum_{n=1}^{K} \left( \alpha \Psi_{j,n} x_{j,n} - P_{j,n}^{+} x_{j,n}^{P_{n}^{sh}} \right), \forall x_{j,n}^{P_{n}^{sh}} \neq x_{j,n}^{P_{n}^{sh}}
\]

\[\text{s.t.} \sum_{j=1}^{24} \left( \sum_{n=1}^{K} P_{j,n}^{+} x_{j,n}^{P_{n}^{sh}} \leq \sum_{k=1}^{K} r P_{k,n}^{-} (\delta) \right), \forall r P_{k,n}^{-} \neq s P_{k,n}^{-}
\]

where \(x_{j,n}^{P_{n}^{sh}}\) are the binary integer decision variables for the users with surplus power in priority-based multiple criteria. These variables are used to update integer matrix of surplus power. The users having surplus power for sharing are denoted by \(x_{j,n}^{P_{n}^{sh}}\) and users who have shared their surplus power are represented as \(x_{j,n}^{P_{n}^{sh}}\). The surplus power at low per-unit cost is preferred first. The power deficient users who meet their shortages by power-sharing are denoted by \(s P_{k,n}^{-}\). The low priority-based power deficient users, still waiting for surplus power are represented by \(r P_{k,n}^{-}\). At any \(n^{th}\) specified timeslot, \(k^{th}\) users, facing power shortages, are prioritized using equation (10), and binary integer variables are updated to prioritize the remaining users.

\[r P_{k,n}^{-} (\delta) = \begin{cases} r P_{k,n}^{-} (\max(\text{cap}_{k,n})), & \text{if } \delta = 1, \\ r P_{k,n}^{-} (\max(\Phi_{k,n})), & \text{if } \delta = 2, \end{cases}\]

where \(\max(\text{cap}_{k,n})\) denotes the RER or ESS capacities of power deficient users. In multiple criteria, power is shared based on a certain priority parameter, \(\delta\). In (10), when \(\delta=1\), the single criterion is used to prioritize energy deficient users based on their 1) RER capacity, or 2) ESS capacity. In multiple criteria, \(\delta = 2\), the power deficient users are prioritized based on their overall contribution, \(\Phi_{k,n}\), which is presented in (11) as follows:

\[
\Phi_{k,n} = w_1 RC_{k,n} + w_2 SC_{k,n} - w_3 Z_{k,n} + w_4 \varsigma_{k,n},
\]

where, \(RC_{k,n}, SC_{k,n}, Z_{k,n}\) and \(\varsigma_{k,n}\) are RER capacity, ESS capacity, per unit selling cost and the power contribution of power deficient users in a day, respectively. The coefficient, \(w_1, w_2, w_3, \text{ and } w_4\) determine the comparative significance and the range of values is in between 0 and 1.

\[\text{Table 4: Capacities (kW) and Per-Unit Selling Cost (USD) of Users.}\]

| User  | User 2 | User 3 | User 4 | User 5 |
|-------|--------|--------|--------|--------|
| RER Capacity (kW) | 7      | 5      | 5      | 9      | 6      |
| ESS Capacity (kW)  | 9      | 7      | 6      | 5      |        |
| Selling Cost (USD) | 0.082  | 0.075  | 0.063  | 0.069  | 0.075  |

B. BINARY INTEGER PROGRAMMING WORKFLOW

The problem given in the objective function is combinatorial optimization problem for scheduling between the prosumers for energy management. To solve this scheduling problem, the proposed scheme employs a special case of linear integer programming i.e., BIP. The workflow of the proposed scheme is explained in Figure 3.

First, the input variables for the BIP are calculated. The total power for each user is determined by (1). The amount of surplus power held with each user is calculated using (2), while the power shortage is calculated in (3). The prosumers with surplus power \(P_{j,n}^{+}\), and the prosumers with power shortages \(P_{k,n}^{-}\) are the input variables in our problem. For the time horizon, \(N = (1, 2, 3, \ldots, 24)\), these variable values are provided to the BIP module.

In the integer linear programs, all the variables are required to be integers. However, in the BIP, the variables are restricted to the binary values 0 or 1. Therefore, in the initial stage of BIP, the energy surplus users are assigned with binary 1 and the energy deficit users are assigned with binary 0. There may be scenarios, where more than one prosumers are facing power deficiency. In this situation, more considerations are required for scheduling. Therefore, to tackle the multiple scenarios of the scheduling problem, the BIP is updated by introducing single and multiple criteria.

**Single-use Criterion**: In the scheduling based on a single-use criterion, the energy cost is minimized by maximizing the use of surplus power utilizing (5) and (6). The BIP prioritizes the power deficit users alternatively considering their renewable capacity or storage capacity parameters. In the absence of ESS, power deficit users are prioritized according to their RER capacity. The power deficit prosumers with higher RER capacity are assigned with higher priority in BIP. In the presence of ESS, the power deficit users are prioritized based on ESS capacity. However, for the scenario when power deficit users carry the same RER and ESS capacities, a single criterion becomes inadequate. To tackle such a situation, multiple criteria are introduced.

**Multiple-use Criteria**: In multiple-use criteria, power deficit users are prioritized by determining their overall contribution utilizing (11). This equation assists the BIP to determine the suitable priority order and to attain the desired objectives presented in (8) and (9). The inclusion of multiple criteria increases the fairness in scheduling and inspires the prosumers for community growth at a large scale. Finally, the BIP will terminate the scheduling task in 24 hours, for sharing maximum surplus power with power deficit users at each specified time slot.

Figure 3 highlights the BIP-based solution flow diagram for presented model. The surplus energy is shared with only a single user at a certain time slot to simplify the cost distribution calculation among users. In addition, we have to maximize the use of surplus power (if available) to minimize the energy expenses by using the weight factor, \(\alpha\). However, the system objectives are not dependent on the uncertainty in demand or supply side. The dynamic behavior of available resources like RER, ESS, and energy losses are not considered here for simplicity and to reduce the computational burden.
IV. PERFORMANCE EVALUATION – A CASE STUDY
In this section, the effectiveness of the proposed model is validated through extensive simulations. A case study is included to validate our proposed model. Sharing and management of power among five prosumers with RER and ESS at their end is analyzed in this case. Different constraints such as seasonal dynamics, energy losses, and depth of charging and discharging are not included in the system modeling for simplicity. Each user has a specified amount of grid supply, power demand, renewable generation, and stored power. The renewable power source (RER) may include wind turbines, solar panels, biogas to evaluate the compromise between the demand and the production. Figure 4 shows the renewable power (kW), stored power (kW), and the power demand (kW) of all users within the community for the time horizon \(N\).

The per-unit selling cost, RER, and ESS capacities of each user are listed in Table 4. It is clear from Table 4 that user 1 has a considerable RER and ESS capacities and will be a source of enough surplus power. The per unit selling cost of user 1 is assumed higher than other participants i.e., 0.082 USD. Generally, in the energy markets, surplus power is shared at low rate to earn more profit. However, while validating the effectiveness of proposed algorithm for making decisions in contradicting conditions: 1) remarkable ESS and RER capacities result into high priority and 2) high per unit selling cost claims low priority to prioritize a power deficient user, we assumed these values. The per-unit selling cost of user 3 is the lowest. Also, its power contribution is comparatively less because of the less generation and storage capacities. Moreover, user 2 and user 3 have the same RER capacities, while user 4 and user 5 have similar storage capacities.

Figure 5 shows the capacities and per-unit selling cost of users. Figure 6 mentions the demand-supply gap of 154kW for the prosumer community without ESS before optimization. The users have a different amount of surplus power as well as power shortage at various time slots that are estimated by using (2) and (3) respectively. Figure 7 shows that there is demand-supply gap of 45kW for the prosumer community with the inclusion of ESS before optimization. Now it’s clear that there is an obstinate reduction in power shortages with the inclusion of ESS. There is no discussion regarding communication technologies and infrastructures as these are beyond the scope of our study.

A. PRIORITY-BASED ON GENERATION CAPACITY
In this case, power deficit users are prioritized based on their RER generation capacity. The optimization is done using grid power and RER, in the absence of ESS. There is no storage system at users’ premises. Previously, the use of RER without ESS was not possible due to fluctuating nature of supply. However, with the advancements in power electronics devices, it is possible to use RER in the absence of ESS [32]. Therefore, we considered only RER for this sub-section Table 4 shows that user 4 has high RER capacity and will be preferred first for surplus power share to minimize the confronted power shortages. Hence, this priority criterion will be a source of motivation for other users to improve their RER capacity.

The per-unit selling price (USD) for energy trading with other users or grid is revealed in Figure 5. For instance, user 1 is charging a high price for his surplus energy share, while user 3 is the most economical to fulfill power needs. Hence, user 3 will be preferred for energy trading to minimize cost. It can be observed from Figures 6 and 8 that at 24th hour, user 2 and user 3 share their surplus power with user 4 because its renewable capacity is higher and per unit selling price is lower than user 1 and user 5 who are also facing energy shortages. Figure 8 depicts that there is a reduction in power shortages from 154kW to 90kW; 41.81% after optimization. The power profile is relatively balanced with only a few peaks. Figure 9 shows the percentage cost distribution, paid by energy deficit users, to minimize their energy shortages. User 1 is paying 48% of total cost; 2.24 USD. The individual cost contribution of user 1 is calculated by the multiplying its surplus power share with the per unit selling cost of different contributing sellers in a day. The sum of these individual costs result into the total cost.

B. PRIORITY-BASED ON STORAGE CAPACITY
In this criterion, the storage system is added at users’ premises and the optimization is done using grid power and RER with the inclusion of ESS to minimize power shortages at an optimal cost. These users have different storage capacities, shown in Figure 5, and get high priority based on their storage capacity. A sufficient amount of surplus power is required to bridge the demand-supply gap effectively. Figure 10 enlightens that there is a reduction from 45kW to 16.80kW in power shortages; 62.66% after optimization. Figure 11 reveals the percentage cost distribution of energy deficit users for a total cost of 2.05 USD to minimize their energy shortages. User 1 is paying 41% of the total cost due to its high power demand low assigned priority for surplus power share.

C. PRIORITY-BASED ON OVERALL CONTRIBUTION
In the case of more than one user with similar RER or storage capacities, the above-mentioned criterion is insufficient to prioritize the power deficit users without any conflict. In such a scenario, the multiple priority criteria based on overall contribution; per-unit selling price, storage and RER capacities, and maximum contribution at a specified timeslot are used according to (11). The weightage of all parameters is considered the same for simplicity.

\[ w_1 = w_2 = w_3 = w_4 = 1/4, \]  

Figure 12 shows the maximum surplus power contribution of each user at a specified timeslot. Figure 13 shows that a shortage reduction of 67.33% is observed after optimization; 45kW to 14.70kW. This reduction is due to the use of remaining surplus power optimally. The percentage cost distribution of total cost i.e., 2.20 USD among the power

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deficit users is shown in Figure 14. User 3 is paying the least amount, that is 5% of the total power cost, while user 1 has 51% contribution towards the total cost. The results show that the presented scheme is effective to reduce the demand-supply gap at an optimal cost. The inclusion of ESS has an obstinate effect on the power mismatch.

Table 5 presents the impact of the promoted study on percentage shortage reduction and the total cost paid by power deficit users. We have introduced the weight factor $\alpha$, while its value varies between 0 and 1 depending on the power requirements or economic concerns. For maximum utilization of surplus power at any cost, the weight factor will be equal to zero.

Table 6 presents the interconnection between the demand-supply gap and the total cost paid by energy deficit users for different values of $\alpha$. It clarifies that the cost can be reduced

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**TABLE 5. COMPARATIVE ANALYSIS OF SINGLE AND MULTIPLE CRITERIA ON OPTIMIZATION RESULTS.**

| Priority                   | Shortage Reduction | Total Cost(USD) |
|----------------------------|--------------------|-----------------|
| Single Criterion           |                    |                 |
| RER capacity (without ESS) | 41.8%              | 4.66            |
| RER capacity (With ESS)    | 62.66%             | 2.05            |
| Multiple Criteria          |                    |                 |
| Multiple factors like selling price, RER, storing capacity and contribution | 67.33% | 2.20 |

**FIGURE 4.** Renewable power, stored power (kW) and the power demand (kW) of all users.

**FIGURE 5.** Capacities and per-unit selling cost.
remarkably by making a compromise on the amount of power demand.

Table 7 shows the impact of large size prosumer community on proposed method to meet optimization goals. It is very clear from the table that by increasing the size of the community i.e., from 5-15 prosumers, the percentage shortage reduction from 67.33-79% is observed. The total cost paid by power deficient users has a linear relation. We intend to extend our work in the future by further expanding the size of the community and applying new optimization techniques that may improve the interactions between the prosumers.

| Weight Factor (α) | Power Deficit Reduction (%) | Power Cost (USD) |
|-------------------|-----------------------------|-----------------|
| 0                 | 67.33                       | 2.20            |
| 0.1               | 61.11                       | 1.99            |
| 0.2               | 42.44                       | 1.39            |
| 0.3               | 37.77                       | 1.23            |

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TABLE 7. THE IMPACT OF PROSUMERS COMMUNITY SIZE ON THE SYSTEM OBJECTIVES

| Prosumers | Priority                              | Shortage Reduction (%) | Total Cost(USD) |
|-----------|--------------------------------------|------------------------|-----------------|
| 5         | RER capacity (without ESS)           | 41.8                   | 4.66            |
|           | ESS capacity                          | 62.66                  | 2.05            |
|           | Overall contribution                  | 67.33                  | 2.20            |
| 10        | RER capacity (without ESS)           | 46.85                  | 9.52            |
|           | ESS capacity                          | 66.66                  | 3.96            |
|           | Overall contribution                  | 75                     | 4.45            |
| 15        | RER capacity (without ESS)           | 49                     | 14.52           |
|           | ESS capacity                          | 70                     | 6.08            |
|           | Overall contribution                  | 79                     | 6.84            |

V. CONCLUSION

This paper promotes, priority-based power sharing, and management approach coupled with storage systems within a prosumer community. We have considered a community of five prosumers to validate our system model and it can be extended to a larger system. BIP is used as an optimization technique to maximize the surplus power sharing at minimum cost within a community. The power deficit users are prioritized on the basis of RER capacity, ESS capacity and their overall contribution. The outcome shows that power shortages can be minimized up-to 41.8% without ESS and 67.33% with the addition of storage systems after the optimization. The weight factor $\alpha$ is culminated to find the interconnection between demand-supply gap and the total cost paid by power deficit users. The prosumer communities are facing many challenges, especially in developing nations; privacy issues, high cost of RER and ESS, insufficient communication and distribution infrastructure for supporting bi-directional flow of data or energy exchange. However, the presented model is progressive, economic, innovative, valid and autonomous like all other previous studies ever since.

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FIGURE 13. Surplus/shortage power with ESS after optimization.

FIGURE 14. Cost distribution.

(No. 2019R1F1A1059125).

REFERENCES

[1] P. A. O'Connor and C. J. Cleveland, “Us energy transitions 1780–2010,” Energies, vol. 7, no. 12, pp. 7955–7993, 2014.

[2] E. Abdelaziz, R. Saïdard, and S. Mehkhilef, “A review on energy saving strategies in industrial sector,” Renewable and sustainable energy reviews, vol. 15, no. 1, pp. 150–168, 2011.

[3] E. G. Allan, M. C. Kander, I. Carmichael, and E. F. Garman, “To scavenge or not to scavenge, that is still the question,” Journal of synchrotron radiation, vol. 20, no. 1, pp. 23–36, 2013.

[4] S. S. Amjid, M. Q. Bilal, M. S. Nazir, and A. Hussain, “Biogas, renewable energy resource for pakistan,” Renewable and Sustainable Energy Reviews, vol. 15, no. 6, pp. 2833–2837, 2011.

[5] C. Cobb, T. Halstead, and J. Rowe, The genuine progress indicator: summary of data and methodology. Redefining Progress San Francisco, 1995, vol. 15.

[6] F. Orecchini and A. Santiangeli, “Beyond smart grids–the need of intelligent energy networks for a higher global efficiency through energy vectors integration,” International Journal of hydrogen energy, vol. 36, no. 13, pp. 8126–8133, 2011.

[7] A. Skoglund, M. Leijon, A. Rehn, M. Lindahl, and R. Waters, “On the physics of power, energy and economics of renewable electric energy sources-part ii,” Renewable energy, vol. 35, no. 8, pp. 1735–1740, 2010.

[8] A. Schwarzenegger, “Integrating new and emerging technologies into the california smart grid infrastructure,” 2008.

[9] N. Zhang, Y. Yan, and W. Su, “A game-theoretic economic operation of residential distribution system with high participation of distributed electricity prosumers,” Applied energy, vol. 154, pp. 471–479, 2015.

[10] W. Tushar, T. K. Saha, C. Yuen, T. Morstyn, M. D. McCulloch, H. V. Poor, and K. L. Wood, “A motivational game-theoretic approach for peer-to-peer energy trading in the smart grid,” Applied energy, vol. 243, pp. 10–20, 2019.

[11] A. D. Rathnayaka, V. M. Potdar, and S. J. Kuruppu, “An innovative approach to manage prosumers in smart grid,” in 2011 World Congress on Sustainable Technologies (WCST). IEEE, 2011, pp. 141–146.

[12] P. G. Da Silva, S. Karnouskos, and D. Ilic, “A survey towards understanding residential prosumers in smart grid neighbourhoods,” in 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe). IEEE, 2012, pp. 1–8.

[13] S. M. Souza, M. Gil, J. Sumaili, A. G. Madureira, and J. P. Lopes, “Operation scheduling of prosumer with renewable energy sources and storage devices,” in 2016 13th International Conference on the European Energy Market (EEM). IEEE, 2016, pp. 1–5.

[14] S. Karnouskos, “Demand side management via prosumer interactions in a smart city energy marketplace,” in 2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies. IEEE, 2011, pp. 1–7.

[15] A. D. Rathnayaka, V. M. Potdar, T. S. Dillon, O. K. Hussain, and E. Chang, “A methodology to find influential prosumers in prosumer community groups,” IEEE Transactions on Industrial Informatics, vol. 10, no. 1, pp. 706–713, 2013.

[16] L. Gkatzikis, G. Iosifidis, I. Koutspoulos, and L. Tassialas, “Collaborative placement and sharing of storage resources in the smart grid,” in 2014 IEEE International Conference on Smart Grid Communications (SmartGridComm). IEEE, 2014, pp. 103–108.

[17] A. Gautier, J. Jacqmin, and J.-C. Poudou, “The prosumers and the grid,” Journal of Regulatory Economics, vol. 53, no. 1, pp. 100–126, 2018.

[18] G. Buist, S. Pront-van Bonnel et al., “Smart grids: naar een gedifferentieerdel distributiestelsel,” 2010.

[19] I. Lampropoulos, G. M. Vanalme, and W. L. Kling, “A methodology for modeling the behavior of electricity prosumers within the smart grid,” in 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe). IEEE, 2010, pp. 1–8.

[20] B. Dursun and C. Gokcol, ‘Impacts of the renewable energy law on the developments of wind energy in turkey,” Renewable and Sustainable Energy Reviews, vol. 40, pp. 318–325, 2014.

[21] J. Cools, S. Broekx, V. Vandenberghe, H. Sels, E. Meynaerts, P. Vercaemst, P. Seuntjens, S. Van Hulle, H. Wustenberghs, W. Bauwens et al., “Coupling a hydrological water quality model and an economic optimization model to set up a cost-effective emission reduction scenario for nitrogen,” Environmental Modelling & Software, vol. 26, no. 1, pp. 44–51, 2011.

[22] L. Brand, A. Calcén, J. Englund, H. Landersjö, and P. Lauenburg, “Smart district heating networks–a simulation study of prosumers’ impact on technical parameters in distribution networks,” Applied Energy, vol. 129, pp. 39–48, 2014.

[23] T. Logenthiran, D. Srinivasan, and T. Z. Shun, “Demand side management in smart grid using heuristic optimization,” IEEE transactions on smart grid, vol. 3, no. 3, pp. 1244–1252, 2012.

[24] B.-C. Neagu, O. Ivanov, G. Grigoras, and M. Gavrila, “A new vision on the prosumers energy surplus trading considering smart peer-to-peer contracts,” Mathematics, vol. 8, no. 2, p. 235, 2020.

[25] H. AlSalloum, R. Rahim, and L. Merghem-Boulahia, “Prioritizing prosumers in the energy trading mechanism: A game theoretic approach,” in 2019 International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob). IEEE, 2019, pp. 1–5.

[26] A. Jiang, H. Yuan, and D. Li, “A two-stage optimization approach on the prosumers energy surplus trading considering smart peer-to-peer,” in 2019 International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob). IEEE, 2019, pp. 1–5.

[27] M. Qi, H. Yang, D. Wang, Y. Luo, S. Zhang, and S. Liao, “Prosumers peer-to-peer transaction decision considering network constraints,” in 2019 IEEE Access.
IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2). IEEE, 2019, pp. 643–647.

[28] Z. Zhang, H. Tang, J. Ren, Q. Huang, and W.-J. Lee, “Strategic prosumers-based peer-to-peer energy market design for community microgrids,” IEEE Transactions on Industry Applications, vol. 57, no. 3, pp. 2048–2057, 2021.

[29] S. Razzaq, R. Zafar, N. A. Khan, A. R. Butt, and A. Mahmood, “A novel prosumer-based energy sharing and management (pesm) approach for cooperative demand side management (dsm) in smart grid,” Applied Sciences, vol. 6, no. 10, p. 275, 2016.

[30] N. Shaukat, B. Khan, S. Ali, C. Mehmood, J. Khan, U. Farid, M. Majid, S. Anwar, M. Jawad, and Z. Ullah, “A survey on electric vehicle transportation within smart grid system,” Renewable and Sustainable Energy Reviews, vol. 81, pp. 1329–1349, 2018.

[31] J. Ubertalli and T. Littler, “Proven energy storage system applications for power systems stability and transition issues,” in Predictive Modelling for Energy Management and Power Systems Engineering. Elsevier, 2021, pp. 85–114.

[32] D. Pandit, A. Muhtadi, and N. Nguyen, “Reliability evaluation of photovoltaic and energy storage integrated systems with frequency security constraint,” in 2020 52nd North American Power Symposium (NAPS). IEEE, 2021, pp. 1–6.