A Revenue-Cost Sharing Methodology for the Peer-to-Peer Energy Trading in a Residential Community

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***Abstract*—Generally, the low selling price of energy to the utility has increased local prosumers' tendency to exchange their surplus power with their neighbors at the distribution level. Nonetheless, to this end, providing an appropriate paradigm based on Peer-to-Peer (P2P) energy trading is highly required. Accordingly, this research work seeks to present a new revenue-cost sharing methodology for trading the generated energy as well as the storage capacity of several types of households with one another in a residential community. The proposed algorithm implements an energy management program in a way to not only optimize the performance of the residential community but also minimize its total operating costs. On the other hand, to determine the P2P electricity price and calculate the electricity cost of each household, one pricing mechanism according to traded powers is employed in this study. In the end, to assess the efficiency of the raised P2P framework, the optimal operation of a typical community in the presence of wide ranges of real as well as virtual resources in two case studies, without and with considering P2P energy sharing, is investigated and compared.**

Keywords— Peer-to-Peer energy trading, Revenue-cost sharing methodology, Pricing mechanism, Residential community, Household

Nomenclature

Acronyms	
BS	Battery Storage
DER	Distributed Energy Resource
DRP	Demand Response Program
P2P	Peer-to-Peer
PV	Photovoltaic System
WT	Wind Turbine
Sets and Indices	
$h \in H$	Households
$t \in T$	Times
Parameters	
D	Electricity demand of households (kW)
DR_{shdn}^{max}, DR_{shup}^{max}	Maximum percentage of shiftable power in DRPs (%)
P_{ch}^{max}, P_{ch}^{min}	Maximum/minimum charge power of BSs (kW)
P_{dch}^{max}, P_{dch}^{min}	Maximum/minimum discharge power of BSs (kW)
P_{PV}	Produced power of PVs (kW)
P_{WT}	Produced power of WTs (kW)
SOC^{fi}, SOC^{in}	Final/initial amount of store energy in BSs (kWh)
SOC^{max}, SOC^{min}	Maximum/minimum amount of store energy in BSs (kWh)
λ_{exp}, λ_{imp}	Electricity price of the export/import power to/from the utility ($/kWh)
η_{ch}, η_{dch}	Charge/discharge efficiency of BSs (%)
Variables	
C, C^{P2P}	Households' consumption without/with considering P2P program (kW)
$Cost$, $Cost^{P2P}$	Households' electricity cost without/with considering P2P program ($/day)
$Cost_{com}$, $Cost_{com}^{P2P}$	Community's operating cost without/with considering P2P program ($/day)
G, G^{P2P}	Households' generation without/with considering P2P program (kW)
O, O^{P2P}	Households' overlap of generation and consumption without/with considering P2P program (kW)
P_{ch}, P_{dch}	Charge/discharge power of BSs without considering P2P program (kW)
P_{ch}^{P2P}, P_{dch}^{P2P}	Charge/discharge power of BSs with considering P2P program (kW)
P_{exp}, P_{imp}	Export/import power of households to/from the utility without considering P2P program (kW)
P_{exp}^{com}, P_{imp}^{com}	Export/import power of the community to/from the utility without considering P2P program (kW)
P_{exp}^{P2P}, P_{imp}^{P2P}	Export/import power of the community to/from the utility with considering P2P program (kW)
P_{shdn}, P_{shup}	Shift up/shift down power of households in DRPs without considering P2P program (kW)
P_{shdn}^{P2P}, P_{shup}^{P2P}	Shift up/shift down power of households in DRPs with considering P2P program (kW)
SOC	Energy stored in BSs (kWh)
λ_{exp}^{P2P}, λ_{imp}^{P2P}	P2P electricity price of the export/import power to/from the utility ($/kWh)
U_{BS}, U_{DR}	BSs/DRPs operation status (0 or 1)

I. Introduction

Typically, in traditional power systems, distribution system-connected household customers receive their energy from the upstream network as passive players [1]. Nevertheless, with the rapid development of distributed energy resources (DERs) at the low-voltage distribution network, customers have gradually become prosumers with their own generation and storage capacities at the local level [2]. These prosumers, as active entities in future power systems, have the ability to not only procure their needed energy but also sell their excess to the utility grid. However, owing to networks' costs, the tariff for the purchased power from the utility is much higher than the buy-back rate that prosumers could achieve from selling surplus energy to the grid [3]. Hence, these players are not able to gain a considerable amount of income through the selling process. For dealing with this challenge, quite recently, a new concept called P2P energy trading to exchange power between prosumers or peers has been proposed. Accordingly, the P2P energy trading model presents an environment in which consumers and producers can compensate for their shortage or supply their excess energy directly, without the presence of an intermediary entity, at agreed prices [4]. In general, energy exchange based on the P2P schemes not only leads to an increase in deployment of local DERs and the system's flexibility but also promotes profit received by peers [5].

In the last few years, various frameworks have been provided to execute P2P-based energy exchange at the residential level, some of them are reported in the following:

A new P2P structure has been developed in [6] to optimize the performance of the grid-connected PV-based prosumers under the Time-of-Use tariff. In the provided scheme, the energy trading costs of prosumers are minimized by maximizing the usage of their own generated energy prior to sharing it with other peers. To model the internal energy exchange among prosumers, a fixed-rate pricing algorithm has been used in this study. A hierarchical P2P approach has been exploited in [7] to enhance the local energy exchange in community microgrid systems. The raised P2P model has been implemented in three different levels, including energy exchange among nanogrids in a microgrid network, among microgrids in a multi-microgrid network, and ultimately, among several multi-microgrid networks. A novel algorithm has been introduced in this work to determine the internal energy sharing prices. A pragmatic framework has been presented in [8] to guide various types of prosumers for trading energy in the P2P platform. The considered optimization-based P2P scheme seeks to reduce the total operating costs of the existing prosumers. In this article, transaction prices in the P2P energy trading have been calculated according to the excess power of each prosumer which is obtained from the utilized optimization problem. One programming scheme has been suggested in [9] for optimizing the P2P energy sharing among multiple prosumers in a local community. This problem's objective function is to improve the social welfare of the studied community with respect to every household's willingness-to-pay for trading energy inside the system instead of exchanging energy with the upstream grid. Accordingly, willingness-to-pay is related to retail electricity price as well as avoiding emissions. An operational mechanism has been proposed in [10] for the P2P energy exchange among different prosumers that are mainly equipped with charging stations and PV generations. In this regard, a new dynamic pricing method based on prices of the stored energy in electric vehicles has been established to specify the involvement of prosumers in the P2P program. The raised pricing scheme in this paper has the ability to not only improve the expected profit of electric vehicle owners but also enhance their contributions to P2P energy sharing.

Based on privileges that arise from P2P energy trading, this paper proposes a new P2P-based platform for energy exchange in a residential community with multiple households. The studied community comprises both consumer-based as well as prosumer-based households [11]. Prosumer-based households are equipped with several real DERs, i.e., rooftop Photovoltaic Systems (PVs) and Wind Turbines (WTs), as well as virtual DERs, i.e., small-scale Battery Storages (BSs) and Demand Response Programs (DRPs). In order to implement the considered P2P paradigm among members of the community, a revenue-cost sharing approach is suggested, in which peers sell/purchase the system's total amount of surplus/shortage energy to/from the utility via performing optimization for the energy management program. The energy management program is performed in a way to minimize the residential community's overall operating costs by enabling the trade of power between members. In this method, each household's contribution to the total amount of traded energy with the grid is specified. Furthermore, in this research work, a pricing mechanism based on traded powers is presented to determine the P2P electricity price and calculate the electricity cost of individual households. Finally, to evaluate the effectiveness of the suggested P2P framework in reducing costs of the community as well as the existing members, its output results are compared with a situation in which each household conducts its energy management program independently.

Fig. 1 displays the P2P energy sharing architecture within a residential community.

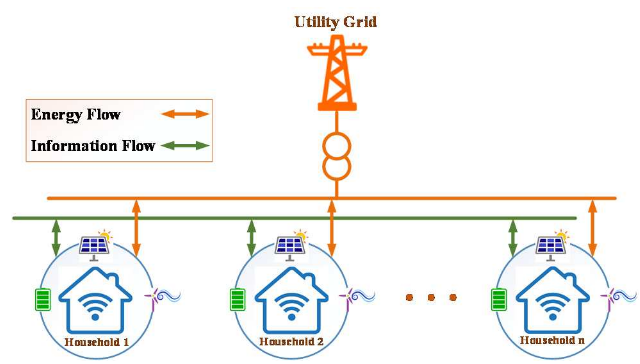

Fig. 1. Structure of P2P energy trading.

II. Methods and Materials

In this part of the paper, the implementation of the proposed revenue-cost sharing paradigm for P2P energy exchange in a residential community is described in more detail. Accordingly, in the first step, the energy management program of each household located in the community is optimized autonomously. In the second step, the energy management program of the whole community is carried out to optimize the system's traded energy with the utility grid. In the last step, one pricing mechanism is exploited to not only determine the P2P electricity price but also compute the electricity cost of households. To better understand the considered revenue-cost sharing algorithm, its outline is illustrated in the form of a flowchart as well.

A. *Community operation without P2P energy trading*

In this section, it is assumed that households are traded their excess or shortage energy with the utility grid individually. The energy management program of these households is adjusted in a way to minimize the total operating costs of the whole community. The objective function of this optimization problem is expressed by Eq. (1).

$$\text{Cost}_{\text{com}}=\text{Min}\sum_{h=1}^{H}\sum_{t=1}^{T}\left\{P_{\text{imp}}(h,t)\cdot\lambda_{\text{imp}}(t)-P_{\text{exp}}(h,t)\cdot\lambda_{\text{exp}}(t)\right\} \quad (1)$$

Since every household is administered separately, its total generation and consumption at each time interval can be expressed by Eqs (2) and (3), respectively.

$$G(h,t)=P_{\text{PV}}(h,t)+P_{\text{WT}}(h,t)+P_{\text{dch}}(h,t)+P_{\text{shdn}}(h,t)\ ;\ \forall h,t \quad (2)$$

$$C(h,t)=D(h,t)+P_{\text{ch}}(h,t)+P_{\text{shup}}(h,t)\ ;\ \forall h,t \quad (3)$$

It is noteworthy that in Eq. (2), P_{PV} and P_{WT} are computed according to expressions presented in [12] and [13].

The amount of export or import power of every household at each time interval is determined by Eqs (4)-(6).

$$O(h,t)=\begin{cases}C(h,t)\ ,\ C(h,t)\le G(h,t)\\ G(h,t)\ ,\ G(h,t)<C(h,t)\end{cases};\ \forall h,t \quad (4)$$

$$P_{\text{exp}}(h,t)=G(h,t)-O(h,t)\ ;\ \forall h,t \quad (5)$$

$$P_{\text{imp}}(h,t)=C(h,t)-O(h,t)\ ;\ \forall h,t \quad (6)$$

BSs' operational constraints, including charge/discharge power as well as stored energy limitations, are stated by Eqs (7)-(12).

$$\begin{aligned}&P_{\text{ch}}^{\min}(h)\cdot U_{\text{BS}}(h,t)\le P_{\text{ch}}(h,t)\ ;\ \forall h,t\\ &P_{\text{ch}}(h,t)\le P_{\text{ch}}^{\max}(h)\cdot U_{\text{BS}}(h,t)\ ;\ \forall h,t\end{aligned} \quad (7)$$

$$\begin{aligned}&P_{\text{dch}}^{\min}(h)\cdot(1-U_{\text{BS}}(h,t))\le P_{\text{dch}}(h,t)\ ;\ \forall h,t\\ &P_{\text{dch}}(h,t)\le P_{\text{dch}}^{\max}(h)\cdot(1-U_{\text{BS}}(h,t))\ ;\ \forall h,t\end{aligned} \quad (8)$$

$$SOC(h,t)=SOC^{\text{in}}(h)\ ;\ \forall h,t=1 \quad (9)$$

$$\begin{aligned}SOC(h,t+1)=&SOC(h,t)+P_{\text{ch}}(h,t)\cdot\eta_{\text{ch}}(h)\\ &-P_{\text{dch}}(h,t)/\eta_{\text{dch}}(h)\ ;\ \forall h,t<24\end{aligned} \quad (10)$$

$$\begin{aligned}SOC^{\text{fi}}(h)=&SOC(h,t)+P_{\text{ch}}(h,t)\cdot\eta_{\text{ch}}(h)\\ &-P_{\text{dch}}(h,t)/\eta_{\text{dch}}(h)\ ;\ \forall h,t=24\end{aligned} \quad (11)$$

$$SOC^{\min}(h)\le SOC(h,t)\le SOC^{\max}(h)\ ;\ \forall h,t \quad (12)$$

Ultimately, constraints related to shiftable DRPs are illustrated by Eqs (13)-(15) [14].

$$0\le P_{\text{shup}}(h,t)\le DR_{\text{shup}}^{\max}(h)\cdot D(h,t)\cdot U_{\text{DR}}(h,t)\ ;\ \forall h,t \quad (13)$$

$$0\le P_{\text{shdn}}(h,t)\le DR_{\text{shdn}}^{\max}(h)\cdot D(h,t)\cdot(1-U_{\text{DR}}(h,t))\ ;\ \forall h,t \quad (14)$$

$$\sum_{t=1}^{T}P_{\text{shup}}(h,t)=\sum_{t=1}^{T}P_{\text{shdn}}(h,t)\ ;\ \forall h \quad (15)$$

B. Community operation with P2P energy trading

In this section, it is presumed that the energy management program of the whole community is optimized through the optimal usage of available DERs to minimize the system's overall operating costs. In this approach, it is possible for every household to exchange its excess or shortage power with the existing peers/neighbors within the community. The objective function of this optimization problem is depicted by Eq. (16).

$$\text{Cost}_{\text{com}}^{\text{P2P}}=\text{Min}\sum_{t=1}^{T}\left\{P_{\text{imp}}^{\text{P2P}}(t)\cdot\lambda_{\text{imp}}(t)-P_{\text{exp}}^{\text{P2P}}(t)\cdot\lambda_{\text{exp}}(t)\right\} \quad (16)$$

The first term of the above expression is related to the cost of the community's import power from the utility. On the contrary, the second term is related to the income of the community's export power to the grid.
Total generation and consumption of the residential community at each time interval can be displayed by Eqs (17) and (18), respectively.

$$\begin{aligned}G^{\text{P2P}}(t)=&\sum_{h=1}^{H}\{P_{\text{PV}}(h,t)+P_{\text{WT}}(h,t)\\ &+P_{\text{dch}}^{\text{P2P}}(h,t)+P_{\text{shdn}}^{\text{P2P}}(h,t)\}\ ;\ \forall t\end{aligned} \quad (17)$$

$$C^{\text{P2P}}(t)=\sum_{h=1}^{H}\left\{D(h,t)+P_{\text{ch}}^{\text{P2P}}(h,t)+P_{\text{shup}}^{\text{P2P}}(h,t)\right\}\ ;\ \forall t \quad (18)$$

The amount of export or import power of the whole community at each time interval is determined by Eqs (19)-(21).

$$O^{\text{P2P}}(t)=\begin{cases}C^{\text{P2P}}(t)\ ,\ C^{\text{P2P}}(t)\le G^{\text{P2P}}(t)\\ G^{\text{P2P}}(t)\ ,\ G^{\text{P2P}}(t)<C^{\text{P2P}}(t)\end{cases};\ \forall t \quad (19)$$

$$P_{\text{exp}}^{\text{P2P}}(t)=G^{\text{P2P}}(t)-O^{\text{P2P}}(t)\ ;\ \forall t \quad (20)$$

$$P_{\text{imp}}^{\text{P2P}}(t)=C^{\text{P2P}}(t)-O^{\text{P2P}}(t)\ ;\ \forall t \quad (21)$$

In addition, operational constraints of the BSs and DRPs are similar to stated expressions in Eqs (7)-(15).

C. Pricing mechanism in P2P energy trading

To specify the share of each individual household in the total amount of P2P energy exchange, it is required to determine export and import P2P electricity prices. To this end, the export and import powers of the community with and without considering the P2P option as well as electricity price of traded powers with the utility grid are utilized.

In this regard, export power of the community to the utility as well as import power of the community from the grid in the presence of P2P energy exchange are obtained by Eqs (20) and (21), respectively.

Moreover, export power of the community to the utility as well as import power of the community from the grid in the absence of P2P energy exchange are achieved by Eqs (22) and (23), respectively.

$$P_{\text{exp}}^{\text{com}}(t)=\sum_{h=1}^{H}P_{\text{exp}}(h,t)\ ;\ \forall t \quad (22)$$

$$P_{\text{imp}}^{\text{com}}(t)=\sum_{h=1}^{H}P_{\text{imp}}(h,t)\ ;\ \forall t \quad (23)$$

According to the aforementioned expressions, P2P electricity prices are computed by Eqs (24) and (25). Clearly, these prices depend on the ratio of traded power with and without considering the P2P option as well as the utility's electricity prices.

$$\lambda_{\text{exp}}^{\text{P2P}}(t)=\lambda_{\text{exp}}(t)\cdot\frac{P_{\text{exp}}^{\text{P2P}}(t)}{P_{\text{exp}}^{\text{com}}(t)}\ ;\ \forall t \quad (24)$$

$$\lambda_{\text{imp}}^{\text{P2P}}(t)=\lambda_{\text{imp}}(t)\cdot\frac{P_{\text{imp}}^{\text{P2P}}(t)}{P_{\text{imp}}^{\text{com}}(t)}\ ;\ \forall t \quad (25)$$

On the other hand, based on the calculated P2P electricity prices, each individual household's electricity cost in the presence of the P2P energy sharing option could be specified by Eq. (26).

$$\text{cost}^{P2P}(h) = \sum_{t=1}^{T} \left\{ P_{imp}(h,t) \cdot \lambda_{imp}^{P2P}(t) - P_{exp}(h,t) \cdot \lambda_{imp}^{P2P}(t) \right\} \quad \forall h \qquad (26)$$

For a better comparison, each household's electricity cost in the absence of the P2P energy trading option could be determined by Eq. (27) as well.

$$\text{cost}(h) = \sum_{t=1}^{T} \left\{ P_{imp}(h,t) \cdot \lambda_{imp}(t) - P_{exp}(h,t) \cdot \lambda_{exp}(t) \right\}; \forall h \qquad (27)$$

In the end, to summarize the mentioned steps, the outline of the presented revenue-cost sharing algorithm for P2P energy trading in communities is indicated in Fig. 2. In this Fig., effective parameters and decision variables are demonstrated.

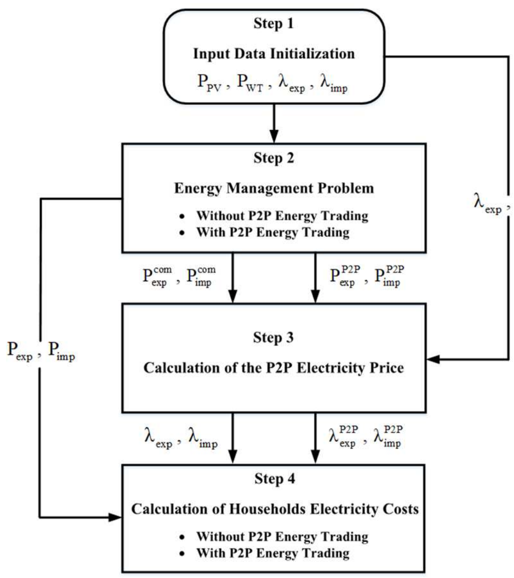

Fig. 2. Scheme of revenue-cost sharing methodology.

III. Results

To assess the role of the P2P energy sharing option in residential communities' energy management program, households' electricity costs are investigated and compared in two cases, with and without considering P2P energy exchange among members. For this aim, a typical community that consists of 10 households is considered. Technical specifications of DERs located in these households are summarized in Table 1.

Table 1. Characteristics of the existing DERs inside the community.

# H	PVs	WTs		BSs			DRPs
	$P_{PV,r}$	$P_{WT,r}$	$V_{WT,r}$	P_{ch}^{max} / P_{dch}^{max}	SOC^{max} / SOC^{min}	η_{ch} / η_{dch}	DR_{shdn}^{max} / DR_{shup}^{max}
1	–	3	12	–	–	–	–
2	–	3	12	–	–	–	0.10
3	–	3	12	–	–	–	0.15
4	–	–	–	2	10 , 1	0.95	0.10
5	–	–	–	2	10 , 1	0.95	–
6	5	–	–	–	–	–	0.10
7	5	–	–	–	–	–	–
8	5	–	–	–	–	–	0.15
9	5	–	–	–	–	–	–
10	7.5	–	–	1	5 , 0.5	0.95	–

Load profiles of studied households are shown in Fig. 3. Also, prices of the export/import power to/from the utility are demonstrated in Fig. 4. As it is clear in Fig. 4, the export electricity price is one-third of the import electricity price.

Traded power of the community with the utility with and without P2P option are compared in Fig. 5-A and 5-B. As shown, in the presence of P2P energy sharing, the community has exported its excess power to the utility in only two hours of the day, hours 10 and 12. However, in the absence of P2P energy exchange, the community has exported its excess power to the utility in most hours of the day. The reason is that individual households tend to sell their surplus power to the utility when the generation is higher than the consumption. On the other hand, the community's import power with the P2P option is lower than its power without the P2P option. That is because, in the presence of P2P energy trading, maximum and optimal usage of generation units and storage capacities have been made.

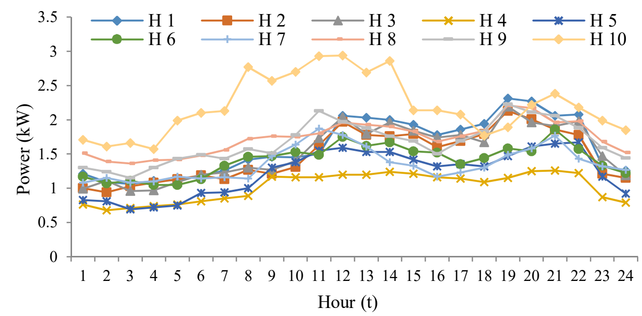

Fig. 3. Households' load profiles.

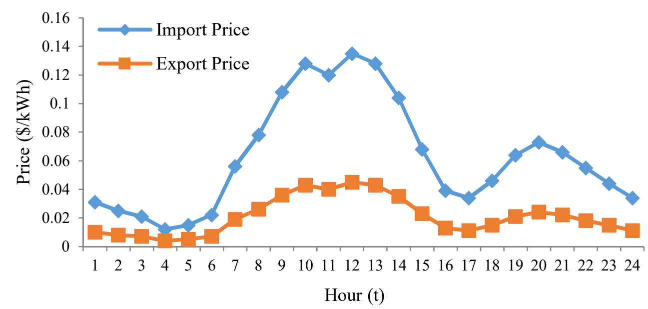

Fig. 4. Utility grid's electricity prices.

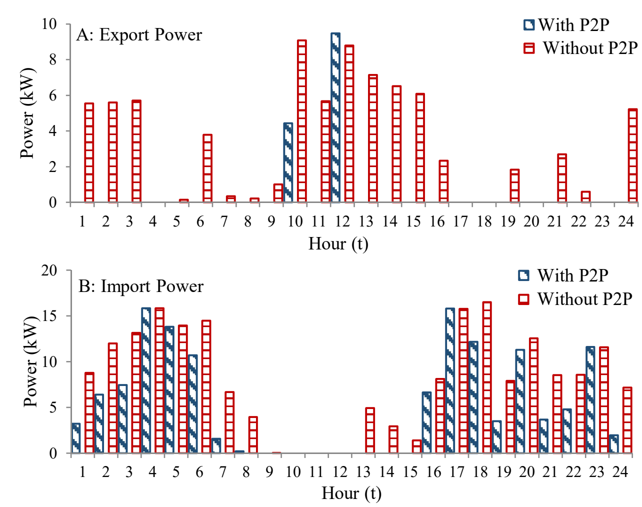

Fig. 5. Community's traded power with the utility grid.

To better clarify the impact of virtual DERs in P2P energy sharing, the operation of BSs, as well as load profiles of households in DRPs, are evaluated for a sample household, household 4, in Fig. 6 and Fig. 7, respectively. As shown in Fig. 6-A and 6-B, in P2P energy exchange, the storage capacity of the BS has been utilized more since in this case, the whole community is able to exploit from the battery unit of household 4. It is notable that for the sake of simplicity, in this work, the degradation of BSs has been neglected.

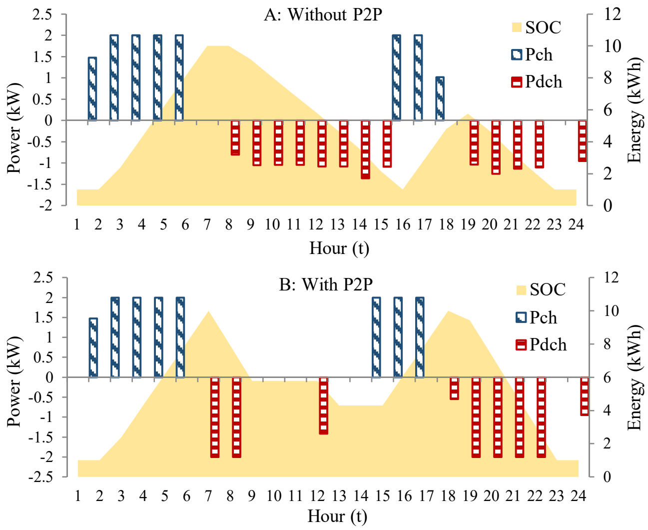

Fig. 6. BS system's performance in household 4.

Moreover, in P2P energy exchange, the shift down capacity of household 4 in DRP has been utilized more during hours 18-23. The reason is that, at these hours, the whole community's total consumption is high as well.

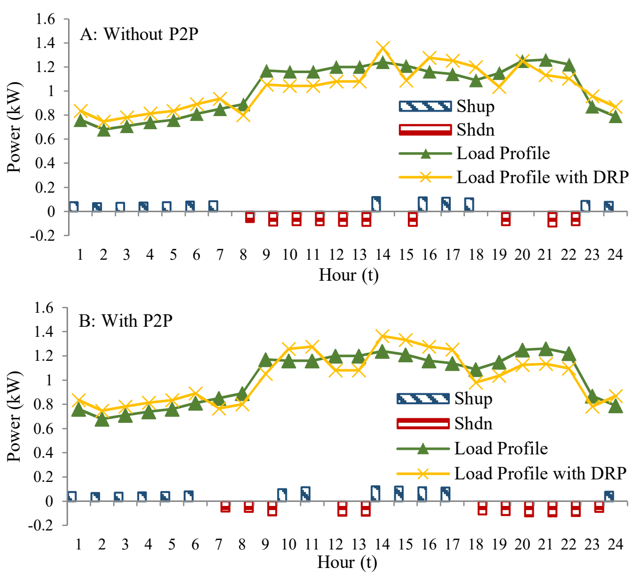

Fig. 7. DRP's performance in household 4.

The daily operation of household 4's virtual DERs, i.e., BSs and DRPs, in both cases, with and without considering the P2P option, is compared with each other in Table 2.

According to Table 2, in the existence of the P2P platform, the amount of charge and discharge energy of the BS has increased 6.8 % and 6.4 %, respectively. Furthermore, by providing the P2P platform, household 4's shifted energy in the DRP has enhanced 5.2 %.

Table 2. Comparison of virtual DERs' performance in household 4.

	Without P2P	With P2P	Variation (%)
Charge energy (kWh/day)	14.49	15.47	6.80
Discharge energy (kWh/day)	14.02	14.92	6.40
Shift up/down energy (kWh/day)	1.16	1.22	5.20

As pointed out in section 2, to compute the electricity cost of individual households in the presence of P2P energy trading, determining P2P electricity prices through the presented algorithm in Fig. 2 is necessary. Accordingly, Fig. 8 indicates P2P import and export electricity prices during a studied day.

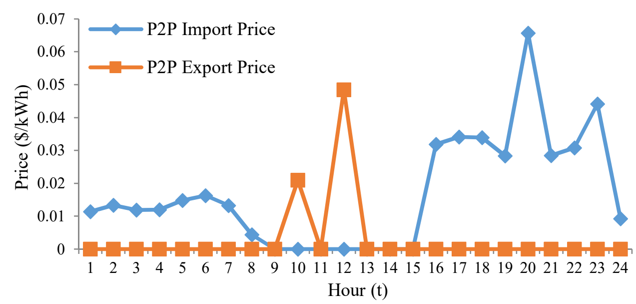

Fig. 8. P2P electricity prices.

As shown in Fig. 8, due to the community's exported power in hours 10 and 12, the P2P export prices in these two hours are non-zero.

By utilizing the provided P2P prices in Fig. 8, each household's electricity cost in the presence of P2P energy sharing is computed and compared with its electricity cost in the absence of P2P energy exchange. In this regard, individual households and also the community's traded energy with the utility grid as well as their daily costs are reported in more detail in Table 3.

According to Table 3, the whole community's export and import energy in the presence of the P2P option has increased as opposed to its traded energy in the absence of the P2P option. Concerning the electricity costs, it is observed that the existing households' daily electricity costs with the P2P energy trading have decreased remarkably. The largest cost reductions are related to households 1, 2, and 3 that are equipped with WTs. On the contrary, the lowest cost reductions are associated with households 5 and 6 that are equipped with PVs. The reason is that PVs' production is in line with the peak of the consumption and import price, while it is not the case for WTs. Hence, considering the P2P option, households equipped with WTs consume more energy from the community's PV production in peak hours. Moreover, the total operating cost of the residential community with P2P energy trading has decreased from 6.93 $ to 4.37 $. This issue results from the reduction in import energy from the utility grid. This amount of cost reduction is approximately equal to 37 %, which indicates the success of the suggested revenue-cost sharing methodology in this research work.

Table 3. Traded energy as well as daily costs of households and the community.

# Household	Without P2P			With P2P			Cost Variation (%)
	Export Energy (kWh/day)	Import Energy (kWh/day)	Daily Cost ($/day)	Export Energy (kWh/day)	Import Energy (kWh/day)	Daily Cost ($/day)	
H 1	14.31	12.12	0.61	14.31	12.12	0.25	-59.30
H 2	15.15	9.63	0.36	15.94	10.42	0.16	-54.20
H 3	13.79	9.59	0.37	15.04	10.85	0.16	-56.70
H 4	0.08	25.01	0.75	6.46	31.49	0.54	-27.50
H 5	0.03	30.04	1.10	4.03	34.24	0.62	-43.00
H 6	7.39	18.03	0.60	7.39	18.04	0.48	-19.50
H 7	8.20	17.65	0.61	8.20	17.65	0.47	-22.50
H 8	5.12	23.50	0.91	5.12	23.50	0.67	-26.30
H 9	6.01	22.76	0.97	6.01	22.76	0.56	-42.60
H 10	8.25	26.69	0.67	8.42	26.79	0.46	-32.30
Community	78.33	195.02	6.93	90.92	207.85	4.37	-36.90

IV. Conclusion

By increasing the penetration of several DERs at the distribution level, prosumers are able to exchange their surplus generated energy with their neighbors. To this end, a pragmatic framework, namely revenue-cost sharing methodology, was presented in this article for implementing P2P energy trading among members of a residential community. In addition, one pricing mechanism based on traded powers was suggested to calculate P2P import and export electricity prices. In the end, to scrutinize the effectiveness of the raised scheme, it was tested on a community with 10 different households to investigate the whole community's operating cost as well as each household's electricity cost. It was observed that, by adding the P2P energy exchange to the energy management program of the community, not only its operating costs but also electricity costs of the entire households are diminished considerably.

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