Energy Management Model Suitable for the Lebanese Case

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***Abstract*—Despite the country's high integration of renewable energy over the last two years, power deficit is still a major issue in Lebanon. This paper proposes a trading platform allowing participants to share their excess energy and fully harness their installed solar systems. To effectively encourage the exchange of surplus solar energy within the community microgrid, a novel allocation method and dynamic pricing strategy for Peer to Peer (P2P) energy trading among local prosumers is introduced. The allocation ensures efficient and reasonable energy allocation, profitability, and ease of interaction. Moreover, the dynamic pricing strategy ensures profitability for all market participants and incentivizes the market to adopt more solar systems.**

Keywords—Microgrid, peer-to-peer energy trading, allocation mechanism, dynamic pricing

I. INTRODUCTION

Lebanon suffers from a major power deficit causing soar high prices of alternative electricity sources. Expanding the system by 900 MW in the 1990s was not enough to meet the demand of a country being rebuilt. In 2018, the power deficit covered by Diesel Generators (DGs) totaled around 8.1 terawatt hours (TWh) [1] .

Such a substantial power deficit has translated into a proliferation of DGs across all Lebanese neighborhoods with a total capacity exceeding 1230 MW in 2018 [1]. DG owners took advantage of the gap between electricity supply and demand to expand their subscription-based businesses and thus created a complex informal economy that has been resistant to regulations and government oversight. Several attempts were made to regulate this informal market but proved unsuccessful except when municipalities worked within their confined jurisdictions to take effective safety and economic measures.

The need for integrating renewable energy in the Lebanese market became inevitable starting 2010. According to the Lebanese Center of Energy Conservation [2], from 2010 until the end of 2020, the cumulative installed solar Photovoltaic (PV) capacity grew by an average rate of 81% per year as shown in Fig. 1. Even more, the Lebanese country has seen an unprecedented rate of PV systems installation. The complete removal of all subsidies from the fuel industry increased the prices of diesel generated energy to 45 cents per kWh. People realized that solar energy costs are very low reaching 9-10 cents per kWh compared to the premium price they are paying for. Hence, Lebanon saw a hysteric growth in the installed rooftop solar projects.

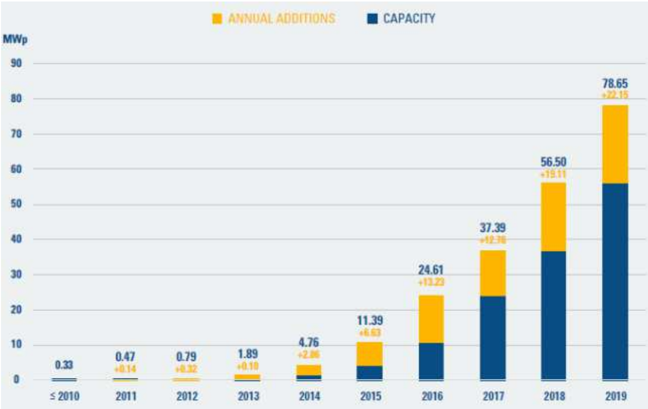

Fig 1. Solar PV capacity and annual additions [2].

Most households installing PV systems have two grids connected to them, the generator grid and the utility grid, while having their own systems. The previous fact demonstrates that one source of electricity from the previously mentioned sources is not enough to provide a reliable and economical source of electricity. Hence, there is a need to have a decentralized platform allowing these sources to interact with each other.

Peer-to-Peer (P2P) energy trading allows customers to share their surplus onsite generation or flexibility of their energy demand with others in need. This creates a mutually beneficial situation for both energy producers and consumers. To effectively encourage the exchange of surplus PV energy within a community microgrid in Lebanon, a novel allocation method for P2P energy trading among local prosumers, who installed an excess of solar panels, is proposed in this paper. It ensures efficient and reasonable energy allocation, profitability, and ease of interaction. The new pricing strategy adopts a dynamic pricing approach for electricity sellers and a uniform pricing strategy for electricity purchasers. Such a strategy would incentivize the market to adopt more PV and ensures that the prosumers are fully capitalizing on the economic benefits of their installed PVs.

Section II will consist of a literature review on the energy sector in Lebanon and the P2P energy trading models. Section III will present the pricing model. Section IV will discuss the methodology followed to develop the allocation algorithm and section V will present the results.

II. Literature Review

Several factors interfere in the increase of the Lebanese energy deficit [1]:

• transmission and distribution technical losses that refer to the energy lost in the transmission and distribution of electricity, due to factors such as resistance in the power lines and different losses in the transformers. Electricité du Liban (EDL) currently estimates transmission and distribution losses to be around 19% [1].

• transmission and distribution non-technical losses that refer to losses occurring due to theft, fraud, or inefficiency in the system, such as meter tampering. Non-technical losses are estimated to be around 28% of the generated electricity.

• the effect of the 2006 war that happened in Lebanon and caused major damage to the Lebanese infrastructure. For example, the Jiyeh, Zouk, and Deir Ammar power stations were greatly damaged during the war causing mass outages.

• diffused governance since the 1990s. The postwar investments lacked proper vision in the 1990s. The political turmoil caused by several assassinations and the 2006 war set the electricity solution on a lesser priority. During the 2010s, the political deadlocks forced the suspension of all electrical improvements.

In order to compensate the deficit of power, private generators were extensively implemented to supply power on a community basis. Historically, three models of commercial generator networks ownership were formed [1]:

• the Private “entrepreneurship” model, which is largely composed of street-savvy owners.

• the cooperative model by which several residents, who often live in the same building, decide to buy, and operate their own DG.

• the municipal model where local authorities, such as municipalities, either started owning DGs as soon as a need for them arose or bought the generator network from an existing private owner and started providing electricity as a municipal service.

Table 1 compares the characteristics of different DGs ownership models.

Table 1. The diesel generator ownership model characteristics.

Ownership Model	Private	Cooperative	Municipal
Relative scale	Large	Small	Large
Relative cost to customers	High	Low	Medium
Relative acceptability	Low	High	High

The installation of PV solar panels extensively increased in the Lebanese households in the past years. When several and distributed energy resources are grouped with interconnected loads, a microgrid is formed within clearly defined electrical boundaries. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island modes [3]. On the other hand, the conventional electricity market is arranged in a unidirectional way, where electricity flows from large power plants to end users.

In order to manage the interaction of different energy sources, a decentralized platform is needed. The three pillars of the Lebanese solution are [4]:

• a successful governance model.

• access to financing since installing a PV system needs a large capital cost.

• decentralization through software. In fact, the Lebanese constitution and laws suggest decentralization as a key to the political function of the country. Lebanon realized the effectiveness of decentralization when municipalities were key to organizing the DGs sector in their respective jurisdictions.

Peer-to-peer (P2P) energy trading refers to the direct exchange of electricity between individuals or small groups of people, typically within a microgrid context [5]. Fig. 2 represents the three possible electrical decentralization models [6]. Option (a) shows the centralized platform coordinating the financial transactions between peers, while option (b) shows the ideal non-achievable complete decentralization of the electrical grid with no coordinator due to the physical, technological and economic challenges needed to achieve it. On the other hand, option (c) shows the distributed model where the coordinator does not issue control signals but merely sends price and measurement signals to users.

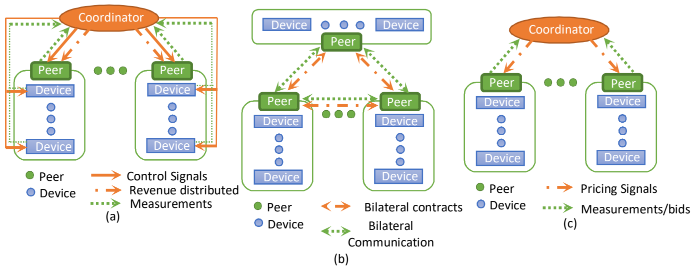

Fig. 2. Electrical decentralization models [6].

In order to promote the exchange of surplus PV energy generation in a community microgrid, a new pricing strategy for electricity purchases will be proposed in the next section.

III. Pricing Model

The aim of this section is to develop an economic formula that specifies the price of energy to be sold by a prosumer. The pricing model is time and prosumer dynamic. Hence, the purchasing price would change due to the following factors:

1. The Supply & demand ratio of the prosumer over a specific period.

2. The installed capacity of cheap and renewable energy that the prosumer adds to the grid.

On the other side, a uniform pricing strategy is adopted at the consumer's side. Hence, the consumer will purchase the electricity from a prosumer peer at a constant price. This price is determined by the highest purchasing price that was fixed for the prosumer by the platform of the Independent System Operator (ISO), plus a margin of profit. The main factor that will differ on the consumer side is the allocation of energy he is getting. The allocation is determined by the factors that will be discussed in the next section.

The prosumer price $P_{i,t}$, at which each prosumer i sells electricity to the grid during a trading round t can be calculated using the following equation that was inspired from previous studies on dynamic pricing of energy [1]:

$$P_{i,t} = LCOE + LCOE \times EOS_i \times UPR_{i,t} \tag{1}$$

where, $LCOE$ is the levelized cost of energy in cents/kWh, EOS_i is the economy of scale multiplier that can be retrieved from [1] and depends on the capacity range of the installed system and $UPR_{i,t}$ is the updated prosumer ratio at a round t for a prosumer i. The former parameter can be found using the following equation [7]:

$$UPR_{i,t} = \frac{2}{\pi}\tan^{-1}\left(\left(\frac{ES_{i,t}}{ED_{i,t}}\right)^{k}\right) \times R_{max} \tag{2}$$

where, $ES_{i,t}$ and $ED_{i,t}$ are the total supply and the total demand at the end of a trading round t for each prosumer i, respectively. k *and* R_{max} are two parameters used by the ISO to set the rate of increase and the upper limit of the price respectively.

The prosumer ratio, PR, is initially defined as the supply/demand ratio during the trading period under consideration. However, if a prosumer's supply greatly exceeds its demand, the corresponding prosumer price will be highly influenced, increasing the uniform peer price. To reduce price volatility in relation to the prosumer price, the updated prosumer ratio UPR was used as mentioned in equation (2).

Fig. 3 shows the variation of prices with respect to the prosumer ratio for two different scenarios. First, the blue increasing line is obtained when the price is multiplied by the prosumer ratio. Second, the red line presents the price variation when the price is multiplied by the updated prosumer ratio instead. It is noticeable that the price stabilized by using UPR which set an upper limit for the price.

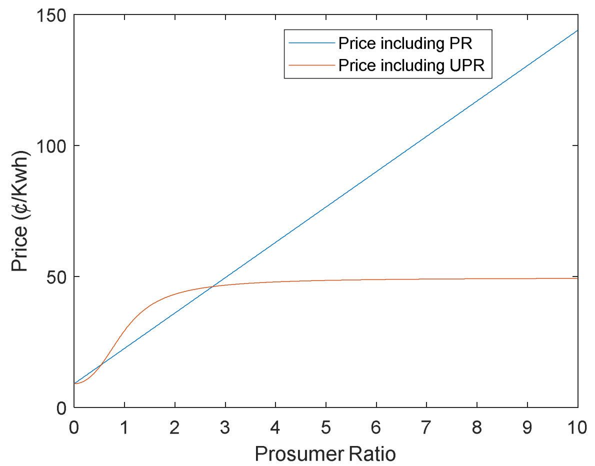

Fig. 3. Comparison between the price including PR and the price including UPR.

In the proposed model, prosumers have different prices, depending on their supply and demand ratio per time interval. However, the price of peer electricity bought by the consumers is equal to the highest price found among all prosumers. Having applied an upper bound on the prosumer price will also set an upper bound on the uniform price of the peer electricity in the microgrid. The ISO will also be able to control consumers' consumption behavior with such an upper bound. For instance, setting a lower upper bound will reduce the uniform peer electricity price during hours when excess electricity is high and consumption is low, encouraging consumers to increase their energy consumption.

Two other parameters are added to the pricing formulas and can be used to further control of the ISO on the prosumers' prices: k and R_{max}. Fig. 4 depicts the price versus the prosumer ratio for $k = 2{,}3\ and\ 5$. As k increases, the price will increase at lower prosumer ratios. In addition to that, Fig. 5 represents the price's variation versus the prosumer ratio as $R_{max} = 3{,}4\ and\ 5$ respectively. The proposed model gives the ability for the ISO to concentrate the convergence rate of the prosumer prices and its corresponding upper bound, by setting the values for the parameters k and R_{max}. This will allow the ISO to better manage its corresponding microgrid as it is a case-by-case problem.

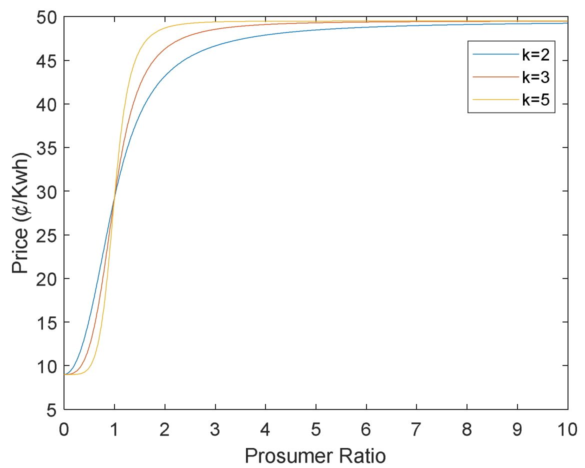

Fig. 4. Effect of the coefficient k on the price.

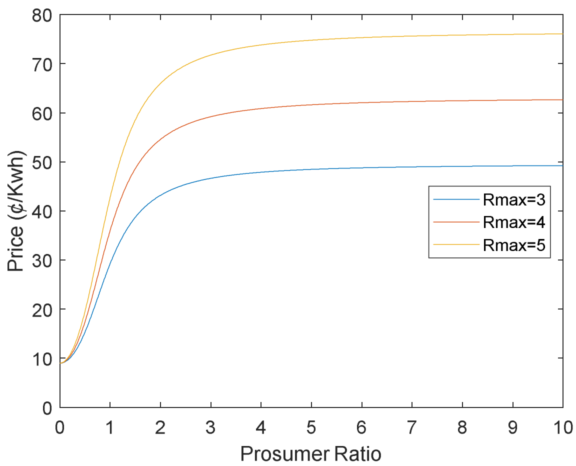

Fig. 5. Effect of R_{max} on the price.

Having discussed the impact of k and R_{max} on the prices, the ISO should decide on the value of k to provide more pricing diversity for prosumers. To put it another way, the ISO may precisely determine the range of prosumer ratios that contains the majority of prosumers, then choose the value of k to ensure that greater price variations are met while still allowing the achievement of the upper bound price. Having some prosumers reach the upper bound prosumer price will encourage other prosumers to install more PV and improve their consumption patterns. The ISO should determine the ideal value of k by applying this concept and a trial-and-error procedure. However, to determine the value of R_{max}, the ISO shall refer to the most expensive alternative electricity source accessible to consumers in the microgrid. The goal is to establish R_{max} so that the prosumer price's upper bound does not surpass the cost of the most expensive alternative electricity source.

IV. Allocation Algorithm

The following suggested energy allocation mechanism will ensure that all households can secure a percentage of their demand bought from renewable energy resources disregarding their physical location in the distribution system. Before discussing the suggested energy allocation mechanism, two concepts were adopted to ensure that such a mechanism can be used:

1. The household can trade energy with the grid at any moment, while its activities are captured by the smart meter and sent back to the ISO's platform.
2. There is no direct matching between one prosumer and another consumer.
3. It is assumed that for a community or a microgrid, the aggregate energy demand will always be greater than the aggregate supply from the excess of PV throughout a holistic view of energy ranging from one day to several days.

As a first step, the daily demand and supply data from each P2P household are captured by its installed smart meter. The data are sent to the ISO's platform. The peers are divided into consumers and prosumers, depending on whether they are injecting power to the grid or not, at a certain time interval. Then, aggregate demand and supply for all households in the community are calculated. Finally, the percentage of aggregate demand that aggregate supply can meet is calculated (initial percentage: P_1).

The Key Performance Indicator (KPI) for each consumer is calculated as a second step. The KPI is an index evaluating the performance of the consumer by considering the two factors below:

1. **Preference:** A house with no installed PV panels should benefit less from the energy of its peers. Such a strategy will encourage households to install PV panels and benefit from lower peer-to-peer energy prices.

2. **The peak-hour ratio:** The peak hour ratio is the total household's daily demand divided by the daily household's demand during the peak hours. A house with a higher peak-hour ratio will benefit more from the energy of its peers. Such a strategy will encourage households to reduce their consumption during peak hours. As a result, the stress on the microgrid would decrease while its reliability would increase.

After calculating the households' KPIs, the consumers are sorted from lowest to highest KPIs. Then, they are divided equally into two groups: households with the highest KPIs **(Group 1: G_1)** and households with the lowest KPIs **(Group 2: G_2).**

The initially allocated energy demand, D_{G_1} and D_{G_2} for groups 1 and 2 respectively, to be purchased at the peer-to-peer price, is calculated as follows:

$$D_{G_1} = \sum E_{t_1} \times P_1 \tag{3}$$
$$D_{G_2} = \sum E_{t_2} \times P_1 \tag{4}$$

where, E_{t_1} and E_{t_2} are the total energies for groups 1 and 2 respectively.

The second phase entails giving the group with higher KPIs the advantage over the group with lower KPIs. To do this, first, the average KPI is calculated for each group, then the relative difference between the two values is calculated. By applying this concept to the considered case study, the relative difference was found to be equal to 15%.

The third step consists on deducting 15% of the energy allocated initially to the second group with lower KPIs and adding it to the first group with higher KPIs.

$$D'_{G_1} = D_{G_1} + D_{G_2} \times 0.15 \tag{5}$$
$$D'_{G_2} = D_{G_2} - D_{G_2} \times 0.15 \tag{6}$$

After determining the total allocated energy for each of the two groups, a consumer, i, in group 1, will be charged the amount of its total energy demand, $E_{a_{i,G_1}}$, at the peer-to-peer energy price according to equation (7), and a consumer, j, in group 2 according to equation (8).

$$E_{a_{i,G_1}} = E_{t_i} \times P_1 + 0.15 \times \frac{D_{G_2}}{n_{G_1}} \tag{7}$$
$$E_{a_{j,G_2}} = E_{t_j} \times P_1 - 0.15 \times \frac{D_{G_2}}{n_{G_2}} \tag{8}$$

where, n_{G_1} and n_{G_2} are the total number of consumers in groups 1 and 2 respectively, and E_{t_i} and E_{t_j} are the total energy demand of consumers in groups 1 and 2 respectively.

The pricing model and the allocation algorithm will be simulated in the following section.

V. Results and Discussion

Data taken from monitoring devices installed in homes in the Lebanese city of Jal Al Dib are utilized to validate the previously constructed models. The installed monitoring system only recorded hourly consumptions for homes without a PV system, whereas for the households that have an installed PV system, the collected data included the hourly output of the installed PV panels, the hourly performance of the installed batteries, and the hourly consumption rates.

The data contain 22 households in Jal Al Dib, which represents the microgrid in this study, and were collected in August 2022. They are used to validate the proposed concept. Eighteen of these households are prosumers and four of them are consumers. Different PV outputs were recorded due to different installed capacities of PV systems. In addition to that, the consumption shows a variation between households during on-peak and off-peak hours resulting in different energy demand patterns.

The prosumer prices can be found using the pricing formula that was presented in the previous section and are shown in Table 2, where, C_d is the daily consumption in kWh and P_d is the daily production in kWh.

In our case study, we consider the price of the Diesel Generator to determine the value of R_{max} because it is the most expensive alternative electric source. Having said that, R_{max}should be set so that the upper bound of the prosumer price is less than or equal to 50 cents/kWh. For example, using R_{max} of 3, the upper bound for the prosumer price with *LCOE* of 9 cents/kWh and *EOS* multiplier of 1.5 would be 49.5 cents/kWh. On the other hand, to calculate the value of k, it was observed that the prosumer ratios in the case study are mostly low, so $k = 2$ was found to be the best fit for the case study.

Table 2. Prosumer Prices for 18 Households.

Prosumer ID	C_d (kWh)	P_d (kWh)	PR	UPR	Price (cents/kWh)
1	4.322	1.750	0.405	0.310	13.190
2	4.559	1.917	0.420	0.334	13.510
3	4.604	2.083	0.452	0.386	14.207
4	4.793	2.250	0.469	0.414	14.594
5	4.564	2.417	0.529	0.522	16.047
6	4.726	2.583	0.547	0.555	16.486
7	4.156	1.833	0.441	0.367	13.955
8	4.444	2.000	0.450	0.382	14.153
9	4.256	2.083	0.490	0.449	15.065
10	4.362	2.167	0.497	0.462	15.235
11	4.120	2.250	0.546	0.554	16.473
12	4.668	2.333	0.500	0.468	15.314
13	4.606	1.583	0.344	0.225	12.033
14	4.237	1.417	0.334	0.213	11.871
15	4.617	1.250	0.271	0.140	10.887
16	4.623	1.083	0.234	0.105	10.415
17	5.101	0.917	0.180	0.062	9.832
18	6.830	0.750	0.110	0.023	9.311

As previously stated, the uniform peer price is set to be the highest price among all prosumers' prices. In this case study, the uniform peer price is 16.486 cents/kWh, and the total daily energy that all prosumers can supply is 32.667 kWh. This energy injected into the grid by all prosumers during the 24 hours must be allocated to all households that are consuming electricity from the grid during the same 24 hours. This can be done by following the earlier suggested allocation pattern.

At the start, the KPI for each household consuming electricity from the grid must be calculated. For this case study, peak hours are considered from 8:00 to 10:00 am and from 6:00 to 11:00 pm. Table 3 summarizes the KPIs calculated using the formulas suggested earlier, where D_d is the total daily demand in kWh and D_{pd} is the total daily peak demand in kWh.

Table 3. KPI of 22 households.

Household ID	D_d (kWh)	D_{pd} (kWh)	KPI	Has installed PV system?
1	4.322	1.832	2.609	YES
2	4.464	1.832	2.437	NO
3	4.559	1.832	2.739	YES
4	4.604	2.114	2.428	YES
5	4.793	2.303	2.331	YES
6	4.564	1.978	2.558	YES
7	4.726	2.075	2.528	YES
8	4.180	1.832	2.281	NO
9	4.156	1.832	2.518	YES
10	4.444	1.793	2.729	YES
11	4.256	1.604	2.903	YES
12	4.362	1.856	2.600	YES
13	4.120	1.711	2.658	YES
14	4.668	1.832	2.798	Y ES
15	3.976	1.832	2.170	NO
16	4.606	1.954	2.607	YES
17	4.237	1.796	2.610	YES
18	4.617	1.796	2.821	YES
19	5.359	2.707	1.980	NO
20	4.623	2.220	2.332	YES
21	5.101	1.832	3.034	YES
22	6.830	2.968	2.551	YES

After calculating the KPIs, consumers were divided into two groups based on their lowest to highest KPI. The first grouped households have the highest KPIs, while the second grouped households have lowest KPIs, as shown in Fig. 6. A household from the first group will receive more energy from its peers, according to the adopted allocation strategy. In other words, at the uniform peer price, a household in the first group will pay a higher percentage of its total bill.

Fig. 6 shows the households with ID 4, 5, 6, 7, 19, 20, and 22 in Group 2 that consume more energy during the identified peak hours, as shown in Table 2. This indicates that consuming more energy during peak hours results in being assigned to Group 2 which receives less energy from peers. Similarly, households with IDs 2, 8, and 15 do not have a PV system installed, and this also results in being assigned to

Group 2. Such results show the capacity of the adopted allocation mechanism to encourage consumers to adopt better consumer behavior, reducing grid stress and ensuring grid reliability. Furthermore, it encourages consumers to adopt green technologies and install PV systems, lowering their monthly bills.

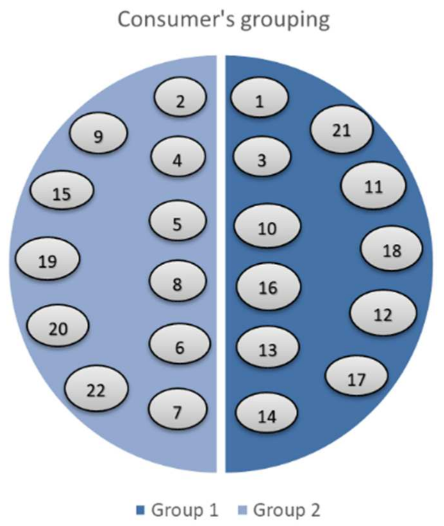

Fig. 6. Households division in two groups.

The daily bill in dollars per user with and without the ability to sell or buy electricity from the peers after allocating the peer's excess energy is calculated and presented in Fig. 7.

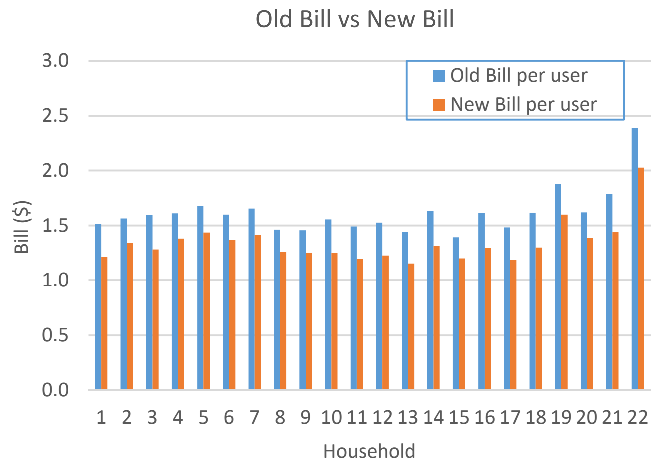

Fig. 7. The old bill compared to the new bill per user.

The effectiveness of the proposed approach is depicted in Fig. 7. Both users with high and low KPIs had their total bill reduced at the end of the day. Participating in the proposed peer-to-peer trading platform guarantees a reduction in the total bill. The percentage by which the bill is reduced is determined by load patterns, consumption habits, the adoption of renewable energy technologies, and the percentage by which the user injects power into the grid in relation to how much he absorbs from it.

Fig. 8 shows the old daily bill that is paid by each household and the new bill that takes into consideration the sold excess energy, and the allocated energy on the uniform peer price. As seen, the percentage of saving money by prosumers is much higher than consumers since they can sell their excess energy in addition to buying energy when needed on the uniform peer price depending on the allocated amount for each prosumer. This difference in savings will encourage consumers to invest in installing PV systems which will have its benefit in return.

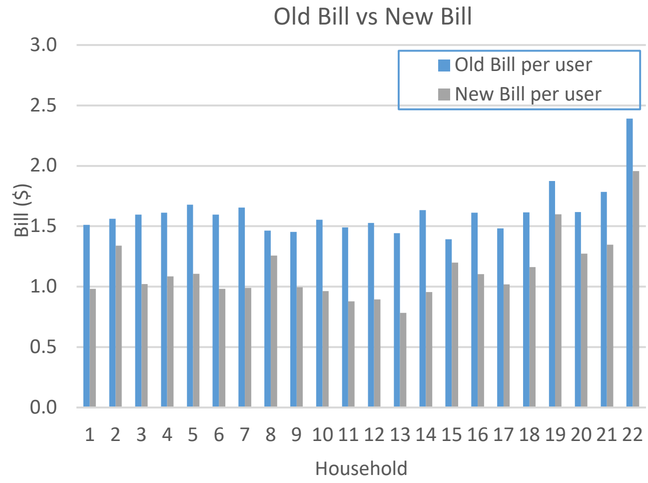

Fig. 8. The old bill compared to the new bill per user taking into account the sold excess energy.

VI. Conclusion

A new energy trading platform is proposed to help Lebanon overcome its severe power shortage by allowing participants to exchange surplus PV energy. A novel allocation mechanism is proposed to distinguish between the participant's behavior through a key performance indicator to ensure a reasonable energy allocation in order to achieve a balanced distribution of this excess energy. Furthermore, this study proposes a dynamic pricing strategy for prosumer prices in order to guarantee profitability for all market participants and encourage the market to adopt more PV systems. A case study was conducted for a city in Lebanon to simulate the proposed methodology, and the results revealed that the daily bill of all households participating in the platform had decreased compared to the previous bill, with households with higher KPIs benefiting from higher energy cost savings.

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