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Peer-to-Peer Energy Trading of a Community Connected with an AC and DC Microgrid

Kuruseelan S and Vaithilingam C *

School of Electrical Engineering, Vellore Institute of Technology, Chennai, Tamil Nadu 632014, India; kuruseelan.s@vit.ac.in

* Correspondence: vaithilingam.c@vit.ac.in; Tel.: +91-044-3993-1475

Received: 26 August 2019; Accepted: 25 September 2019; Published: 27 September 2019

Abstract: The awareness of self-consumption of grid-connected roof-top solar photovoltaic (PV) owners in a community and the advancement in information and communication technologies (ICT) led to the development of a novel peer-to-peer energy trading mechanism for next-generation power systems. In the peer-to-peer (P2P) energy trading landscape, the prosumers and consumers self-organize and trade energy among themselves. In recent years, the large penetration of distributed energy resources, as well as the advancement of technologies in the fields of protection, power electronics, and storage devices, led to the use of direct current (DC) home appliances by the end-users, i.e., consumers in a community. In this paper, the operational costs of an individual household and community when operated with alternating current (AC) and DC home appliances are calculated using bill sharing and the mid-market rate method for various degrees of PV penetration. The bill sharing method shares the operational cost and income among all the peers in proportion to the amount of energy they consume/generate. The mid-market rate method calculates the P2P internal price at the median of the import and export price based on the relationship between total generation and demand. In terms of operational cost, both producers and consumers benefit fairly when the mid-market rate method is used when the households in a community are operated with DC home appliances.

Keywords: peer-to-peer energy trading; AC community; DC community; PV penetration

1. Introduction

In vertically integrated utility (VIU) generation, transmission and distribution are bundled together, where a consumer can buy electricity from the utility at a monopolistic price. The power flow and cash flow in a regulated or VIU market is unidirectional. Due to technical, political, economic, and financial reasons, the restructuring of vertically integrated utility leads to the unbundling of generation, transmission, and distribution. As a result of unbundling, the wholesale electricity market evolved with local utilities as a key player, where transmission and distribution are non-tradeable entities. In a wholesale deregulated electricity market, the bulk consumers can exercise their choice among the local utilities available, to trade with them under the supervision of the market operator. The deregulated wholesale electricity market allows the penetration of bulk renewable energy sources to lower the gap between increasing demand and conventional generation. With a limited number of local utilities, there is no competition among them to evolve and the consumer also has less choice. Ultimately, this leads to the local utility becoming a monopoly once more. With the decreasing feed-in tariff, the non-availability of a transmission corridor, and the delayed settlement of payments, the bulk of renewable energy producers lack motivation to participate in the wholesale deregulated market. This leads to further deregulation of the electricity sector to retail the electricity market at the distribution level with the evolution of microgrids and smart grids.

The deregulated retail electricity market encourages the penetration of rooftop solar photovoltaic (PV) systems for domestic, industrial, and commercial customers by providing increased subsidy. In a deregulated retail electricity market, the individual solar PV consumers who produce solar power for their self-consumption are called as prosumers. The prosumers can sell their solar energy when not in use back to the grid for their returns. The grid also suitably incentivizes the prosumers. However, with an increasing subsidy burden, several countries started curtailing the subsidy. With the decreased subsidy and feed-in tariff, and with the increased awareness of self-consumption and self-sustainability, a new paradigm of electricity trading evolved at the low-voltage distribution level in the deregulated retail electricity market. The surplus prosumers in a community hereinafter referred to as selling peers can share/sell their superfluous energy to the energy-starving consumer, i.e., the deficit prosumer or non-PV consumer in the community, locally for the collective individual and community welfare. This type of trading is called peer-to-peer (P2P) energy trading, leading to the diversification of the energy ecosystem at the edge of the distribution level.

P2P trading can be performed at the scale of an individual premise, microgrid, or a collection of microgrids or multiple connections of microgrids in either on-grid or off-grid mode [1]. The prosumers at different levels can generate their own power for self-consumption from various sources like roof-top PV systems and wind. Prosumers become the key player in the energy ecosystem [2]. In a P2P energy market, prosumers and consumers undertake a proactive role, which led to the concept of a federated power plant which combines the benefit of both a virtual power plant and P2P energy trading [3]. The optimal value of generation from renewables is determined with the help of a P2P index, which is the proportion of renewable generation with respect to the gross system load [4].

In conventional energy trading, the surplus energy is sold to the grid, hereinafter referred to as peer-to-grid (P2G). With the increasing deployment of renewable energy sources in P2G energy trading, the gain to access advantages like improved power quality, energy balance, and reliability is circumscribed by the congestion of transmission lines [5]. However, P2P energy trading, in addition to the local energy balance, alleviates the congestion at the edge of the distribution level, eventually lessening the burden on transmission lines [6,7]. The energy flow and cash flow for P2G trading are shown in Figure 1.

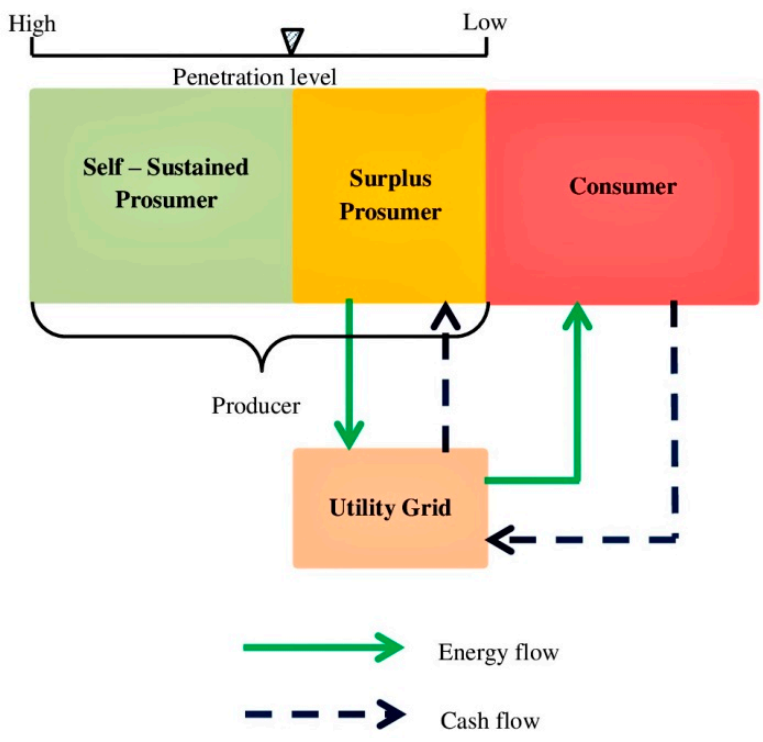

Figure 1. Conventional peer-to-grid (P2G) trading.

The prosumers are fitted with a bidirectional smart meter to assess the import and export of energy [8]. After assessing the surplus of the prosumer, the superfluous energy is shared/traded with the deprived consumers in the community, which necessitates a sharing corridor within the community without violating the physical limits [9,10]. In a P2P energy market, the prosumers and consumers organize themselves at each instant in time and trade with each other, thereby reducing the overall demand of the community by slashing the upstream generation and transmission expenditure [11]. The energy flow and cash flow for P2G trading are shown in Figure 2.

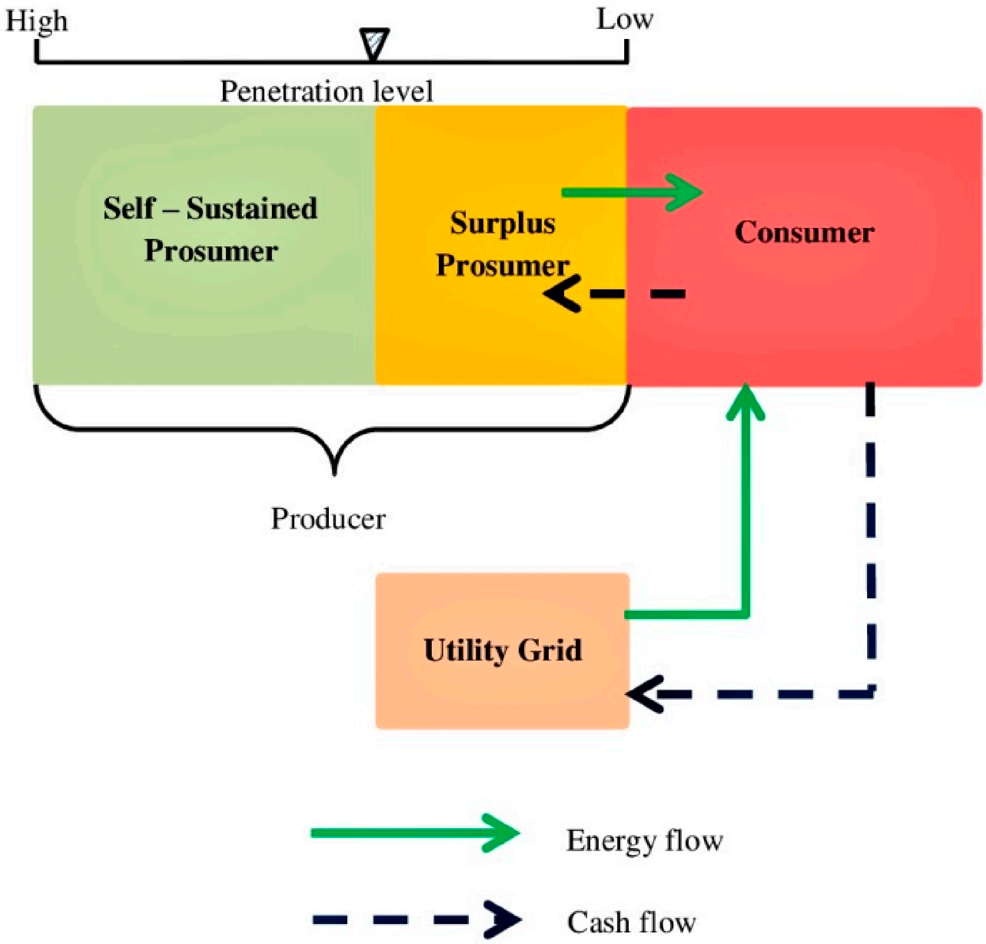

Figure 2. Novel peer-to-peer (P2P) energy trading.

Although P2P trials all over the world focused on a business model, the interaction between the prosumers and consumers necessitates innovative information and communication technologies (ICT) and electronic trading platforms such as cloud-based and block-chain-based technologies [12,13]. A robust, transparent, and innovative information system is required to link the consumers and prosumers to trade electricity within the community for local energy balance [14].

A suitable market model was developed for P2P energy trading in a centralized or distributed manner [15,16]. A community-based electricity market was proposed with the concept of energy collectives [17]. The energy cost model for the peer can not only be modeled from the economic perspective but can also include the complex process of socio-cultural understanding [18]. Game theory was used for bidding in P2P energy trading by the prosumers and consumers [19–21].

Internet of things (IoT)-based smart homes are the solution for the energy crisis, which connects the real physical world with the digital world [22], a mandate for P2P energy trading. The usefulness of the smart home in achieving the optimized energy management between the utility and grid in a deregulated energy market can be adapted in a deregulated retail market at the distribution level to enable P2P energy trading [23,24]. A smart home is furnished with appliances with their own purpose to satisfy the consumer connected to the alternating current (AC) or direct current (DC) micro grid. Although AC dominates the entire world, in parallel with the revival of DC at the transmission and distribution levels, the integration of renewable energy sources such as solar, native DC, and wind, connected to the AC grid through a DC link led to the development of DC micro grids. With the spur of DC microgrids, several household appliances were developed with the operating supply as DC.

In a digitally electrified network and with the advancement of ICT technologies, P2P energy trading offers several advantages when operated with AC and DC home appliances in terms of the operational cost of an individual and community. Although there are several advantages in implementing P2P energy trading, there is no systematic methodology to evaluate the operational cost. A fair pricing methodology is required to implement P2P energy trading. Cintuglu et al. [25] created a competitive market for independent power producers by designing a reverse auction model. Shamshi et al. [26] proposed that prosumers can trade energy with others in a community-based energy market. However, the authors of References [25,26] did not consider flexible demand. Paolo et al. [27] proposed a pricing-based scheme considering flexible demand but did not consider distributed generation. In this paper, the consumption profiles of individual homes are plotted without compromising the user convenience when the household appliances are operated using AC and DC supply with their respective power ratings. The operational costs for operating the homes using AC and DC home appliances are calculated from the perspective of P2P energy trading, and the results are compared.

2. P2P Energy Market Mechanism

2.1. Self-Consumption

The definition of self-consumption is the on-site consumption of PV power. Self-consumption can be maximized by load shifting. The intermittent nature of renewable energy generation may lead to the absorption/injection of power from/to the grid in an uncoordinated manner at the distribution level. Utility grids are also unable to incentivize/penalize the prosumers accordingly. This emphasizes the necessity for the self-organization of prosumers and consumers in a community to maximize their individual and community self-consumption [28,29].

2.1.1. Individual Self-Consumption

The individual self-consumption of a prosumer is defined as the instantaneous utilization of PV power generated by the prosumer without injection at the transmission or distribution level. The individual self-consumption is calculated as shown below. The individual electricity load demand of house h at time t is $L^h(t)$ and the on-site PV power produced is $P^h_{PV}(t)$. The individual self-consumption, $SC_h(t)$, of house h at time t is calculated as follows:

$$SC_h(t) = \min\left\{L^h(t), P^h_{PV}(t)\right\}. \tag{1}$$

2.1.2. Community Self-Consumption

The community self-consumption of a prosumer is defined as the instantaneous utilization of total PV power generated by the prosumers without injection at the transmission or distribution level. The community self-consumption, $SC_c(t)$, is calculated as follows:

$$SC_c(t) = \min\left\{\sum_{h=1}^{H} L^h(t), \sum_{h=1}^{H} P^h_{PV}(t)\right\}. \tag{2}$$

2.2. Power Import/Export

2.2.1. Individual Power Import/Export

In P2G trading, as the individual prosumers and consumers can interact only with the utility grid, the power import/export of the individual household from/to the utility grid is of great interest. It is determined by whichever quantity is smallest in Equation (2). The individual power import from the utility grid, $P^h_{im}(t)$, and the individual power export to the utility grid, $P^h_{ex}(t)$, are calculated as follows:

$$P^h_{im}(t) = L^h(t) - SC_h(t), \tag{3}$$

$$P^h_{ex}(t) = P^h_{PV}(t) - SC_h(t). \tag{4}$$

2.2.2. Community Power Import/Export

In P2P trading, as the individual prosumers and consumers can self-organize and interact with each other, the power import/export of the community from/to the utility grid is of great interest. It is determined by whichever quantity is smallest in Equation (2). The individual power import from the utility grid, $P^h_{im}(t)$, and the individual power export to the utility grid, $P^h_{ex}(t)$, are calculated as follows:

$$P^c_{im}(t) = \sum_{h=1}^{H} L_h(t) - SC_c(t), \tag{5}$$

$$P^c_{ex}(t) = \sum_{h=1}^{H} P^h_{PV}(t) - SC_c(t). \tag{6}$$

3. P2G Trading

In P2G trading, the total energy imported by the entire individual household in a community from the utility grid, $E^{P2G}_{T,im}$, and the energy exported to the utility grid, $E^{P2G}_{T,ex}$, are calculated as follows:

$$E^{P2G}_{T,im} = \sum_{h=1}^{H}\left(\int_{t=1}^{T} P^h_{im}(t)dt\right), \tag{7}$$

$$E^{P2G}_{T,ex} = \sum_{h=1}^{H}\left(\int_{t=1}^{T} P^h_{ex}(t)dt\right). \tag{8}$$

In conventional P2G, the operational cost of the individual peers is calculated as follows:

$$OC_h = \left(\int_{t=1}^{T} P^h_{im}(t)dt\right) \times C^{im}_U - \left(\int_{t=1}^{T} P^h_{ex}(t)dt\right) \times C^{ex}_U, \tag{9}$$

where C^{im}_U is the import cost of energy from the utility grid, and C^{ex}_U is the export cost of energy to the utility grid.

4. P2P Trading

In P2P trading, total energy imported by the entire community from the utility grid, $E^{P2P}_{T,im}$, and energy exported to the utility grid, $E^{P2P}_{T,ex}$, are calculated as follows:

$$E^{P2P}_{T,im} = \int_{t=1}^{T} P^{c}_{im}(t)dt, \tag{10}$$

$$E^{P2P}_{T,ex} = \int_{t=1}^{T} P^{c}_{ex}(t)dt. \tag{11}$$

4.1. Bill Sharing Method

Using the bill sharing method, the benefits of the P2P energy trading are prorated according to their energy share with their peers. With P2P energy trading, as the surplus energy is consumed by the neighbors within the community, $E^{P2P}_{T,im}$ and $E^{P2P}_{T,ex}$ are smaller than $E^{P2G}_{T,im}$ and $E^{P2G}_{T,ex}$, respectively. Hence, the import cost, C^{im}_{bs}, and the export cost, C^{ex}_{bs}, for the bill sharing method are calculated as follows:

$$C^{im}_{bs} = C^{im}_{U} \times \frac{E^{P2P}_{T,im}}{E^{P2G}_{T,im}}, \tag{12}$$

$$C^{ex}_{bs} = C^{ex}_{U} \times \frac{E^{P2P}_{T,ex}}{E^{P2G}_{T,ex}}. \tag{13}$$

The prorated operational cost of individual peers using the bill sharing method is calculated as follows:

$$OC^{bs}_{h} = \left(\int_{t=1}^{T} P^{h}_{im}(t)dt\right) \times C^{im}_{bs} - \left(\int_{t=1}^{T} P^{h}_{ex}(t)dt\right) \times C^{ex}_{bs}. \tag{14}$$

4.2. Mid-Market Rate Method

Using the mid-market rate, the fairest P2P energy trading price, C^{mmr}_{P2P}, is calculated as a median value between the energy import cost from the utility, C^{im}_{U}, and the energy export cost from the utility, C^{ex}_{U}, as follows:

$$C^{mmr}_{P2P} = \frac{C^{im}_{U} + C^{ex}_{U}}{2}. \tag{15}$$

At every instant of time, the generation and load vary. The import cost, $C^{im}_{mmr}(t)$, and the export cost, $C^{ex}_{mmr}(t)$, depend on whichever quantity is at a minimum within the available PV generation and load. Three different conditions are likely to occur as described below.

4.2.1. Self-Sustained State

When the on-site PV generation is equal to the load at a particular instant of time, the community is completely self-sustained and does not require energy import (export) from (to) the main utility grid. The import cost, $C^{im}_{mmr}(t)$, and the export cost, $C^{ex}_{mmr}(t)$, in the self-sustained state are calculated as follows:

$$C^{im}_{mmr}(t) = C^{mmr}_{P2P}, \tag{16}$$

$$C^{ex}_{mmr}(t) = C^{mmr}_{P2P}. \tag{17}$$

4.2.2. Community as a Seller

At the instant when the on-site PV generation of a community is higher than the load, the excess energy of the community is sold to the main grid with the import cost, $C_{mmr}^{im}(t)$, and the export cost, $C_{mmr}^{ex}(t)$, as follows:

$$C_{mmr}^{im}(t) = C_{P2P}^{mmr}, \tag{18}$$

$$C_{mmr}^{ex}(t) = \frac{\left(\sum_{h=1}^{H} L^h(t) \times C_{P2P}^{mmr}\right) + \left(P_{ex}^h(t) \times C_U^{ex}\right)}{\sum_{h=1}^{H} P_{PV}^h(t)}. \tag{19}$$

4.2.3. Community as a Buyer

When the load of a community at a particular instant of time is less than the available PV generation, the remaining generation is supported by the main utility grid. The import cost, $C_{mmr}^{im}(t)$, and the export cost, $C_{mmr}^{ex}(t)$, are calculated as follows:

$$C_{mmr}^{im}(t) = \frac{\left(\sum_{h=1}^{H} P_{PV}^h(t) \times C_{P2P}^{mmr}\right) + \left(P_{im}^c(t) \times C_U^{im}\right)}{\sum_{h=1}^{H} L_h(t)}, \tag{20}$$

$$C_{mmr}^{ex}(t) = C_{P2P}^{mmr}. \tag{21}$$

The import cost, $C_{mmr}^{im}(t)$, and the export cost, $C_{mmr}^{ex}(t)$, vary according to the available on-site PV generation and demand at every instant of time. After evaluating the import and export cost at different conditions, the operational cost of the individual households can be calculated as follows:

$$OC_h = \left(\int_{t=1}^{T} P_{im}^h(t)dt\right) \times C_{mmr}^{im}(t) - \left(\int_{t=1}^{T} P_{ex}^h(t)dt\right) \times C_{mmr}^{ex}(t). \tag{22}$$

5. System Description

Figure 3 shows the structure of a community connected to the utility main grid.

There are a number of households connected together with power lines and to the main grid at the point of common coupling (PCC). A few of the households are equipped with rooftop solar PV panels as prosumers. The prosumers and consumers are equipped with a smart meter to assess the individuals' import/export [8]. The community as a whole is connected to the utility main grid through a bidirectional meter to assess the total community's import/export. The prosumers managing themselves with on-site PV generation are termed self-sustained prosumers. The prosumers who, when they are in surplus, sell their excess energy to their peers are termed prosumers (sellers), whereas the prosumers who, when in deficit, buy energy from their peers are termed prosumers (buyers). The households with no rooftop solar PV are termed non-PV consumers. The solid lines in Figure 3 show conventional P2G trading. The prosumer (seller) exports the surplus energy to the utility grid, while the self-sustained prosumer neither imports nor exports energy from the utility grid; lastly, the prosumer (buyer) and non-PV consumer import power from the utility grid. The dashed lines in Figure 3 show P2P energy trading, where the self-organized prosumers and consumers in a community pursue their energy trade through the virtual energy sharing corridor. The virtual energy sharing corridor in a P2P environment enables the interaction between prosumer (seller), prosumer (buyer), and consumers with their surplus and deficit of energy to be traded among themselves for financial benefit and to reduce their grid dependency. The prosumers take different roles as sellers or buyers, or they are self-sustained based on their PV generation and load at a particular instant of time.

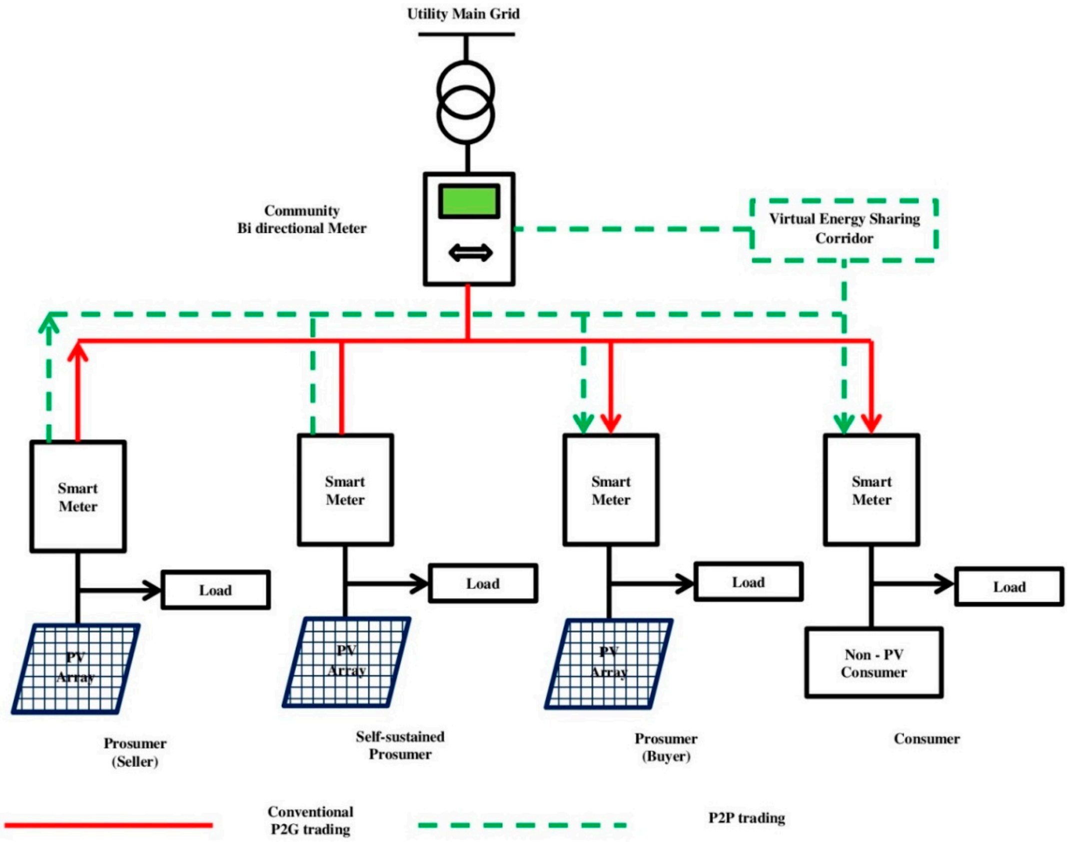

Figure 3. Community connected to the utility main grid.

The depletion of conventional sources for electricity generation and the exponentially growing load demand with the increasing population led various countries to alter their energy policies toward promoting renewable energy sources. By 2023, 40% of global energy consumption will be satisfied with the continuing expansion of renewables. Among the renewables, solar PV capacity is forecasted to expand by 600 GW, which will be twice the total capacity of Japan of 1 TW. China will hold 40% of the global installed PV capacity by 2023 due to its policy changes. The second largest growth market for solar PV is the United States, followed by India, whose capacity will quadruple [30]. In the post-world oil crisis, solar photovoltaic (SPV) research and development commenced in India. By 1995, 22 MW of SPV units were installed, making India the third largest user of solar PV. By 2002, the export had a share of almost 46%. Meanwhile, domestic solar rooftop PV systems were encouraged [31]. The 2010 Jawaharlal Nehru National Solar Mission (JNNSM) aims to achieve 20 GW of grid-connected installed capacity. In 2015, the solar policy was accelerated to achieve 100 GW by 2022 [32]. By 2030, India's total electricity demand is expected to cross 950,000 MW. Two-thirds of rural India is still energy-starving. Being a tropical country with average sunshine of eight hours per day, depending on location, India can harness its enormous solar potential.

Of the available renewable energy sources, solar power gained more attention with the advancement of PV technology, even at the edge of the distribution level. Simultaneously, the solarization of grid-connected and off-grid communities, the advancement in power electronics, and the evolution of technology with respect to protection at the low-voltage distribution level increased.

A number of P2P projects and trails are carried out globally at the consumer/prosumer level and distribution grid level. At the consumer/prosumer level, P2P energy trading was done in apartments in western Australia [33] and in east London [34]. P2P energy projects were also deployed at a university campus at the North-western University Evanston campus in Illinois, which enables the university to trade clean energy within the campus and between campuses [35]. At the distribution grid level, the Brooklyn microgrid provides a peer-to-peer energy trading marketplace for the locally generated renewable energy [36,37]. Countries like the United States of America (USA), United Kingdom (UK), Germany, Spain, Greece, Sweden, South Korea, Denmark, and Belgium focus on P2P energy trading at a consumer/prosumer level [38]. Countries like Finland, Norway, Switzerland, Malta, and the Netherlands concentrate on implementing P2P energy trading at the distribution gird level. It is also observed that there is growing interest in P2P energy sharing in off-grid rural areas of countries like India, Bangladesh, and Kenya. The socio-cultural understanding and nature of human relationships in a rural off-grid village in India with P2P energy sharing were discussed in Reference [18]. Progressively, the state of Uttar Pradesh (UP) in India issued rooftop solar PV grid interactive systems gross/net metering (RSPV) regulations in 2019, making UP the first state in India to propose peer-to-peer energy trading [39]. The advent of DC home appliances at the end usage encourages exploring the benefits of a DC community connected to a DC grid [40–43]. The hourly load profiles of households were plotted for a day when operated with AC home appliances connected to an AC microgrid based on circumstantial conditions such as the time of use of appliances, the number of appliances, the time of activity, and occupancy. The hourly load profiles for the same set of households when operated with DC home appliances were obtained by considering the same set of circumstantial conditions with the corresponding power consumption values of DC appliances. Table 1 shows the list of appliances and the AC and DC power consumption values considered for this study.

Table 1. Rating of alternating current (AC) and direct current (DC) home appliances.

No.	Appliance	Wattage	
		AC	DC
1	Ceiling fan	75	25
2	Lights	18	5
3	Cell phone	6	5
4	Television (TV)	215	25
5	Induction stove	1500	400
6	Refrigerator	110	25
7	Mixer/grinder	750	100
8	Cooler	165	50

Figure 4 shows the hourly load curve for one day of one household. The household is equipped with four ceiling fans, six lights, two cell phones, and one television (TV), induction stove, refrigerator, mixer/grinder, and cooler, with an occupancy of four members. Based on the time of activity and use of appliances, the hourly load curve was obtained when the house was equipped with AC home appliances connected to an AC microgrid and DC home appliances connected to a DC microgrid.

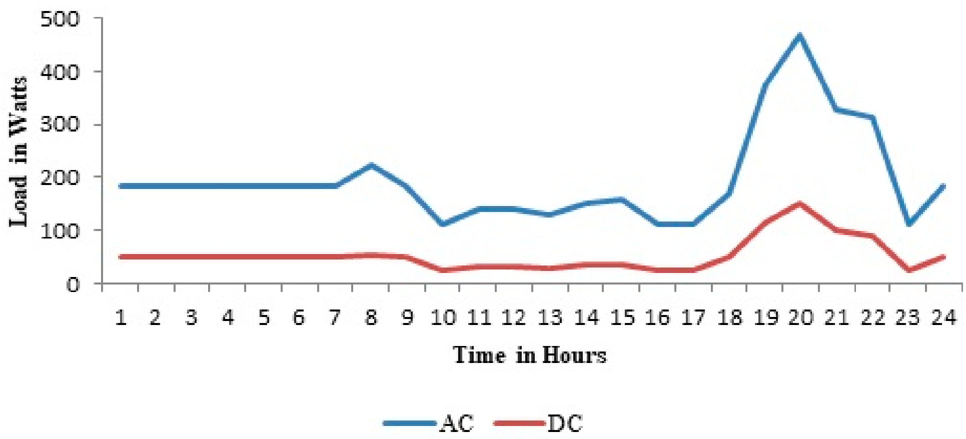

Figure 4. Load curve of an individual household with alternating current (AC) and direct current (DC) home appliances.

In this paper, we considered 10 households in a community connected to the utility main grid. Two different methods of calculating the operational cost using a P2P trading mechanism were explored and applied to the community when the households were equipped with AC and DC home appliances, and the results are also presented for various degrees of PV penetration for two different conditions. The rooftop PV generation was assumed to have the same generation profile, as the households in a community are relatively close to each other. Figure 5 shows the PV generation profile with a generation peak of 2 kWp considered for this study. The import cost of energy from the utility main grid (C_U^{im}) was taken as 6.6 Indian rupee (INR) per kWh, and the export cost to the utility main grid (C_U^{ex}) was taken as 4 INR per kWh.

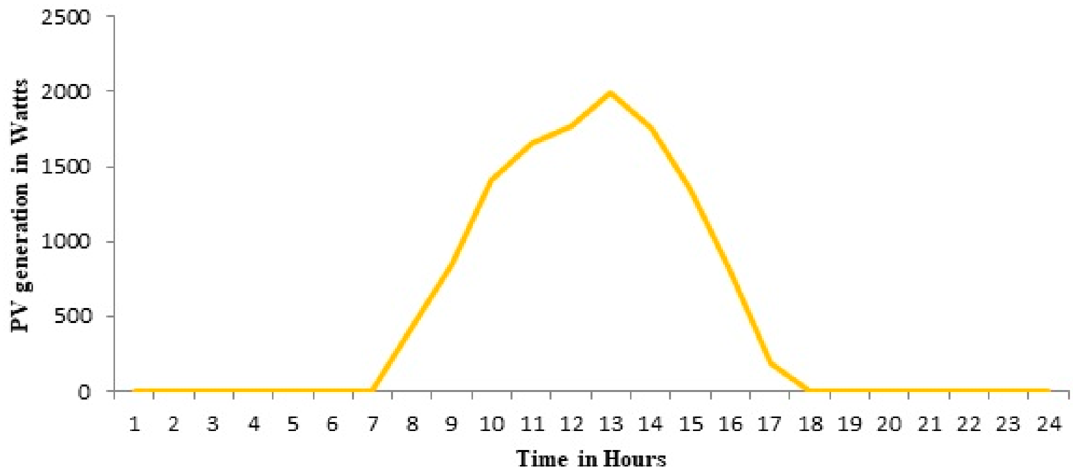

Figure 5. Photovoltaic (PV) generation profile.

6. Results and Discussion

In a conventional P2G environment, non-PV consumers in a community rely on the utility grid for the electricity supply. Prosumers manage themselves from an individual perspective by exploiting self-consumption. If the prosumers are in surplus, then they sell the surplus energy to the utility grid. When the prosumers are in deficit, then they purchase energy from the utility grid as the consumers do. There is no interaction between prosumer and consumer in a P2G environment. The operational cost of the individual household in a conventional P2G environment when there is no prosumer or PV penetration ware calculated using Equation (9), and the results are shown in Table 2. The community's operational cost was computed by summing the operational costs of individual households.

Table 2. Operational costs of individual households using peer-to-grid (P2G) method. INR—Indian rupee.

	P2G (INR)	
	AC	**DC**
Household 1	31.05	8.41
Household 2	36.83	10.81
Household 3	33.00	9.41
Household 4	26.53	7.85
Household 5	29.24	8.25
Household 6	43.94	12.38
Household 7	42.12	12.01
Household 8	58.23	16.17
Household 9	29.92	8.15
Household 10	35.54	9.64
Community	366.40	103.07

With PV penetration, the prosumers are motivated to trade their surplus energy with the main utility grid in conventional P2G trading and with energy-starving consumers in a P2P energy trading-enabled community.

The level of PV penetration also plays an appreciable role in the operational cost of the individual and community. Table 3 shows the operational costs of individual households for various levels of penetration using P2G trading. With various levels of penetration (number of solar PV prosumers to consumers), it was observed that the surplus prosumers are able to trade their energy with the main utility grid and generate a suitable income. It is evident from Table 3 that the income is considerably more when the home appliances are operated with DC supply connected to a DC microgrid. In this paper, the various levels of penetration were taken as 10% for low, 50% for medium, and 100% for high.

Table 3. Operational costs of individual households for one day using P2G trading.

Household	PV Penetration (No. of Prosumers)					
	Low		Medium		High	
	AC (INR)	DC (INR)	AC (INR)	DC (INR)	AC (INR)	DC (INR)
1	−21.61	−41.35	−21.61	−41.35	−21.61	−41.35
2	36.83	10.79	−18.98	−40.13	−18.98	−40.13
3	33.00	9.42	−19.76	−40.61	−19.76	−40.61
4	26.53	7.85	−25.50	−41.93	−25.50	−41.93
5	29.24	8.24	−25.44	−42.24	−25.44	−42.24
6	43.94	12.39	43.94	12.39	−12.64	−38.90
7	42.12	12.03	42.12	12.03	−14.00	−38.86
8	58.23	16.17	58.23	16.17	2.18	−35.42
9	29.92	8.15	29.92	8.15	22.29	−41.50
10	35.54	9.64	35.54	9.64	−17.05	−40.43

Negative cost means income.

As the main utility grid is not able to settle the surplus of prosumers due to increased financial burden, the prosumers and consumers are motivated to organize themselves in a community to form a P2P-enabled community where the surplus prosumers can trade their excess energy with their peers (consumers) and generate a suitable income, while reducing the technical and financial burden on the main utility grid.

Tables 4 and 5 show the operational costs of individual households for various levels of penetration using the bill sharing method of P2P trading.

Table 4. Operational costs of individual households for one day using the bill sharing method of peer-to-peer (P2P) trading.

Household	PV Penetration (No. of Prosumers)					
	Low		Medium		High	
	AC (INR)	DC (INR)	AC (INR)	DC (INR)	AC (INR)	DC (INR)
1	14.19	−25.42	−17.84	−40.14	−22.01	−41.35
2	30.06	7.66	−15.68	−38.87	−19.35	−40.13
3	26.94	6.69	−16.40	−39.51	−20.28	−40.61
4	21.66	5.57	−20.90	−40.56	−25.71	−41.93
5	23.87	5.85	−20.76	−40.56	−25.48	−42.24
6	35.86	8.80	34.21	9.03	−13.36	−38.90
7	34.38	8.54	32.80	8.77	−14.66	−38.86
8	47.53	11.48	45.35	11.79	0.50	−35.42
9	24.43	5.79	23.30	5.94	−22.68	−41.50
10	29.01	6.85	27.68	7.03	−17.75	−40.43

Negative cost means income.

Table 5. Operational costs of individual households for one day using the mid-market rate method of P2P trading.

Household	PV Penetration (No of Prosumers)					
	Low		Medium		High	
	AC (INR)	DC (INR)	AC (INR)	DC (INR)	AC (INR)	DC (INR)
1	−34.60	−47.29	−25.67	−42.84	−23.88	−42.10
2	34.64	9.93	−22.42	−41.53	−20.89	−40.83
3	32.03	8.98	−23.60	−42.05	−21.85	−41.33
4	25.61	7.47	−29.71	−43.43	−27.85	−42.68
5	27.77	7.58	−28.74	−43.66	−27.29	−42.95
6	41.73	11.39	40.02	11.17	−14.77	−39.58
7	40.04	11.16	38.80	11.02	−15.76	−39.57
8	56.33	15.25	54.13	14.81	−0.83	−36.01
9	28.99	7.84	28.46	7.75	−24.58	−42.25
10	34.53	9.25	33.68	9.04	−19.73	−41.13

Negative cost means income.

It is evident from Tables 4 and 5 that the incomes generated by prosumers are higher when using the mid-market rate method when compared to the bill sharing method. It is also evident that the income is higher when household appliances are operated with DC home appliances connected to a DC microgrid.

Table 6 shows the operational cost of the community when all household appliances in a community are operated with AC home appliances and DC home appliances connected to AC and DC microgrids, respectively.

Table 6. Community's operational costs for one day with various levels of penetration and different trading methodologies.

No. of Prosumers	Operational Cost (INR)					
	P2G		P2P Bill Sharing		P2P Mid-Market Rate	
	AC	DC	AC	DC	AC	DC
0	366.40	103.07	366.40	103.07	366.40	103.07
1	313.75	53.33	287.92	41.82	287.07	41.55
2	257.94	2.41	229.91	−9.90	227.15	−10.80
3	205.18	−47.61	177.16	−59.34	172.78	−60.72
4	153.15	−97.39	124.46	−108.20	119.02	−110.10
5	98.47	−147.87	71.76	−157.06	64.96	−159.73
6	41.90	−199.16	19.05	−205.92	10.64	−209.72
7	−14.22	−250.05	−31.63	−254.78	−42.49	−259.58
8	−70.28	−301.64	−81.63	−303.64	−94.92	−309.65
9	−122.48	−351.29	−131.63	−352.50	−146.43	−358.96
10	−175.07	−401.36	−180.78	−403.66	−197.43	−408.42

Negative cost means income.

It can be found from Table 6 that the operational cost is reduced with an increased level of penetration, and the community starts generating income after a certain level of PV penetration. From 0% to 70% PV penetration, the operational cost of the community as expenditure is reduced. From 70% to 100%, the operational cost of the community as income increases. It is also evident from the results that the operational cost as expenditure shifts to income when a community consists of DC home appliances connected to a DC microgrid.

7. Conclusions

The energy trading business models of conventional peer-to-grid (P2G) and novel peer-to-peer (P2P) were detailed for the present scenario of a power system. The different mechanisms of calculating the P2P operational cost of the individual household and community were probed for different levels of PV penetration, i.e., numbers of prosumers in a community. This paper investigated the economic benefit of the individual household and community from the perspective of market integration of renewable energy sources. Furthermore, this paper also examined the economic benefit when a household has AC home appliances connected to an AC microgrid and when a household has DC home appliances connected to a DC microgrid. It was found that the operational cost shifted from expenditure to income as the penetration was varied from low to high. The results also show the huge savings in operational cost when households equipped with DC home appliances connected to a DC microgrid participate in P2P energy trading.

Author Contributions: Conceptualization, K.S. and V.C.; methodology, K.S.; software, K.S.; validation, K.S. and V.C.; formal analysis, K.S. and V.C.; investigation, K.S.; resources, K.S. and V.C.; data curation, K.S.; writing—original draft preparation, K.S.; writing—review and editing, V.C.; visualization, K.S. and V.C.; supervision, V.C.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

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