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Ganguly, Boudhayan
International Management Institute Kolkata

Nag, Tirthankar
GITAM School of Technology

Guha, Dibyajyoti
GITAM School of Technology

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P2P Prosumer Networks: A Model for Electricity Trading

Boudhayan Ganguly[1], Tirthankar Nag[1,*], Dibyajyoti Guha[2,3]
[1]International Management Institute Kolkata, India
[2]GITAM School of Technology, India
[3]Indian Institute of Information Technology Dharwad, India

*Author to whom correspondence should be addressed:
E-mail: t.nag@imi-k.edu.in

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Abstract: Consumers having capabilities of Distributed Electricity Generation, through renewable sources of electricity, are known as Prosumers, in the context of electric electricity generation. Trade occurs between the prosumers when the excess electricity generated by some prosumers is sold, at a price that is lower than the one that one pays for buying from the electricity grid to other prosumers having deficit production. This trading between the prosumers is not only beneficial to the seller and buyer but also to the environment as most electricity grid companies use fossil fuel to generate electricity as the prosumers use renewable sources of energy in the form of solar electricity. This paper uses a simulation model, based on aggregate data available from different domestic and commercial facilities of Kolkata, to develop a framework for electricity trading between prosumers. Our model shows the both commercial viability of such a peer-to-peer trading network and the environmental sustainability of such models.

Keywords: Prosumer; renewable energy; electricity trading; distributed electricity generation; electricity grid

1. Introduction

In the past decade, a lot of research focus has been on sustainability. Renewable energy has increasingly become the alternative source of electrical energy that does not rely on fossil fuels. The increase in distributed energy resources has changed the way we produce, deliver and consume energy[23)]. Energy is fundamental to monetary development[4]. With a steady increase in research on energy generation from renewable sources such as solar, wind, etc., and through interconnected technologies, many citizens can generate their electricity. Many citizens have achieved this through the installation of solar panels on rooftops and electric vehicles. In this context, a prosumer is defined as a producer and consumer of electric energy. It is also necessary to compensate such prosumers in different ways[6)]. The rise in the number of prosumers is a trend in this sector of renewable energy. Nugraha[18)] noted how households are changing from passive consumers of electricity to active prosumers. Scholars such as Camilo, Kanakadhurga and Prabaharan[13)] has three major benefits such as reduced reliance of the consumer on the electricity grid, reduced electricity bill for the consumer, and ability of the prosumer to exchange electricity with the electricity utility company.

It is imperative that a provision and legal framework, for the citizens, for such trade can minimize the damage to the natural environment and simultaneously drive economic development. This would also provide the citizens with more energy choices thereby bringing in more competition and innovation in the energy sector. Further, this would also require new ways of setting the price in the decentralized market according to Goldthau[8)]. Mengelkamp[16)]noted the need to create local markets for trading energy between these prosumers without intervention from intermediaries. Several governments such as the U.S. Department of Energy's Grid Modernization Initiative (GMI) of the USA have been working with private and public partners to create a smart electric grid that would ease electricity trading between prosumers. The purpose of GMI is to support prosumers with more flexibility and options to trade electric electricity.

India launched National Solar Mission (NSM) in 2010 with a view of meeting India's energy security challenges by promoting ecologically sustainable growth. India has a total solar grid capacity of 50.3 GW as on 31st January 2022 which is way more than the Government's initial target of 20 GW. The NSM intends to install 100 GW by the end of 2022. With a mission of achieving the aforementioned target, the Indian Government has launched various schemes such as Solar Park Scheme, Canal bank & Canal top Scheme, Grid Connected Solar Rooftop Scheme, etc. to encourage the generation of solar electricity in the country. India is also a founder member of the International Solar Alliance whose purpose is to have an alliance of countries for efficient consumption of solar energy.

The purpose of this paper is as follows

- To develop a model based on simulations that uses recent historical values of electricity consumption in a given city.
- Analyze and cost and benefits of such electricity trade between the various prosumers of electric electricity.

Our results show that when nodes trade with each other, they reduce their dependence on the electricity grid. This reduces carbon emissions, as most grids run on thermal electricity. In addition, our model also suggests that the nodes that act as prosumers can reduce their electricity costs.

The contents of our paper is organized into five sections. After the introductory section, we present the extant literature review and model development in the second section. In the third section, we have described the methodology before discussing the results and findings in the fourth. In the last section, we have presented the conclusions from the study, and their implications and given directions for future work.

2. Literature Review and Theoretical Model Development

Several scholars have researched the area of peer-to-peer (P2P) electricity trading. Different scholars have highlighted the different dimensions of the trade, for example, Guelpa and Verda[9] noted that the cost of electricity on prosumers could be reduced by shifting the load from peak hour to off-peak hour by proper Demand Side Management. Ozkan[19] observed that Demand Side Management based on Real-Time Pricing could minimize cost and maximize energy efficiency. Lauinger [14] developed an LP model to minimize the cost of electricity and 〖CO〗_2emissions in a residential system.

Vahedipour − Dahraie [26] suggested P2P energy trading, based on bidding, between electricity producers who use wind energy. Umer [25] developed another model for P2P electricity trading. Paudel suggested a decentralized market clearing mechanism for such P2P energy trading. Studies by Alam[2], Liu[15] developed energy-sharing models to minimize cost. Anoh[3] suggested grouping the prosumers within a short distance by telecommunication links to form a virtual microgrid. These models provide some guidelines for intraday trading. However, Kanakadhurga and Prabaharan[13] noted that this might not give consumers the comfort they need, as they do not consider appliance scheduling.

Esmat[7] suggested the use of Blockchains for achieving a decentralized market-clearing mechanism.

Distributed energy generation is one of the latest trends in sharing economy. In traditional grids, electricity was carried from a few centralized sources or generators to the customers. However, in today's complex world, there is an exigency of using grids in energy networks that would allow the bidirectional flow of energy and information. Further, the evolution of AI has led to smart meters and grids that can instantly figure out and respond to the changes in the demand and supply of electricity.

3. Methodology

Scholars[23] have used simulation for comprehending P2P power trading as it is a powerful technique to numerically understand a process or system[20]. Besides, Wu [27] had used simulation to determine the price in the context of power trading. Further, Hayes [10] proposed a simulation methodology for P2P energy platforms and energy distribution networks. At first actual data was segregated into domestic and commercial consumer categories. Commercial data was taken from three different facilities in Kolkata with three different electricity installations. The domestic data was taken from one of the residential gated communities in Kolkata. The electricity consumption in terms of BOT units (kilowatt hours or kWh) was noted from the respective meters daily for a month. The average electricity consumption from each of the installations, along with the standard deviations, was calculated for one month. The model was developed to simulate a peer-to-peer electricity trading experience as such trading is not prevalent in the country yet and is expected to be developed in the future. Those with excess of supply over demand became sellers and those with deficits of supply over demand became customers for such peer to peer trade. This data was utilized to simulate each day's consumption pattern. The consumption was assumed to follow a Gaussian distribution with the mean and standard deviations obtained. The probability density function (pdf) of such a distribution is given by

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \ldots\ldots\ldots\ldots\text{(1)}$$

Where μ and σ are the mean and standard deviations of the distribution respectively.

The values of the mean, standard deviations of 'x', and a randomly generated probability 'p' was fed to the model to generate the demand 'x' which follows normal distribution i.e. an inverse normal distribution. The probability density function for such as distribution is given by

$$f(x, \mu, \boldsymbol{\lambda}) = \sqrt{\frac{\boldsymbol{\lambda}}{\pi x^3}}\; \boldsymbol{e}^{-\frac{\lambda(x-\mu)^2}{2\mu^2 x}} \ldots\ldots\ldots\ldots\ldots\text{(2)}$$

The function is defined $\forall x > 0, \mu > 0$ and $\lambda > 0$ where, $\boldsymbol{\lambda}$ is a shape parameter.

The production 'p' of each node was set to the average consumption for the day. Once the demand 'x' is generated for all nodes the excess (Ex) or the deficits (Def) were computed as follows

Ex = max(p-x,0) for excess …………(3)
and Def = max (x-p,0) for deficit……….(4)

The mean electricity consumption and the standard deviations were subsequently used in the trials for each of the simulations. The entire day of 24 hours was divided into 96 slots of 15 minutes each. In each slot, all the nodes were generating and consuming electric electricity. The electricity consumption pattern was modeled to follow a normal distribution with the mean and standard deviations obtained from the previous step. The total electricity demand was thereafter computed by integrating the demand for each slot.

Demand = $\int_{x_1}^{x_2} f^{-1}dx$ …….(5)

Where f^{-1} is obtained from equation 2 and x_1 and x_2 are 1 and 96 respectively.

The generation was the mean of daily consumption. This led to excess production in some slots and deficit production in others. In case of excess production, the nodes were allowed to sell excess electricity to other nodes, whereas for deficit production, they were allowed to purchase electricity from other nodes. The price of electricity for such trade was modelled to follow a uniform distribution with price per unit varying from ₹6 to ₹8. For this, random numbers in the closed interval [0,1] with uniform probability distribution were generated. This is expressed as follows

Price = a + (b-a)*r…………..(6)

Where a and b are the lower and upper limits of price respectively (i.e. ₹6 and ₹8) and r is the random number between 0 and 1.

Thus, for every slot of the day the nodes met their demand for electricity by peer-to-peer trading. Electricity was taken from the grid whenever there was a shortage of electricity that could not be met by purchasing from other nodes or peers.

4. Results and Findings

The demand and production of each node in each of the two categories i.e. domestic and commercial were modeled. For the domestic category, the mean was 156919 units with a standard deviation of 6639 units. The following Figures depicts the story for the domestic category in one slot.

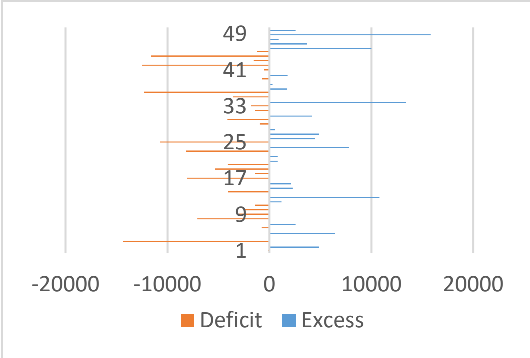

Fig. 1: Excess and Deficit in Kwh across 50 nodes participating in the peer to peer trading

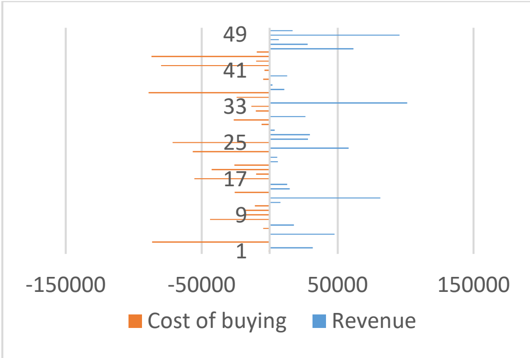

Fig. 2: Revenue and Cost of purchasing electricity in Rs. INR across 50 nodes

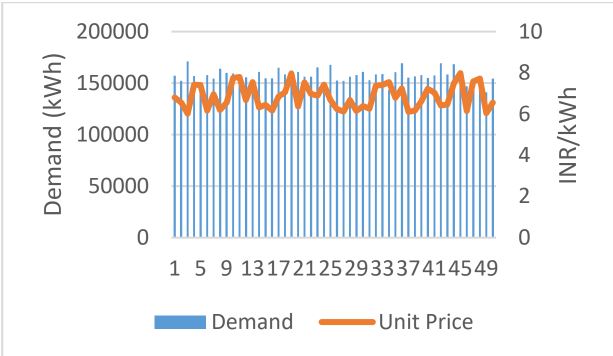

Fig. 3: Demand in kWh and Unit price of electricity in Rs. INR/kWh across 50 nodes

The total demand for the nodes was 7865115.41 units, as depicted in Fig 3. The total excess and deficit were 104107.10 units and 123272.52 units, respectively, as provided in Fig 1. There was an excess in 26 nodes and a deficit in 24.

Our results show that each node had excess and deficit productions in different slots. The nodes that had a deficit of electricity were modeled to purchase from peers instead of drawing from the grid. This is shown for one such simulation in table 1. The total revenue earned by the 50 nodes is ₹708282.42 at an average of ₹14165.64. The total cost incurred by all the nodes is ₹836922.38 at an average of ₹16738.44 as shown in Fig 2.

Our simulated data based on real observations show that at any point in time, there are buyers and sellers in the market, making peer-to-peer trading workable. Going beyond implementability, our model demonstrates that this market mechanism may be a beneficial alternative for consumers having their own generating sources like solar electricity. Our results show that when nodes traded with each other they reduced their dependence on the electricity grid. This reduces carbon emissions as most grids run on thermal electricity. Besides, our models also suggest that the nodes that act as prosumers can also reduce their electricity costs as they produce most of the electricity that they need. Additionally, they also sell their excess production to peers and earn revenue. Better estimates of the demand can lead to production that is more accurate and less waste of electricity.

5. Managerial Implications Conclusions and Limitations

The Commitment made by various governments in western countries toward a low-carbon future has put immense pressure on traditional energy grids. Thus, to minimize the loss of electricity, there must be a balance between electricity production and consumption. Keeping this in mind we infer that in near future many electricity networks are more likely to face several challenges. First, they will have to find out the new patterns of electricity consumption. Secondly, they will need to have planning under increasing uncertainty. Thirdly, as pointed by Akasiadis and Georgogiannis [1] large-scale implementation of such P2P models would be a big challenge as it would span cities or states. Fourthly, Mylrea, and Gourisetti [17] expressed concerns about security issues of such large-scale implementations. Last but not the least, they will have to deal with the increasing complexity of the network as a large number of small independent devices shall be getting connected to the network.

Our framework and simulation model would help practitioners comprehend the demand and supply of such networks. The results from our study can be utilized for better load management at the consumers' end. The findings from our paper can be used in conjunction with other studies such as that of Soares, Antunes and Oliveira[21], who in a study on load management, at the consumer end, used genetic algorithms to study a time-varying penalty for each time slot.

Low-carbon future and the electrification of our society from renewable energy sources (RES) are highly interlinked. In this paper, we focused on electricity generation at the household level through communities. However, the generation of such electric electricity can be done centrally at the national level with adequate support from governments. This can be through the creation of large generating facilities, like massive solar plants or wind farms.

Moreover, a low carbon future should also include other areas such as the transport sector whereby the use of solar electric vehicles can reduce carbon footprint. Future vehicles are more likely to have solar electricity on car rooftops to generate their electricity and sell any extra electricity that they might generate. Besides, low carbon would also include non-solar energy sources as well, for example, Jessam [12]had researched how wind emanating from air conditioning exhausts can be used for producing electricity.

Reliance on renewable energy is good not just at the individual level but at the macro level too. In the context of Japan, Barai and Saha [5]argued how one can continue with sustainable growth by relying on renewable and non-conventional energy sources. Sato[22]through a case study had shown how societies suffering from serious environmental problems have successfully come out of the same and become ecologically sustainable by balancing between economic growth and an ecologically friendly environment.

One fundamental assumption of our proposed model is that all the users of electricity are motivated to be prosumers, However, one has to model different motivations of the various users to be a part of the P2P network[24]. Future studies need to focus on such sectors and how suitable models can be developed around such shared economies as well.

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