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Multi-Stage Bargaining of Smart Grid Energy Trading Based on Cooperative Game Theory

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Abstract: Due to global warming and climate change, it is essential to produce power using renewable sources, such as solar, wind, fuel cells, etc. The traditional grid shifts towards the smart grid by infusing digital communication techniques and information technology. As the current power system is shifting towards a smart grid, the utility and prosumers participate in the energy trading process. Due to the distributed nature of the smart grid, providing a fair price among them is becoming a difficult task. The article introduces a model for energy trading in a smart grid by allowing participants to negotiate in multiple stages using a game-theory-based multi-stage Nash Bargaining Solution (NBS). The model's application of game theory enables the participants to decide on a mutually acceptable price, thereby encouraging the utility, private parties and prosumers (those who are able to generate and consume energy) to participate in the trading process. Since all parties participate in the trading procedure, greenhouse gas emissions are reduced. The proposed model also balances the benefits of consumers and producers in the final agreed fixed price. To demonstrate the efficacy of the proposed work, we compare the analytical results with feed-in-tariff (FiT) techniques in terms of consumers' energy bills and producers' revenue. For experimental analysis, 20 participants are considered, where the percentage reduction in the bill of each consumer and the percentage increment of revenue of each producer are compared to FiT. On average, the overall bill of the consumer is reduced by 32.8%, and the producers' revenue is increased by 64.83% compared to FiT. It has been shown further that the proposed model shows better performance as compared to FiT with an increase in the number of participants. The analysis of carbon emission reduction in the proposed model has been analyzed, where, for 10 participants, the carbon emission reduction is approximately 28.48 kg/kWh, and for 100 participants is 342.397 kg/kWh.

Keywords: smart grid; energy trading; distributed energy resources; renewable energy; prosumers; cooperative game theory; multi-stage bargaining; peer-to-peer (P2P) trading

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1. Introduction

Global warming and climate change have become of significant concern for future generations. In addition, the increasing demand for energy leads to fossil fuel depletion as the current energy generation depends on fossil fuel. This method of energy generation eventually causes environmental issues due to the greenhouse gas emission in the process. Integrating the distributed renewable energy resources in small scale or large scale generation is one of the most promising solutions for these issues [1–4]. In a traditional power grid, some large generators produce energy in bulk and deliver it to many consumers. It supports only a one-way flow of information and electricity which is shown in Figure 1. Therefore, managing these distributed energy resources may be difficult or not possible in the existing traditional electricity grid. Here, the concept of smart grid (SG) comes in this field to manage the above problem [5].

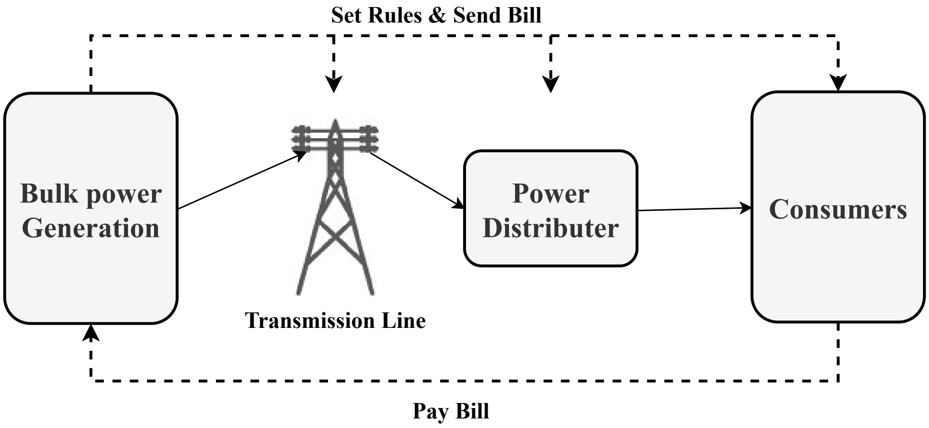


Figure 1. Traditional power grid.

A secure and fair trading platform is required to facilitate trading among these distributed energy generators (DERs). Information and communication technologies (ICT) are employed in the energy sector to avail trading among DERs [6,7]. With the emergence of ICT in the energy sector, the small-scale energy generators are allowed to trade with the main grid, where producers can sell their surplus energy to the grid and consumers can buy energy from main grid, called the Feed-in-Tariff (FiT) technique. Figure 2 represents this FiT scheme. The FiT technique gives more benefits to the main grid, so small-scale energy generators are not interested in participating in the trading process. So, to motivate these small-scale energy generators to participate in the trading process, there is a need for a prosumer-centric market mechanism. A trading technique known as peer-to-peer trading has been introduce to give this facility [8].

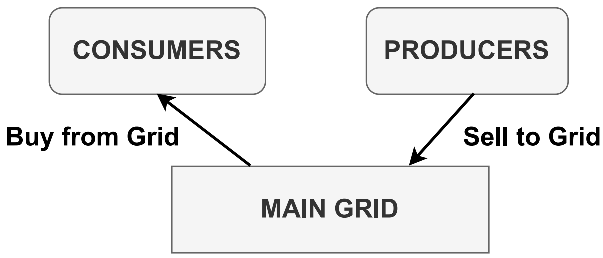


Figure 2. Feed-in-Tariff (FiT) architecture.

The peer-to-peer trading technique facilitates energy trading between producers and consumers instead of buying from the grid and selling to the grid. Prosumers can take advantage of themselves in this type of trading. One of the most important things to make the market successful is making prosumers participate in the trading market. Therefore, this paper motivates the prosumers by assuring a mutually agreed price via a multi-stage negotiation.

The main contributions of the proposed work are as follows:

- Proposes an architecture for P2P energy trading market based on a multi-stage Nash Bargaining Solution (NBS) among the prosumers.
- Design a methodology for determining the bargaining power of producers and consumers using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) algorithm based on parameters, such as consumers' and producers' prices, the amount of energy demand, and the amount of energy surplus.

- Proposes a heterogeneous trading model that allows P2P energy trading and trading with the main grid.
- Comparative studies of the proposed methodology have been carried out on various aspects, such as bill reduction in consumers, revenue increment of prosumers, satisfactory factors of both consumers and producers, etc.

The organization of the article is as follows. The overview of the state-of-art in energy trading in smart grid is discussed in Section 2. In Section 3, the overall proposed trading architecture is explained in detail. A detailed explanation of the mathematical formulation of the proposed bargaining model, bill, and revenue determination of the proposed model is performed in Section 4. Further, in Section 5, the analytical results of the proposed trading method are discussed. Finally, the proposed method is concluded in Section 6.

2. Related Work

In this section, the contribution of the various researchers around the globe on the smart grid energy trading and energy management is presented.

The authors in [9] designed an optimization method based on game theory to minimize the cost of energy used by households. In this approach, fairness criteria should be used to distribute the coalition's value (or revenue), which is achieved by the amount of cost savings the coalitional group. The authors in [10], introduce an adaptive dynamic power management technique that supervises the overall power flow in the microgrid system. The bus voltage variation increases when the mode of operation is continuously altered, and the system's stability also reduces. Morstyn et al. [11] proposed a bilateral contract network for P2P energy trading which offered energy contracts between traditional fossil-fuel-based providers, intermediaries, and prosumers with rigid, time-coupled flexible loads. Rahimiyan et al. [12] proposed an energy management system that regulates price-responsive demand within a cluster and offers an interface for energy trading between suppliers and buyers. The authors in [13] developed a new day-ahead price-determining mechanism to manage the uncertainty related to energy generation, demand, and pricing. The scheme incorporates a non-cooperative Stackelberg model to trade energy between prosumers and a power utility. According to classical game theory, the anticipated profits of the prosumers were maximised by a unique pure-strategy Nash equilibrium. Hakimi et al. [14] proposed a method for evaluating the viability of implementing a novel controller for a cooling system in a smart grid environment with a significant proportion of renewable energies. The authors in [15] proposed a motivational framework to motivate prosumers psychologically for energy trading participation based on game theory to provide a stable alliance. Amin et al. [16] designed a non-cooperative game-theoretical approach to encourage prosumers to participate in energy trading mechanisms, including both islanded and grid-connected scenarios in which the participants determine the trading price. It solves a centralized optimization problem and transmits signals to the individual participants. Anoh et al. [17] proposed a clustering scheme for various prosumers to trade energy in their locality through a game theoretical framework. In this scenario, interactions between prosumers are modeled as a competitive game. Amin et al. [18] proposed a new framework based on contracts for aggregating surplus power in a hierarchical energy trading system with dynamic pricing. This will increase system uncertainty because renewable resources are not dispatchable. Zhang et al. [19] developed a market for peer-to-peer energy trading for the distribution grid. The author's utilized auxiliary services to address issues such as trade price-fixing for peer-to-peer energy sharing. Zhang et al. [20] proposed a PV power forecasting indicator that maximizes flexible demand utilization. In addition, they incentivize PV owners to submit lower bids and users to maximize energy consumption. Lee et al. [21] proposed a promising approach for a peer-to-peer (P2P) energy trading system that maximized the economic welfare that characterized the optimal price and allocations. Li et al. [22] treated electric energy as a homogeneous commodity irrespective of the sources, considered the heterogeneity in energy-supplying reliability of DERs, and classified the energy into multiple grades. Wang et al. [23] proposed a centralized residential P2P energy trading platform that ensured all the participant's fairness and transparency using the supply function method. The residential energy trading and Battery Energy Storage System (BESS) management problem is formulated by considering social welfare and fair benefit distribution. Yang et al. [24], the authors introduced an energy supply point (EPS) that collects the surplus energy from the retail customers and supplies energy continuously to the telecom operator. They developed a three-stage game optimization problem to determine the power allocation and energy transaction pricing strategy among utilities, telecom operators, and ESP. Devi et al. [25] proposed an energy trading model based on the priority values of participants considering the various parameters of participants.

Synthesis: The dynamic pricing technique for energy trading between consumers and producers is proposed; in addition to this, the proposed approach allows energy trading with the main utility grid if necessary. Apart from this, we also determine the bargaining power of each of the participants based on their parameters, such as their initial price bid, energy demand, and surplus energy, to facilitate the multiple stages of bargaining between consumers and producers to decide the satisfied price among them. This determined value is also used to map between consumers and producers. Table 1 shows the comparative study of features with some of the existing P2P approaches. Those features give a great impact on carrying out the trading model successful. The dynamic pricing features provides the fairness among the participants. All the participants participate and agreed on one price which provides benefit to both the parties. The satisfaction with price decision for all the participants is obtained by providing the price negotiation in multiple stages before fixing the price. This satisfaction factor is important to motivate the participants into participating in the proposed trading model. P2P trading is a very important feature for removing the existing centralised authorities to avoid single point failure and unfair decisions for participants. A gaming approach in energy trading is adopted to make the model interactive and profitable. Energy production using renewable energy depends on time duration and the weather conditions; there may be energy deficiency and energy wastage problems. To avoid these problems, the proposed model adopts the heterogeneous energy trading approach. Further, the main contribution and the limitation of the some of the closely related existing works are presented in Table 2. From this, it can be concluded that the final price of energy trading for a time duration is decided without the opinion of the prosumers. This may cause the demotivation of the small scale prosumers about participating in the trading model. Therefore, the proposed trading model considered the opinion of the prosumers while deciding the final trading price by providing multiple stage of bargaining. From the above-discussed existing literature, it is noticed that none of the previous research takes any of these approaches into consideration. Thus, the proposed work facilitates multiple stages of negotiation according to their bargaining power to fix the trading price between producers and consumers.

Table 1. Comparative study of features with previous P2P works.

Papers	Dynamic Pricing	Multi-Stage Negotiation	P2P Trading	Gaming Approach	Heterogeneous Trading
Rahimiyan [12]	×	×	✓	✓	✓
Rahi [13]	×	×	×	✓	×
Tusher [15]	×	×	✓	✓	✓
Amin [16]	✓	×	✓	✓	✓
Li [26]	×	×	✓	✓	×
Proposed Work	✓	✓	✓	✓	✓

Table 2. Research gap and contribution of some of the existing works.

Papers	Contribution	Limitations
Rahimiyan [12]	Coordinates the price-responsive demands within the cluster and maximizes the utility of demands.	Customers have to agree to the price fixed by the system operators.
Rahi [13]	Optimized the energy trading between prosumers and main grid by considering the price uncertainty.	The trading price is fixed by the system coordinator and consumers has to agree on this price.
Tusher [15]	Identified motivational psychological tool for designing the trading model using the non-cooperative game-theoretic model to motivate prosumers to participate in the trading model.	The existence of the Nash equilibrium of the trading model is not discussed.
Amin [16]	Motivational trading platform for prosumers to make the trading process successful using non-cooperative game theory.	Lack of fairness while sharing energy and pricing scheme.
Li [26]	Construct a stable coalition among prosumers based on the cooperative game, which provides benefit to the participants.	The strategy used for a multi-hierarchical energy trading system is not investigated properly.

3. Trading Model Architecture

In this section, we describe the detailed structure and functionalities of the proposed trading model architecture. Figure 3 represents the overall components and functionality of the architecture. The proposed architecture is based on two-layered architecture—the first layer consists of the end-users like consumers and producers (i.e., prosumers). The second layer is the control unit, where the management, negotiation, and mapping process between consumers and producers are performed before the peer-to-peer energy trading process is initiated. In this work, we considered m number of consumers and n numbers of producers. Further, we discuss the detail of each of these components.

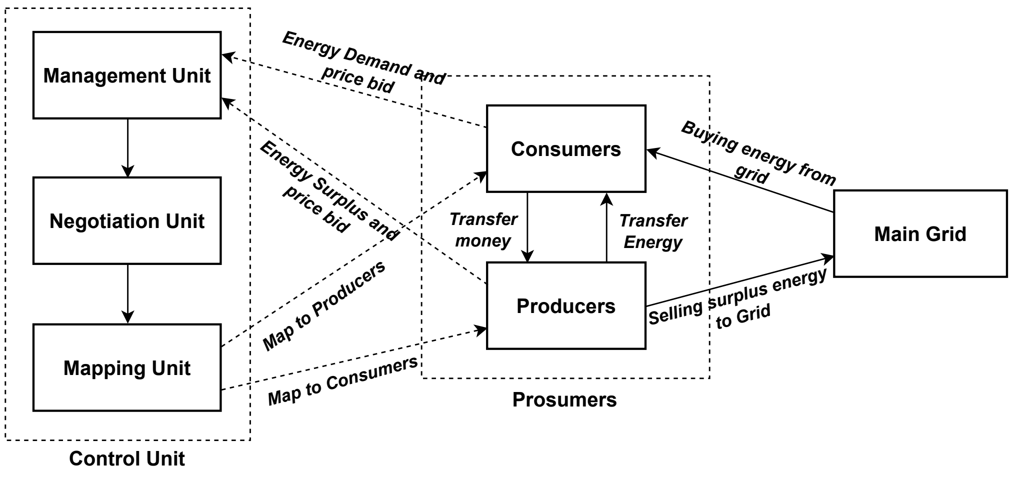


Figure 3. Proposed trading model.

3.1. End Users

The end user consists of consumers and producers.

- **Consumers:** *Consumers are those who purchase energy from producers, the main grid, or both for their needs. Consumers also include prosumers (who can also produce energy) with insufficient power for their use.*
- **Producers:** *Producers are those who have surplus energy for selling purposes. These include prosumers with surplus energy, distributed energy producers like solar energy farms or wind energy farms.*

3.2. Control Unit

The distributed energy trading model is not straightforward to make fair and prosperous. For the trading model to be successful, prosumers must be motivated to participate in the trading process. This proposed trading model is mainly focused on this by making it a prosumer-centric market. The control unit makes it possible for all the prosumers to participate in the bargaining process. This unit consists of three subunits, the management unit, the negotiation unit, and the mapping unit. Further, we will discuss the detail of these components.

3.2.1. Management Unit

The management unit is responsible for categorizing consumers and producers according to the energy demand and surplus energy, respectively, and calculating participants' bargaining power in the trading process. The trading participants will provide their initial bidding price, consumers' energy demand, and producers' energy surplus. Then, using those parameters of consumers and producers, the bargaining power of the consumers and producers is calculated using the TOPSIS technique.

3.2.2. Negotiation Unit

The Negotiation Unit is responsible for the bargaining process between producers and consumers to produce the agreement price. The negotiation process between the consumers and producers continues until it reaches the agreed price in multiple stages cooperatively. Algorithm 1 is responsible for the negotiation process. In this, the consumer raises their price as shown in line 21 according to Equation (27). At the same time, the producer lowers their price by a fraction based on their negotiation power at each stage, which is shown at line 15 with respect to Equation (25), respectively. After negotiating some stages, there comes a situation where the price of the consumer is greater than the producer's price, as shown in Line 26. At this stage, the negotiation process will end. The final price between them will be fixed by taking the mean value of consumer and producer price of this stage, which is shown at line 27. In this way, the price between consumers and producers will be finalized and stored in a final price matrix.

3.2.3. Mapping Unit

The Mapping Unit is responsible for mapping consumers and producers. Algorithm 2 describes the steps involved in mapping process. This unit utilizes the price matrix calculated in the negotiation process to finalize the price between consumers and producers, as shown in Equation (1).

$$Price\_Matrix = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_m \end{array} \begin{array}{c} \begin{array}{cccc} P_1 & P_2 & \cdots & P_n \end{array} \\ \begin{pmatrix} \rho_{1,1} & \rho_{1,2} & \cdots & \rho_{1,n} \\ \rho_{2,1} & \rho_{2,2} & \cdots & \rho_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{m,1} & \rho_{m,2} & \cdots & \rho_{m,n} \end{pmatrix} \end{array} \tag{1}$$

where $\rho_{i,j}$ is the price of ith consumer and jth producer after negotiation.

In the trading process, consumers seek minimum prices, and producers try to maximize their prices, as shown in line 2 and 5, respectively. The price is set by taking the mean value of consumers' minimum price and producers' maximum price to meet the balance price between them, as shown in line 9. After this process, the mapping between the consumer and producers is performed concerning the following given conditions.

1. $ED_{total} = ES_{total}$**:** In this, the total energy demand and total energy surplus are equal. Here, the consumer with the highest bargaining power will obtain the highest priority and have the opportunity to buy energy from the producer who agrees to trade at a

lower price. In this way, the energy trading process will be carried on with respect to their bargaining power. This process is performed in lines 36–47.

2. $ED_{total} < ES_{total}$**:** In this case, the total energy demand is less than the total energy surplus. The consumers will buy part of the energy from their energy demand from producers to facilitate all consumers to trade with producers in P2P trading which is performed in line 13. The amount of energy that consumer i buy from P2P trading is calculated as follows:

$$\vartheta_i = ED_i \times \frac{ES_{total}}{ED_{total}} \quad (2)$$

3. $ED_{total} > ES_{total}$**:** This condition specifies that the total energy surplus is less than the total energy demand. In this condition, some producers will not participate in P2P energy trading. They can trade their surplus energy with the main grid. Therefore, to allow all the producers to participate in P2P trading, producers trade their part of surplus energy in the P2P trading process and trade the remaining amount with the main grid as shown in line 20. For producer j, the amount of energy to be sold in P2P trading is decided using the following equation.

$$\varphi_j = ES_j \times \frac{ED_{total}}{ES_{total}} \quad (3)$$

Algorithm 1 Negotiation unit

Input:
1. Initial Price bid - $CP_{i,t}^{min}$ (Consumer) and $PP_{j,t}^{max}$ (Producer)
2. Initial Energy Demand - $ED_{i,t}$
3. Initial Energy Surplus - $ES_{j,t}$
$\forall i = 1, \ldots, m, \; j = 1, \ldots, n$
Output: Negotiated price matrix $(Price\_Matrix)$

1: Calculate bargaining powers σ_i and γ_j using TOPSIS $\forall i = 1, \ldots, m, \; j = 1, ..., n$ ▷ $\sigma_i, \gamma_j \rightarrow$ priority value of C_i and P_j
2: Sort Consumers (C_i) according to the decreasing order of their σ_i $\forall i = 1, \ldots, m$
3: Sort Producers (P_j) according to the decreasing order of their γ_j, $\forall j = 1, \ldots, n$
4: $stage \leftarrow 0$
5: **if** $stage = 0$ **then** // Initializing variables in first stage
6: $CP_{i,t} \leftarrow CP_{i,t}^{min}$
7: $PrevCP_{i,t} \leftarrow CP_{i,t}^{min}$
8: $PP_{j,t} \leftarrow PP_{j,t}^{max}$
9: $PrevPP_{j,t} \leftarrow PP_{j,t}^{max}$
10: **end if**
11: **Repeat:**
12: **for** $j = 0$ *to* n **do**
13: **if** $ES_j > 0$ **then** // Checking for available energy surplus of jth producer at time t
14: $PrevPP_{j,t} = PP_{j,t}$
15: $PP_{j,t} = F(PrevPP_{j,t}, PP_{j,t})$ ▷ $PrevPP_{j,t}$: input
16: **end if** ▷ $PP_{j,t}$: output
17: **end for**
18: **for** $i = 0$ *to* m **do**
19: **if** $ED_i > 0$ **then** // Checking for energy demand of ith consumer at time t
20: $PrevCP_{i,t} = CP_{i,t}$
21: $CP_{i,t} = F(CP_{i,t}, PrevCP_{i,t})$ ▷ $PrevCP_{i,t}$: input
22: **end if** ▷ $CP_{i,t}$: output
23: **end for**
24: **for** $i = 0$ *to* m **do**
25: **for** $j = 0$ *to* n **do**
26: **if** $CP_{i,t} \geq PP_{j,t}$ && $Price\_Matrix_{i,j}$ is not assigned **then**
27: $Price\_Matrix_{i,j} \leftarrow (PrevCP_{i,t} + PrevPP_{j,t})/2$
28: **end if**
29: **end for**
30: **end for**
31: $stage \leftarrow stage + 1$
32: Reset t
33: $StopNegotiation \leftarrow false$
34: **if** $Price\_Matrix_{i,j}$ is fill, $\forall i = 1, \ldots, m, \; j = 1, \ldots, n$ **then**
35: $StopNegotiation \leftarrow true$
36: **end if**
37: **if** $StopNegotiation \; != \; true$ **then**
38: *goto* **Repeat**
39: **end if**

Algorithm 2 Mapping procedure

Input: Negotiated price matrix ($Price\_Matrix$)
Output: Mapping between Consumers (C) and Producers (P)

for $i = 0$ *to* m **do**
  $Min_i \leftarrow \text{Minimum}\{Price\_Matrix_{i,j}, \forall j = 1, \ldots, n\}$
end for
for $j = 0$ *to* n **do**
  $Max_j \leftarrow \text{Maximum}\{Price\_Matrix_{i,j}, \forall i = 1, \ldots, m\}$
end for
for $i = 0$ *to* m **do**
  for $j = 0$ *to* n **do**
    $Final\_Price\_Matrix_{i,j} \leftarrow Avg(Min_i, Max_j)$
  end for
end for
Sort Consumers (C_i) according to the decreasing order of their σ_i $\forall i = 1, \ldots, m$
if $ED_{total} > ES_{total}$ **then** //Checking for consumer to buy deficit energy from grid
  for $i = 0$ *to* m **do**
    $\vartheta_i \leftarrow ED_i \times \frac{ES_{total}}{ED_{total}}$
  end for
  for $j = 0$ *to* n **do**
    $\varphi_j \leftarrow ES_j$
  end for
else if $ED_{total} < ES_{total}$ **then** // Checking for producers to sell extra surplus energy to grid
  for $i = 0$ *to* m **do**
    $\vartheta_i \leftarrow ED_i$
  end for
  for $j = 0$ *to* n **do**
    $\varphi_j \leftarrow ES_j \times \frac{ED_{total}}{ES_{total}}$
  end for
else
  for $i = 0$ *to* m **do**
    $\vartheta_i \leftarrow ED_i$
  end for
  for $j = 0$ *to* n **do**
    $\varphi_j \leftarrow ES_j$
  end for
end if
for $i = 0$ *to* m **do**
  Sort Producers (P_j) according to the increasing order of $Final\_Price\_Matrix_{i,j}, \forall j = 1, \ldots, n$
  for $j = 0$ *to* n **do**
    if $\vartheta_i > 0$ && $\varphi_j > 0$ **then**
      if $\vartheta_i < \varphi_j$ **then**
        $\varphi_j = \varphi_j - \vartheta_i$
        $\vartheta_i = 0$
      else if $\vartheta_i > \varphi_j$ **then**
        $\vartheta_i = \vartheta_i - \varphi_j$
        $\varphi_j = 0$
      else
        $\vartheta_i = 0$
        $\varphi_j = 0$
      end if
    end if
  end for
end for

4. Mathematical Framework

This section will discuss the mathematical models for calculating consumers' and producers' bargaining power and the proposed multi-stage bargaining solution. To calculate the proposed mathematical model, we assume that the energy demand and supply of prosumers are fixed for a time duration t. We also consider m and n number of consumers and producers, respectively, to describe the mathematical models mentioned above. Further, we demonstrate the mathematical solution of participants' bargaining power and multi-stage NBS for the negotiation process.

4.1. *Mathematical Framework for Bargaining Power*

The bargaining power of the consumers and producers is calculated based on their attributes, such as the amount of surplus energy, energy demand, and initial bidding price. To obtain the value which is far from the worst choice and nearer to the best solution, we used a multi-criteria decision analysis technique called TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) considering the above-mentioned specifications [27]. Further, we present the mathematical models involved in TOPSIS with x number of attributes (A) for each producer.

1. **Evaluation Matrix Calculation:** For producer P, the evaluation Matrix is formed by parameters like initial price bid and energy surplus of producers. If the number of parameters and the number of producers is x and n, respectively, then the evaluation matrix (EM) with $n \times x$ is formed as follows:

$$EM = \begin{array}{c} \\ P_1 \\ P_2 \\ \vdots \\ P_n \end{array} \begin{array}{c} \begin{array}{cccc} A_1 & A_2 & \cdots & A_x \end{array} \\ \begin{pmatrix} \beta_{1,1} & \beta_{1,2} & \dots & \beta_{1,x} \\ \beta_{2,1} & \beta_{2,2} & \dots & \beta_{2,x} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{n,1} & \beta_{n,2} & \dots & \beta_{n,x} \end{pmatrix} \end{array} \tag{4}$$

where $\beta_{j,k}$ is kth parameter of jth producer.

2. **Matrix Normalization:** The normalization of EM between 0 and 1 is performed to simplify the calculation process. Here, NM represents the normalization matrix of producers.

$$NM = \begin{array}{c} \\ P_1 \\ P_2 \\ \vdots \\ P_n \end{array} \begin{array}{c} \begin{array}{cccc} A_1 & A_2 & \cdots & A_x \end{array} \\ \begin{pmatrix} l_{1,1} & l_{1,2} & \dots & l_{1,x} \\ l_{2,1} & l_{2,2} & \dots & l_{2,x} \\ \vdots & \vdots & \ddots & \vdots \\ l_{n,1} & l_{n,2} & \dots & l_{n,x} \end{pmatrix} \end{array} \tag{5}$$

where, $l_{j,k} = \frac{\beta_{j,k}}{\sqrt{\sum_{j=1}^{n} \beta_{j,k}^2}}$, $j = 1, 2, \dots, n$ and $k = 1, 2, \dots, x$

3. **Selection of ideal best and ideal worst:** Further, we select the ideal best (I_b) and worst (I_w) from the column of NM concerning the impact of those parameters on the process of decision-making. Given below is the mathematical form of the I_b and I_w.

$$I_b = \begin{cases} max(l_{i,j}), & \text{if } A_j \in \Gamma \\ \\ min(l_{i,j}), & \text{if } A_j \in \Gamma' \end{cases} \tag{6}$$

$$I_w = \begin{cases} min(l_{i,j}), & \text{if } A_j \in \Gamma \\ \\ max(l_{i,j}), & \text{if } A_j \in \Gamma' \end{cases} \tag{7}$$

where Γ and Γ' represent the positive impact attribute and the negative impact attribute, respectively.

4. **Euclidean distance from ideal best and ideal worst:** Euclidean distance from I_b and I_w is calculated as follows:

$$d_{jb} = \sqrt{\sum_{k=1}^{x} (l_{j,k} - I_b)^2}, \quad \forall\, j = 1, \dots, n. \tag{8}$$

$$d_{jw} = \sqrt{\sum_{k=1}^{x} (l_{j,k} - I_w)^2}, \quad \forall\, j = 1, \dots, n. \tag{9}$$

5. **Calculation of bargaining power:** Finally, the bargaining power of producers (γ_j) is calculated as:

$$\gamma_j = \frac{d_{jw}}{d_{jb} + d_{jw}}, \quad \forall\, j = 1, \ldots, n. \tag{10}$$

The bargaining power of consumers ($\sigma_i, \forall\; i = 1, \ldots, m$) is calculated in the same manner as producers, which involved the equations mentioned above.

4.2. Mathematical Framework for Bargaining Solution

In this part, we present a price negotiation problem among producers and consumers in a cooperative game theoretical manner, where the consent of each of the participants is considered to fix the price. The consumer tries to minimize the price, and the producers try to maximize the price. From the work [28], we are motivated to use a multi-stage bargaining solution to decide the price of consumers and producers in a cooperative manner that benefits both parties.

We considered the m and n number of consumers and producers, respectively, participating in the bargaining process. They place their initial price bidding, energy demand, and energy surplus in relation to the control unit. From this, we procure the utility function of all the consumers and producers based on their initial bidding price. The price utility function of ith consumer and jth producer at time t is expressed as $U_i(CP_{i,t})$ and $U_j(PP_{j,t})$, where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$. Further, we can represent the possible joint utility set or the feasible set of consumers and producers by closed set J_{CP} and J_{PP}, respectively, [29].

$$J_{CP} = \{U_1(CP_1), U_2(CP_2), \ldots, U_m(CP_m)\} \in \mathbb{R}^m \tag{11}$$

$$J_{PP} = \{U_1(PP_1), U_2(PP_2), \ldots, U_n(PP_n)\} \in \mathbb{R}^n \tag{12}$$

Definition 1. (Utility of producer): The utility of jth producer at time t is defined as:

$$\begin{aligned} &U_j(PP_{j,t}) = PP^{max}_{j,t} - PP_{j,t} \\ &\text{subject to}\,, \sum_{j=1}^{n} PP_{j,t} \geq n \cdot g_s \end{aligned} \tag{13}$$

where g_s is the price per unit of energy when producer sell to grid and n is the number of producers at time t. In this, $n \cdot g_s$ gives total price when n producer sell their energy to the main grid. $PP_{j,t}$ and $PP^{max}_{j,t}$ are the producer jth price at time t and initial bidding price of jth producer, respectively.

Definition 2. (Utility of consumer): The utility of ith consumer at time t is defined as:

$$\begin{aligned} &U_i(CP_{i,t}) = CP^{min}_{i,t} + CP_{i,t} \\ &\text{subject to}\,, \sum_{i=1}^{m} CP_{i,t} \leq m \cdot g_b \end{aligned} \tag{14}$$

where g_b is the price per unit when consumer buy energy from the grid at time t, $CP_{i,t}$ and $CP^{min}_{i,t}$ are the consumer ith price at time t and initial bidding price of ith consumer, respectively.

Theorem 1. *The joint utility set or the feasible set J_{PP} and J_{CP} are convex.*

Proof. If $\mu p + (1 - \mu)q \in F, \forall p, q \in F$ and $0 < \mu < 1$ for any μ, then a set F is convex. In this, the joint utility set is $J_{PP} = \{U_1(PP_1), U_2(PP_2), \ldots, U_n(PP_n)\}$.

Let s and t be two utility point in set J_{PP}. Then, J_{PP} is convex if $\mu s + (1 - \mu)t \in J_{PP}$. From Equation (13), we obtain

$$PP_{j,t} = PP^{max}_{j,t} - U_j(PP_{j,t}) \tag{15}$$

$$\implies \sum_{j=1}^{n} PP_{j,t} = \sum_{j=1}^{n} PP_{j,t}^{max} - \sum_{j=1}^{n} U_j(PP_{j,t})$$

$$\implies \sum_{j=1}^{n} U_j(PP_{j,t}) \leq \sum_{j=1}^{n} PP_{j,t}^{max} - n.g_s$$

Then, we can express the set of utility function as,

$$J_{PP} = \left\{ U_{j,t} \sum_{j=1}^{n} U_j(PP_{j,t}) \leq \sum_{j=1}^{n} PP_{j,t}^{max} - n.g_s \right\} \quad (16)$$

Next, we need to prove $f(\xi) = \sum_{j=1}^{n} \xi U_j(p_{j,t}) + (1-\xi) U_j(q_{j,t})$ is convex to prove the convexity of J_{PP}.

For this, $f(\xi)$ should be non-negative function for $\xi = 0$ and 1, and the first derivative of $f(\xi)$ is also a non-negative $\forall\ 0 < \xi < 1$.

In function $f(\xi)$, $U_j(p_{j,t})$, and $U_j(q_{j,t})$ is non-negative utilities so, $f(\xi)$ is non-negative for $\xi = 0$ and 1. Then, $f_j^{\prime}(\xi) = \sum_{j=1}^{n} U_j(p_{j,t}) - U_j(q_{j,t})$ is also a non-negative function. Hence, the function $f_j(\xi)$ is a convex function. Therefore, $f(\xi)$ is also a convex function as the sum of the convex functions is also convex.

Similarly, we can prove that the utility set of consumer J_{CP} is also a convex set. □

The price negotiation's optimization function for the bargaining solution $F(PP_t^{max}, PP_t)$ must satisfy the four NBS Nash axioms described in [29]. The following points show how the proposed function $F(PP_t^{max}, PP_t)$ satisfies the NBS axioms for a pair of user.

(i) ***Pareto Efficiency:*** Suppose there exist $PP_{1,t}^{\prime}$ and $PP_{2,t}^{\prime}$, such that $PP_{1,t}^{\prime} > PP_{1,t}$ and $PP_{2,t}^{\prime} > PP_{2,t}$, then $(PP_{1,t}^{max} - PP_{1,t}^{\prime})(PP_{2,t}^{max} - PP_{2,t}^{\prime}) > (PP_{1,t}^{max} - PP_{1,t})(PP_{2,t}^{max} - PP_{2,t}^{\prime})$, implies $F(PP_t^{max}, PP_t^{\prime}) > F(PP_t^{max}, PP_t)$. This violates the notion of optimization function. Hence, it satisfies the Pareto Efficiency.

(ii) ***Symmetry:*** The maximum value of function, $F(PP_t^{max}, PP_t)$ remains unchanged, even if the value of the each of the user is interchanged, as it is symmetry.

(iii) ***Invariance:*** If $PP_t^{l,max}$ and PP_t^{l} be the linear transformation of bargaining solution of PP_t^{max} and PP_t, then we can express $F(PP_t^{l,max}, PP_t^{l})$ as $(a_1 PP_{1,t}^{max} + b_1 - a_1 PP_{1,t} - b_1)(a_2 PP_{2,t}^{max} + b_2 - a_2 PP_{2,t} - b_2)$, implies $a_1 a_2 F(PP_t^{max}, PP_t)$. Therefore, the proposed function is invariance.

(iv) ***Independence of irrelevant alternatives:*** Suppose (PP_t^{max}, P_t^{a}) and (PP_t^{max}, PP_t) be two bargaining solutions, where $P^a \subseteq J_{PP}$. If $F : (PP_t^{max}, PP_t) \in P^a$, then $F : (PP_t^{max}, P_t^{a}) = F : (PP_t^{max}, PP_t)$. We may deduce that if the utility area J_{PP} is in a solution F, that lies in the subset P^a of J_{PP} then, the bargaining in a smaller region P^a will obtain the same result. Hence, it is independence of irrelevant alternatives.

A unique solution for price negotiation among producers and consumers should exist as it satisfies the four axioms. Now, we can derive the unique solution of the optimization function for n producers and m consumers using the Lagrange Multiplier approach.

The following optimization function is the price negotiation optimization function for n producers.

$$\begin{aligned} F(PP_t^{max}, PP_t) &= \underset{(PP_{1,t} \dots PP_{n,t})}{\arg\max} \prod_{j=1}^{n} U_j(PP_{j,t})^{\gamma_{j,t}} \\ \implies F(PP_t^{max}, PP_t) &= \underset{(PP_{1,t} \dots PP_{n,t})}{\arg\max} \prod_{j=1}^{n} (PP_{j,t}^{max} - PP_{j,t})^{\gamma_{j,t}} \\ &\text{subject to, } \sum_{j=1}^{n} PP_{j,t} \geq n.g_b \text{ and } PP_{j,t} \leq PP_{j,t}^{max}. \end{aligned} \tag{17}$$

We simplify the Equation (17) by taking the logarithm of the same as this operation does not affect the expected outcome of the function. Then, the Equation (17) is express as follows:

$$F(PP_t^{max}, PP_t) = \underset{(PP_{1,t} \dots PP_{n,t})}{\arg\max} \sum_{j=1}^{n} \gamma_{j,t} log(PP_{j,t}^{max} - PP_{j,t}) \tag{18}$$

To maximize the above Equation (18), we used the Lagrange Multiplier technique as follows:

$$L = \sum_{j=1}^{n} \gamma_{j,t} log(PP_{j,t}^{max} - PP_{j,t}) - \lambda(\sum_{j=1}^{n} PP_{j,t} - n.g_b) \tag{19}$$

Now, after taking partial derivatives with respect to $PP_{j,t}$, we obtain

$$\begin{aligned} \frac{\delta L}{\delta PP_{1,t}} &= \gamma_{1,t} \frac{1}{(PP_{1,t}^{max} - PP_{1,t})} - \lambda = \frac{\gamma_{1,t}}{(PP_{1,t}^{max} - PP_{1,t})} - \lambda \\ \frac{\delta L}{\delta PP_{2,t}} &= \frac{\gamma_{2,t}}{(PP_{2,t}^{max} - PP_{2,t})} - \lambda \end{aligned} \tag{20}$$

Then, the nth term of partial derivative is

$$\frac{\delta L}{\delta PP_{n,t}} = \frac{\gamma_{n,t}}{(PP_{n,t}^{max} - PP_{n,t})} - \lambda \tag{21}$$

and the partial derivative with respect to λ is

$$\frac{\delta L}{\delta \lambda} = n.g_b - \sum_{j=1}^{n} PP_{j,t} \tag{22}$$

After equating Equations (20) to (21) to zero and solving the individual equation, we obtain the jth term as follows

$$PP_{j,t} = PP_{j,t}^{max} - \frac{\gamma_{j,t}}{\lambda} \tag{23}$$

and after equating Equation (22) to zero, we obtain the following equation.

$$\frac{1}{\lambda} = \frac{\sum_{j=1}^{n} PP_{j,t}^{max} - n.g_b}{\sum_{j=1}^{n} \gamma_{j,t}} \tag{24}$$

After solving Equations (23) and (24), we obtain the bargaining solution as follows:

$$PP_{j,t} = PP_{j,t}^{max} - \frac{\gamma_{j,t}}{\sum_{j=1}^{n} \gamma_{j,t}} \left(\sum_{j=1}^{n} PP_{j,t}^{max} - n.g_b \right) \tag{25}$$

For consumers, the price negotiation optimization function of m consumers is as follows:

$$\begin{aligned} F(CP_t, CP_t^{min}) &= \underset{(CP_{1,t} \ldots CP_{m,t})}{\arg\max} \prod_{i=1}^{m} U_i(CP_{i,t})^{\sigma_{i,t}} \\ \implies F(CP_t, CP_t^{min}) &= \underset{(CP_{1,t} \ldots CP_{m,t})}{\arg\max} \prod_{i=1}^{m} (CP_{i,t}^{min} + CP_{i,t})^{\sigma_{i,t}} \\ \text{subject to, } & \sum_{i=1}^{m} CP_{i,t} \leq m.g_s \text{ and } CP_{i,t} \geq CP_{i,t}^{min} \end{aligned} \tag{26}$$

After solving Equation (26), we obtain the following bargaining solution for ith consumer at time t with $\sigma_{i,t}$ bargaining power.

$$CP_{i,t} = CP_{i,t}^{min} + \frac{\sigma_{i,t}}{\sum_{i=1}^{m} \sigma_{i,t}} \left(m.g_s - \sum_{i=1}^{m} CP_{i,t}^{min} \right) \tag{27}$$

The overall flow of the proposed mathematical formulation discussed above is presented in Figure 4. In this, how the bargaining power of the proposed model is determined and also how the bargaining solution is determine using cooperative game theory are presented step by step.

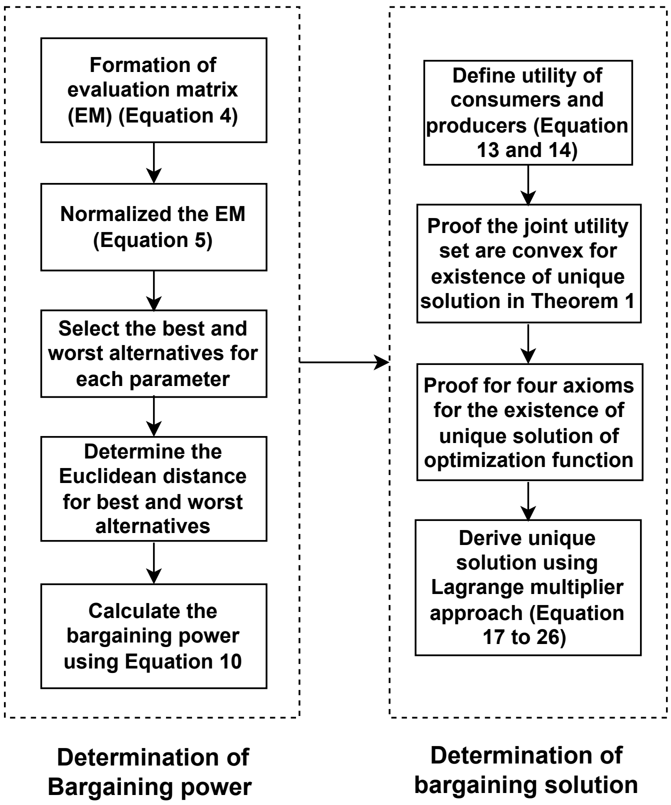


Figure 4. Flow diagram of the overall process of the above defined equations.

4.3. Mathematical Framework for Energy Bill and Revenue

Definition 3. ***Energy Bill of consumer (B):*** *The energy bill of the consumer is calculated in two ways.*

- *First:* When consumers buy the whole amount of energy demand from the producers.
- *Second:* When some consumers buy a part of energy demand from producers and the remaining portion from the main grid

Mathematically, the energy bill of consumer can be expressed as:
In the first case,

$$B_i = \sum_{j=1}^{n} p_{ij} \times E_{ij} \tag{28}$$

where p_{ij} is the final price after the negotiation between ith consumer and jth producer, and E_{ij} is the amount of energy buy by ith consumer from jth producer.

In the second case,

$$B_i = \sum_{j=1}^{n} p_{ij} \times E_{ij} + g_s \times (E_{id} - \sum_{j=1}^{n} E_{ij}) \tag{29}$$

where g_s is the selling price per unit of main grid, and E_{id} is the energy demand for ith consumer.

Definition 4. ***Revenue of producer (R):*** *The producers' revenue is evaluated in two cases.*

- *Case 1:* When producers sell the whole amount of their surplus energy to consumers.
- *Case 2:* When some producers sell a portion of the energy surplus to the consumers and remaining to the main grid.

The revenue of the producer can be calculated by using the following equations. Case 1:

$$R_j = \sum_{i=1}^{m} p_{ij} \times S_{ij} \tag{30}$$

where S_{ij} denotes the amount of surplus energy sell by the jth producer to the ith consumer, and p_{ij} is the final fixed price after the negotiation process for ith consumer and jth producer.

Case 2:

$$R_j = \sum_{i=1}^{m} p_{ij} \times S_{ij} + g_b \times (E_{js} - \sum_{i=1}^{m} S_{ij}) \tag{31}$$

where g_b is the buying price of energy per unit by grid from producer, and E_{js} is the total amount of energy surplus of jth producer.

Definition 5. ***Carbon Emission Reduction (*** Υ ***):*** *The carbon emission reduction in the proposed work is calculated using the following equation.*

$$\Upsilon = CE \times ES_{total} \tag{32}$$

where Υ is the carbon emission reduction, CE is the rate of carbon emission reduction in kg/kWh, and ES_{total} is the total energy surplus for producers.

Definition 6. ***Satisfactory factor of consumers and producers (*** ς_c ***and*** ς_p ***):*** The satisfactory factor of consumers (ς_c) and producers (ς_p) in terms of price is the difference between the average price fixed for consumers and the initial price bid of consumers and the difference between the average price fixed for producers and the initial price bid of producers, respectively. The smaller the difference the higher is the satisfaction. The mathematical formulation of the percentage satisfactory factor of consumers and producers as follows.

$$\varsigma_c = \left[1 - \left(\frac{finalfixedprice - Initialbid}{Initialbid}\right)\right] \times 100 \tag{33}$$

$$\varsigma_p = \left[1 - \left(\frac{Initialbid - finalfixedprice}{Initialbid}\right)\right] \times 100 \quad (34)$$

5. Results and Discussion

5.1. Experimental Setup

This section presents the analytical result of the proposed work with 10 producers and 10 consumers. Table 3 contains the assumption of amount of energy demand, and energy surplus to analyze the proposed model and also contains the initial bidding price of consumers and producers, which is generated randomly between the grid selling (g_s) and buying (g_b) price [25]. This also contains the cost of energy per unit of the main grid (these values are referenced from the electricity price in Brisbane, Australia, as an example) [30]. We analyzed the result of the proposed method based on these data. The experimental analysis has been carried out on a system with an Intel i5-9300H, 2.40 GHz, 4 cores, 8 GB RAM, Window 11, and for implementation, the C++ programming language is used.

Table 3. Simulation parameters [25].

Producer ID	jth Producer Initial Price Bid	Energy Surplus for Producer	Consumer ID	ith Consumer Initial Price Bid	Energy Demand for Consumer
P1	15.48	8.85	C1	12.08	15.86
P2	18.47	9.98	C2	14.6	12.6
P3	22.92	6.13	C3	10.71	16.8
P4	24.33	8.45	C4	13.77	6.48
P5	16.58	18.37	C5	11.59	5.03
P6	19.16	10.04	C6	11.45	14.6
P7	24.51	17.66	C7	15	17.17
P8	21.84	17.05	C8	11.31	11.75
P9	21.41	13.98	C9	14.96	5.52
P10	19.37	10.33	C10	14.82	18.26

Selling Price of Grid to prosumers (g_s) = $24.6 kW/h; Buying Price of grid from prosumers (g_b) = $10 kW/h; Range of Energy Demand for Consumer (ED) = (5–20) kW; Range of Energy Surplus for Producer (ES) = (5–20) kW; Carbon Emission rate (CE) = 0.55 kg/kWh.

5.2. Analytical Results

The bargaining power of the consumers and the producers are calculated based on the attributes, such as energy demand, energy surplus, and initial price bidding. Figure 5 shows how the parameters of the consumers and the producers impact their bargaining power. From this, we can clearly say that consumers with higher values of attributes (energy demand and price bid) will obtain higher bargaining power, and producers with higher surplus energy and low price bid will obtain a higher value of bargaining power. This value is used in the process of price negotiation or bargaining between producers and consumers. According to this value, consumer increases their price and producers reduces their price in each stage of negotiation. From Figure 5a,b, we can conclude that $C10$ and $P5$ have the highest bargaining power among consumers and producers, respectively. Figure 6 shows the price negotiation performed in multiple stages in the proposed model. Figure 6a,b shows price negotiation performed for different set of consumer (m) and producer (n). In this, the price per unit means the price of the particular consumer and the producer of the energy in unit ($/kWh) by considering various number of participants in each stages.

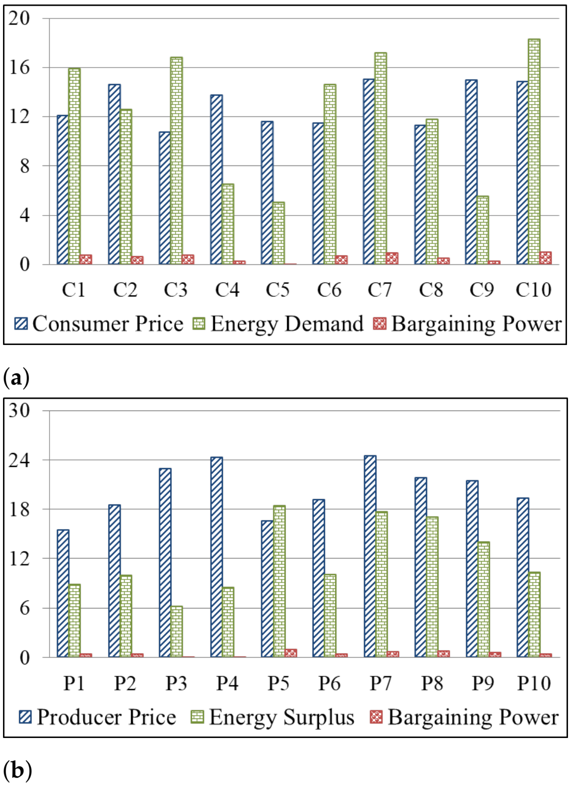


Figure 5. Parameters value and bargaining power of producers and consumers. (**a**) Consumers and (**b**) Producers.

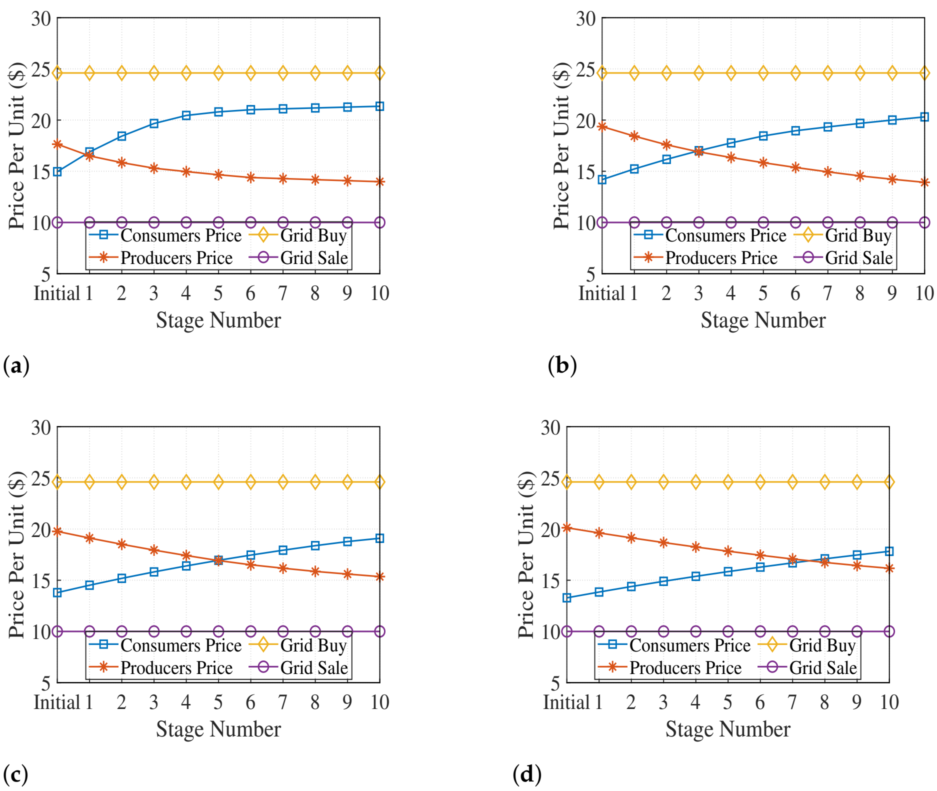


Figure 6. Average Price Negotiation in different stages for different sets of consumers and producers. (**a**) For m = 5 and n = 5, (**b**) For m = 10 and n = 10, (**c**) For m = 15 and n = 15, (**d**) For m = 20 and n = 20.

The energy price per unit is fixed and calculated by taking an average of g_b and g_s in [15], and the final price is fixed by taking an average of the consumers and producers' initial price bidding in [16]. In our proposed work, the final price between consumers and producers is fixed after negotiating in various stages. Table 4 shows how the price of consumers and producers are changing in each stage. In each stage, consumers increase their price, and producers reduce their price according to their bargaining power. The negotiation process can be stopped on two conditions. One, when the consumer and producer had finally agreed upon a price between them. Second, it will be automatically stopped when consumer price had reached the grid selling or producer price has gone down the grid buying price. If the negotiation is stopped on the second condition, then the proposed model computes the final price by taking the average of the price of consumers and producers at the final stage.

Table 4. Price changes in different stages for consumers and producers.

C/P ID	Price/Unit in Different Stages											
	Initial		Stage 1		Stage 2		Stage 3		Stage 4		Stage 5	
	C	P	C	P	C	P	C	P	C	P	C	P
1	13.60	14.61	14.97	13.82	16.21	13.11	17.32	12.48	18.31	11.90	19.21	11.37
2	15.83	17.62	16.94	16.86	17.94	16.17	18.84	15.55	19.65	14.99	20.38	14.47
3	12.19	22.77	13.52	22.63	14.72	22.50	15.79	22.39	16.76	22.29	17.64	22.19
4	14.23	23.95	14.64	23.62	15.02	23.31	15.35	23.04	15.66	22.79	15.93	22.56
5	11.72	14.48	11.83	12.59	11.93	10.89	12.02	10	12.11	10	12.18	10
6	12.79	18.34	13.99	17.60	15.08	16.93	16.05	16.33	16.93	15.79	17.72	15.29
7	16.89	23.03	18.60	21.70	20.13	20.49	21.51	19.41	22.75	18.43	23.87	17.52
8	12.28	20.24	13.16	18.80	13.94	17.49	14.65	16.30	15.29	15.26	15.87	14.28
9	15.48	20.12	15.95	18.95	16.37	17.91	16.75	16.96	17.09	16.11	17.40	15.32
10	16.85	18.52	18.67	17.75	20.31	17.06	21.79	16.44	23.12	15.88	24.32	15.36

C → Consumers, P → Producers.

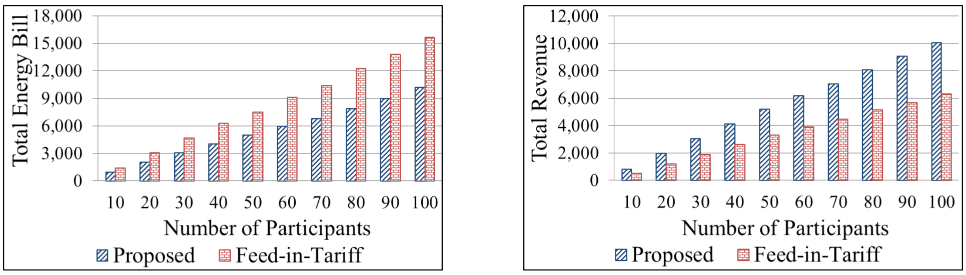
We compare our proposed work with the feed-in-tariff scheme on energy bill of consumers and revenue of producers. Figure 7a shows how the bill of the consumer is reduced for different numbers of participation in the proposed trading model. The revenue increases for producers as the number of participants in the trading model is increases, which is shown in Figure 7b. Table 5 contains the reduction in energy bill and increase in revenue for each consumer and producer, respectively, as compared to the FiT scheme. Compared to FiT, the overall percentage reduction in the bill for consumers is 32.86%, and the overall percentage increase in revenue for producers is 64.83% according to the assumed values. The proposed model integrates the green energy resources in the trading process. Therefore, it will reduce carbon emissions due to fossil fuel use in power generation. We calculate the carbon emission reduction in the proposed model by using Equation (32). Table 6 shows that using the proposed model the carbon emission reduces as the number of participants increases.

Table 5. Comparison of a consumers' bill and producers' revenue.

Consumer	Proposed Bill	FiT Bill	Reduction of Bill (%)	Producer	Proposed Revenue	FiT Revenue	Increase in Revenue (%)
C1	267.92	390.16	31.33	P1	134.48	88.5	51.95
C2	215.29	309.96	30.54	P2	162.16	99.8	62.49
C3	268.57	413.28	35.02	P3	114.41	61.3	86.65
C4	105.81	159.41	33.62	P4	155.90	84.5	84.50
C5	76.50	123.74	38.18	P5	278.31	183.7	51.50
C6	250.46	359.16	30.27	P6	155.37	100.4	54.75
C7	299.22	422.38	29.16	P7	299.86	176.6	69.80
C8	191.59	289.05	33.72	P8	284.07	170.5	66.61
C9	95.02	135.79	30.03	P9	230.40	139.8	64.81
C10	284.39	449.19	36.69	P10	160.34	103.3	55.22

Table 6. Analysis of carbon emission reduction in proposed model for different number of participants.

Number of Participants	10	20	30	40	50	60	70	80	90	100
Carbon Emission Reduction (kg/kWh)	28.48	62.06	99.06	139.08	177.85	212.01	242.42	279.34	308.86	342.40



(**a**) Consumers (**b**) Producers

Figure 7. Total Energy Bill and Revenue Comparison Between Proposed Work and Feed-in-Tariff. (**a**) Total Energy Bill Proposed vs. FiT. (**b**) Total Revenue Proposed vs. FiT.

5.3. Discussion and Future Work

Furthermore, we compare the proposed trading model with [15] and Amin et al. [16] in terms of the satisfactory factor with respect to the price fixing in the trading model, as presented in Table 7. The proposed work considered both consumers' and producers' price bids in the process of price fixing by providing multiple stages of negotiation, considering their bargaining power. Therefore, the proposed technique obtained a higher percentage of satisfaction factors. Thus, the proposed trading model motivates small-scale prosumers to participate in the trading process that results in a successful trading platform. The proposed model also achieved a reduction in consumers' bills and an increase in producers' revenues as compared to FiT.

The proposed trading model is simulated based on randomly generated data due to the lack of infrastructure and the availability of real time data. However, these results will be close to the actual solution as we considered the real-time range of data. Further, we will be considering real-time data and simulating based on that real data in the future.

Table 7. Comparison on satisfactory factor with some existing works.

Buyer Bid Price	Seller Bid Price	Proposed				Amin				Tusher			
		AFPC	**AFPP**	**SS %**	**BS %**	**AFPC**	**AFPP**	**SS %**	**BS %**	**AFPC**	**AFPP**	**SS %**	**BS %**
12.08	15.48	16.89	15.195	60.16	98.16	21.84	10	19.20	64.60	17.3	17.3	56.79	111.76
14.6	18.47	17.08	16.2486	82.97	87.97	20.17	18.47	61.86	100	17.3	17.3	81.51	93.66
10.71	22.92	15.98	18.6646	50.74	81.43	18.89	22.92	23.59	100	17.3	17.3	38.47	75.48
13.77	24.33	16.32	18.4499	81.42	75.83	24.6	24.33	21.35	100	17.3	17.3	74.36	71.11
11.59	16.58	15.21	15.1501	68.78	91.38	24.6	13.82	0	83.36	17.3	17.3	50.73	104.34
11.45	19.16	17.15	15.4747	50.18	80.77	21.44	10	12.71	52.19	17.3	17.3	48.91	90.29
15	24.51	17.43	16.9796	83.82	69.28	24.47	24.51	36.89	100	17.3	17.3	84.67	70.58
11.31	21.84	16.31	16.6608	55.83	76.29	19.39	21.84	28.53	100	17.3	17.3	47.04	79.21
14.96	21.41	17.21	16.4809	84.94	76.98	24.6	21.41	35.56	100	17.3	17.3	84.36	80.80
14.82	19.37	15.57	15.5217	94.91	80.13	24.51	19.37	34.59	100	17.3	17.3	83.27	89.31

BS → Buyer Satisfactory, SS → Seller Satisfactory, AFPC → Average final price unit for consumer, AFPP → Average finale price per unit for producer.

6. Conclusions

This paper proposed an energy trading model based on a generic Nash bargaining solution that facilitates multi-stage negotiation and provides a mutually agreed trading price between consumers and producers. In this approach, consumers and producers negotiate in multiple stages before settling the price between them to provide a mutually agreed price. We used the bargaining power of each consumer and producer, which is calculated by using parameters such as the amount of energy demand, the amount of surplus energy, and their initial price bidding amount in the negotiation process. This approach motivates energy trading participants to participate in the energy trading process. Experimental analysis has been carried out assuming 20 participants (10 producers and 10 consumers) participating in the negotiation process. It is shown that there is a change in the price at each stage in the negotiation process due to the price bids by producers and consumers. Finally, the mutually agreed price has been fixed. This process has given equal opportunity to all types of consumers and producers in deciding the trading price, thereby motivating them to use the proposed model. To show the efficacy of the proposed work, we compare the proposed work with feed-in-tariff and found that, on average, the bill of the consumer is reduced by 32.86% and the revenue of the producer is increased by 64.83% as compared to FiT as per the assume the initial price of consumers and producers. We have also shown the carbon emission reduction rate per number of participants. As per our result, we obtained from 10 participants the carbon emission reduction is approximately 28.48 kg/kWh and for 100 is 342.397 kg/kWh. The proposed trading model also facilitates the reduction in carbon emissions when the number of participants increases. A secure energy trading framework with the privacy preservation of participants could be a possible future work.

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Abbreviations

The following abbreviations are used in this manuscript:

C_i	ith consumer
ED_{total} (kW/h)	Total energy demand of consumers
ES_{total} (kW/h)	Total energy surplus of producers
ϑ_i	Amount of energy buy by consumer i at time t
φ_j	Amount of energy sell by producer j at time t
$Price\_Matrix$	Price matrix after negotiation
Min_i	Minimum price from the price of consumer i with n producers
Max_j	Maximum price from the price of producer j with m consumers
$Final\_Price\_Matrix$	Final Price matrix of consumers and producers
$CP_{i,t}^{min}$	Consumer Initial Price bid
P_j	jth producer
$PP_{j,t}^{max}$ ($/kWh)	Producer Initial price bid
m	Number of consumer
$ED_{i,t}$ (kW/h)	Energy demand of consumer i at time t
n	Number of producer
$ES_{j,t}$ (kW/h)	Energy surplus of producer j at time t
$stage$	Stage number
$PrevCP_{i,t}$ ($/kWh)	Previous stage price of consumer i
$StopNegotiation$	Stopping Criteria of Negotiation
$PrevPP_{j,t}$ ($/kWh)	Previous stage price of producer j
$\phi_{ij,t}$ ($/kWh)	Average price after negotiation
σ_i ($/kWh)	Bargaining power of consumer i
$p_{ij,t}$ ($/kWh)	Final price of consumer i and producer j at time t
γ_j	Bargaining power of producer j
Υ (kg/kWh)	Carbon emission reduction
B_i	Bill of consumer i
R_j	Revenue of producer j
$U_i(CP_{i,t})$	Utility of consumer i at time t
$U_j(PP_{j,t})$	Utility of producer j at time t

References

1. Facchini, A. Distributed energy resources: Planning for the future. *Nat. Energy* **2017**, *2*, 17129. [CrossRef]
2. Fares, R.L.; Webber, M.E. The impacts of storing solar energy in the home to reduce reliance on the utility. *Nat. Energy* **2017**, *2*, 17001. [CrossRef]
3. Abbas, A.O.; Chowdhury, B.H. Using customer-side resources for market-based transmission and distribution level grid services—A review. *Int. J. Electr. Power Energy Syst.* **2021**, *125*, 106480. [CrossRef]
4. Cherukuri, S.H.C.; Saravanan, B. A novel energy management algorithm for reduction of main grid dependence in future smart grids using electric springs. *Sustain. Energy Technol. Assess.* **2017**, *21*, 1–12. [CrossRef]
5. Neffati, O.S.; Sengan, S.; Thangavelu, K.D.; Kumar, S.D.; Setiawan, R.; Elangovan, M.; Mani, D.; Velayutham, P. Migrating from traditional grid to smart grid in smart cities promoted in developing country. *Sustain. Energy Technol. Assess.* **2021**, *45*, 101125.
6. Pinto, S.J.; Panda, G.; Peesapati, R. An Implementation of Hybrid Control Strategy for Distributed Generation System Interface Using Xilinx System Generator. *IEEE Trans. Ind. Inform.* **2017**, *13*, 2735–2745. [CrossRef]
7. Bana, P.R.; Panda, K.P.; Panda, G. Power Quality Performance Evaluation of Multilevel Inverter With Reduced Switching Devices and Minimum Standing Voltage. *IEEE Trans. Ind. Inform.* **2020**, *16*, 5009–5022. [CrossRef]
8. Jogunola, O.; Ikpehai, A.; Anoh, K.; Adebisi, B.; Hammoudeh, M.; Son, S.Y.; Harris, G. State-of-the-art and prospects for peer-to-peer transaction-based energy system. *Energies* **2017**, *10*, 2106. [CrossRef]
9. Chiş, A.; Koivunen, V. Coalitional Game-Based Cost Optimization of Energy Portfolio in Smart Grid Communities. *IEEE Trans. Smart Grid* **2019**, *10*, 1960–1970. [CrossRef]
10. Naidu, B.R.; Panda, G.; Siano, P. A Self-Reliant DC Microgrid: Sizing, Control, Adaptive Dynamic Power Management, and Experimental Analysis. *IEEE Trans. Ind. Inform.* **2018**, *14*, 3300–3313. [CrossRef]
11. Morstyn, T.; Teytelboym, A.; Mcculloch, M.D. Bilateral Contract Networks for Peer-to-Peer Energy Trading. *IEEE Trans. Smart Grid* **2019**, *10*, 2026–2035. [CrossRef]
12. Rahimiyan, M.; Baringo, L.; Conejo, A.J. Energy Management of a Cluster of Interconnected Price-Responsive Demands. *IEEE Trans. Power Syst.* **2014**, *29*, 645–655. [CrossRef]

13. El Rahi, G.; Etesami, S.R.; Saad, W.; Mandayam, N.B.; Poor, H.V. Managing Price Uncertainty in Prosumer-Centric Energy Trading: A Prospect-Theoretic Stackelberg Game Approach. *IEEE Trans. Smart Grid* **2019**, *10*, 702–713. [CrossRef]
14. Hakimi, S.M.; Hajizadeh, A.; Shafie-khah, M.; Catalão, J.P. Demand response and flexible management to improve microgrids energy efficiency with a high share of renewable resources. *Sustain. Energy Technol. Assess.* **2020**, *42*, 100848.
15. Tushar, W.; Saha, T.K.; Yuen, C.; Morstyn, T.; McCulloch, M.D.; Poor, H.V.; Wood, K.L. A motivational game-theoretic approach for peer-to-peer energy trading in the smart grid. *Appl. Energy* **2019**, *243*, 10–20. [CrossRef]
16. Amin, W.; Huang, Q.; Umer, K.; Zhang, Z.; Afzal, M.; Khan, A.A.; Ahmed, S.A. A motivational game-theoretic approach for peer-to-peer energy trading in islanded and grid-connected microgrid. *Int. J. Electr. Power Energy Syst.* **2020**, *123*, 106307. [CrossRef]
17. Anoh, K.; Maharjan, S.; Ikpehai, A.; Zhang, Y.; Adebisi, B. Energy Peer-to-Peer Trading in Virtual Microgrids in Smart Grids: A Game-Theoretic Approach. *IEEE Trans. Smart Grid* **2020**, *11*, 1264–1275. [CrossRef]
18. Amin, U.; Hossain, M.J.; Tushar, W.; Mahmud, K. Energy Trading in Local Electricity Market With Renewables—A Contract Theoretic Approach. *IEEE Trans. Ind. Inform.* **2021**, *17*, 3717–3730. [CrossRef]
19. Zhang, K.; Troitzsch, S.; Hanif, S.; Hamacher, T. Coordinated Market Design for Peer-to-Peer Energy Trade and Ancillary Services in Distribution Grids. *IEEE Trans. Smart Grid* **2020**, *11*, 2929–2941. [CrossRef]
20. Zhang, Z.; Li, R.; Li, F. A Novel Peer-to-Peer Local Electricity Market for Joint Trading of Energy and Uncertainty. *IEEE Trans. Smart Grid* **2020**, *11*, 1205–1215. [CrossRef]
21. Lee, J.T.; Henriquez-Auba, R.; Poolla, B.K.; Callaway, D.S. Pricing and Energy Trading in Peer-to-Peer Zero Marginal-Cost Microgrids. *IEEE Trans. Smart Grid* **2021**, *13*, 702–714. [CrossRef]
22. Li, J.; Xu, D.; Wang, J.; Zhou, B.; Wang, M.; Zhu, L. P2P Multi-Grade Energy Trading for Heterogeneous Distributed Energy Resources and Flexible Demand. *IEEE Trans. Smart Grid* **2022**, *14*, 1577–1589. [CrossRef]
23. Wang, J.; Zhang, J.; Li, L.; Lin, Y. Peer-to-Peer Energy Trading for Residential Prosumers With Photovoltaic and Battery Storage Systems. *IEEE Syst. J.* **2022**, *17*, 154–163. [CrossRef]
24. Yang, J.; Zhang, Y.; Yuan, Y.; Ma, K.; Li, J. Energy Trading and Power Allocation Strategies for Relay-Assisted Smart Grid Communications: A Three-Stage Game Approach. *IEEE Trans. Mob. Comput.* **2022**. [CrossRef]
25. Devi, N.N.; Thokchom, S. Multi-attribute based prosumers prioritization for energy trading in Smart Grid. In Proceedings of the 2021 IEEE 18th India Council International Conference (INDICON), Guwahati, India, 19–21 December 2021; IEEE: Piscataway, NJ, USA, 2021; pp. 1–6.
26. Li, J.; Ye, Y.; Papadaskalopoulos, D.; Strbac, G. Computationally Efficient Pricing and Benefit Distribution Mechanisms for Incentivizing Stable Peer-to-Peer Energy Trading. *IEEE Internet Things J.* **2021**, *8*, 734–749. . [CrossRef]
27. Hwang, C.; Yoon, K. Multi-objective decision making–methods and application. In *A State-of-the-Art Study*; Springer-Verlag: New York, NY, USA, 1981.
28. Moulik, S.; Misra, S.; Gaurav, A. Cost-effective mapping between wireless body area networks and cloud service providers based on multi-stage bargaining. *IEEE Trans. Mob. Comput.* **2016**, *16*, 1573–1586. [CrossRef]
29. Han, Z.; Niyato, D.; Saad, W.; Başar, T.; Hjørungnes, A. *Game Theory in Wireless and Communication Networks: Theory, Models, and Applications*; Cambridge University Press: Cambridge, UK, 2012.
30. Tushar, W.; Yuen, C.; Li, W.T.; Smith, D.B.; Saha, T.; Wood, K.L. Motivational psychology driven AC management scheme: A responsive design approach. *IEEE Trans. Comput. Soc. Syst.* **2018**, *5*, 289–301. [CrossRef]