Billing Models for Peer-to-Peer Electricity Trading Markets with Imperfect Bid-Offer Fulfillment

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***Abstract*—This paper proposes four new billing models for peer-to-peer electricity trading markets that take into account electricity volume deviations of market participants from their bids and volumes. These billing models incorporate different cost sharing mechanisms so that (i) the costs incurred due to these deviations are minimal for consumers and prosumers and (ii) include non peer-to-peer participants as well. The former is achieved by designing cost sharing mechanisms which split the cost socially, while the latter is achieved by introducing a mid market that clears all the available supply from the P2P market. Through simulations of a small-scale community, we have demonstrated the effectiveness of our billing models in significantly increasing prosumers' rewards and reducing consumers' bills.**

***Index Terms*—P2P electricity market, Billing model, Imbalance cost.**

I. Introduction

Smart grid is an electrical grid enhanced with two-way electricity and communication flow capabilities [1]. It is equipped with various smart devices/sensors which can sense and report (in real time) various measurements from all parts of the grid such that informed decisions can be made timely. From all these devices, smart meters are thought to be the ones that will help transform user behaviour. They are devices that can measure fine-grained electricity consumption and production volumes of users and make such data available for new smart grid applications [2].

Peer-to-peer (P2P) electricity trading is one of these applications that has gained attention in recent years due to its potential to engage users in balancing the electricity grid [3]. It allows electricity to be traded between users who can determine the trading price based on their current demand and supply needs. The trading price is usually determined at an auction to which users submit their bids and offers in advance [4]. When there is more demand for electricity, the trading price will be high, so that more prosumers are encouraged to sell electricity, while consumers are encouraged to consume less electricity. Similarly, if there is more supply available, the trading price will be low encouraging prosumers to keep their excess electricity, while consumers to increase their demand to take advantage of the low electricity price [5].

Most P2P markets require users to submit bids/offers for future trading periods in advance (ranging from a day to 30 minutes in advance). In order to do so, users will have to accurately predict how much demand or supply they will need or provide. However, these predictions might not always be accurate or users might require/have unexpected extra demand/supply. As a result, users might not be able to accurately fulfil their demand/supply commitments at the P2P market; hence, their actual demand/supply volumes during the trading slot (measured by their smart meters) might deviate from their committed demand/supply volumes at the P2P market (i.e., the volumes submitted with their bids/offers and accepted at the P2P market). These deviations can disrupt the operation of the grid and increase the cost of the balancing of the grid [6], which could be passed on to the users. Therefore, to minimise these costs, there is a need for billing models that incentivise prosumers/consumers to minimise their deviations. However, existing work on P2P markets have largely ignored this issue. They have either assumed a perfect fulfilment of the committed volumes [7] did not consider any billing models that incorporate these deviations [8] or proposed symmetric imbalance charge mechanisms which penalise market participants irrespective of the direction of their energy imbalance deviation [9]. A simple billing mechanism was also proposed in [10], however, the focus of the work was on calculating the bill in a private way.

To address this gap, we propose four novel billing models that incorporate these deviations and split the cost associated with these deviations amongst users fairly; without any of them being heavily penalised. Specifically, the novel contributions of this paper are:

- We design four novel billing models that take into account the individual deviations of P2P market participants and split the cost incurred amongst the P2P participants. Each billing model has a distinct cost splitting mechanism: (i) individual cost split, where individual users are responsible for their own individual deviations; (ii) social cost split, where individual deviations of prosumers/consumers are aggregated and the total supply/demand cost is split amongst deviating prosumers/consumers socially, (iii) universal cost split, where we compare the total supply/demand deviation in order to derive the total deviation per trading slot. Based on this total deviation, the deviating P2P participants are penalized. (iv) universal cost split with mid market, where non-P2P participants participate in order to fulfill the deviations of P2P consumers/prosumers; hence, reducing the penalty for deviating participants. Additionally, by utilizing the mid-market, non-P2P participants also trade amongst each other at a better price than the retail market.
- We run simulations on a small-scale community (15 participants: 10 consumers and 5 prosumers) to demonstrate the effectiveness of our proposed billing models in reducing the cost for consumers and increasing the profits of prosumers.

The rest of the paper is organised as follows; in Sec. II we depict our novel billing models and describe them in detail. In Sec. III we evaluate our billing models and show their effect on consumer bills, prosumer rewards and supplier income. Finally, in Sec IV we conclude our work and list some interesting future work venues.

II. Billing Models

In this section, we first provide a billing model used in a typical retail market, before proposing four new billing models dedicated to a P2P market that deal with the deviations of individual prosumers/consumers. By deviations, we mean the difference between

TABLE I: Abbreviations and Notations

Symbol	Description
P2P, MM	Peer-to-Peer, Mid Market
TD	Total deviation
InDev_x	Individual deviation of a participant
InDev_i	Individual deviation of a consumer
InDev_j	Individual deviation of a prosumer
TSD	Total supply deviation
TDD	Total demand deviation
TP, RP	Trading price, Retail price
MMP_p, MMP_c	Mid-market sell price, Mid-market buy price
FiT	Feed-in tariff
C_n	Total no. of Non-P2P consumers
C_i	Individual consumer
$P2P_n^c$	Total no. of P2P consumers
$P2P_i^c$	Individual P2P consumer
C_{dem}	Individual demand of Non-P2P consumer
T_{dem}^c	Total demand of Non-P2P consumers
C_{dem}^{P2P}	Individual demand of P2P consumer
T_{dem}^{P2P}	Total demand of P2P consumers
P_n	Total no. of Non-P2P prosumers
T_{over}^c	Total volume over-consumed
$P2P_{over}^c$	Total no. of P2P prosumers over-consuming
T_{under}^c	Total volume under-consumed
$P2P_{under}^c$	Total no. of P2P prosumers under-consuming
P_j	Individual prosumer
$P2P_n^p$	Total no. of P2P prosumers
$P2P_j^p$	Individual P2P prosumer
P_{sup}	Individual supply of Non-P2P prosumer
T_{sup}^p	Total supply of Non-P2P prosumers
P_{sup}^{P2P}	Individual supply of P2P prosumer
T_{sup}^{P2P}	Total supply of P2P prosumers
T_{over}^p	Total volume over-supplied
$P2P_{over}^p$	Total no. of P2P prosumers over-supplying
T_{under}^p	Total volume under-supplied
$P2P_{under}^p$	Total no. of P2P prosumers under-supplying
S_n	Total suppliers
S_k	Individual supplier
S_k^{inc}	Individual supplier income
S_k^{exp}	Individual supplier expenditure
S_k^{bal}	Individual supplier balance

Algorithm 1 Billing Model for Retail Markets

```
procedure CONSUMER BILLS, PROSUMER REWARDS, SUPPLIER BALANCE
for each timeslot do
    for each i, j, k in C_n, P_n, S_n do
        C_i bill = C_dem × RP
        P_j reward = P_sup × FiT
        S_k^inc += C_i bill
        S_k^exp += P_j reward
        S_k^bal += S_k^inc − S_k^exp
    end for
end for
```

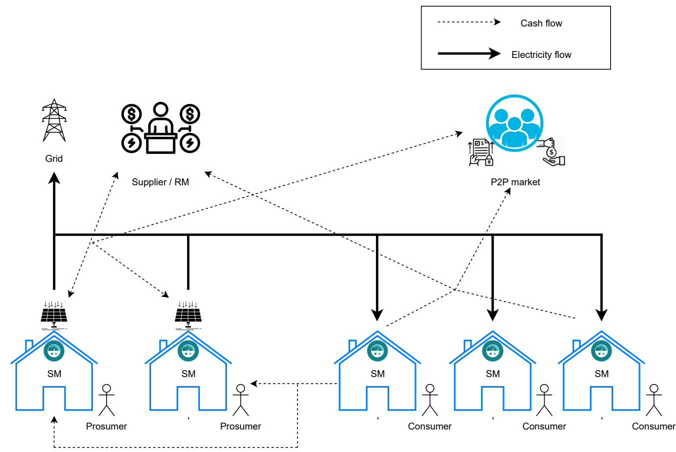

Fig. 1: P2P market with RM as a fall-back option.

the volumes that these participants commit at the P2P market from the volumes they actually fulfil. Three of these billing models use only the Retail Market (RM) as a back-up option to deal with the deviations, while the last billing model uses an additional market, called a mid-market, as a default back-up market for dealing with deviations before falling back, if necessary, to the RM. These billing models use three different methods for splitting the cost incurred due to the individual deviations of prosumers/consumers. These methods are called individual, social and universal cost split. These billing models are detailed next. Notations are listed in Table I.

A. Billing Model for Retail Markets – the status quo

Most liberalised electricity retail markets allow prosumers and consumers to trade only with suppliers they have contracts with. The tariff that suppliers use to buy any excess electricity supplied to the grid by the prosumers is regulated and set to a fixed price by the market regulators of each country. This tariff is called Feed-in-Tariff (FiT). No electricity trading between consumers and prosumers is allowed. There are no or little incentives for consumers/prosumers to change their load profiles. A summary of the billing model used in a typical retail market is given below as well as shown in Alg. 1.

- Consumers buy electricity only from their suppliers at a retail buy price. Retail buy prices are determined by the suppliers; suppliers usually have several tariffs consumers can choose from; these tariffs are set such that they are competitive compared to the tariffs offered by other suppliers.
- Prosumers sell electricity only to suppliers at a fixed price, the FiT. In some countries, FiT is set to a different value depending on the type and size of the electricity source used to generate the electricity at the prosumer side.
- Suppliers sell electricity to their customers (contracted consumers) and buy back any electricity their customers (contracted prosumers) feed back to the grid.

B. Billing Models for P2PM with RM as Back-up

P2P trading markets allow prosumers and consumers to trade electricity among each other. They involve the following steps.

- Consumers/Prosumers submit bids/offers for electricity;
- A market operator (e.g., trading platform) clears the P2P market. It determines the total cleared volume of electricity at the market, the market clearance price and the consumers/prosumers whose bids/offers have been accepted. Consumers/Prosumers whose bids have not been accepted use the RM to meet their needs as the RM acts as a fall-back option.
- At the end of the trading period, data from the smart meters of consumers/prosumers is used to calculate their bills/rewards.
- If the data from the smart meters of prosumers/consumers whose bids have been accepted is not the same as their respective committed value in the bid/offer, the difference (deviation) is compensated by the RM. This compensation could come with an extra cost for some of the prosumers/consumers.

The cost associated with compensating the deviations of the individual prosumers/consumers will have to be distributed amongst all (some) of the prosumers/consumers. There could be different mechanisms to share these costs amongst prosumers/consumers. Next, we propose three different methods of how these costs could be shared: individual, social and universal cost split. An example P2P market with a RM as a fall-back option is shown in Fig. 1.

1) Billing with individual cost split: In this billing model, individual consumers/prosumers who partake in the P2P market bear the cost of their respective deviations from their committed

Algorithm 2 Billing Model with Individual Cost Split

procedure CUSTOMER BILLS, PROSUMER REWARDS, SUPPLIER BALANCE
for each timeslot **do**
  if bid accepted **then**
    for each i, j and k in $P2P_n^c$, $P2P_n^p$ and S_n **do**
      if InDev$_x = 0$ **then**
        $P2P_c^i$ bill = C_{dem}^{P2P} $\times$ TP
        $P2P_p^j$ reward = P_{sup}^{P2P} $\times$ TP
        S_k^{inc} = 0; S_k^{exp} = 0
        S_k^{bal} += $S_k^{inc} - S_k^{exp}$
      end if
      if InDev$_x < 0$ **then**
        $P2P_c^i$ bill = C_{dem}^{P2P} $\times$ TP + InDev$_i$ $\times$ FiT
        $P2P_p^j$ reward = P_{sup}^{P2P} $\times$ TP + InDev$_j$ $\times$ RP
        S_k^{inc} = InDev$_j$ $\times$ RP
        S_k^{exp} += InDev$_i$ $\times$ FiT
        S_k^{bal} += $S_k^{inc} - S_k^{exp}$
      end if
      if InDev$_x > 0$ **then**
        $P2P_c^i$ bill = C_{dem}^{P2P} $\times$ TP + InDev$_i$ $\times$ RP
        $P2P_p^j$ reward = P_{sup}^{P2P} $\times$ TP + InDev$_j$ $\times$ FiT
        S_k^{inc} += InDev$_i$ $\times$ RP
        S_k^{exp} += InDev$_j$ $\times$ FiT
        S_k^{bal} += $S_k^{inc} - S_k^{exp}$
      end if
    end for
  end if
  if bid not accepted **then**
    for each i, j and k in C_n, P_n and S_n **do**
      goto Algorithm 1
    end for
  end if
end for

bids/offers. The positive deviations are traded at the RM while the negative deviations are compensated from the RM. This billing model is described below and shown in Alg. 2.

- Positive deviations of prosumers (i.e., when a prosumer supplies more volume than they committed) are sold for the FiT to their respective supplier. Positive deviations of consumers (i.e., when a consumer consumes more volume than they committed) are bought for the RP from their respective supplier.
- Negative deviations of prosumers (i.e., when a prosumer supplies less volume than they committed) are compensated by the RM – prosumers buy their individual negative deviation at the RM for the RP and sell it at the P2P market for the TP in order to fulfill their commitment.
- Negative deviations of consumers are also compensated by the RM – consumers buy all their individual committed value at the P2P market at the TP, but since they have not managed to consume all of their bought value, they sell the deviation immediately to their respective supplier at the FiT price.
- Suppliers sell electricity at RP to consumers who consumed more volume than they bought, and to prosumers who supplied less volume than they committed at the P2P market.
- Suppliers buy electricity at FiT from prosumers who supply more volume than they committed, and from consumers who could not consume all the volume they bought at P2P market.
- Consumers/prosumers whose bids were not accepted at the P2P market trade with their suppliers at the RP and FiT.

2) Billing with social cost split: In this billing model, the individual deviations of prosumers are aggregated and the cost of the total supply deviation is socially split among the prosumers. Similarly, the individual deviations of consumers are aggregated and the cost of the total demand deviation is socially split among the consumers. This is described below and shown in Alg. 3.

- All individual deviations of the prosumers are aggregated to compute the total supply deviation.
- If the total supply deviation is equal to zero, then there is no collective supply deviation, hence all prosumers are paid at the P2P price for all their supplied volumes regardless of their individual deviations. Prosumers who oversupplied benefit as they sell even their individual deviation at the P2P price rather than the FiT. Prosumers who undersupplied benefit too as they do not have to compensate their individual deviation from RM.
- If the total supply deviation is positive (negative), then the total deviation of prosumers who underdelivered (overdelivered) partially compensate for the prosumers who overdelivered (underdelivered); Prosumers who underdelivered (overdelivered) sell all their supplied electricity at the P2P price regardless of their individual deviation, while the prosumers who overdeliv-

Algorithm 3 Billing Model with Social Cost Split

for each timeslot **do**
  if bid accepted **then**
    procedure CUSTOMER BILLS, SUPPLIER INCOME/EXPENDITURE
    for each i and k in $P2P_n^c$ and S_n **do**
      if TDD = 0 **then**
        $P2P_c^i$ bill = C_{dem}^{P2P} $\times$ TP
        S_k^{inc} = 0
      end if
      if TDD < 0 **then**
        if InDev$_x = 0$ or InDev$_x > 0$ **then**
          $P2P_c^i$ bill = C_{dem}^{P2P} $\times$ TP
          S_k^{inc} = 0
        end if
        if InDev$_x < 0$ **then**
          $P2P_c^i$ bill = C_{dem}^{P2P} $\times$ TP + (InDev$_i$ + $\frac{T_{over}^c}{P2P_{under}^c}$) $\times$ FiT
          S_k^{exp} += (InDev$_i$ + $\frac{T_{over}^c}{P2P_{under}^c}$) $\times$ FiT
        end if
      end if
      if TDD > 0 **then**
        if InDev$_x = 0$ or InDev$_x < 0$ **then**
          $P2P_c^i$ bill = C_{dem}^{P2P} $\times$ TP
          S_k^{inc} = 0
        end if
        if InDev$_x > 0$ **then**
          $P2P_c^i$ bill = C_{dem}^{P2P} + $\frac{T_{under}^c}{P2P_{over}^c}$ $\times$ TP + (InDev$_i$ - $\frac{T_{under}^c}{P2P_{over}^c}$ $\times$ RP
          S_k^{inc} += (InDev$_i$ - $\frac{T_{under}^c}{P2P_{over}^c}$ $\times$ RP
        end if
      end if
    end for
      procedure PROSUMER REWARDS, SUPPLIER INCOME/EXPENDITURE
    for each j and k in $P2P_n^p$ and S_n **do**
      if TSD = 0 **then**
        $P2P_p^j$ reward = P_{sup}^{P2P} $\times$ TP
        S_k^{exp} = 0
      end if
      if TSD < 0 **then**
        if InDev$_x = 0$ or InDev$_x > 0$ **then**
          $P2P_p^j$ reward = P_{sup}^{P2P} $\times$ TP
          S_k^{exp} = 0
        end if
        if InDev$_x < 0$ **then**
          $P2P_p^j$ reward = P_{sup}^{P2P} $\times$ TP + (InDev$_j$ + $\frac{T_{over}^p}{P2P_{under}^p}$) $\times$ RP
          S_k^{inc} += (InDev$_j$ + $\frac{T_{over}^p}{P2P_{under}^p}$) $\times$ RP
        end if
      end if
      if TSD > 0 **then**
        if InDev$_x = 0$ or InDev$_x < 0$ **then**
          $P2P_p^j$ reward = P_{sup}^{P2P} $\times$ TP
          S_k^{exp} = 0
        end if
        if InDev$_x > 0$ **then**
          $P2P_p^j$ reward = P_{sup}^{P2P} + $\frac{T_{under}^p}{P2P_{over}^p}$ $\times$ TP + (InDev$_j$ - $\frac{T_{under}^p}{P2P_{over}^p}$ $\times$ FiT
          S_k^{exp} += (InDev$_j$ - $\frac{T_{under}^p}{P2P_{over}^p}$ $\times$ FiT
        end if
      end if
    end for
    $S^{bal} = S^{inc} - S^{exp}$
  end if
  if bid not accepted **then**
    for each i, j and k in C_n, P_n and S_n **do**
      goto Algorithm 1
    end for
  end if
end for=0

Algorithm 4 Billing Model with Universal Cost Split

procedure CUSTOMER BILLS, PROSUMER REWARDS, SUPPLIER BALANCE
for each timeslot **do**
  if bid Accepted **then**
    for each i, j and k in $P2P_n^c$, $P2P_n^p$ and S_n **do**
      if TD = 0 **then**
        $P2P_c^i$ bill = C_{dem}^{P2P} × TP
        $P2P_p^j$ reward = P_{sup}^{P2P} × TP
        S_k^{inc} += 0; S_k^{exp} += 0
        S_k^{bal} += $S_k^{inc} - S_k^{exp}$
      end if
      if TD $<$ 0 **then**
        $P2P_p^j$ reward = P_{sup}^{P2P} × TP
        S_k^{exp} += 0
        if InDev$_i = 0$ or InDev$_i < 0$ **then**
          $P2P_c^i$ bill = C_{dem}^{P2P} × TP
          S_k^{inc} += 0
          S_k^{bal} += $S_k^{inc} - S_k^{exp}$
        end if
        if InDev$_i > 0$ **then**
          $P2P_c^i$ bill = (C_{dem}^{P2P} - $\frac{TD}{P2P_n^c}$) × TP + $\frac{TD}{P2P_n^c}$ × RP
          S_k^{inc} += $\frac{TD}{P2P_n^c}$ × RP
          S_k^{bal} += $S_k^{inc} - S_k^{exp}$
        end if
      end if
      if TD $>$ 0 **then**
        $P2P_c^i$ bill = C_{dem}^{P2P} × TP
        S_k^{inc} += 0
        if InDev$_j = 0$ or InDev$_j < 0$ **then**
          $P2P_p^j$ reward = P_{sup}^{P2P} × TP
          S_k^{exp} += 0
          S_k^{bal} += $S_k^{inc} - S_k^{exp}$
        end if
        if InDev$_j > 0$ **then**
          $P2P_p^j$ reward = (P_{sup}^{P2P} - $\frac{TD}{P2P_n^p}$) × TP + $\frac{TD}{P2P_n^p}$ × FiT
          S_k^{exp} += $\frac{TD}{P2P_n^p}$ × FiT
          S_k^{bal} += $S_k^{inc} - S_k^{exp}$
        end if
      end if
    end for
  end if
  if bid not accepted **then**
    for each i, j and k in C_n, P_n and S_n **do**
      goto Algorithm 1
    end for
  end if
end for

ered (underdelivered) reduce their individual deviation with a share of the total deviation of prosumers who underdelivered (overdelivered). As a result, prosumers either sell all their individual deviation at the P2P price or reduce their individual deviations which they need to compensate for from the RM.

- Similarly, if the total demand deviation is positive (negative), then the total deviation of consumers who under-consumed (over-consumed) partially compensate for the consumers who over-consumed (under-consumed); Consumers who under-consumed (over-consumed) buy all their electricity at the P2P price regardless of their individual deviation, while the consumer who over-consumed (under-consumed) reduce their individual deviation with a share of the total deviation of consumers who under-consumed (over-consumed).
- Suppliers sell/buy electricity only to/from those prosumers/consumers whose individual deviation is in the same direction as the total supply/demand deviation.

3) Billing model with universal cost split: This billing model aggregates all the individual deviations of all P2P market participants (prosumers and consumers) and the cost of the total deviation is socially split amongst the prosumers (consumers) whose individual deviation is in the same direction as the total deviation. This is described below and shown shown in Alg. 4.

- All individual deviations are aggregated to calculate the total deviation of the P2P market.
- If the total deviation is equal to zero, all prosumers (consumers) sell (buy) at the P2P trading price, regardless of their individual deviations.
- If the total deviation is positive (total supply is more than the total demand), then all consumers buy all their consumed volume at the trading price, regardless of their individual deviation, whereas prosumers proceed as in the social split case, splitting the reward calculated based on the total deviation.
- If the total deviation is negative (total supply is less than the total demand), then all prosumers sell all their supplied volume at the P2P trading price, regardless of their individual deviation, whereas the consumers proceed as in the social split case, splitting the cost calculated based on the total deviation.
- Suppliers only sell/buy volumes equal to the total deviation of the P2P market.

C. Billing Models for P2PM with Mid Market as Back-up

In the previous billing models, the RM was the first and only back-up option for prosumers/consumers when they had to trade or compensate for their deviations. The prosumers/consumers whose bids were not accepted at the P2P market also had to trade at the RM. To maximise the volumes traded between prosumers and consumers there should be a follow-up market for the unsuccessful bids at the P2P market. In this paper, we assume that there is a Mid-Market (MM) where volumes of users with unsuccessful bids are matched. We assume that the electricity at this market is traded at mid-market prices. These mid-market prices are calculated based on the trading, retail and FiT prices; similarly to the market models proposed in [11]. The prices are set such that prosumers and consumers are always better off trading at the P2P market. However, if they are not successful at the P2P market, then they automatically trade at the MM. Only volumes that are still uncleared after the MM are traded at the RM. The inclusion of such MM models increases the local supply-demand match provided by the prosumers and cosnumers and minimises volumes traded at the RM. A billing model with universal cost split and MM is shown in Alg. 5.

III. EVALUATION

We evaluate our billing models by running simulations on a small-scale use-case to calculate profits and bills for prosumers and consumers, respectively and the balances of the suppliers.

A. Use-case

Our use-case consists of a small community consisting of fifteen market participants (five prosumers and ten consumers) contracted with three suppliers: Supplier A, Supplier B and Supplier C. The customers of these suppliers are allocated as follows. Supplier A has three customers, two consumers and one prosumer. Supplier B has five customers, three consumers and two prosumers. Supplier C has seven customers, five consumers and two prosumers. Each trading slot has a duration of one hour.

In scenarios with the RM only, prosumers/consumers do not submit any bids. Their rewards and bills are calculated based on the the volumes of electricity they supply/consume over each trading slot using the retail prices they are contracted with and FiT. Suppliers buy all of the supply of their contracted prosumers as well as sell to their contracted consumers all of their demand volumes. In scenarios with a P2P trading market, a double auction mechanism is used to clear the P2P market. It determines a unified P2P trading price, the cleared supply and demand volumes and the auction winners. If MM is not present, the RM plays the role as

Algorithm 5 Billing Model with Universal Cost Split and MM

procedure CUSTOMER BILLS, PROSUMER REWARDS, SUPPLIER BALANCE
for each timeslot **do**
  if bid Accepted **then**
    for each i, j and k in $P2P^c_n$, $P2P^p_n$ and S_n **do**
      if TD = 0 **then**
        $P2P^i_c$ bill = $C^{P2P}_{dem} \times$ TP
        $P2P^j_p$ reward = $P^{P2P}_{sup} \times$ TP
        S^{inc}_k += 0; S^{exp}_k += 0
        S^{bal}_k += $S^{inc}_k - S^{exp}_k$
      end if
      if TD < 0 **then**
        $P2P^j_p$ reward = $P^{P2P}_{sup} \times$ TP
        S^{exp}_k += 0
        if InDev$_i = 0$ or InDev$_i < 0$ **then**
          $P2P^i_c$ bill = $C^{P2P}_{dem} \times$ TP
          S^{inc}_k += 0
          S^{bal}_k += $S^{inc}_k - S^{exp}_k$
        end if
        if InDev$_i > 0$ **then**
          $P2P^i_c$ bill = $(C^{P2P}_{dem}$ - $\frac{TD}{P2P^c_n}) \times$ TP + $\frac{TD}{P2P^c_n} \times MMP_c$
          S^{inc}_k += 0
          S^{bal}_k += $S^{inc}_k - S^{exp}_k$
        end if
      end if
      if TD > 0 **then**
        $P2P^i_c$ bill = $C^{P2P}_{dem} \times$ TP
        S^{inc}_k += 0
        if InDev$_j = 0$ or InDev$_j < 0$ **then**
          $P2P^j_p$ reward = $P^{P2P}_{sup} \times$ TP
          S^{exp}_k += 0
          S^{bal}_k += $S^{inc}_k - S^{exp}_k$
        end if
        if InDev$_j > 0$ **then**
          $P2P^j_p$ reward = $(P^{P2P}_{sup}$ - $\frac{TD}{P2P^p_n}) \times$ TP + $\frac{TD}{P2P^p_n} \times MMP_p$
          S^{exp}_k += 0
          S^{bal}_k += $S^{inc}_k - S^{exp}_k$
        end if
      end if
    end for
  end if
  if bid not accepted **then**
    for each i, j and k in C_n, P_n and S_n **do**
      if TD = 0 **then**
        C_i bill = C_{dem} - $(\frac{T^p_{sup}}{C_n}) \times$ RP + $\frac{T^p_{sup}}{C_n} \times MMP_c$
        P_i reward = $T^p_{sup} \times MMP_p$
        S^{inc}_k += C_{dem} - $(\frac{T^p_{sup}}{C_n}) \times$ RP
        S^{exp}_k += 0
        S^{bal}_k += $S^{inc}_k - S^{exp}_k$
      end if
      if TD > 0 **then**
        C_i bill = C_{dem} - $(\frac{T^p_{sup}+TD}{C_n}) \times$ RP + $\frac{T^p_{sup}+TD}{C_n} \times MMP_c$
        P_i reward = $T^p_{sup} \times MMP_p$
        S^{inc}_k += C_{dem} - $(\frac{T^p_{sup}+TD}{C_n}) \times$ RP
        S^{exp}_k += 0
        S^{bal}_k += $S^{inc}_k - S^{exp}_k$
      end if
      if TD < 0 **then**
        C_i bill = C_{dem} - $(\frac{T^p_{sup}-|TD|}{C_n}) \times$ RP + $\frac{T^p_{sup}-|TD|}{C_n} \times MMP_c$
        P_i reward = P_{sup} - $\frac{|TD|}{P_n} \times MMP_p$ + $\frac{|TD|}{P_n} \times$ TP
        S^{inc}_k += C_{dem} - $(\frac{T^p_{sup}-|TD|}{C_n}) \times$ RP
        S^{exp}_k += 0
        S^{bal}_k += $S^{inc}_k - S^{exp}_k$
      end if
    end for
  end if
end for

the only fall-back option for prosumers and consumers. If MM is present, then the MM is the first fall-back option for the P2P market participants. The MM sell and buy price is determined by a function of the P2P price, average RM price and the FiT.

B. Data Generation

We randomly generate our data by utilizing the findings of Abidin et al. [12]. In their paper, they used a real dataset where the total generation of solar electricity was 2382 MW on 5/5/2016 between 13:00h and 13:30h. A Belgian household, on average, consumed 0.637 kW of electricity during that time slot [13]. Additionally, we assume that each prosumer has a solar panel installed at their home, with a capacity of 6 kW. Based on the chosen efficiency factor of the solar panels, i.e., 90%, we calculate the amount of excess electricity each prosumer has per trading slot randomly. Based on the aforementioned assumptions, we deduce that each consumer places a bid to consume electricity in the range of 0.4 - 1.1 kWH and each consumer places an offer to supply electricity in the range of 0.6 - 1 kWH per trading slot. From these ranges, we randomly assign a predicted demand/supply value to each consumer/prosumer. Once the predicted values are assigned, we assign fixed deviations that each consumer/prosumer would have as follows. The consumers/prosumers have a 0 deviation from their predicted values in 10% of the trading slots. The consumers/prosumers have a high ($>$ +/- 0.1 kWH) deviation from their predicted values in 20% of the slots. The consumers/prosumers have a medium deviation (between +/- 0.1 to 0.5 kWH) from their predicted values in 20% of the trading slots. The consumers/prosumers have a low deviation ($\leq$ +/- 0.5 kWH) from their predicted values in 50% of the slots. Using these deviations, we deduce the volume the consumers/prosumers actually consumed/delivered. In our data, the positive and negative deviations are distributed equally.

We set the retail electricity price of suppliers to 0.20€/kWh, 0.21€/kWh and 0.19€/kWh for Supplier A, B and C, respectively. The FiT is set to 0.05€/kWh for each supplier. Additionally, based on the double auction algorithm provided in [12], we determine the auction winners in each trading slot along with the trading price for the respective slot. Finally, from this trading price we determine the mid-market buying/selling price by taking the average of trading

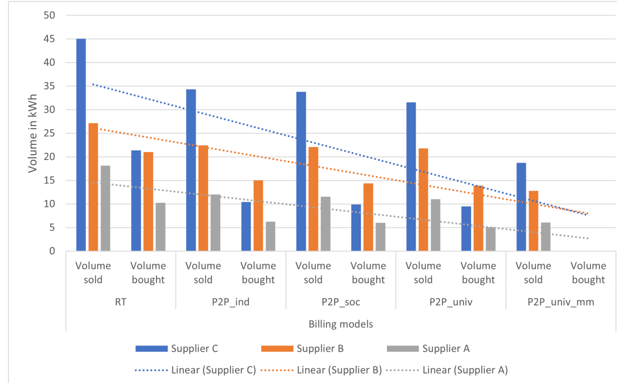

Fig. 2: Suppliers' trading volumes at RT and P2P billing models.

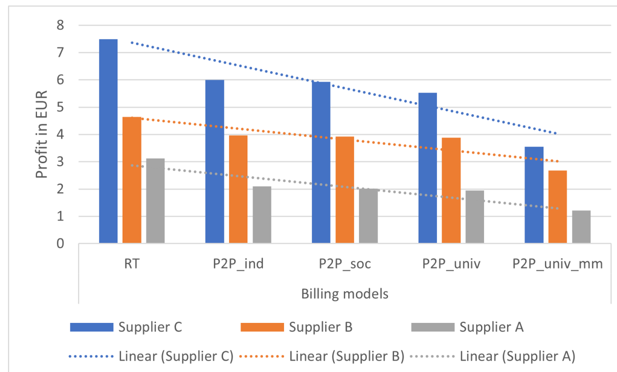

Fig. 3: Suppliers' profits at RT and P2P billing models.

C. Simulation Results

We simulate the demand/supply of each of the market participants for 12 trading slots (corresponding to half a day) and calculate the

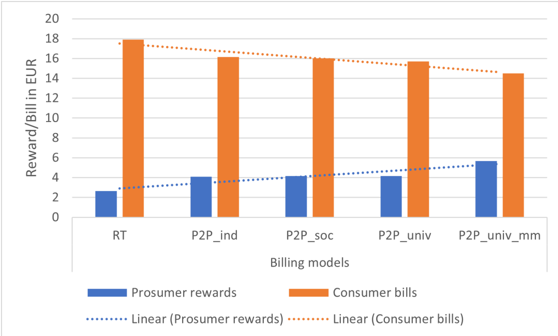

Fig. 4: Difference in Bills/Rewards of all participants.

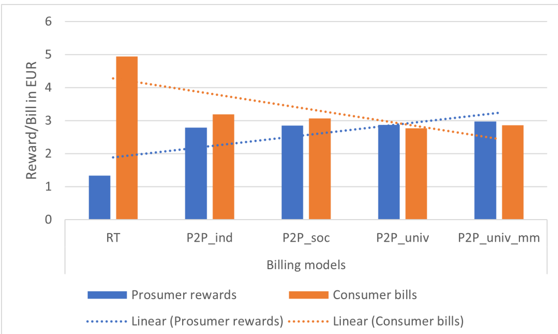

Fig. 5: Difference in Bills/Rewards of P2P participants.

rewards and bills of prosumers and consumers along with suppliers' profits based on our billing models.

As can be seen in Fig. 2, having a P2P market reduces the volume of electricity traded at the RM significantly. For instance, Supplier C loses $\sim$ 25% of the electricity volume sold while transitioning from RM to P2P. This drop is more severe when comparing RM to P2P markets along with mid-market, where Supplier C loses $\sim$ 60% of electricity volume sold. On the other hand, the volume of electricity bought by the suppliers' also reduces when transitioning from RM to P2P market, eventually falling to 0 when mid-market is introduced. As a result of this drop in the volumes traded by the suppliers', we observe that the suppliers' income also reduces. This can be seen in Fig. 3.

Fig. 4 depicts the benefits for prosumers/consumers when transitioning from RM to P2P markets. Both, the rewards of prosumers and bills of consumers rise and fall respectively when moving from RM to P2P. However, between each P2P billing model, not much difference is noticed except when mid-market is introduced. For instance, the average reward of a prosumer doubles when we compare RM to P2P universal split market with mid-market. In comparison, such a significant change is not observed in the bills of consumers.

Fig. 5 depicts that P2P billing models have a significant effect on prosumer/consumer rewards/bills; however, P2P billing models when compared to each other do not introduce much change. With Fig. 6, we aim to show how the introduction of mid-market in our billing models benefits everyone, including and mainly the prosumers/consumers with bids not accepted at the P2P market. Since the prosumers/consumers who do not get selected to trade on the trading market have to trade electricity on the RM, their profits do not change much unless mid-markets are introduced.

IV. Conclusions and Future Work

In this paper, we devise novel P2P billing models to incentivise P2P participants such as prosumers and consumers. Our

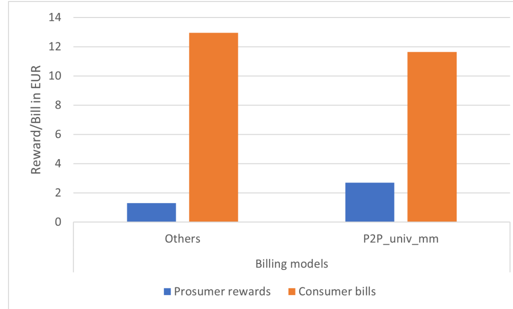

Fig. 6: Difference in Bills/Rewards of non-P2P participants

evaluations show how these proposed billing models could have a significant impact on the volumes traded at the P2P market and RM; thus on the bills of consumers, rewards of prosumers and profits of suppliers. We also show how the introduction of MM significantly increases the profits of the prosumers/consumers who do not get selected to trade on the trading market. Additionally, prosumers/consumers who trade on the trading market also gain significant advantages with the introduction of MM.

As a future work, we plan to run large-scale simulations on a larger number of market participants and longer duration to see the full effect of these billing models on the market participants and suppliers. Additionally, we also plan to improve these billing models such as they are less privacy invasive; hence, more usable.

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