Fair pricing model for Smart Grids

Veniamin Boiarkin
School of Mathematics, Computer Science and Engineering
City, University of London
London, UK
Veniamin.Boiarkin@city.ac.uk

Asif, Waqar
School of Computing and Engineering
University of West London,
London, UK
waqar.asif@uwl.ac.uk

Muttukrishnan, Raj
Department of Electrical and Electronic Engineering
City, University of London
London, UK
r.muttukrishnan@city.ac.uk

***Abstract*—The demand for electricity is constantly growing, which leads to an increase in production, which in turn adversely affects the environment. Many countries integrate renewable energy sources (RES) with the aim of decreasing the use of fossil fuels. Although there is more and more power coming from RES, some part of it is still lost due to the lack of motivation on the participants' side to interact with each other. In order to attract more participants to the Smart Grid, thereby reducing the demand from the Utility Grid, it is necessary to ensure fair prices within the Smart Grid, that will be beneficial to all participants. Firstly, we consider the pricing issue taking into account the principle of how smart meters operate. Secondly, we propose a fair pricing model for the Smart Grid, as well as a method for determining an equilibrium price of buying and selling electricity. Finally, we evaluate the proposed model and provide the results, that prove its effectiveness.**

***Index Terms*—Smart Grid, Pricing, Smart Metering**

I. INTRODUCTION

The demand for electricity grows every year, which entails an increase in the level of production. The utilization of energy sources, such as nuclear power and fossil fuels leads to an increase in emissions and toxic waste, that may lead to devastating consequences and even to a cataclysm. In this regard, most countries are integrating RES into the grid, aiming to reduce the level of emissions [1]. At the sametime, some households install PV panels to generate electricity within their homes and to pay less.

Currently, the power grid consists of many components (participants), some of which supply electricity, while others consume, in some cases both options are possible. Moreover, some participants can produce more electricity than they need, while they do not supply surplus to the grid. The Smart Grid concept involves the smart utilization of electricity with the aim of reducing the demand from the Utility Grid, which subsequently leads to lower emissions.

In order to motivate participants to interact with each other within the Smart Grid, it is necessary to offer such conditions that will be more beneficial in comparison with the Utility Grid. This means that it is necessary to formulate a pricing mechanism, which will afford buying electricity at lower price than from the Utility Grid, and selling at higher price.

To address the issue of price formation, researchers have proposed different approaches. The authors in [2] propose a pricing mechanism for demand response programs, which allows to generate non-discriminatory individualized prices for each user. First of all, data from users' smart meters are collected in order to get consumption profiles, and then the prices are calculated according to these profiles and aggregated electricity price signal obtained from the Utility Grid. It is also assumed, that all users get power from the Utility Grid. If any user consumes more energy, the price for this user will be higher. Although, the results show that the price can be decreased by 23.77%, it is not enough to consider the Utility Grid as only one possible producer of electricity, since the concept of Smart Grid implies the presence both producers and consumers. In [3], a Home Energy Management System (HEMS) and demurrage mechanism proposed to minimize the costs of electricity consumption. The same as in [4], the prices are generated based on SDR, but the selling and buying prices are not identical. Although the evaluation results showed, that the electricity cost can be reduced up to 44.73%, the problem of the same price for all participants wasn't addressed. It is not fair to charge different participants at the same price, while one of them followed predicted profile, while another one not. The authors in [5] propose a fair pricing scheme, based on power demand forecasting to reduce extra bills of low energy consumers (LEC), while high energy consumers (HEC) will be fined, because of their high demand. First, a machine learning demand forecasting model is developed to differentiate LECs and HECs. The simulation results demonstrate that the cost for LECs can be reduced by 11%. The important remark here is that the peak demand may be caused not by HECs, but by LECs, because of the high number of LECs, and in this case it becomes unfair to charge HECs at higher price.

The main contributions of this paper are:

- We propose an algorithm of calculating participants' cost and profit, taking into account the principle of operation of smart meters.

- We formulate a fair pricing model, as well as a model for determining penalties, based on the participants' impact factor.
- We propose a method of determining an equilibrium price within the Smart Grid, which is based on SDR (supply and demand ratio).

The rest of the paper is organized as follows. In Section II we propose a novel fair pricing model for Smart Grids. The question of determining an equilibrium price is discussed in Section III. The simulation results are shown in Section IV, and the conclusion is given in Section V.

II. Fair Pricing Model

In this section, we explain a fair pricing model for Smart Grids. We use the concept of Smart Grid Node (SGN) from our previous work [6], by applying which we represent any participant within the Smart Grid as a SGN. Every SGN may represent a consumer with zero production level or producer with zero consumption level, and in some cases a SGN may represent a prosumer with non-zero production and consumption levels. Thus, we consider the Smart Grid as a grid of SGNs that have different characteristics, namely levels of electricity consumption and production. The idea of utilizing the SGN concept is to focus on the overall result and fairness.

The main aim of this work is to achieve fairness while calculating electricity bills, and to provide beneficial prices, that will attract more SGNs to participate within the Smart Grid. Thus, the price of purchasing electricity from the Smart Grid should be less than the price of purchasing electricity from the Utility Grid (λ_{buy}), and the price of selling electricity to the Smart Grid should be higher than the price of selling electricity to the Utility Grid (λ_{sell}). Moreover, we are aiming to set purchase and selling prices within the Smart Grid equal to each other. In other words, there is only one equilibrium price (λ_e) within the Smart Grid. In order to support different tariffs, we assume that λ_{buy} and λ_{sell} may be different and may change over time.

Initially, we assume that we have got predicted profiles of consumption and production of electricity for the next operational period T (in this work, T is equal to 1 hour). Hence, in terms of economics, we have got QD_P (predicted quantity demanded) and QS_P (predicted quantity supplied) for all SGNs. It should be noted, that we don't say the way we get these profiles. On the one hand, participants may submit their predictions manually, and on the other hand these profiles can be predicted by utilizing some machine learning algorithms, based on historical data.

At the next step, we propose to aggregate the data from SGNs' smart meters to get actual levels of production and consumption of electricity. Smart meters may submit data at some interval t (15 min / 30 min / 60 min), in this work we assume, that data are submitted every 15 min. After aggregating the data from smart meters, we get the actual quantity demanded (QD_R) and actual quantity supplied (QS_R) during the operational period T (Table I).

t	00:15	00:30	00:45	01:00
QD_t	2 kW	1 kW	0.5 kW	2 kW
QD_{R_T}	5.5 kW			

TABLE I: Actual quantity demanded

where t is the time of receiving data from a smart meter (an interval at which smart meters submit the data), QD_t is the quantity demanded (consumption) during the interval t, QD_{R_T} is the total quantity demanded during the operational period T.

Putting together predicted profiles and actual data from the smart meters, we get the following result (Table II).

n	QD_{P_T}	QD_{R_T}	QS_{P_T}	QS_{R_T}
1	1 kW	2 kW	0 kW	1 kW
2	0 kW	0 kW	3 kW	1 kW

TABLE II: Predicted profiles and actual data from the smart meters

where n is the number of SGN, QD_{P_T} is the predicted quantity demanded at time slot T, QD_{R_T} is the actual quantity demanded at time slot T, QS_{P_T} is the predicted quantity supplied at time slot T, QS_{R_T} is the actual quantity supplied at time slot T. It can be noted, that predicted profiles do not coincide with actual data, namely SGN_1 predicted to consume 1kW, but in fact consumed 2kW, and the similar situation can be observed with SGN_2, which predicted to supply 3kW, but supplied only 1kW. Fig. 1 depicts all the possible states, that may occur when comparing predicted and actual quantity demanded.

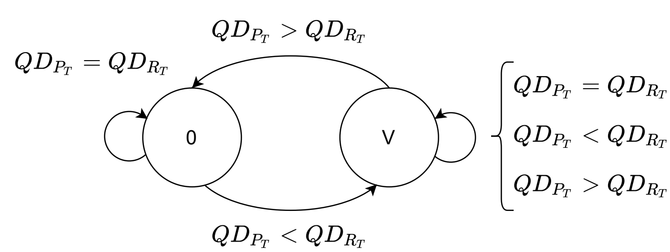

Fig. 1: Changes in quantity demanded (supplied)

where 0 means zero consumption, V means non-zero (some value) consumption. For example, in case when QD_{P_T} and QD_{R_T} are equal to some values, there are three possible options can be, namely $QD_{P_T} = QD_{R_T}$ (predicted and actual values are equal), $QD_{P_T} > QD_{R_T}$ (actual quantity demanded is lower than predicted) and $QD_{P_T} < QD_{R_T}$ (actual quantity demanded is greater than predicted).

Since predicted and actual profiles of electricity consumption and production may not be the same, the Smart Grid's state may also change, such as it may be predicted to operate as a seller, but in fact, based on actual data from smart meters, it may operate as a buyer. Fig 2 depicts all the possible states and transitions between them.

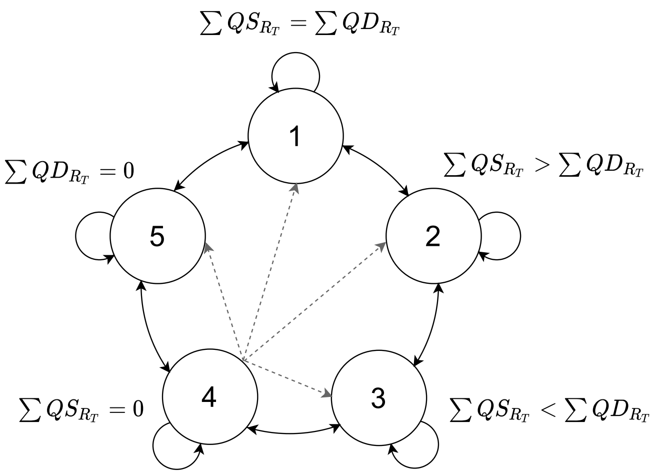

Fig. 2: The states of Smart Grid

For example, at some time slot T, Smart Grid is predicted to operate as a seller ($\sum QS_{P_T} > \sum QD_{P_T}$), thus covering the demand within the Smart Grid, and also selling surplus to the Utility Grid (state 2), but according to the changes on participants' side, the Smart Grid becomes a buyer ($\sum QS_{R_T} < \sum QD_{R_T}$), thus it may cover only some part of the demand within the Smart Grid, while the shortage must be covered with the help of the Utility Grid (state 3).

In order to understand how to ensure fair billing, we have to consider all the possible Smart Grid's states separately. If we consider state 4, when there is no generation within the Smart Grid, the whole demand will be covered by buying electricity from the Utility Grid at price λ_{buy_T}. Likewise, if there is no demand within the Smart Grid (state 5), all the generated electricity will be sold to the Utility Grid at price λ_{sell_T}.

A. The total quantity supplied is equal to the total quantity demanded

In this case, the total quantity demanded $\sum QD_{R_T}$ within the Smart Grid is equal to the total quantity supplied ($\sum QS_{R_T}$) within the Smart Grid, which means that SDR_T (supply and demand ratio) at time slot T is equal to 1, and there is no need to buy electricity from the Utility Grid. Hence, electricity is sold and bought within the Smart Grid at some equilibrium price λ_{e_T}. The method of determining an equilibrium price is discussed in Section III. Thus, from the point of view of buyers, the cost can be defined as:

$$C_{i_T} = QD_{i_{R_T}} * \lambda_{e_T} \tag{1}$$

where C_{i_T} is the cost of buying electricity from the Smart Grid by i-th SGN at time slot T, $QD_{i_{R_T}}$ is the quantity demanded by i-th SGN at time slot T, λ_{e_T} is the equilibrium price at time slot T. Since the purchase and selling prices are the same, and the total quantity demanded is equal to the total quantity supplied, we define SGN's profit as:

$$P_{i_T} = QS_{i_{R_T}} * \lambda_{e_T} \tag{2}$$

where P_{i_T} is the profit of selling electricity to the Smart Grid by i-th SGN at time slot T, $QS_{i_{R_T}}$ is the quantity supplied by i-th SGN at time slot T, λ_{e_T} is the equilibrium price at time slot T.

If we consider the case, when two SGNs (SGN$_1$, SGN$_2$) consumed the same amount of electricity $QD_{1_{R_T}} = QD_{2_{R_T}}$ at some time slot T, then the cost for these two SGNs will be the same. However, in the case, when SGN$_1$ followed its predicted profile ($QD_{1_{P_T}} = QD_{1_{R_T}}$), and SGN$_2$ decided to consume more than it was predicted ($QD_{2_{P_T}} < QD_{2_{R_T}}$), it becomes unfair from the point of view of SGN$_1$ to pay the same bill.

For fairness, we propose to use penalties, but what is important is that the final cost must be lower or equal to the cost of interacting with the Utility Grid, otherwise we won't be able to attract SGNs to participare in the Smart Grid. Thus, the final cost should satisfy the condition (Eq. 3).

$$QD_{i_{R_T}} * \lambda_{e_T} + \Psi <= QD_{i_{R_T}} * \lambda_{buy_T} \tag{3}$$

where $QD_{i_{R_T}}$ is the quantity demanded by i-th SGN at time slot T, λ_{e_T} is the equilibrium price at time slot T, Ψ is the penalty.

We cannot add any fixed penalty to the cost, because in this case the final cost may exceed the cost of interacting with the Utility Grid. What we can do is to define penalty, based on the difference between the cost of interacting with the Utility Grid and the cost of interacting with the Smart Grid. The difference between the costs can be defined as:

$$D_{i_{D_T}} = QD_{i_{R_T}} * (\lambda_{buy_T} - \lambda_{e_T}) \tag{4}$$

where $D_{i_{D_T}}$ is the difference between the costs for i-th SGN at time slot T, $QD_{i_{R_T}}$ is the quantity demanded by i-th SGN at time slot T, λ_{buy_T} is the price of purchasing electricity from the Utility Grid at time slot T, λ_{e_T} is the equilibrium price at time slot T.

By adding the difference between the costs ($D_{i_{D_T}}$) to the cost of interacting with the Smart Grid (C), we will get the same cost, as by interacting with the Utility Grid, hence we can use only some part of the difference as a penalty. First, we identify an overall change in quantity demanded within the Smart Grid (Eq. 5).

$$CH_{D_T} = \sum_{i=1}^{n} |QD_{i_{R_T}} - QD_{i_{P_T}}|, QD_{i_{R_T}} > 0 \tag{5}$$

where CH_{D_T} is the overall change in quantity demanded at time slot T, i is the index of SGN, n is the number of SGNs.

Since we don't want SGNs to change their predicted profiles and make the state of the Smart Grid is unpredictable, we propose to fine participants according to their impact on the overall change. Hence, the much impact, the higher the penalty will be. To identify SGN's impact, we introduce an impact coefficient, which can be defined as:

$$K_{i_T} = \frac{|QD_{i_{R_T}} - QD_{i_{P_T}}|}{CH_{D_T}} \tag{6}$$

Putting together the cost of interacting with the Smart Grid and penalty, the final cost can be defined as:

$$C_{i_{F_T}} = QD_{i_{R_T}} * \lambda_{e_T} + K_{i_T} * D_{i_{D_T}} \tag{7}$$

where $C_{i_{F_T}}$ is the final cost of interacting with the Smart Grid for i-th SGN at time slot T, $QD_{i_{R_T}}$ is the quantity demanded by i-th SGN at time slot T, λ_{e_T} is the equilibrium price at time slot T, K_{i_T} is the impact coefficient for i-th SGN at time slot T, D_{D_T} is the difference between the costs for i-th SGN at time slot T.

B. The total quantity supplied is greater than the total quantity demanded

In this case, the total quantity supplied $\sum_{i=1}^{n} QS_{i_{R_T}}$ is equal to the total quantity demanded $\sum_{i=1}^{n} QD_{i_{R_T}}$, which means, that SDR_T is greater than 1.

In real world scenarios, it is highly unlikely, that the Smart Grid will generate enough electricity to cover its demand and sell surplus to the Utility Grid, but we have to consider this case anyway.

From the point of view of buyers, the cost of purchasing electricity from the Smart Grid should be the same, as in case when the total quantity supplied is equal to the total quantity demanded. From the point of view of sellers (producers), some part of generated electricity is sold within the Smart Grid at equilibrium price λ_{e_T}, while another part is sold to the Utility Grid at price λ_{sell_T}.

Here, we have to identify what part of generated electricity may be sold by each SGN to the Smart Grid. It is important because we don't want one producer to get all the profit, because of its high generation profile. We propose to distribute the profit between all the producers according to the inverse SDR_T, thus we allow all producers to sell at least some part (Eq. 8) to the Smart Grid, while another part (Eq. 9) will be sold to the Utility Grid.

$$S_{i_{SG}} = QS_{i_{R_T}} * SDR_T^{-1} \tag{8}$$

$$S_{i_{UG}} = QS_{i_{R_T}} * (1 - SDR_T^{-1}) \tag{9}$$

where $S_{i_{SG}}$ is the quantity supplied by i-th SGN to the Smart Grid at time slot T, $S_{i_{UG}}$ is the quantity supplied by i-th SGN to the Utility Grid at time slot T.

In the same way we applied penalties for SGS, that changed their predicted consumption profiles, we propose to apply penalties for SGNs, that changed their predicted generation profiles during the operational period. First, we define an overall change in quantity supplied:

$$CH_{S_T} = \sum_{i=1}^{n} |QS_{i_{R_T}} - QS_{i_{P_T}}|, QS_{i_{R_T}} > 0 \tag{10}$$

where CH_{S_T} is the overall change in quantity supplied at time slot T, i is the index of SGN, n is the number of SGNs. An impact coefficient in this case can be defined as:

$$K_{i_T} = \frac{|QS_{i_{R_T}} - QS_{i_{P_T}}|}{CH_{S_T}} \tag{11}$$

Since, some part of generated electricity is sold to the Utility Grid, we can only decrease the profit of interacting with the Smart Grid, thus the difference between the profits can be defined as:

$$D_{i_{S_T}} = S_{i_{SG}} * (\lambda_{e_T} - \lambda_{sell_T}) \tag{12}$$

where $D_{i_{S_T}}$ is the difference between the profits for i-th SGN at time slot T, $S_{i_{SG}}$ is the quantity supplied by i-th SGN to the Smart Grid at time slot T, λ_{e_T} is the equilibrium price at time slot T, λ_{sell_T} is the price of selling electricity to the Utility Grid at time slot T.

Putting together the profit of interacting with the Smart Grid and penalty, the final profit can be defined as:

$$P_{i_{F_T}} = S_{i_{SG}} * \lambda_{e_T} + S_{i_{UG}} * \lambda_{sell_T} - D_{i_{S_T}} * K_{i_T} \tag{13}$$

where $P_{i_{F_T}}$ is the final profit for i-th SGN at time slot T, $S_{i_{SG}}$ is the part of quantity supplied by i-th SGN, and sold to the Smart Grid at time slot T, $S_{i_{UG}}$ is the part of quantity supplied by i-th SGN, and sold to the Utility Grid at time slot T, λ_{e_T} is the equilibrium price at time slot T, λ_{sell_T} is the price of selling electricity to the Utility Grid at time slot T, $D_{i_{S_T}}$ is the difference between the profits for i-th SGN at time slot T, K_{i_T} is an impact coefficient for i-th SGN at time slot T.

C. The total quantity supplied is lower than the total quantity demanded

This state of the Smart Grid is most common, since SGNs generate some electricity and supply it to the Smart Grid, but it is not enough to cover the Smart Grid's demand, thus the missing part is purchased from the Utility Grid. In this case, the total quantity supplied $\sum_{i=1}^{n} QS_{i_{R_T}}$ is lower than the total quantity demanded $\sum_{i=1}^{n} QD_{i_{R_T}}$, which means, that SDR_T is lower than 1.

The main problem in this scenario is that the total quantity supplied can cover only some part of the total quantity demanded, thus this part is bought at the equilibrium price λ_{e_T} from the Smart Grid, while the rest is bought from the Utility Grid at price λ_{buy_T}. The question here is how to distribute generated electricity in fair manner between all the buyers. If we cover the demand in full only for a small number of buyers, it may lead to the case, when the rest of buyers will buy electricity from the Utility Grid at price λ_{buy_T}, which is unfair. For fairness, each SGN should get some part of its demand from the Smart Grid, and the rest to buy from the Utility Grid. In the same way we did for the previous Smart Grid's state, we identify, what part (Eq. 14) can be bought from the Smart Grid, and what part (Eq. 15) will be bought from the Utility Grid.

$$D_{i_{SG}} = QD_{i_{R_T}} * SDR_T \tag{14}$$

$$D_{i_{UG}} = QD_{i_{R_T}} * (1 - SDR_T) \tag{15}$$

where $D_{i_{SG}}$ is the quantity demanded by i-th SGN from the Smart Grid at time slot T, $D_{i_{UG}}$ is the quantity demanded by i-th SGN from the Utility Grid at time slot T.

By distributing generated electricity between all buyers, we reduce their costs, but at the same time, we want these SGNs to follow predicted profiles, thus we also propose to apply penalties according to the impact on the overall change in quantity demanded. Moreover, since some part is bought from the Utility Grid, we can only add penalties to the part, which is purchased from the Smart Grid. The difference between the costs can be defined as:

$$D_{i_{D_T}} = D_{i_{SG}} * (\lambda_{buy_T} - \lambda_{e_T}) \tag{16}$$

where D_{D_T} is the difference between the costs for i-th SGN at time slot T, $D_{i_{SG}}$ is the quantity demanded by i-th SGN from the Smart Grid at time slot T, λ_{e_T} is the equilibrium price at time slot T, λ_{buy_T} is the purchase price of electricity from the Utility Grid at time slot T.

Putting together the costs and penalty, which is calculated, based on (Eq. 16) and (Eq. 6), the final cost for this scenario can be defined as:

$$C_{i_{F_T}} = D_{i_{SG}} * \lambda_{e_T} + D_{i_{UG}} * \lambda_{buy_T} + D_{i_{D_T}} * K_{i_T} \tag{17}$$

where $C_{i_{F_T}}$ is the final cost for i-th SGN of interacting with the Smart Grid at time slot T, $D_{i_{SG}}$ is the part of quantity demanded, which is bought by i-th SGN from the Smart Grid at time slot T, $D_{i_{UG}}$ is the part of quantity demanded, which is bought by i-th SGN from the Utility Grid at time slot T, λ_{e_T} is the equilibrium price at time slot T, λ_{buy_T} is the purchase price of electricity from the Utility Grid at time slot T, $D_{i_{D_T}}$ is the difference between the costs for i-th SGN at time slot T, K_{i_T} is an impact coefficient for i-th SGN at time slot T.

From the producers point of view, the profit consists of two parts. The first part is calculated in accordance to (Eq. 2), while the second part represents the penalty, which is calculated based on the impact coefficient (Eq. 11) and the difference between the profits (Eq. 12), thus the final profit can be defined as:

$$P_{i_{F_T}} = QS_{i_{R_T}} * \lambda_{e_T} - K_{i_T} * D_{S_T} \tag{18}$$

III. Equilibrium price model

In this section we propose a model, by utilizing which, we can define an equilibrium internal price for the Smart Grid. Thus, SGNs purchase and sell electricity within the Smart Grid at the equilibrium price λ_{e_T}.

This model is based on supply and demand ratio (SDR_T). If SDR_T is equal to zero, which means there is no generation ($\sum QS_T = 0$) within the Smart Grid, then SGNs will buy electricity from the Utility Grid at price λ_{buy_T}. When SDR_T is between 0 and 1 ($\sum QS_T < \sum QD_T$), the internal prices may be calculated in accordance to different algorithms. In case when SDR_T is greater than 1 ($\sum QS_T > \sum QD_T$), some part of electricity is sold to the Smart Grid, while another part is sold to the Utility Grid. In order to make the equilibrium price low, in this scenario it can be equal to the selling price to the Utility Grid. Hence, we have got two point (0; λ_{buy_T}), (1, λ_{sell_T}), that we can use to identify the relationship between SDR_T and the equilibrium price within the Smart Grid (Fig. 3).

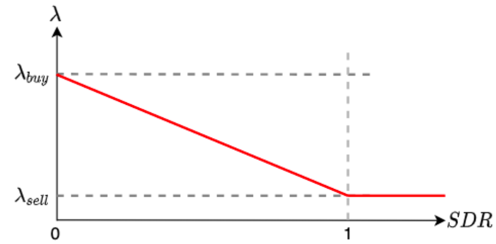

Fig. 3: Relationship between SDR_T and λ_{e_T}

In some models [3], [4], internal prices (Pr_{sell}, Pr_{buy}) are not the same, but since we aim to attract as much SGNs as possible to participate in Smart Grid, we identify one equilibrium price, at which the SGNs purchase and sell power within the Smart Grid. The price basically is calculated as cost (profit) divided by quantity, hence by applying the penalty mechanism, based on the impact coefficient, the prices for different SGNs won't be the same.

IV. Case study

In order to simulate proposed model, we took the average price of purchasing electricity from the Utility Grid λ_{buy} = 14.37p/kW [7], and the price of selling electricity to the Utility Grid λ_{sell} = 5.24p/kW [8].

Next, we generated 200 SGNs with different consumption and production profiles. The quantity demanded at a certain time slot is generated randomly within the interval [0; 6kW], while the quantity supplied at a certain time slot is also generated randomly within the interval [0; 3kW]. Moreover, there may be changes between predicted profiles and actual data, that are randomly generated within the interval [0; 1kW]. The changes may both increase or decrease original quantity demanded (supplied), and to make it more unpredictable, we also generate an action, which will be applied to the original value, and it may be addition, subtraction or in some cases the action may decline the change (SGN follows its predicted profile).

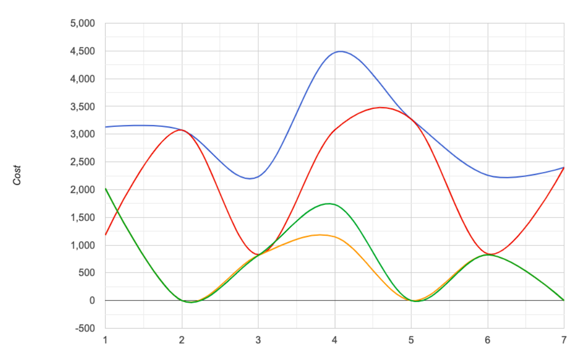

Fig. 4: Simulation over a period of 7 days

Fig. 4 shows the simulation results over a period of 7 days, where blue curve represents the original cost of purchasing power from the Utility Grid, red curve represents the cost of purchasing power from the Smart Grid, yellow curve represents the profit of selling power to the Utility Grid, and green curve represents the profit of selling power to the Smart Grid. As we can see, the cost of purchasing power from the Smart Grid is lower than from the Utility Grid, and at the same time profit may be higher than the profit of interacting with the Utility Grid.

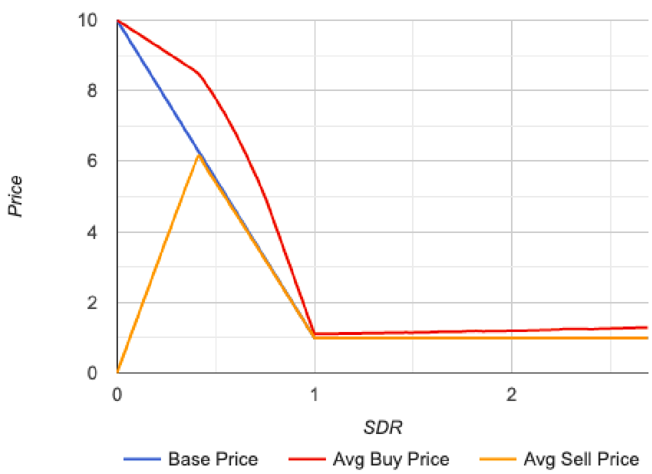

Fig. 5: Relationship between SDR_T and λ_{e_T}

Fig. 5 shows the relationship between the SDR_T and average purchase and selling prices. Since we generate data randomly, the final cost and profit are different for all SGNs. In order to show the relationship between prices and SDR, we calculated the average final prices. As we can see from the results, the price of purchasing power is higher than λ_{e_T}, because of the changes in quantity demanded. The difference between selling price and base price is smaller than between the purchase price and base price, because in most operational periods, Smart Grid operated in state 3, when $\sum QS < \sum QD$.

T	$\sum QD$	C_{UG}	C_{SG}
1	189.4	2721.69	1025.09
2	155.44	2233.71	2233.71
3	214.01	3075.36	3075.36
4	165.14	2373.09	901.09
5	212.2	3049.4	1132.97
6	201.79	2899.83	1089.56
7	358.21	5147.59	4102.81
Total	1496.22	21500.69	13560.62

TABLE III: Cost over a period of 7 days

Table III shows the total cost of purchasing power from the Smart Grid over a period of 7 days. As we can see, the cost of interacting with the Smart Grid is always lower than the cost of interacting with the Utility Grid. The overall cost of purchasing power from the Utility Grid is equal to 21500.69p, while the cost of purchasing power from the Smart Grid is equal to 13560.62p, hence the cost C_{SG} decreased by 37%.

T	$\sum QS$	P_{UG}	P_{SG}
1	330.94	1734.12	1734.12
2	0	0	0
3	0	0	0
4	356.3	1867.03	1867.03
5	212.2	1111.95	1111.95
6	291.88	1529.45	1529.45
7	203.36	1065.65	1851.43
Total	1394.7	7308.22	8094.01

TABLE IV: Profit over a period of 7 days

Table IV shows the total profit of selling power to the Smart Grid over a period of 7 days. As we can see, when $\sum QS > \sum QD$, the profit P_{SG} is the same as P_{UG}, because power is sold at price $\lambda_{e_T} = \lambda_{sell_T}$. On the other hand, when $\sum QS < \sum QD$, the equilibrium price is set according to SDR, and even taking into account penalties applied, the profit $P_{SG} > P_{UG}$, hence the profit P_{SG} increased by 10%. In case of a particular time interval (T = 7), the profit increased by $\tilde{7}0\%$.

V. Conclusion

In this paper, we have proposed a novel pricing mechanism for Smart Grids with the aim of calculating fair bills for all participants with the Smart Grid. First, an equilibrium price is determined, based on SDR, but final cost and profit may change for a particular SGN, according to its impact factor on overall change in quantity demanded or supplied. The simulation results demonstrate, that the cost of interacting with the Smart Grid is lower by 37% than with the Utility Grid, while the profit of selling power to the Smart Grid may be increased by 70% in comparison with the Utility Grid.

References

[1] UK government, *New plans to make UK world leader in green energy*, 2020 (accessed May 23, 2021). https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy.

[2] M. B. Rasheed, M. A. Qureshi, N. Javaid, and T. Alquthami, "Dynamic pricing mechanism with the integration of renewable energy source in smart grid," *IEEE Access*, vol. 8, pp. 16876–16892, 2020.

[3] A. S. Yahaya, N. Javaid, F. A. Alzahrani, A. Rehman, I. Ullah, A. Shahid, and M. Shafiq, "Blockchain based sustainable local energy trading considering home energy management and demurrage mechanism," *Sustainability*, vol. 12, no. 8, 2020.

[4] N. Liu, X. Yu, C. Wang, C. Li, L. Ma, and J. Lei, "An energy sharing model with price-based demand response for microgrids of peer-to-peer prosumers," *IEEE Transactions on Power Systems*, vol. PP, 06 2017.

[5] K. Aurangzeb, S. Aslam, S. M. Mohsin, and M. Alhussein, "A fair pricing mechanism in smart grids for low energy consumption users," *IEEE Access*, vol. 9, pp. 22035–22044, 2021.

[6] V. Boiarkin, W. Asif, and M. Rajarajan, "Decentralized demand response power management system for smart grids," pp. 70–74, 2020.

[7] UK government, *Feed-in tariffs: get money for generating your own electricity*, 2020 (accessed May 23, 2021). https://www.gov.uk/feed-in-tariffs.

[8] UKPower.co.uk Limited, *Comparison of electricity prices*, 2020 (accessed May 23, 2021). https://www.ukpower.co.uk/home_energy/tariffs-per-unit-kwh.