Optimal Time of Use of Renewable Electricity Pricing: Three-Player Games Model

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***Abstract*—Currently, the electricity demand is exponentially increasing due to the population growth. Therefore, the demand side management (DSM) is becoming unavoidable especially with the increasing use of renewable energy sources. One of the most known tactics of DSM is the use pricing strategies to threaten users to schedule their loads by controlling their own appliances. In this paper, a new model of electricity market operators is proposed based on three actors: the utility grid (G) with renewable energy (RE) generation, the electricity consumer (U) and a storage company (S). This approach aims to develop the adequate hourly prices which optimize the utility function of each operator. Then, in order to deal with this objective, two related games are defined. The first one is based on the satisfaction function of U and the G and aims to give the hourly prices of consumers' electricity bills. While the second one is based on the satisfaction function of G and S in order to optimize the hourly prices of G's electricity bills. Finally, a case study based on a given RE production and consumers load forecasts has been considered. Simulation results show that the obtained hourly prices allows the consumer load curve to follow the RE curve generation while achieving the main objective of the proposed approach.**

***Index Terms*—Renewable Energy based generation, optimization, game theory three players, outsourced storage.**

I. Introduction

For a long tome, the utility grid has been providing users with electricity for their appliances to function well. Nevertheless, it's still having problems with the load curves' daily fluctuations. In fact, the load curve usually presents peak hours, semi-peaks, and off-peak hours. This unregulated variations are very uncomfortable for the utility companies, since they have to turn on and off some of their massive generators to meet the necessary demand which might result in a huge loss in generation capacities in case of traditional production. Additionally, in the case of renewable energy based production, companies usually seek a perfect consumption, that is when users use up all what has been generated by the suppliers. Therefore, they often seek to keep the curve within a specific pattern in order to avoid any technical problems that might harm their equipments. Demand side management is when the utility grid interferes with users' demand to regulate the bumps on the load curve and get a steady curve eventually [1]. It is done through many measures [2]. A famous technique is the use of pricing to motivate users to lower or increase their loads in times of peak or off-peak hours. This is called time of use pricing [3], [4], it's when suppliers set their electricity prices in advance based on users' response and/or customer's satisfaction.

In this paper, we focus on renewable sources of energy (RE) as the main source of generation. We also assume that we only have a single generation company or that they are all grouped together under one company G. Furthermore, we suppose that all storage services have been completely externalized to storage companies. Likewise, we gather them all under one company S. The same goes for users, we use U to indicate all users of all kinds. We assume that each of the above participants stick to their assigned tasks. That is, users' unique task is to consume energy unlike [5] where they're participating in both storage and generation. The generation company G satisfies users' demand by all means. And, the storage company's single task is to purchase electricity from G when they have excess and sell it back when G needs it again. All these assumptions have been done primarily to simplify our modeling process. Nevertheless, this model can still be extended into different scenarios, like for instance when each player participates in other tasks not just the one we assigned to him. One more thing to point out is that we use game theory to optimize the utility functions of G, S and U because of their usual selfishness and eagerness to win. Thereby, we ought to call the interactions between them games and the actors players to emphasize the fact that each of them will only play winning strategies.

The rest of this paper is organized like this: Section II models all players roles and defines their tasks as well as their utility functions, Section III contains our derivation of the equilibrium, Section IV supports our model with a study case including its performance analysis and Section V concludes this paper.

II. Presenting the proposed model

A. Defining the players' roles and their utility functions

In this section, the three players G, S and U play in two different games. Game 1, between G and U and Game 2 between G and S, are shown in Fig.1. First, in Game 1, users

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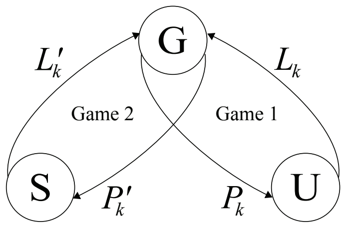

Fig. 1: Three-Player Games Model

buy electricity from G with the price P_k per unit to satisfy their load L_k, but given that G has no control over its active power generation g_k as it uses renewable sources of energy which are unreliable because they often rely on the weather, we obtain situations where G also needs to purchase or sell the difference between the generation and users' load L_k to storage owners S with the price P_k' per unit, this is Game 2. Therefore, on one hand we model G as a supplier for users in Game 1 and as a client of S in Game 2. Next, we associate each player U, G and S with a utility function. Let U_u, U_g and U_s be their utility functions respectively.

To begin with, we define two functions s_k and s_k'. The first one denotes users' satisfaction towards the price P_k by comparing the load L_k with the nominal users' demand d_k. If $d_k > L_k$ then users aren't satisfied with the price P_k. But when $d_k < L_k$, it's completely the opposite since users find P_k suitable to the extent of increasing their load above the nominal value d_k.

In Game 2, G duplicates users' actions in Game 1 as it acts as a client to S, the second function s_k', has exactly the same signification of s_k but this time we consider that G has a load L_k' needed to meet users' demand of energy in the cases of $g_k < L_k$, $g_k = L_k$ and $g_k > L_k$. This means that L_k' could be either positive, null or negative depending on the situation of G either having a surplus or is in need. And the same goes for P_k', the price by which S sells/purchases L_k' to/from G. Although, it seems that G is always the buyer and S is always the seller in Game 2, it all depends on the users in Game 1. In fact, if users ask for more than what G has, S provides that difference buy selling it to G. And if users' load is below the generation curve, G purchases a negative load from S. This is what we mean by L_k' not always being positive.
Let $d_k' = d_k - g_k$ be the nominal value that G needs to satisfy all users' nominal demand.

In the rest of this paper, we will be using the same satisfaction function that has been used in [6] to represent our model. The functions s_k and s_k' both must first satisfy the following conditions:

- For s_k:
  1) If $d_k = L_k$, $\quad s_k(L_k, d_k) = 0$
  2) $L_k > d_k$
  $$\frac{\partial s_k}{\partial L_k} < 0,\ \frac{\partial^2 s_k}{\partial L_k^2} > 0$$
  3) $L_k < d_k$
  $$\frac{\partial s_k}{\partial L_k} < 0,\ \frac{\partial^2 s_k}{\partial L_k^2} > 0$$
- For s_k':
  1) If $d_k' = L_k'$, $\quad s_k'(L_k', d_k') = 0$
  2) $L_k' > d_k'$
  $$\frac{\partial s_k'}{\partial L_k'} < 0,\ \frac{\partial^2 s_k'}{\partial L'^2_k} > 0$$
  3) $L_k' < d_k'$
  $$\frac{\partial s_k'}{\partial L_k'} < 0,\ \frac{\partial^2 s_k'}{\partial L'^2_k} > 0$$

The following two functions respect the above conditions [6].

$$\begin{aligned} s_k(L_k, d_k) &= d_k \beta_k \left(\left(\frac{L_k}{d_k} \right)^{\alpha_k} - 1 \right) \\ s_k'(L_k', d_k') &= d_k' \beta_k' \left(\left(\frac{L_k'}{d_k'} \right)^{\alpha_k'} - 1 \right) \end{aligned} \quad (1)$$

It is important to realize that as long as $\alpha_k < 0$, $\alpha_k' < 0$ and $\alpha_k \beta_k < 0$, $\alpha_k' \beta_k' < 0$, our model can be modified while still having the same results. Fig. 2 shows a simple example of how s_k and s_k' could look like.

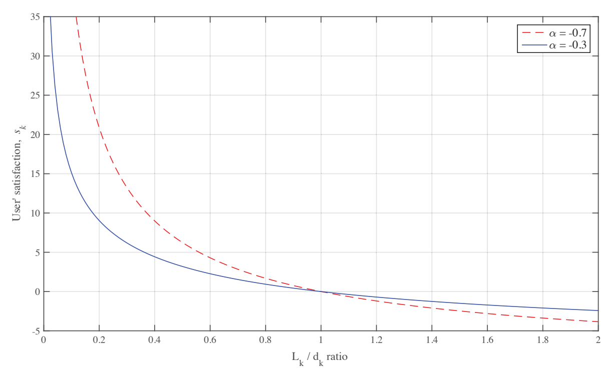

Fig. 2: Satisfaction function for $\beta = 5$, and for alpha values $\alpha = -0.7$ (Dashed line) and $\alpha = -0.3$ (Solid line)

Finally, we define all players' objective functions to be their (electricity sales - purchases - costs - satisfaction function) since they are all concerned with minimizing their costs and maximizing their profits [7]. The same applies to users, we take out the electricity sales since in this scenario they are not participating in the production nor in the storage.

B. Problem formulation

This section is about developing utility functions of the players in each game. We divide a day into multiple time slots, $k \in \mathcal{N} = \{1, \ldots, N\}$.

First in Game 1, users buy electricity L_k from G with P_k per unit. Therefore, their purchases are $P_k L_k$. By subtracting their satisfaction function, we get the following utility function:

$$U_u = -\sum_{k=1}^{N} \left[P_k L_k + d_k \beta_k \left(\left(\frac{L_k}{d_k} \right)^{\alpha_k} - 1 \right) \right] \quad (2)$$

Bear in mind that users' load can not exceed a certain value $L_{k,\max}$ which is normally the sum of all users' appliances turned on all at once, nor fall behind $L_{k,\min}$ which is the minimal load that users require from G. Under this condition, users' optimization problem becomes:

$$\begin{aligned} \max_{L_k} \quad & U_u \\ \text{subject to} \quad & L_{k,\min} \leq L_k \leq L_{k,max} \\ & L_{k,\max} = \min(d_{k,max}, (d'_{k,max} + g_{k,max})) \\ & L_k, \; \forall k \in \{1, 2, \ldots, N\} \end{aligned} \tag{3}$$

Next, we said that G takes on two roles, a provider of electricity to users in Game 1 and a mere user to S in Game 2. Hence, his utility function consists of two parts U_1 and U_2 of the first and second roles correspondingly.

When G is supplying electricity in the first game, G earns $P_k L_k$. And since his source of energy is mainly renewable we consider his operating and maintaning costs C_g instead of his production costs. Consequently, G's profit is $(P_k L_k - c_g g_k)$. We also take into consideration the costs proceeding the variations between the generation g_k and the average $\bar{g}$ multiplied by a factor μ [6], such that:

$$f(g) = \sum_{k=1}^{N} \mu (g_k - \bar{g})^2 \tag{4}$$

We then write:

$$U_1 = \sum_{k=1}^{N} \left[P_k L_k - c_g g_k - d_k \beta_k \left(\left(\frac{L_k}{d_k} \right)^{\alpha_k} - 1 \right) \right] - f(g) \tag{5}$$

In the second situation, G purchases $P'_k L'_k$ from S, and expresses his satisfaction through s'. Thus, the latter half of his utility function U_2 is similar to users' objective function U_u:

$$U_1 = - \sum_{k=1}^{N} \left[P'_k L'_k + d'_k {\beta'}_k * \left(\left(\frac{L'_k}{d'_k} \right)^{\alpha'_k} - 1 \right) \right] \tag{6}$$

To obtain G's utility function we sum both U_1 and U_2 together:

$$\begin{aligned} U_g = & \sum_{k=1}^{N} \left[P_k L_k - c_g g_k - d_k \beta_k \left(\left(\frac{L_k}{d_k} \right)^{\alpha_k} - 1 \right) \right] \\ & - f(g) \; - \sum_{k=1}^{N} \left[P'_k L'_k + d'_k {\beta'}_k \left(\left(\frac{L'_k}{d'_k} \right)^{\alpha'_k} - 1 \right) \right] \end{aligned} \tag{7}$$

Therefore, the optimization problem of G becomes:

$$\begin{aligned} \max_{L'_k, P_k} \quad & U_g \\ \text{subject to} \quad & L'_{k,min} \leq L'_k \leq L'_{k,max}, \qquad c_g \leq P_k \\ & L'_{k,\max} = \min \left(d'_{k,max}, \frac{g'_{k,max}}{\phi} \right) \\ & L'_k, P_k \;\; ; \forall k \in \{1, 2, \ldots, N\} \end{aligned} \tag{8}$$

The variable g' stands for storage owners' active generated power required by G. We add a constraint on g' to imply that S only sells/purchases what he receives from G on a timely basis no more no less, multiplied by a coeffecient:

$$g'_k = \left(\frac{1}{\eta_d} + \eta_c \right) L'_k \tag{9}$$

To simplify, we put :

$$\phi = c_s \left(\frac{1}{\eta_d} + \eta_c \right) \tag{10}$$

Whereas η_c and η_d are respectively the charging and discharging efficiencies of storage equipements owned by S and c_s is their operations and maintenance costs [8].

As for storage owners S, and by following the footsteps of G when he's acting as a supplier in Game 1, we get this utility function:

$$U_s = \sum_{k=1}^{N} \left[P'_k L'_k - c_s g'_k - d'_k * {\beta'}_k \left(\left(\frac{L'_k}{d'_k} \right)^{\alpha'_k} - 1 \right) \right] - f(g') \tag{11}$$

So using (10) U_s becomes:

$$U_s = \sum_{k=1}^{N} \left[P'_k L'_k - \phi L'_k - d'_k \beta'_k \left(\left(\frac{L'_k}{d'_k} \right)^{\alpha'_k} - 1 \right) \right] - f(g') \tag{12}$$

Again, $f(g')$ stands for the costs resulting of the variations between the delivered amounts and the average $\bar{g'}$ taking into account a coefficient μ'.

$$f(g') = \sum_{k=1}^{N} \mu' (g_k - \bar{g'})^2 \tag{13}$$

Thus, the storage company's optimization problem is:

$$\begin{aligned} \max_{P'_k} \quad & U_s \\ \text{subject to} \quad & P'_k \geq \phi \; \forall k \in \{1, 2, \ldots, N\} \end{aligned} \tag{14}$$

Now that all players' utility functions have been set, we need to explain the rules of the games. In Game 1, G decides on the time of use price beforehand and users react upon that price. Identically in Game 2, S sets his pricing strategy and G responds by demanding a suitable load. Let $\mathcal{U}$, $\mathcal{G}$ and $\mathcal{S}$ be the strategy set of U, G and S respectively.

$$\mathcal{S} = \{P' | P' \in \mathrm{I\!R}^{\mathrm{N}}, L'\min \leq L'(P') \leq L'\max, \; P' \geq \phi\} \tag{15}$$

$$\mathcal{G} = \{(P, L') | P, L' \in \mathrm{I\!R}^{\mathrm{N}}, L\min \leq L(P) \leq L\max, \; P \geq cg, L'\min \leq L' \leq L'\max\} \tag{16}$$

$$\mathcal{U} = \{L | L \in \mathrm{I\!R}^{\mathrm{N}}, L\min \leq L \leq L\max\} \tag{17}$$

L and L' are set to be functions of P and P' because it's usually the prices that are being set first and determine how the loads will go.

The purpose of the two games is to find a Nash equilibrium for each [9], such that none of the players is motivated to change his strategy because no other choice has better payoffs than that one. We obtain a Nash equilibrium in Game 2 when:

$$\forall P' \in \mathcal{S}, P' \neq P'^* : U_s(P'^*, L'^*) \geq U_s(P', L'^*) \tag{18}$$

$$\forall L' \in \mathcal{G}_2, L' \neq L'^* : U_2(P'^*, L'^*) \geq U_2(P'^*, L') \tag{19}$$

Likewise, we get a Nash equilibrium in Game 1 when:

$$\forall P \in \mathcal{G}_1, P \neq P^* : U_1(P^*, L^*) \geq U_1(P^*, L) \tag{20}$$

$$\forall L \in \mathcal{U}, L \neq L^* : U_u(P^*, L^*) \geq U_u(P^*, L) \tag{21}$$

III. Optimizing all three utility functions

In our proposed model, S takes action first by setting the electricity price P'_k per unit and G responds by adjusting his load L'_k. Next, G sets the price P_k followed by users who also accommodate their load L_k to P_k. Thus, we ought to start with Game 2 and then Game 1. Both games are multistage games. So, we will use backward induction to solve them [9].

A. Optimal demand reponse of G to the pricing strategy of S

By taking $P'_k, k \in \{1, 2, \dots, N\}$ as given, we compute the first order derivative of U_g with respect to $L'_k, k \in \{1, 2, \dots, N\}$.

$$\frac{\partial U_g}{\partial L'_k} = -P'_k - \alpha'_k \beta'_k \left(\frac{\partial L'_k}{\partial d'_k}\right)^{\alpha_k - 1} \tag{22}$$

When setting $\frac{\partial U_g}{\partial L'_k} = 0$, we obtain :

$$L'^*_k = d'_k \left(\frac{-P'_k}{\alpha'_k \beta'_k}\right)^{\frac{1}{\alpha'_k - 1}}, k \in \{1, 2, \dots, N\} \tag{23}$$

Next, we need to compute the hessian matrix of U_g. The second order derivative of U_g is :

$$\frac{\partial^2 U_g}{\partial L'_k \partial L'_i} = \begin{cases} 0 & \text{if } k \neq i \\ \alpha'_k \beta'_k (\alpha'_k - 1) \dfrac{{L'_k}^{\alpha'_k - 2}}{{d'_k}^{\alpha'_k - 1}} & \text{if } k = i \end{cases} \tag{24}$$

The off-diagonal elements of the hessian matrix of U_g are all equal to zero and its diagonal elements are all negative since $\alpha_k < 1$ and $\alpha_k \beta_k < 0$. This implies that the solution L'_k that we found is indeed the local maximum.

B. Optimal pricing strategy of S based on the response of G

In the previous sub-section, we obtained the utility grid's optimal demand reponse to the storage company's price. In this section, we will be looking for the storage company's best pricing strategy that maximizes its utility function by replacing L'_k with L'^*_k in the utility function of S.

$$U_s = \sum_{k=1}^{N} \left[P'_k L'^*_k - \phi L'^*_k - d'_k \beta'_k \left(\left(\frac{L'^*_k}{d'_k}\right)^{\alpha'_k} - 1 \right) \right] - f(g') \tag{25}$$

The constraints on the sides of G define also the constraints on the price P'_k, that is:

$$P'_{k,\min} \leq P'_k \leq P'_{k,max} \tag{26}$$

Whereas

$$P'_{k,min} = \max\left(\phi, -\alpha'_k \beta'_k \left(\frac{L'_{k,max}}{d'_k}\right)^{\alpha_k - 1}\right)$$

and

$$P'_{k,\max} = -\alpha'_k \beta'_k \left(\frac{L'_{k,\min}}{d'_k}\right)^{\alpha_k - 1}$$

Thereby, the second optimization problem is:

$$\begin{aligned} \max_{P} \quad & U_s \\ \text{subject to} \quad & P'_{k,min} \leq P'_k \leq P'_{k,max} \quad \phi \leq P'_k \\ & P'_k, \ \forall k \in \{1, 2, \dots, N\} \end{aligned} \tag{27}$$

This problem is non linear with linear constraints, it could be resolved either by using an optimization software. To insure the existence of such optimum, we need to prove the negative definiteness of the hessian matrix which in this situation is parameter dependent. This has been done in [6].

C. Users' optimal demand reponse to the utility company's prices

This section is similar to section III.A. We replace the previously mentioned parameters of Game 2 by those of Game 1. We know that G plays first by setting his selling price per unit P_k and then users regulate their load L_k accordingly. Therefore, since also Game 1 is a multistage game, once again we use backward induction that dictates that we move backwards from L_k to P_k.

Hence, Users optimal demand response to the utility company's prices is found by following the same steps as before. Given that the utility function of users is:

$$U_u = -\sum_{k=1}^{N} \left[P_k L_k + d_k \beta_k \left(\left(\frac{L_k}{d_k}\right)^{\alpha_k} - 1 \right) \right] \tag{28}$$

When setting $\frac{\partial U_u}{\partial L_k} = 0$, we get :

$$L^*_k = d_k \left(\frac{-P_k}{\alpha_k \beta_k}\right)^{\frac{1}{\alpha_k - 1}} \tag{29}$$

Again, the second order derivative is as follows:

$$\frac{\partial^2 U_u}{\partial L_k \partial L_i} = \begin{cases} 0 & \text{if } k \neq i \\ \alpha_k \beta_k (\alpha_k - 1) \dfrac{{L_k}^{\alpha_k - 2}}{{d_k}^{\alpha_k - 1}} & \text{if } k = i \end{cases} \tag{30}$$

Based on our choice of α_k and β_k ($\alpha_k < 1$ and $\alpha_k \beta_k < 0$), we say that $L_k, k \in \{1, 2, \dots, N\}$is the optimal load for users givenP_k.

D. Optimal pricing based on users response

Now, we should find the optimum pricing strategy P^*_k that G must adopt to maximize his utility function with respect to L^*_k. But instead of going through the same demonstrations again, we use power balance between users' demand and G's demand. So, P^*_k is limited by on one hand L^*_k found in Game 2 and on the other hand by L^*_k of Game 1. Though G hopes that the difference between users demand and his own generation does not surpass nor fall behind his own optimal load L'^*_k that:

$$L'^*_k(P'^*_k) = L^*_k(P^*_k) - g_k \tag{31}$$

We can write the following equation:

$$d'_k \left(\frac{-P'^*_k}{\alpha_k \beta_k}\right)^{\frac{1}{\alpha_k - 1}} = d_k \left(\frac{-P^*_k}{\alpha_k \beta_k}\right)^{\frac{1}{\alpha_k - 1}} - g_k \tag{32}$$

By solving this equation we get:

$$P_k = -\alpha_k \beta_k \left(\frac{d'_k \left(\frac{-P'^*_k}{\alpha'_k \beta_k}\right)^{\frac{1}{\alpha_k - 1}} - g_k}{d_k}\right)^{\alpha_k - 1} \tag{33}$$

The interpretation of this formula is that when G is setting his selling priceP^*_k, he also takes in consideration Ss selling price P'^*_k, the nominal load values d_k and d'_k and the generation g_k, $k \in \{1, 2, \ldots, N\}$.

IV. Performance analysis

In this example we will be using wind as the only available source of energy. Nevertheless, this model can still be adjusted to contain different sources or a mix of different renewable sources of energy (RE). We collected data of the daily active power generation and users nominal and actual loads from [10] and [11]. As for the fixed costs of operating and maintaining a renewable power generation plant, it is generally said that they decrease as the size of the project increases [12] and it is not much compared to the costs of producing energy with traditional sources. The parameter $e = \frac{1}{(\alpha_k - 1)}$ is similar to the price elasticity [13].

Since in this example we are collecting data of Ameren Illinois of over 11 000 residential we will be using their elasticity values. n and n' could be considered as the nominal prices corresponding to the nominal demand d and d'. This has been done to simplify our demonstration. We take n and n' to be both 2.5. However, each of these parameters should be considered carefully before choosing appropriate values [14], [15]. Last but not least, we go with $u = 1$ and $u = 1$. For storage owners, [16]–[18] present a cost analysis of different energy storage technologies.

To begin with, in game two, G acts as a client towards S. Fig .3a shows the prices that S must set in order to optimize its utility function while taking in consideration the buyer's reaction G. We notice from Fig.4b that when the price is set too high or too low, the actual load curve happens to fall behind or surpass the nominal demand. This leads to an increase or decrease in the satisfaction function of G (s') and adds up to its objective function. By comparing the actual load curve to the nominal curve, we can clearly see that it's almost constant and flat. In fact, there are no longer huge differences between the maximum and the minimum values, no more big bumps all over the curve. This respects the traditional norms and decisions made upon the application of time of use pricing strategies (TOU) in case of non renewable energy production, when the provider usually adjusts his generation capacities to meet the purchasers' demand and seeks an almost constant level of demand. It is indeed the case, in this scenario S is similar to a traditional producer since he's not providing unconditional quantities all day long based on the desire of G. S will always wish to stick to what he has in store and keep the curve within a specific pattern.

Next in Game 1, Fig. 3a gives an idea about how the prices must be set to keep up with users' demand. And Fig. 4a shows how users react to that price. We see that first, when the price is too high, users lower their loads, therefore their actual load curve stays below the nominal curve. Second when electricity is cheap, they increase their loads, that is why the curve goes above the nominal values. Finally, when the price is just right, the two curves intersect allowing the nominal and the actual values to be equal. It is important to realize that at one point users' actual load curve doesn't exactly achieve the goals of Time of Use pricing because the curve isn't flattened as in the previous Fig. 4b. It is not flat nor follow a specific pattern. In fact, if this was about non-renewable resources it would be completely wrong. However, bearing in mind that in case of renewable resources (RE), the utility company's main purpose is to have users use up all the daily generation. Even if the load curve stays bumpy all day long, it won't matter as long as it copies the generation pattern.

To conclude, Fig.5 gives us an idea on how all three curves ought to look like. It demonstrates how users' actual load curve is duplicating the wind curve and that the generation company's load curve is flattened. All of this has been done throught Time Of Use pricing strategies of both S and G.

V. Conclusion

In this paper, we have demonstrated how to achieve an optimal time of use pricing strategy of renewable energy (RE) with externalized storage and based on a model of three player games. We first defined and customized each players' objective function that gets him a better payoff. Next, we proposed a two games three players situation where the utility company G acts as a supplier of renewable energy (RE) towards users in the first game and as a mere user to the storage company S in the second game. Therefore, we constructed two identical games with the same objectives but different parameters. The results of our simulations supports our suggested idea. In fact, in game one, users' reactions to the prices of G copies the pattern of the generation curve, which means that they almost consume it all, while not having to pay much since the load curve itself is a result of an optimization problem. As for Game 2, the generation company's load curve that corresponds to the difference between their supply and users' demand is flattened and stayed within a constant level.

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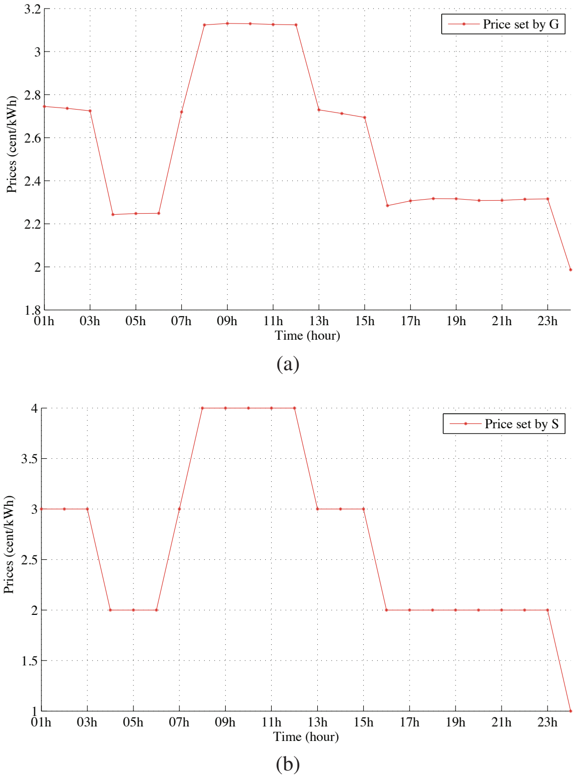

Fig. 3: TOU pricing per kWh for both (a) G and (b) S

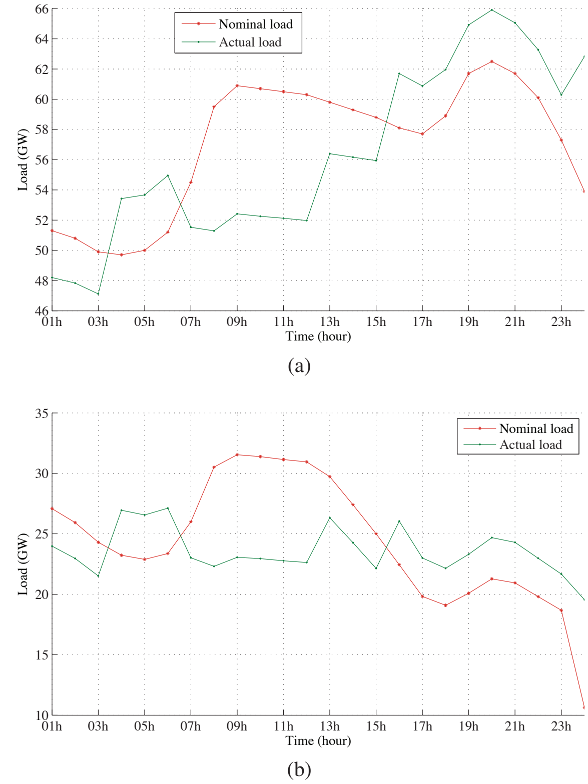

Fig. 4: Comparing the responses of U (a) and G (b) towards the TOU strategies with the nominal values

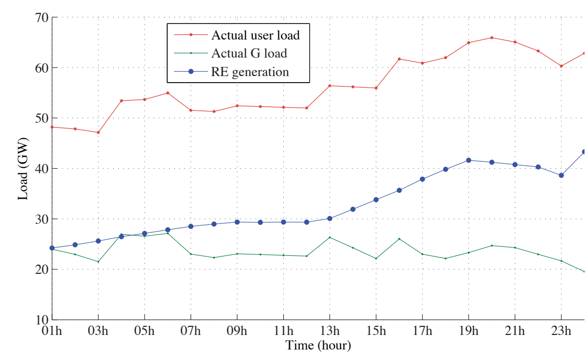

Fig. 5: Comparing the load curves of G and U and the renewable energy (RE) generation curve

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