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A Peak-Shaving-Oriented Incentive Mechanism for Smart Grids

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***Abstract* -** Prosumers play a crucial role in smart grids, especially within local energy communities (LECs), since they can both consume and produce energy. When peer-to-peer (P2P) energy trading is available, prosumers can exchange their produced energy with each other: if done properly, this may lead to better energy self-consumption throughout the grid, resulting in reduced transmission losses, lower energy costs, and decreased wear and tear to the grid. Previous work on this topic led to a mechanism capable of obtaining several such goals, like preventing intentional energy production curtailment, disincentivizing simultaneous energy consumption that may lead to congestions, encouraging users to consume their own produced energy as much as possible, and ensuring that even if users initially create schedules with a selfish approach, they will ultimately converge upon a configuration that garners mutual agreement. However, this mechanism has not yet been analyzed from the perspective of peak shaving. Therefore, this paper aims to cover this shortcoming. Our objective in this work is to create a new mechanism that, under certain conditions, guarantees the achievement of optimal peak shaving. We will use it as a baseline to compare the existing mechanisms and understand under which conditions it leads to peak shaving. We performed simulations on a dataset from a grid in Cardiff, UK, and the results show that the existing mechanisms achieve optimal peak shaving both if the users act selfishly, and if they are allowed to form coalitions among themselves.

***Keywords*:** Energy flexibility, Game theory, Peak shaving, Local energy community, Peer-to-peer energy trading

1. Introduction

In the last decades, the topic of exploiting renewable energy sources has become of utmost importance. Many measures have been designed to encourage grid users to join production and therefore become *prosumers*. One effective approach to attain this goal is by implementing financial incentives, such as compensating for the generated energy or providing free energy at a later time. However, the uncertainty carried by energy production brings new problems to face [1], such as the need to align consumption to production. For this, the capability of changing energy loads in time or amount, called *energy flexibility*, is of paramount importance. Several mechanisms exploit flexibility by proposing payment systems that encourage users to consume energy when the production is high [2,3,4,5]. Specifically, the NRG-X-Change [2] mechanism influences user behavior by introducing a selling and a buying function for determining energy prices. Several studies have built on this mechanism, improving its performance and reducing its shortcomings [6,7]. Specifically, a game theory approach has been taken to study how the mechanism adapts to users behaving selfishly or forming small coalitions [8]. Several objectives have been taken into account for those improvements, such as reducing production curtailment and improving self-consumption. However, none of the previous studies has considered peak shaving [9] among those objectives. Hence, the objective of this paper is to advance the current state of the art by constructing an additional buying function that ensures the attainment of peak shaving. The paper also aims to provide a comparative analysis of the performance of existing mechanisms concerning the newly proposed approach.

2. Preliminaries

In this section, we show the state of the art and the necessary premises for our work. Our game formulation has been inspired by [10,11].

2.1. Game definition

A game is defined as a set $G = (U, S, Q)$. Here, $U = (U_1, \ldots, U_n)$ is the set of players, and $S = (S_1, \ldots, S_n)$ are the strategies, and $q = (q_1, \ldots, q_n)$ the payoff functions. For each k, S_k and q_k are the set of strategies of U_k and the payoff function of U_k, respectively. In the context of a local grid, we define a game as follows: the players are the grid users, the strategies are their possible energy consumption/production profiles, and the payoff functions are the difference between the profits they make by selling energy, and the cost they pay for buying energy. In this work, we will assume that grid users cannot change their energy production, and their energy consumption has a fixed part and a shiftable part, i.e., a part that can be shifted over time. We also assume that the users can form coalitions: in this case, the players of the game are the coalitions, the strategies for every single coalition are the possible combined energy profiles of the users belonging to the coalition, and the payoff function for each coalition is the sum of the payoff functions of the users in the coalition.

2.2. Incentive mechanisms

The payoff functions described in the previous subsection depend on the cost of energy consumption and the reward for energy production. Those two quantities often are key points in defining incentive mechanisms: this holds for the NRG-X-Change mechanism [2], where the operational dynamics predominantly rely on two key functions: g, describing the reward for selling energy, and h, describing the cost for buying energy. For each user, the payoff function in the previous subsection is the difference between the selling and the buying function. In the original mechanism, those functions were defined as

$$g(x) = x \cdot \frac{q}{e^{\frac{(t_p - t_c)^2}{a}}} \; ; \; h(y) = y \cdot \frac{r \cdot t_c}{t_c + t_p} \tag{1}$$

here, x and y are the amounts of produced and consumed energy respectively, t_p and t_c are the total amount of energy produced and consumed across the grid respectively, and a, q and r are parameters. The work performed in [6] has improved those functions to discourage production curtailment and encourage energy self-consumption from prosumers. The study carried out in [7] further improved them for the games to guarantee a Nash Equilibrium (NE), i.e., a state where no player would want to change his/her strategy. These are the functions that have been proposed:

$$g_1(x) = k_1 \cdot ln(\frac{x + Z + a_1}{Z + a_1}) \; ; \; h_1(y) = k_2 \cdot ((y - Z + a_2)^n - (a_2 - Z)^n) \tag{2}$$

$$g_2(x) = k_1 \cdot ((x - Z + a_2)^{\frac{1}{n}} - (a_2 - Z)^{\frac{1}{n}}) \; ; \; h_2(y) = k_2 \cdot ((Z + a_2)^{\frac{1}{n}} - (Z + a_2 - y)^{\frac{1}{n}}) \tag{3}$$

here, g_i and h_i are the selling and buying functions respectively, Z is the net amount of energy produced and consumed across the grid outside of the considered user, and k_i, a_i and n are parameters.

2.3. Game mechanics

The game described in Section 2.1 works as follows. For simplicity, we assume that we have N users $U_i, \dots, U_N$, and each of them has one shiftable load. First, the user U_1 calculates the value that the payoff function would have with each possible allocation of the shiftable load and moves it to its most profitable allocation. Then, the user U_2 does the same, and this is done sequentially by all the users, extending until U_N. This is called an *iteration*. Then, we verify whether the present load allocations match those from a previous iteration. If there is a disparity, the game proceeds, initiating a new iteration once again, starting with U_1. If the iteration equal to the last one is the second-last, it means that the game reached an NE, and so the game ends. If the iteration equal to the last one is not the second-last, it means that the game has reached a loop, and the allocations will cycle endlessly at each iteration. This means that the game will never reach an NE, and so we terminate it.

3. Proposed function

To verify whether the previously defined functions perform peak shaving, we have to compare them with a baseline that guarantees that the user behavior will lead to obtaining peak shaving. For this purpose, in the context of the mechanism described above, we propose the following buying function:

$$h_{new}(y) = k_1 \cdot \frac{y}{t_c} \cdot (\frac{y + Z + k_2}{k_2})^2 \tag{4}$$

with the same notation from earlier. Note that t_c depends on y. We prove that, if the buying function is h_{new}, the cooperative game with only one coalition formed by all the users leads to peak shaving. More precisely:

Proposition: At a given time t, call $ec_t = t_c - t_p$. In the game described in Section 2.3, if the buying function is h_{new} and all the users form one single coalition, then the users will shift their loads to minimize the highest values for ec_t through the day, and maximize the lowest values for ec_t through the day.

Proof: By hypothesis, the price for consumption for a single user at a certain time is $k_1 \cdot \frac{y}{t_c} \cdot (\frac{y+Z+k_2}{k_2})^2$. Now, the optimization goal is to maximize the profit; as we are looking at the cost function, this means minimizing the costs inside the coalition. We are considering the case where all the users belong to the same coalition (which is called *grand coalition*). Therefore, by summing costs across the grid for all users, the function to minimize becomes

$$\sum_{i=1}^{N} k_1 \cdot \frac{y_i}{t_c} \cdot (\frac{ec_t + k_2}{k_2})^2 = k_1 \cdot \frac{\sum_{i=1}^{N} y_i}{t_c} \cdot (\frac{ec_t}{k_2} + 1)^2 \tag{5}$$

Now, since t_c is the sum of all y_i, the second fraction cancels out, and the expression becomes

$$k_1 \cdot (\frac{ec_t}{k_2} + 1)^2 \tag{6}$$

Therefore, our objective becomes to minimize the cost through the day, expressed by

$$\sum_{t=1}^{T} k_1 \cdot (\frac{ec_t}{k_2} + 1)^2 \tag{7}$$

Under the constraint $\sum_{t=1}^{T} ec_t = TC$ for some number TC that represents the global net energy consumption through the day. It is easy to show that the expression (7) reaches its minimum when all its terms have the same value, for example by using the inequality between quadratic and arithmetic means for the terms in the expression (6). Therefore, since the shiftable loads will move in a way that minimizes expression (7), they will be moved in a way that decreases the highest values for ec_t and increases the lowest values for c_t , which is what we wanted to prove.

4. Simulations

As our purpose is to show how well the existing mechanisms (i.e., the ones defined by the functions g_1, h_1 and g_2, h_2) perform in terms of peak shaving, we ran simulations to measure that. Data for users, flexible loads, energy consumption, and production comes from a grid in Cardiff, UK. The grid contains 184 users, 40 of which can produce energy [12].

The simulations have been run as follows. First, we chose a grid to simulate: this is done by randomly choosing N users in the grid, with the constraint that M of them are prosumers. In our case, we chose grids of size 40, with 20 prosumers each. After this, the game is performed as described in Section 2.3, and the results are collected. The game is performed within different cooperation scenarios, where the users either operate selfishly or are bound to form coalitions of predetermined size with other users.

Table 1: Peak energy consumption across the grid, in kWh.

Size	g_1, h_1	g_2, h_2	g_2, h_{new}
1	75.06	75.06	106.16
5	75.06	75.06	103.20
10	75.06	75.06	102.79
20	75.06	75.06	92.74
40	75.06	75.06	75.06

We report the results for the grid peak in Table 1. The rows describe the size of the coalitions, while the columns describe the pairs of functions used for selling and buying energy. The numbers are expressed in kWh and refer to the grid peak. We simulated 5 different grids, excluded the highest and the lowest peaks, and averaged the remaining 3. The pair g_2, h_{new} is guaranteed to achieve optimal peak shaving for coalitions of size 40. The existing mechanisms, described by the function pairs g_1, h_1 and g_2, h_2, obtain optimal peak shaving no matter the coalition size for both choices of the functions.

5. Conclusion

The incentive mechanism that has been initially introduced in [6] and refined in subsequent works [7,8], encourages grid users to shift their loads in a way that improves self-consumption, prevents unnecessary production curtailment and congestions, and takes into account the possibility for users to behave selfishly or form coalitions. This paper aims to analyze the performance of this mechanism regarding peak shaving. To achieve this goal, we created a function for buying energy with the specific aim of maximizing peak shaving when users unite as the grand coalition, and compared the results with the existing mechanisms. The simulations we performed reveal that the existing mechanisms achieve optimal peak shaving outcomes, both when coalition formation is allowed and when it is not allowed, as the results are the same as the mechanism proposed in this paper with the grand coalition. Future research will focus on further refining this mechanism, exploring additional objectives, and refining the game theory formulation. Additionally, we will delve into multi-objective optimization, considering factors such as user comfort and CO2 emissions.

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