Efficient Incentive-Driven Consumption Curtailment Mechanisms in Nega-Watt Markets

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Abstract—In this paper we model and analyze Nega-Watt markets, in which a utility operator wishes to curtail some amount of demand load during peak hours, in order to save energy generation costs. The problem for the operator is to select the consumers and the portions of demand load to curtail from each consumer. The major novelty in this setup stems from the arising uncertainty due to consumer non-engagement: even if an a priori agreement is reached between the operator and a consumer about the load to curtail, it is entirely up to the consumer to consume the load or not. The second element that makes the problem different from other markets is the incentive design per se. The operator needs to employ a two-branch incentive, that is, provide consumers with a reward if they actually curtail the load and charge them a fine if they do not. We study various instances of operator-consumers interaction such as bilateral negotiation through non-cooperative games and Stackelberg-game-like interactions. Our results reveal interesting insights about the impact of the arising consumer competition and the consumer-operator interaction on the expected benefits for the operator and the consumers.

I. INTRODUCTION

In recent years, the holy grail of sustainable and reliable power distribution systems through a smart power grid has begun to materialize. On the one hand, demand-response (DR) methods help in peak-load alleviation through controlling consumer load, either directly (e.g. through intelligent scheduling of power demands or use of energy storage facilities) or indirectly (e.g. through dynamic, time-varying pricing schemes).

On the other hand, advanced market-driven methods coordinate the flow of energy from wholesale markets at the power generation level, up to the distribution level and the end-consumer. In a wholesale energy market, wholesale prices are time-varying and are determined by the marginal cost of energy generation, depending on the type or the number of generation facilities that need to be activated. Utility operators purchase energy from the wholesale market at time-varying prices and resell it to consumers at fixed tariffs. These methods promise benefits for consumers (e.g. in the form of electricity bill savings through incentive payments) and for operators (e.g. lower wholesale prices), and they aid in better control of the system, especially in peak times, where the marginal cost of power generation is much larger than the retail price.

In this paper, we study and analyze a Nega-Watt market, in which a utility operator wishes to curtail some amount of demand load during peak hours. A Nega-Watt is defined as a unit of energy that is curtailed-not consumed. Nega-Watt markets belong in the class of DR methods but they have started appearing in the wholesale market as well. The players in that market are the energy generation company and large-scale consumers. The latter trade Nega-Watts (i.e. amounts of energy saved) in a similar manner as supply companies do with generated MWatts. Towards this direction, in 2011 the Federal Energy Regulatory Commission (FERC) updated a regulation according to which the Nega-Watts incurred by reducing electricity use may have the same market prices as real MWatts of generated electricity. Some real-life examples of Nega-Watt markets are the New England Independent System Operator (NE ISO), [1] the New York ISO (NYISO) [2] and the Pennsylvania-Jersey-Maryland (PJM) [3] market.

In our model, an operator is assumed to buy energy at the wholesale market at price $C$ per unit of energy, where $C$ is equal to the marginal generation cost. Next, it resells it to consumers at fixed price $p$. In periods of high demand, there holds $C > p$. Assume that the total demand load for such a period is $d$. Then the net loss of the operator is $(C - p)d$, and the operator has to resort to DR methods to reduce this load. We assume that the operator wishes to select a consumer to curtail a particular volume $\Delta d$ of load. This is considered as fixed, and thus will be referred to as the ‘unit’ of load to be curtailed. The benefits of this load curtailment to the operator are two-fold: (i) The amount of demand load to be bought becomes $d - \Delta d$ and the loss becomes lower, i.e. equal to $(C - p)(d - \Delta d)$. This is important in peak-load times where the marginal cost $C$ is high. (ii) If the consumer is a large one, e.g. an industry, and the unit of load curtailment $\Delta d$ is large, then this load reduction could also lead to a reduction of the marginal cost to a value $C' < C$. This would apply if the reduced demand can be supplied in its entirety by less costly energy generation facilities, all with lower marginal cost that does not exceed $C'$. Then, the losses for the operator are reduced to $(C' - p)(d - \Delta d)$. Without loss of generality, we henceforth set $\Delta d = 1$MWh, but we omit the units. (Note: The terms consumer and user are used with the same meaning.)

Perhaps the most important challenge in such a setup is the
uncertainty about ultimate load curtailment stemming from end-consumer non-engagement. Even if an a priori agreement is reached between the operator and a user about the load to curtail, it is entirely up to the user to consume the load or not. Thus, the consumer may not conform to this agreement and consume the load that was deemed to be curtailed. Various factors may account for that, such as necessity to ultimately consume the load, inadequate familiarization with the process or other subjective factors. We capture this uncertainty for the user through the definition of a conformance probability, that is, a probability of actually performing load reduction. For simplicity we assume that the load reductions is fully achieved by the consumer, or that it is not achieved at all.

The uncertainty about load curtailment gives a novel twist to the problem. Competing consumers offer their Nega-Watt procurement prospect, and a selection needs to be made out of participating users. Even if the winner is selected, it cannot actually commit to deliver the promised good (curtailed load). This also calls for the design of novel incentive mechanisms that shape consumer participation and conformance to load curtailment. The operator needs to employ a two-branch incentive, that is, provide consumers with a reward if they actually curtail the load and charge them a fine if they do not.

In this work, we model and study various modes of interaction between the operator and consumers in a Nega-Watt market. The contributions of our work are as follows:

- We introduce the uncertainty in load curtailment through the definition of a conformance probability that depends on consumer valuation and on the provisioned incentives. This probability is inserted in appropriately defined utility functions for the consumers and the operator which capture the expected benefit from the curtailment.
- We incorporate incentive mechanisms in the utility functions in the form of rewards and fines for consumers, depending on whether they perform load reduction or not.
- We study different models of interaction between the operator and the consumers in Nega-Watt markets, such as: (i) bilateral negotiation between one operator and one user aiming at characterizing the conflict of interest between the two entities, (ii) Stackelberg game interaction with the operator as leader and the user as follower, that captures instances in which the operator drives the market.
- We extend these models to multiple users and the inherent competition among them to be selected for load curtailment.
- We analyze the models above and derive interesting intuitions and guidelines related to the competition among consumers and between consumers and the operator, and its impact on expected derived utility for involved entities. These guidelines also shed light into market design.

A. Related Work

DR methods use two types of incentives to motivate participation in electricity markets: price-based and reward-based. The former refer to dynamic retail pricing schemes that guide consumers to reduce their demand when prices are high, thus reducing their electricity bill. The works [4] and [5] present incentive-based consumption scheduling problems. Reward-based incentives on the other hand give financial rewards to users for curtailing their load during peak-demand [6], [7]. These works propose mechanisms where users submit their bids or supply functions, and then the operator decides on a market-clearing price for maximizing total market benefit. A hierarchical market model for smart grid is proposed in [8], where the aggregators act as intermediaries between the operator and the home users. Aggregators sell DR services to the operator and provide compensation to end-users to modify their consumption. In [9] the authors propose a Stackelberg game between utility companies and end-users to maximize the revenue of each utility company and each user payoff.

Uncertainty in resource supply has been studied in a general framework in [10]. Two suppliers are considered, an expensive and reliable one, and a cheaper but unreliable in terms of producing the good. The buyer decision is to allocate appropriate amounts of goods to purchase from each supplier, after they specify prices for different portions of the purchases allocated to them. Uncertainty is modeled with a probability of carrying out the order. Uncertainty in DR has been mainly studied in terms of user behavior in domestic environments, in response to real-time prices and weather conditions [11]. Contrary to the above, our work addresses uncertainty at the demand-side, which is heavily dependent on the user itself through the valuation it places on the load and on the incentives provided. The innovative aspect of our work is that it brings together all the above in the user and operator utility functions.

DR programs are already being implemented in energy markets such as NEISO, NYISO and PJM, and in several cases therein the operator imposes fines to consumers if they fail to fulfill the load reduction. We take a step ahead and introduce a model of operator-consumer interaction assuming rational, self-interested parties. The various modes of interaction proposed aim to bring uncertainty in the foreground and extract interesting guidelines for designing a Nega-Watt market.

The rest of the paper is organized as follows. In section II we present the model and our assumptions, and in section III we develop the game-theoretic market mechanisms. In section IV we numerically evaluate these mechanisms, and conclude the paper in section V.

II. THE MODEL

We consider one operator and a set \( N \) of \( N \) consumers that participate in the market, and we fix attention to a specific time instance when the operator wishes to curtail one unit of load. The total demand load is assumed to be known, and consumers are assumed to inform the operator in advance (e.g. from the previous day) about their demand load throughout the day. The unit of load to be curtailed is fixed and known in advance, i.e. it can be a given percentage of the total demand load. In order to be close to real-life scenarios, the unit of load to be curtailed is large, e.g. of the order of 1 or few MWatts. Without loss of generality we assume that the operator will select one user to curtail the load from out of the \( N \) ones that declared they are willing do so. This implies that the plausible users

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to participate are industries or other types of big consumers. Note however that the approach does not place limitations on the types of users in general. For example, multiple smaller-scale consumers could also be selected, perhaps through a proxy aggregator entity that would aggregate the small-load curtailments of users to the required unit of load to curtail.

In a Nega-Watt market, the operator needs to convince consumers to curtail their load. After consumers declare their interest, the operator selects one to recruit for the curtailment. However, although an a priori agreement is reached between the operator and a consumer about the load to curtail, it is entirely up to the consumer to consume the load or not.

Incentives: The operator uses a two-branch incentive, depending on whether the selected user curtails the load or not. If the user reduces its load, the operator provides a reward \( r \), while if the user does not reduce the load, it pays a fine \( f \). The values of \( r, f \) are agreed in advance before curtailment takes place. The uncertainty on whether the consumer will reduce the load or not is captured through a consumer conformance probability \( s_i(\cdot) \), to be defined in sequel.

Consumer: Each consumer \( i \) is characterized by a positive parameter \( v_i \) that models its valuation for the unit of load under tentative curtailment. The valuation reflects the importance of that unit of load for the consumer, and it may depend on various factors such as the consumer profile or time of day. A selected user \( i \) that ultimately curtails its load receives a reward \( r_i \); otherwise it pays a fine \( f_i \). In the latter case, the operator also has to pay the electricity bill for the load, and let \( p \) be the fixed-tariff retail price for that unit of load. Further, in that case, the consumer still enjoys valuation \( v_i \). It is reasonably assumed that this valuation \( v_i \) exceeds the retail price \( p \), and thus the user has a positive net benefit by consuming electricity. Both quantities can be taken of the same order of magnitude.

Conformance probability: The conformance probability \( s_i(\cdot) \) for user \( i \) is a function of valuation \( v_i \), reward \( r_i \) and fine \( f_i \). Clearly, for larger values of \( r_i \) and \( f_i \), the user strives more to achieve the curtailment. Also, the user is more likely to perform the curtailment if the load is of low importance. Hence, \( s_i(\cdot) \) is increasing in \( r_i \), \( f_i \) and decreasing in \( v_i \).

Also, as the value of reward or fine increases, a unit of additional increase in reward or fine is expected to have diminishing impact on the conformance probability. This essentially dictates that \( s_i(\cdot) \) be a concave function of \( r_i \) and \( f_i \).

Our model and subsequent analysis work in general for functions \( s_i(\cdot) \) with the properties above. However, in order to perform the analysis in the sequel, we select:

\[
s_i(r_i, f_i) = \frac{r_i}{2(r_i + \Delta r \cdot \frac{v_i}{p})} + \frac{f_i}{2(f_i + \Delta r \cdot \frac{v_i}{p})}.
\]  

Recall that \( p \) is the price per MWh, and thus it will be seen that it is of the order of 100$; see Section IV. Thus \( v \) is also of the order of 100$, and reasonable values of \( r \) and \( f \) will in general be of the same order. We select a small value for the sensitivity factor \( \Delta r \), so that it does not dominate the denominator. In particular, we take \( \Delta r = 10 \$. Implicitly we assume that \( r \) and \( f \) are also expressed in Dollars.

The expected net utility of user \( i \), \( U_i(\cdot) \) is,

\[
U_i(r_i, f_i) = r_i s_i(r_i, f_i) + (v_i - f_i - p)(1 - s_i(r_i, f_i)) - p/2.
\]  

The consumer is willing to participate in the market selection process about load curtailment if the expected benefit exceeds the one it would obtain if it did not participate. Thus, the participation constraint of the user is \( U_i(r_i, f_i) \geq v_i - p \).

Operator: Assume that the total demand is \( d \). If the user does not perform the curtailment, the operator needs to buy load \( d \) at a wholesale electricity price \( C \) and resell it to users at fixed retail price \( p \). The operator receives the fine \( f_i \) for user non-conformance in load reduction. On the other hand, if the user performs load curtailment, the operator needs to buy load \( d - \Delta d = d - 1 \) at a wholesale electricity price \( C' \leq C \), while it offers reward \( r_i \) to the consumer. The expected payment by the operator to others, i.e. supply-side resources (generators) and the demand-side resource (user), if user \( i \) is selected is,

\[
L_{op}(r_i, f_i) = [r_i + (C' - p)(d - 1)]s_i(r_i, f_i) + [(C - p)d - f_i](1 - s_i(r_i, f_i))
\]  

The operator benefits from user recruitment for load curtailment if its expected payment is less or equal to the one it would pay if users did not participate in the market. The participation constraint of the operator is thus \( L_{op}(r_i, f_i) \leq (C - p)d \). The participation constraints for the operator and the user define a feasible region for \((r_i, f_i)\) which we denote by \( R(r_i, f_i) \).

Remark I: The operator is assumed to know valuations of users. This is realistic for large users (e.g. industries) with known consumption profiles, but it could also be assumed in other cases as well based on prior interaction between the operator and users. This assumption is an essential first step towards understanding structural properties of the problem and the outcomes of the interaction. Also, when expression (1) is employed in (2)-(3), meaningful monotonicity properties apply, i.e. the net benefit of user \( i \) is increasing in \( r \) and the payment by the operator is decreasing in \( f \) respectively.

III. FULL-INFORMATION GAME THEORETIC MARKET MECHANISMS

In this section we study different possible game-theoretic modes of interaction between the operator and the consumers. Our aim is through comparison of these mechanisms to identify valuable intuitions about the market and the impact of competition on expected utilities of consumers and expected payment by the operator. All entities involved are rational, self-interested ones that aim at optimizing their expected utility or payment. In order to better understand the interaction, we begin with the case of one large-scale consumer interacting with the operator, and then we extend that to the case of \( N \) interacting consumers, out of which one is to be selected by the operator for tentative load curtailment.

A. One consumer and one operator

Consider that one consumer participates in the interaction with the operator. This situation may arise if other consumers fail to participate because of high valuations or other reasons,
or in case the operator chooses to interact in a point-to-point fashion with selected consumers, e.g. large industrial ones. We consider two modes of interaction: (i) a Bilateral negotiation between the consumer and the operator, and (ii) a leader-follower Stackelberg game, where the operator acts as leader and the consumer acts as follower. In this subsection, we drop index $i$ from the notations.

1) Iterative bilateral negotiation: In bilateral negotiation, we assume that the two entities, the consumer and the operator, have equal negotiation power. The entities negotiate over the values of the reward and the fine. The negotiation is carried out in rounds. At each round, the operator suggests an amount of reward in case of load curtailment, and the user responds by agreeing with the proposed reward and by suggesting an amount of fine in case of non-conformance to load curtailment. At each round, each entity makes the suggestion in a best-response fashion, i.e. so that it optimizes its expected net utility or payment, given the suggestion of the other entity.

Best-response strategies can be computed by applying KKT first- and second-order optimality conditions to equations (2) and (3). The best-response functions are as follows. For a fixed $r$ from the operator, the best-response function for the consumer is $F_u(r) = \arg \max_f U(r, f)$. For a fixed $f$ from the user, the best-response function of the operator is $L_{op}(f) = \arg \min_r L_{op}(r, f)$. Best-response strategies characterize the iterative bilateral negotiation mode of interaction. The negotiation process amounts to a sequence of best-responses applied interchangeably by the operator and the consumer.

The best-response mode of interaction that describes the negotiation mechanism can be summarized as follows.

- **STEP 0:** Initialization. Set iteration count $n = 0$. The operator starts the negotiation by choosing an arbitrary amount of reward $r^{(0)}$. Go to Step 3.
- **STEP 1:** Consumer responds with best-response fine $f^{(n)} = \arg \max_f U(r^{(n-1)}, f)$.
- **STEP 2:** Operator responds with best-response reward $r^{(n)} = \arg \min_r L_{op}(r, f^{(n)})$
- **STEP 3:** $n \leftarrow n+1$. If $|r^{(n)} - r^{(n-1)}| < \varepsilon$, STOP. Otherwise go to Step 1.

Here $\varepsilon$ is a small number in the termination condition to signify convergence. By using Brower’s theorem, it can be shown that this sequence of best-responses above has a fixed point $(r^*, f^*)$ to which it converges. This point is the Nash Equilibrium point of the negotiation, since none of the entities can further improve its net utility (or payment) by changing its strategy, while the other player keeps its strategy unchanged.

Remark II: In this work we abide to the rule that the user suggests the amount of fine and the operator responds with the amount of reward. Having instead the user computing the reward and the operator responding with the fine would lead to a situation where in each iteration the expected payment of the operator is increasing in $f$ and the net utility of the consumer is increasing in $r$, and therefore convergence of the best-response iterations cannot be achieved (see Remark I).

2) Stackelberg Leader-Follower Game: We consider now that the operator acts as leader in the market. This gives rise to an one-shot Stackelberg game, with the consumer acting as follower. The operator first offers the reward and the consumer responds by declaring the fine he is willing to pay in case of non-conformance. The game is solved by backward induction. The operator considers a priori the best-response of the consumer in terms of fine (i.e. the fine that maximizes the consumer net utility) for a given $r$. Then, the operator picks the value of reward that minimizes its expected payment, predicting the anticipated response of consumer. The latter observes this reward, and in equilibrium it picks the fine as a response. The operator solves the following problem:

$$\min_r L_{op}(r, F_u(r))$$
subject to:
$$U(r, F_u(r)) \geq v - p, \text{ and } L_{op}(r, F_u(r)) \leq (C - p)d$$

B. N consumers and an operator

We assume that $N$ consumers offer to do the load reduction, but only one of them will be selected. We also assume that the operator knows the valuations of users and that they are truthful in declaring them. We study two market mechanisms: (i) $N$ leader-follower Stackelberg games where users are not aware of the existence of others (extension of case in III-A2 to $N$ users), (ii) a Stackelberg game where the operator announces a reward, and users respond each with a different fine while being aware of the competition among them.

1) $N$ separate Stackelberg games: We assume that $N$ consumers offer to do the load reduction without being aware of the competition. The operator runs a separate one-shot Stackelberg game with each one of them. The operator announces a different reward $r_i$ to each consumer $i$ through predicting its anticipated best-response, $F_u(r_i)$. The operator selects the user $j$ so that its expected payment is minimized. For each user $j$, the operator solves a problem similar to (4) with $r_j$ as variable. It then chooses user $r^* = \arg \min \min_{r_j} L_{op}(r_j^*, F_u(r_j^*))$, where $(r_j^*, f_j^*)$ is the Stackelberg equilibrium point of the game between the operator and user $j$.

2) One Leader-$N$-Followers Stackelberg game with uniform reward: In this one-shot Stackelberg game, the operator acts as leader and announces a reward which is identical for all users (followers). Given this reward, users interact in a game-theoretic fashion among themselves and compete by making offers of fines to the operator. Assume that for a given $r$, $F^*(r) = (f_1^*(r), \ldots, f_N^*(r))$ is the Nash equilibrium point of this game-theoretic interaction of users, and that the operator selects the user $j$ whose response $f_j^*(r)$ minimizes operator expected payment. In fact, due to monotonicity, the operator’s selects the user $j$ proposing the highest fine $f_j^*(r)$. The operator considers a priori the equilibrium outcome of the subgame and selects the value of reward $r$ that minimizes its expected payment. The operator optimization problem is,

$$\min_r L_{op}(r, \max_j \{f_j^*(r)\}) \text{ s.t. } L_{op}(r, f_j^*(r)) \leq (C - p)d$$

Sub-game among consumers. The best-response strategy of each consumer to that of others is as follows. For given $r$, each
consumer computes a fine to declare so as to maximize its net utility subject to being selected for curtailment, i.e. subject to being ranked first by the operator in terms of incurred expected payment by the operator. The sub-game between consumers evolves in rounds. At each round $n$, consumer $i$ sees the fines announced by others and solves the optimization problem:

$$\max_{f_i} U_i(r, f_i)$$

s.t. $L_{op}(r, f_i) \leq \min_{j \neq i} L_{op}(r, f_j^{(n-1)}), U_i(r, f_i) \geq v_i - p$  \hspace{1cm} (6)

Recall that, for a fixed reward $r$, the operator expected payment decreases as the value of fine increases. Thus, the winner of the sub-game is the user that offers the highest fine.

IV. NUMERICAL EVALUATION

In order to evaluate and compare the performance of the mechanisms introduced, we consider meaningful cases that wholesale market prices exceed by far the retail ones and take into account data from the PJM market [12] and the electricity sector in Finland [13]. We assume that $C' = C$, i.e. load curtailment does not lead to reduction of the wholesale price. Recall that the curtailed load $\Delta L = 1$MWh. To lower complexity and without loss of generality, we define as operator expected profit the quantity below and work with it in sequel.

$$P_{op}(r, f) = (C - p)d - L_{op}(r, f) \geq 0 \implies$$

$$P_{op}(r, f) = (C - p) - rs(r, f) - (C - p - f)(1 - s(r, f)) \geq 0$$

We consider customers whose retail rate is 100$/MWh and wholesale prices in the range of [300$/MWh, 1000$/MWh]. The other parameters of the model, $r$, $f$ and $v$ are also measured in $$/MWh. In the sequel we omit the various units.

A. One consumer and the operator

First, we assume the case of one consumer interacting with the operator. For figures 1-3 we assume wholesale electricity price $C = 1000$. Figure 1 shows the convergence of the iterative negotiation process between the consumer and an operator for consumer valuation $v = 150$.

In figure 2 we depict the values of the reward and the fine at the end of the Stackelberg game as a function of user valuation. We observe that both the reward and the fine increase as the user valuation increases, as expected. However, the reward needs to be increased by the operator with a much higher rate (slope) than the fine by the consumer. As the user valuation increases (which means that the consumption of that unit of load is more important), the consumer is less confident about ultimately curtailing the load. Thus, it hesitates to increase substantially its penalty offer.

In figure 3 we plot the expected profit of the operator and the expected utility of the consumer as function of user valuation. We see that the expected profit of the operator decreases as the valuation of user increases. This is because the operator needs to motivate the consumer with a higher reward to reduce the load without achieving a commensurate increment in fine (see Fig. 2). On the other hand, the two-branch incentive mechanism seems to favor the consumer and increases its expected net benefit as its valuation increases.

Table I shows the impact of different wholesale prices on the outcomes of the Stackelberg game. Higher wholesale electricity prices lead to higher expected profit for the operator and higher expected net benefit for the consumer.

In Table II we compare the Stackelberg game and bilateral negotiation cases. It is shown that the Stackelberg game results in higher expected utility for the user and higher expected profit for the operator than the bilateral negotiation. Also, at Stackelberg game equilibrium, we observe a higher user conformance probability. Notice that at the Stackelberg equilibrium, for $v = 100$, the conformance probability is about 5% larger for $v = 100$ and 15% larger for $v = 150$ than the conformance probability at the end of the bilateral negotiation. This is because at the bilateral negotiation, the entities compete with each other and limit each other in their myopic best-response strategies, which leads both of them to a less efficient outcome. On the other hand, in the Stackelberg-game interaction, the operator predicts the strategy of the user, it perceives the importance of appropriate incentives and offers a relatively high reward, which however leads the game to a more beneficial equilibrium point for both entities.

B. $N$ consumers and the operator

We consider that $N = 20$ consumers offer to reduce the load, with valuations $v_i \in [150, 400]$. We ran $N$ separate one-operator-one-consumer Stackelberg games for $C = 1000$ and found that consumer $j^* = \arg \min_i v_i$, is the one that
maximizes the operator expected profit and thus it is the one selected for load reduction. Also, we observed that consumer \( j \) is the user with higher conformance probability. The outcomes at equilibrium are: \( v_j = 150 \), \( r^*_j = 135.04 \), \( f^*_j = 87.517 \), \( s^*_j = 0.8769 \), \( P^*_j = 681.5 \) and \( U^*_j = 113.8 \).

Table III presents the outcomes of the Leader-N-followers Stackelberg game. Again, the selected consumer is \( j^* = \arg \min \{ v_i \} \). Here we wish to see the impact of the competition of consumers on the outcomes of the game. We have fixed the user with the smallest valuation, \( v_j = 150 \) and have changed the smallest valuation of the rest of the users excluding \( j \). We see that, as the competition among consumers becomes more intense (i.e. the second smallest consumer valuation becomes closer to that of the selected consumer, \( v_j = 150 \)), the operator expected profit increases. If the competition among consumers is even lighter, (i.e. \( v_j = 150 \), and \( v_i \geq 270 \) for consumers \( i \neq j \)), the rest of the consumers cannot effectively compete with the one with smallest valuation. Therefore the mechanism essentially becomes similar to an one-leader-one-follower Stackelberg game between the operator and the most favorable consumer, i.e the one with the smallest valuation. The comparison of the two mechanisms reveals that a higher competition among users is more favorable for the operator, since it forces consumers to respond with increasing fines.

### V. CONCLUSION

In this paper we model and analyze Nega-Watt markets, in which a utility operator wishes to curtail some amount of demand load during peak hours. The paper serves as a starting work for identifying the relevant trends and studying appropriate interaction models. The novelty in our setup stems from the arising uncertainty due to users’ possible non-engagement for load reduction which in turn gives rise to two-branch incentive mechanisms that include both rewards and fines. From the comparison of the user-selection mechanisms introduced, we obtain that: (i) both the user and the operator are better off in Stackelberg equilibrium than in bilateral negotiation, (ii) as a result of the above, N-parallel Stackelberg games is better for both entities than N-parallel negotiations (in both cases users are not aware of the existence of competition), (iii) when competition is announced to users the operator is better off in Stackelberg game with N-followers than in N-parallel Stackelberg games. In our future work we intend to extend our model so that the operator may select multiple users for the curtailment of the desired load and to study the use of auctions to realize the two-branch incentives when neither the users nor the operator have complete information.

### REFERENCES