COOPERATIVE CONSUMERS IN A DEREGULATED
ELECTRICITY MARKET
– DYNAMIC CONSUMPTION STRATEGIES AND PRICE COORDINATION[†]

RAIMO P. HÄMÄLÄINEN¹, JUHA MÄNTYSAARI^{1‡},
JUKKA RUUSUNEN² and PIERRE-OLIVIER PINEAU¹

¹Systems Analysis Laboratory, Helsinki University of Technology,
P.O. BOX 1100, FIN-02015 HUT, Finland, Fax. +358-9-451 3096,
URL: www.hut.fi/Units/SAL

²IVO Group, Strategic Planning, Malminkatu 16, Helsinki, 00019 IVO, Finland.

Abstract – As the trend in electricity markets is strongly towards deregulation, new players, new rules and new behaviors will continue to emerge. One of the new phenomena that are developing on the demand side is the purchase by a coalition of consumers. When it is worth, a coalition will be constituted. One of the energy needs, especially important in the Nordic countries such as Finland, is electrical space heating. We consider here the consumption strategies of individual electricity buyers within a coalition. The decision problem each consumer faces is to find the optimal use of his space heating system with respect to change in electricity price and to his tolerance to indoor temperature variation. A mathematical model for this problem is defined. Physical parameters of example houses were gathered from an experimental field test conducted in Helsinki during the winter 1996. The coalition buys in the market at marginal cost. However, as marginal cost pricing may not always fulfill metering and communication needs of the members of the coalition, we consider Time-Of-Use (TOU) pricing within the coalition. Different groups of consumer behaviour are constructed to simulate this coalition. Optimal marginal price is used as a reference point to estimate the nearest TOU price within the coalition.

1. INTRODUCTION

The deregulation of the electricity market not only increases the number of players in the industry, but also affects the behavior of each of them. On the supply side, utilities cannot anymore make investment and pricing decisions in the same way. They have to take into account competitors and the new possibilities available to customers. These customers, on the demand side, will be increasingly aware of saving opportunities arising from new flexibility in supply. Indeed, these customers are free to choose their supplier and will look for the deal fitting best their specific energy needs.

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[‡] Corresponding author.

Such a change in the market structure may seem to mean that models and tools from the pre-deregulated electricity world are out of date (see Ref. 1 for an overview of new issues and models in the electricity industry). This is true, for example, for topics related with the transmission system, which should now be completely distinct from producers and therefore be managed as an independent entity. Investment models in transmission where all cost were recovered by a vertically integrated utility are not anymore usable. But there are situations where models of the pre-deregulated market, far from being discarded, start to have a new relevance. Here we develop a complete application of a new type of customer behaviour, based on a hierarchical framework first designed to describe a monopolistic utility and its captive customers. The new customer behaviour we are studying here is the one of individual consumers constituting a coalition in order to have access the wholesale supply market. Supply from the wholesale market is done through a portfolio of contracts and periodic purchases on the spot market. However, fluctuations of prices may not suit each individual consumer, so a simpler price needs to be developed. Furthermore, if it can technically be done, each member of the coalition will try to maximize his own benefit by adjusting the elastic part of his consumption to the dynamic price used within the coalition.

To show how feasible this application could be, we develop a complete example following the main guideline given above. A Time-Of-Use (TOU) price easy to use for individual consumers is even simulated to show how realistic and simple maximum benefit can be approached for the coalition. We study in detail the reaction of each consumer to this TOU.

In the next section we introduce the hierarchical framework used and show how it could be applied in the free electricity market. We also describe the example developed. In Sec. 3 the model used for the coordination of this coalition is presented. The elastic parts of consumer's demand allowing adjustments to the price pattern used are studied in Sec. 4. In Finland, heating represents an important share of total electricity usage and peoples tolerance to indoor temperature changes can be exploited to make savings. We thus describe how such a system can be controlled to the benefit of each individual consumer, according to his specific tastes and situation. Finally, in Sec. 5, we compute an optimal TOU price to illustrate how different consumer groups would react to such a price. This simulation aims to show the feasibility of the whole model. By describing and analyzing the reaction of each consumer group, we go a step further in the study of this kind of framework where the reaction of these followers is generally only assumed, but not characterized precisely. A conclusion with a summary ends the paper.

2. A HIERARCHICAL FRAMEWORK IN A DEREGULATED ENVIRONMENT

The most common situation in electricity markets until recently was the one of a vertically integrated utility aiming at the maximum total welfare. Customers were captive and could not respond more than the utility allowed them to do, usually by means of prices designed to induce specific reactions. A particularly interesting set of behaviours were those aiming at improving the load pattern. These efforts are part of resource allocation issues and in the case of electricity are called *Demand-Side Management* (DSM) (see for example Ref. 3 and Ref. 4 for a Finnish study). A hierarchical framework using a two-level game model can be extremely relevant to study this kind of interaction between a utility (leader) and its many individual consumers (followers). For example Ref. 5 studies price coordination in this setting to develop an appropriate resource allocation scheme between a leader and its followers. In the case of electricity practical implementation of these tools can be done with the Power Agents software (see Refs. 6-7). Hobbs and Nelson⁸ also develop a hierarchical framework to study the case of a total welfare maximizing utility aiming at the optimal investment in DSM tools by its benefit maximizing customers.

We show in this paper, by developing a comprehensive example, that this hierarchical setting seemingly out of date is still relevant in the new deregulated electricity markets, even if resource allocation misses a clear coordinator and if DSM programs are not anymore a priority for utilities (see for example Ref. 9 for more details on falling investment in DSM programs).

We now introduce in more detail the general hierarchical framework and show after that how it could be relevant in the new market setting. We finally present the example we develop thereafter to portray a possible real application.

The hierarchical framework

In pre-deregulated market, the general framework involves, in an upper level, a total welfare maximizing utility. This utility is vertically integrated and has a monopoly over a territory. In this territory, many individual consumers (constituting the lower level) behave in order to maximize their own benefit only. In this case, they develop energy consumption strategies to maximize their benefit from the policies of the utility, consisting mainly of a price policy. With DSM goals in mind, the utility has to design a policy inducing a socially efficient consumption of electricity, knowing that the consumers will react to that policy with only self-maximizing goals. This is clearly a Stackelberg setting, where the utility is the leader, followed by many individuals consumers. For more details, we refer to Ref. 5 where the model is fully stated.

Hierarchies in the deregulated electricity market

How a setting such as the one depicted above can be applied if (i) consumers can now react to many utilities instead of a single one and (ii) social goals are not anymore in the objectives of the utilities? The answers to these questions lies in the new behaviors we can expect - and also already observe - in the retail electricity market.

Individual customers can now choose their supplier in many countries and states (for example New Zealand, Norway, California, Finland) and a free market also exists at the wholesale level. Obviously, a single utility could not reason in the terms of the Stackelberg setting. But customers can form coalitions, or a cooperative, to have access to the wholesale market and increase their power. For example, some large residential buildings in Helsinki (Finland) are taking care of the supply of all their residents by looking for supply opportunities that each individual consumer alone could not have access to. These supply opportunities searched in the wholesale market are priced in a way that is not suitable for individual consumers. Typically, a portfolio of contracts covering base and peak load is constituted, with many different pricing structures. Individual consumers still want to be billed in a simple manner, creating a need to design a new price.

The new upper level player can then be called the "coalition coordinator", buying in the name and interest of the whole coalition, and reselling to each member, at the lower level. The total welfare maximizing assumption of the upper level player can still be used because it is a coalition, and lower level players can still maximize their own benefit from consumption. In addition to this, each individual consumer will react to the price set by the coalition coordinator according to the elastic portion of his consumption. One interesting issue is the problem of designing a simple price structure inducing maximal total welfare for the coalition, knowing that each individual consumer will do his single optimization to benefit the most from his consumption strategy. Figure 1 illustrates the situation and summarizes the features of each player.

Fig. 1. A hierarchical market model in the deregulated electricity sector.

Applications of this type of hierarchies in the actual electricity sector could be numerous. We already mentioned a residential building with many apartments, but we can also think of other types of communities sharing some common elements and thus having a natural incentive to create a coalition. A neighborhood of individual houses could for example decide to organize some common electricity buying. Each house would respond to the total welfare maximizing price of the coalition with a consumption strategy optimizing its own benefit. In Finland, as space heating is an important share of total consumption (more than 10%, see Ref. 10) and can be elastic for some consumer groups, the consumption strategy can be based on adaptation of heating to the price proposed. For more on the Finnish situation, see Refs. 1, 11. The next sub-section presents in general term this example.

Example of a coalition of space heating consumers

In this example, we consider individual consumers living in houses. They choose to form a coalition and name a coalition coordinator to make their common buying. As mention before, this coalition coordinator buys electricity from the wholesale market through contracts and spot transactions. For simplicity, we will consider here that all his purchases can be represented with a single "purchase function", or cost function. As shown later in Sec. 3, we take the analytical form of a quadratic cost function in our example, with quantity as argument. Although prices in contract portfolio are more likely to be dependent on *time* of consumption rather than on *quantity*, because of peak load effects, high prices correspond to periods of high demand. It is therefore a reasonable approximation to use a purchase function with a quantity argument.

In this example, we also assume that individual consumers want the coalition coordinator to resell electricity using a TOU price, for its simplicity. They all consume some electricity, that can be segmented in an inelastic base load consumption and some elastic space heating consumption. In addition, individual consumers differ in the level of elasticity in their space heating consumption. They belong to some distinct groups called responding, normal or non-responding, according to their willingness to change their electricity consumption. This will affect the way they react to the TOU price set by the coalition coordinator. As he wants to maximize the coalition's welfare, he will seek the optimal TOU price for these different consumers.

All the rest of this paper is now solely concerned by this example. Its full development gives a real illustration of how such a general hierarchical setting can be implemented if an adequate technology is available for all houses of the coalition. The next section sets the problem in its mathematical form. The lower level decision problem of consumption is fully depicted in Sec. 4. It will be seen that in this case the problem is reduced to a space heating problem, because all other consumption is considered inelastic. The optimal TOU price is computed in Sec 5, where the strategic behaviors of the different consumer groups are simulated. This illustrates how realistic these heating strategies are, with only minimal technological requirements.

3. COORDINATION MODEL FOR THE COALITION

In this section we define the total welfare function of the coalition of consumers. This leads to a marginal price for the coalition. This price vector can however be difficult to implement when consumers want to use a simple dynamic price. In such a case, one can calculate the closest TOU price (see Sec. 5).

The electricity demand depends on numerous factors, such as the time of day, weekday and season. Therefore only a part of the total production capacity is needed continuously. Reverse capacity is brought on line when there is a danger of exceeding the active production capacity. The base demand is usually satisfied by large power generation plants, such as nuclear or coal-steam plants. On one hand, the financial investment they require is substantial, but on the other hand they produce electricity at a very low marginal cost. Smaller plants with high marginal costs are used for meeting the varying peak demands.

As we are considering a competitive electricity market, price will tend to be equal to marginal cost. The cost function of the coalition is then simply a marginal cost function.

As consumption increases, a higher share of the local need is to be purchased from the spot market with a greater marginal price. For this reason, the shape of the cost function is taken to be strictly quasi-convex. For example, a non-decreasing piecewise linear function¹² or a quadratic function¹³ can be used. In this

paper, we use a quadratic cost function. Let the number of different consumer groups be M and define the total heating consumption $\mathbf{q} \in \mathbb{R}^N$ to be

$$\mathbf{q} = \sum_{k=1}^M \mathbf{q}_k, \quad (1)$$

i.e. the sum of the consumption of the M space heating consumer groups. The quadratic cost function of the coalition can be written as

$$C(\mathbf{q}) = \mathbf{d}^T \mathbf{q} + \mathbf{q}^T \mathbf{E} \mathbf{q}, \quad (2)$$

where $\mathbf{d} = (d_0, \dots, d_{N-1})$, $\mathbf{e} = (e_0, \dots, e_{N-1}) \in \mathbb{R}^N$ and $\mathbf{E} = \text{diag}(\mathbf{e})$ are constants and $\text{diag}(\bullet)$ refers to a diagonal matrix with given elements.

One part of the coalition's total utility is the profit function, i.e.

$$U_P(\mathbf{q}, \mathbf{p}) = \mathbf{p}^T \mathbf{q} - C(\mathbf{q}). \quad (3)$$

The other part is the sum of the utilities of the consumer groups U_k . The goal of the coalition coordinator is the maximization of the total welfare U , defined as the sum of the utilities of the consumer groups U_k and coalitions profit U_P , i.e.

$$U(\mathbf{q}, \mathbf{p}) = \sum_{k=1}^M U_k(\mathbf{q}_k, \mathbf{p}) + U_P(\mathbf{q}, \mathbf{p}). \quad (4)$$

4. THE INDIVIDUAL CONSUMER'S DECISION PROBLEM

The space heating system aims at keeping the indoor temperature within comfortable limits. Heating costs depend on the outdoor temperature, the indoor temperature and the price of the electricity. A consumer will be able to save in heating costs if he can combine two different strategies, namely lowering the indoor temperature levels and taking an advantage of the time varying electricity price. In the latter case, one uses the house as a heat storage by heating more intensively during off-peak price hours and let the heating and temperature drop during peak price hours. The optimization of this strategy requires a model of the dynamics of the house. Other types of consumer reactions have been discussed in Refs.4, 14.

Dynamics of the house

Houses are considered as heat storages subject to losses due to ventilation, convection and radiation. A discrete time model will be used with a time interval Δt of one hour. In the model, the state of the house in period t_i is the amount of heat energy Q_i in kWh stored in it. The dynamics of the house are described by changes in the total heat energy

$$Q_i = Q_{i-1} + \Delta t q_{i-1} - d_{i-1}, \quad (5)$$

where Q_{i-1} is the previous state of the house, q_{i-1} is the heating power during previous period, and d_{i-1} is the heat transfer out of the house. It is assumed to be linearly dependent on the difference between the indoor and the outdoor temperatures T_i and T_i^{out}

$$d_i = \alpha \Delta t (T_i - T_i^{\text{out}}), \quad (6)$$

where α in kW/°C is a constant describing the heat transfer. We assume that the stored heat is related to the uniform indoor temperature through the aggregated heat capacity equation

$$T_i = Q_i / C, \quad (7)$$

where C is the total heat capacity of the house ($[C] = \text{kWh}/^\circ\text{C}$). By marking $\beta = 1/C$ we can write Eq. 5 using Eq. 6 and Eq. 7 as

$$T_i + (\alpha \beta \Delta t - 1) T_{i-1} - \beta \Delta t q_{i-1} = \alpha \beta \Delta t T_{i-1}^{\text{out}}. \quad (8)$$

Tradeoff between living comfort and heating costs

Consumer groups can save in heating costs by lowering their indoor temperature. To model the willingness of the consumer to trade cost savings to living comfort, we measure the differences between ideal indoor temperature levels T_i^{ref} and actual level, e.g. $(T_i - T_i^{\text{ref}})^2$. This measure will be called degradation of living comfort. Consumer's objective to save in heating costs is assumed to be the weighted sum of the total heating costs and the total degradation of living comfort. We will use the term "total generalized cost" for this weighted sum. This gives us a dynamic optimization problem

$$\min_{T_i, q_i} \sum_{i=0}^{N-1} \left(p_i q_i + \lambda_{i+1} (T_{i+1} - T_{i+1}^{\text{ref}})^2 \right) \quad (9)$$

subject to the dynamics of the house (8),

where q_i is the heating power, p_i is the electricity price and λ_i is the consumer's willingness to trade cost savings to living comfort at time point t_i . The time horizon is taken to be e.g. a day. The heating power at the last discretization point of the day (t_N) is excluded from the objective function in Eq. 9 since it will have no effect to the indoor temperature levels of the day considered.

For normal days, it is appropriate to introduce a periodicity constraint for indoor temperature as

$$T_0 = T_N, \quad (10)$$

i.e. the indoor temperature at the last discretization point of the previous day is required to be equal to the indoor temperature at the last discretization point of the day.

Applying also some natural upper and lower bounds for the indoor temperature and the heating power, we can write the *optimization problem of the electric space heating consumer* as the following quadratic problem

$$\begin{aligned} \min_{\mathbf{T}, \mathbf{q}} \quad & \frac{1}{2} \mathbf{T}^T \mathbf{Q} \mathbf{T} + \mathbf{c}^T \mathbf{T} + \mathbf{p}^T \mathbf{q} \\ \text{subject to} \quad & \mathbf{A} \mathbf{T} + \mathbf{B} \mathbf{q} = \mathbf{b} \\ & \mathbf{T}_{\min} \leq \mathbf{T} \leq \mathbf{T}_{\max} \\ & \mathbf{0} \leq \mathbf{q} \leq \mathbf{q}_{\max} \end{aligned}, \quad (11)$$

where the decision variables are $\mathbf{T} = (T_0, \dots, T_N) \in \mathbb{R}^{N+1}$, $\mathbf{q} = (q_0, \dots, q_{N-1}) \in \mathbb{R}^N$, the quadratic object function matrix is $\mathbf{Q} = \text{diag}(0, 2\lambda_1, \dots, 2\lambda_N) \in \mathbb{R}^{N+1} \times \mathbb{R}^{N+1}$ and the linear object function vectors are $\mathbf{c} = (0, -2\lambda_1 T_1^{\text{ref}}, \dots, -2\lambda_N T_N^{\text{ref}}) \in \mathbb{R}^{N+1}$, $\mathbf{p} = (p_0, \dots, p_{N-1}) \in \mathbb{R}^N$. The constraint matrixes are

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & \dots & 0 & -1 \\ \alpha\beta\Delta t - 1 & 1 & 0 & \dots & 0 \\ 0 & \alpha\beta\Delta t - 1 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & \alpha\beta\Delta t - 1 & 1 \end{bmatrix} \text{ and } \mathbf{B} = \begin{bmatrix} 0 & 0 & \dots & 0 \\ -\beta\Delta t & 0 & \dots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & -\beta\Delta t \end{bmatrix}, \quad (12)$$

where $\mathbf{A} \in \mathbb{R}^{N+1} \times \mathbb{R}^{N+1}$, $\mathbf{B} \in \mathbb{R}^{N+1} \times \mathbb{R}^N$ and the vector is $\mathbf{b} = (0, \alpha\beta\Delta t T_0^{\text{out}}, \dots, \alpha\beta\Delta t T_{N-1}^{\text{out}}) \in \mathbb{R}^{N+1}$. It is worth noticing that by setting the tradeoff coefficients λ_i to zero reduces Eq. 12 to a linear programming problem. For other linear pricing models see Ref. 15.

Specification of the tradeoff coefficients λ_i sets the behavior of the consumer. Different consumer groups are defined via tradeoff coefficients. The utility function for the consumer group k is

$$U_k(\mathbf{q}_k, \mathbf{p}) = K_k - \left(\frac{1}{2} \mathbf{T}_k^T \mathbf{Q}_k \mathbf{T}_k + \mathbf{c}_k^T \mathbf{T}_k + \mathbf{p}^T \mathbf{q}_k \right), \quad (13)$$

where K_k is a scaling constant. This utility function could be interpreted as the difference between utility gained from the used electricity and the total price of the electricity corresponding to the total generalized cost shown in Eq. 9. This interpretation coincides with the utility functions of electricity consumers used in Refs. 15, 16.

5. SIMULATION OF THE ELECTRICITY MARKETS FOR OPTIMAL TOU PRICE

The main purpose of the simulation is to identify an optimal TOU price based on the optimal marginal price. Related studies using the Power Agents software to coordinate prices can be found in Refs. 5-7. We shall concentrate our simulation on a cold winter day as seen in Fig. 2, because the system peak load occurs in the middle of winter and thus this is the time of a potentially high cost of electricity in the spot market.

Simulations are carried out as follows: first the reactions from responding to non-responding space heating consumer groups defined by the level of given tradeoff coefficient are reviewed under a preliminary TOU price. Next, we use the fixed point iteration to calculate a marginal price maximizing the total welfare in Eq. 4. In the last step, we seek for TOU prices minimizing the quadratic difference between TOU and marginal price.

Fig. 2. Outdoor temperature profile for a cold winter day.

Description of simulation parameters

The parameters of the simulation can be divided into four categories: physical (see Table 1.), environmental (outdoor temperature T^{out}), behavioral (ideal T^{ref} as well as lower and upper bounds of the indoor temperature, and the tradeoff coefficient) and economical (cost function) parameters. More precisely, the physical parameters of a consumer group are the heat capacity of the house (C) giving $\beta = 1/C$, the loss coefficient (α) and the maximum heating power of the house (q_{max}). These parameters have been estimated in a field test conducted in the Helsinki area during 1996⁷. Some illustrative houses and their parameters are shown in Table 1.

Table 1. Description of houses and estimated parameters

	House 1	House 2	House 3
Type of the house	Two family house	Middle unit in a row houses	Single family house
Building material	Insulated rock material with a brick surface	Wood with a brick surface	Wood
Floor area [m²]	170	92	139
Number of floors	2	1	1
Heating equipment	Ceiling and floor heating	Wall radiators	Ceiling and floor heating
b [°C/kWh]	0.038	0.340	0.380
a [kWh/°C]	0.170	0.090	0.077
Heating power q_{max} [kW]	9.0	5.0	8.7

Consumer groups are assumed to have lower (T_{min}) and upper (T_{max}) bounds of the indoor temperature, an ideal level of indoor temperature (T^{ref}) and a willingness to trade cost savings to living comfort

characterized by the constant tradeoff coefficient (λ). In the current simulation, the indoor temperature is allowed to vary between 20-22 °C during the day with ideal temperature level at 21°C.

For illustrative purposes we select here the following quadratic cost function for the coalition

$$C = 0.00003\bar{q}^2 - 2.8\bar{q} + 70000, \quad (14)$$

where $\bar{q}$ is the total consumption (inelastic and space heating consumptions). It is to be taken as a rough estimate of the real cost function. The inelastic consumption of the coalition over the day is presented in Fig. 8.

The peak price is used from 7:00 am to 11:00 pm. The off-peak price is used otherwise. The preliminary off-peak and peak prices are 0.196 FIM and 0.554 FIM. In our simulation the duration and timing of the periods are kept fixed but the price levels are under consideration.

Reactions of different consumer groups

The total generalized cost of a consumer group depends on the electricity price and the willingness to trade cost savings for living comfort as seen in Eq. 9. Figures from Fig. 3 to Fig. 5 show the reactions of consumers with responding to non-responding behaviors living in House 1 and reacting under preliminary TOU price. Responding and normal consumers will typically try to save in heating costs by maximum heating during off-peak hours and reducing the heating during peak hours. Non-responding consumers are more concerned with keeping the indoor temperature close to the ideal level as seen in Fig. 5, so they only make very limited use of their house as a heat storage device. Indeed, only during 6:00 to 7:00 am they increase heating to reduce consumption later in the day (at peak price).

The cost difference in the house between responding and non-responding consumer is approximately 7 FIM (about 1.5 US dollars) for the chosen winter day. Total saving of a responding consumer within a typical calendar year in Finland and Nordic countries with about 10 cold winter days (temperature below minus ten degrees during the whole day) might be approximately 70 FIM. Responding consumers will also consume less electricity during peak hours. This behavior is environmental friendly since during high peak hours it is likely that more polluting production units are used than during off-peak hours.

During the simulation every house is used three times to construct responding, normal and non-responding consumer groups, giving altogether nine different consumer groups. Responding consumer groups have their tradeoff coefficient near zero level, whereas normal and non-responding between [0.4, 2] and between [4, 50] respectively. Consumption of every consumer group is multiplied by 200 to scale the results.

Fig. 3. Temperature and price of electricity (A) and heating power (B);
A responding consumer, $\lambda = 0.1$.

Fig. 4. Temperature and price of electricity (A) and heating power (B);
A normal consumer, $\lambda = 0.4$.

Fig. 5. Temperature and price of electricity (A) and heating power (B);
A non-responding consumer, $\lambda = 20$.

It can be observed in Fig. 6 that as the cost increases more rapidly for non-responding consumers compared to the responding ones, when the peak price increases, the preference for a flatter price will be more intense for the non-responding group than for the other ones. The coalition coordinator, when choosing the levels of the TOU price and the rule to share the coalition's profit, will have to pay attention to the different impacts of these decisions on consumer groups' total cost. If some groups feel to be treated unfairly, they could leave the coalition. This issue, although important, is not covered in this paper. General conditions under which the coalition is sustainable and rules for sharing the coalition's profit are left for further research.

Fig. 6. Heating cost (dashed line) and total generalized cost (solid line) for responding, $\lambda = 0.2$, (left) and non-responding, $\lambda = 20$, (right) consumer groups as a function of the peak price.

Fig. 7. Level of heating cost and degradation of living comfort in the optimum solution for a growing tradeoff coefficient λ .

In Fig. 7, levels of heating cost and degradation of living comfort in the optimum are plotted as the tradeoff coefficient λ is growing. Heating cost is increasing and degradation of living comfort decreasing as the function of the tradeoff coefficient. This means that responding consumer groups associated with small λ have smaller cost but also larger degradation of living comfort than non-responding consumer groups with larger λ . An interesting observation in Fig. 6 and Fig. 7 is that the electricity cost term accounts for most of the total generalized cost in the optimum. This reflects the fact that with a non-zero tradeoff coefficient λ the sum of quadratic degradation terms in Eq. 9 dominates the solution and is therefore driven to near zero. For other dynamic pricing experiments see Refs. 18-19. It should be emphasized that this kind of study of consumer's reaction is very seldom done in real time. Our research shows the benefit it can give under very realistic conditions.

Setting TOU prices

The results of the simulation using parameters described earlier and the fixed point iteration are presented in Fig. 8.

Fig. 8. Total consumptions (A) with respect to the inelastic consumption (lower dashed line in A) resulting from marginal (solid line) and flat (dashed line) prices of electricity (B).

It can be seen that the total load pattern is a little flatter than the corresponding consumption pattern of flat price. This is due to the consumption shift of the responding consumer groups. After the calculation of marginal price, we can set the TOU price such that it follows the marginal price. Minimizing the overall distance between them does this, when measured, e.g. by quadratic sense.

The minimum occurs when peak price is considerably higher than off-peak price. The corresponding TOU price is shown and compared with the flat price in Fig. 9.

Fig. 9. Total consumptions (A) with respect to the inelastic consumption (lower dashed line in A) resulting from TOU (solid line) and flat (dashed line) prices of electricity (B).

In Fig. 9 the shift of the first load peak from 7:00 - 8:00 am to 6:00 - 7:00 am is apparent. Evening peak is also reduced since responding consumer groups shift their load towards the break of the off-peak price.

before the midnight. TOU price was set to minimize the distance to marginal price and do not include other considerations, such as the impact on each consumer group as discussed previously. Knowledge of impacts would be important for the coalition sustainability, but our goal here was only to show the possibility to compute a TOU price in such a context.

6. CONCLUSIONS

As market reforms decrease the coordination role of utilities, it might be thought that hierarchical models of coordination become less relevant. We develop here an example where this coordination is done by a coalition, for its own total benefit. This kind of consumer behaviour will probably increase in the following years, as more opportunity to do so arise and competition brings efficiency matters in the minds of consumers. The model we develop here is based on real houses in order to illustrate and characterize the possible reactions of consumers. The results of this experiment show the feasibility of the setting and the benefits it can give. How the total benefit of the coalition can be shared and how to extend this setting to other consumption segments are still unexplored research areas.

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