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Decision Support

Designing coalition-based fair and stable pricing mechanisms under private information on consumers' reservation prices[☆]

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ABSTRACT

We model the relation between an aggregator and consumers joining a coalition to reduce the risk resulting from the unpredictability of their base load demand, as a Stackelberg game formulated as a mathematical bilevel program with private information on the consumers' reservation prices. At the upper-level of the Stackelberg game, the aggregator optimizes his daily price profile so as to reach a net targeted profit which is the maximum value guaranteeing that no consumer will leave the coalition - to contract with a conventional retailer considered here as a fixed alternative - while meeting fairness criterion imposed by the cost-sharing mechanism. At the lower-level, the consumers are asked to provide in day ahead an estimate of their base load hourly demand profile and to schedule their shiftable loads depending on the price signal sent by the aggregator. We provide algorithms that determine the unique price profile and consumer shiftable load schedules as functions of the reservation price estimates. The Stackelberg game between the aggregator and the consumers being repeated for a period of time, the aggregator has the possibility to update his estimates of the reservation prices relying on a feedback function which depends on the percentage of activated loads. A randomized algorithm for consumers' reservation price learning based on regret minimization is provided. For four cost-sharing mechanisms such as uniform allocation, stand-alone cost, Shapley value, separable and non-separable costs, we determine the closed form of the aggregator's optimal net targeted profit guaranteeing the stability of the coalition. We also determine conditions guaranteeing the core non-emptiness and prove that for a profit-maximizing aggregator, the stand-alone cost is always preferable to the Shapley value, which coincides with the uniform allocation. Furthermore, the optimal size of the coalition - in terms of the aggregator's profit - can be determined analytically when the Shapley value is implemented as cost-sharing mechanism. The results are illustrated on a case study where we show that there exists an optimal net targeted profit below which the consumers energy bill is lower when joining the aggregator than with the conventional retailer. Coalition dynamics is also analyzed numerically depending on the consumer inertia in their energy supplier choice process, for each cost-sharing mechanism.

1. Introduction

Up to now, conventional consumers have a contractual relation with a retail electricity provider that supplies them electricity at a per unit price defined by a contract. Various pricing mechanisms are currently proposed such as flat rate, Time-Of-Use, etc. In all these mechanisms, the price pattern is defined a priori, contrary to progressive and dynamic pricing in which price evolves online according to the consumers' demand. Most of the tariff schemes proposed in the literature do not discriminate on the basis of consumer predictability, therefore poorly capturing the structure of the costs that energy suppliers face by interacting with the wholesale electricity market (Robu, Vinyals, Rogers, & Jennings, 2017). Recently, Prediction-Of-Use tariffs in which consumers are asked to provide in advance a prediction of their consumption during a specific period of time and are then penalized based on the deviation between the estimated and the realized demand profiles have

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Nomenclature

We use the following convention for notation: vectors and matrices are represented in **bold** characters whereas standard characters are used for scalars (constants, parameters and variables).

Sets

N	consumers
G	aggregator coalition
L_i	consumer i's shiftable loads
B_i	consumer i's block loads
I_i	consumer i's interruptible loads
$D(\boldsymbol{A})$	interval of integers from 1 to $dim(Ker(\boldsymbol{A}))$
Z	indexes of Langrange multipliers equal to zero
R	reservation price finite discrete set of definition

Parameters

T	number of time periods per day
t	generic time period index
n	number of days considered
K	number of priority levels
m	generic number of repetitions for the Stackelberg game
$\bar{m}$	maximum number of repetitions for the Stackelberg game
$\underline{t}_{i,l}$	earliest time period for the load to start
$\bar{t}_{i,l}$	latest time period for the load to finish
$\mu_{i,l}$	consumer i load l duration
$w_{i,l}$	consumer i load l power rate
$k_{i,l}$	consumer i load l priority level
$r_i(k_{i,l})$	consumer i load l reservation price
$\boldsymbol{r_i}$	vector of consumer i reservation prices per priority level
$\hat{r}_i(k_{i,l})$	consumer i priority level $k_{i,k}$ estimated reservation price
$\boldsymbol{\hat{r}_i}$	vector of consumer i estimated reservation prices
$d_i(t)$	consumer i base load demand at t
$\hat{d}_i(t)$	consumer i estimated demand in day ahead at t
σ_i	standard deviation of random variable $\epsilon_i(t)$
$\rho_{i,j}$	correlation between error variables i and j
$p^f(t)$	day-ahead market price at t
$p^+(t)$	balancing price in case of excess power at t
$p^-(t)$	balancing price in case of missing power at t
$p_{retailer}(t)$	conventional retailer price at t
β	consumer inertia
$\gamma_i, \tilde{\gamma}_i$	learning parameters

Functions

$\Pi(\boldsymbol{p^\star})$	aggregator's net profit
$B_i(t)$	consumer i imbalance penalty at t
$c(\mathscr{G}, t)$	coalition cost at t
$c_{retailer}(i, t)$	conventional retailer cost at t
$\nu(.)$	characteristic function of the TU game
$\psi_i(.)$	coalition cost-sharing function
$\mathcal{N}(0; \sigma)$	Gaussian density function with zero mean and σ standard deviation
$f_i(0; \sigma_i)$	pdf associated with consumer i demand estimation error
$f_{r_i}(.)$	pdf associated with consumer i reservation price
$F_{r_i}(.)$	cdf associated with consumer i reservation price
$h_{r_i(k)}(.)$	pdf associated with consumer i kth priority level
$\hat{f}_{\boldsymbol{r_i},m}(.)$	estimated pdf associated with consumer i reservation prices at round m
$\Delta(\boldsymbol{r_i}, \boldsymbol{\hat{r}_i})$	aggregator's loss function in consumer i reservation prices learning
$\Theta(\boldsymbol{r_i}, \boldsymbol{\hat{r}_i})$	aggregator's feedback function in consumer i reservation prices learning
$\boldsymbol{\Delta^i}, \boldsymbol{\Theta^i}$	aggregator's loss and feedback matrix in consumer i reservation prices learning

Variables

$x_{i,l}(t)$	consumer i load l power consumption at t
$\boldsymbol{x_{i,l}}$	consumer i load l power consumption profile
$x_i(t)$	consumer i shiftable loads power consumption at t
$\boldsymbol{x_i}$	vector of consumer i shiftable loads power consumption profile
$p^\star(t)$	aggregator's price at time period t
$\boldsymbol{p^\star}$	aggregator's price profile
$\boldsymbol{p^\sharp}$	Moore-Penrose approximate of $\boldsymbol{p^\star}$
y_i	bill paid by consumer i to the aggregator over time horizon nT
Π_{agg}	aggregator's net targeted profit
Π^*_{agg}	aggregator's optimal net targeted profit
$\boldsymbol{y}$	vector of bills paid by each consumer over time horizon nT
$\epsilon_i(t)$	error in consumer i demand estimation at t
$w_{r,m}$	weight allocated to reservation price r at round m of the learning algorithm

Mathematical operators

$\boldsymbol{A}^+$	Moore–Penrose pseudo-inverse of matrix $\boldsymbol{A}$
$Ker(\boldsymbol{A})$	Kernel space of matrix $\boldsymbol{A}$
$Im(\boldsymbol{A})$	linear span of $\boldsymbol{A}$ columns
$card(.)$	cardinality function
$\boldsymbol{1}_{(.)}$	indicator function
$\boldsymbol{p^{Ker,k}}$	k th element of $Ker(\boldsymbol{A})$
$\lfloor . \rfloor$	floor function
$dim(.)$	dimension of vector space
$\lVert \boldsymbol{p} \rVert$	l^2-norm $\sqrt{\sum_{t=0}^{nT-1}(p(t))^2}$
$\boldsymbol{x}^T$	transpose of vector $\boldsymbol{x}$

been discussed in Robu et al. (2017) and Vasirani and Ossowski (2013).

In France since 2007, the historical electricity provider EDF has been facing the entry of multiple energy suppliers on the retail market. This trend has been accelerating following the Nome Law[1] voted in December 2010, since consumers can now freely terminate their contract with one energy provider to subscribe to another. In Table 1, we have listed the price per kWh for different energy suppliers for same subscribed power (6 kVA) for flat rate and peak / off-peak time period tariffs in 2018. While EDF follows the regulated tariff for pricing its annual subscription and kWh, competitors offer significant reductions in the annual subscription (20 % for Planète Oui, 5 % for Proxelia) or in the kWh price (5 % in average). Furthermore, many energy suppliers now propose in their contract 'green certificates' on the origin of their production or even direct supply from small renewable energy producers like Enercoop, which advocates a militant and ecological approach based on a cooperative model connecting local renewable energy producers to local consumers. 'Green certificates' have

[1] Nome Law, Online December 2010: http://www.cre.fr/glossaire/loi-nome

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