Energy Pricing Problems for Demand side and Revenue Management

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Outline

Context
Demand Side Management
Energy Pricing Problem
Bilevel Programming

Deterministic Formulation

Stochastic Formulation

Numerical Results

Conclusion
Motivation: Peak Load

Illustrative Load Profile Over 24 Hours

DSM Techniques

- Peak Clipping (LM)
- Valley Filling (LM)
- Load Shifting (LM)
- Energy Efficiency (EE)
- Electrification
- Flexible Load Shape

Source: Primer on Demand-Side Management, World Bank Document CRA No. D06090, 02/2005

► Our tool: time-of-use pricing.
Motivation: Smart Grids

- Scattered energy resources.
- Communication facilitated by smart meters.
ENERGY PRICING PROBLEM

Leader
Energy producer or energy seller
Maximizes its profit
Controls: Prices

Follower
Smart grid operator
Minimizes costs and inconvenience
Manages: Renewable energy, Storage

Usage schedule
Customer 1, Appliances

Time windows
Customer 2, Appliances
Customer n, Appliances

Hourly electricity prices
Optimal reaction to leader's prices
Bilevel Programming

Decision process involving two decision-makers with a hierarchical structure:

- Two decision levels: a leader and a follower, controlling their decision variables, seeking to optimize their objective function.
- The leader sets his decision variables first. Then the follower reacts based on the choices of the leader.

Bilevel programming is strongly NP-hard. Originated from Stackelberg games, related to principal-agent problem, mathematical programs with equilibrium constraints.
ENERGY PRICING PROBLEM

Objectives

▶ Leader maximizes (revenue - buying cost on the spot market) by deciding on prices,
▶ Follower minimizes (billing cost + inconvenience cost) by deciding on the schedule of consumption.

Assumptions

▶ 24-hours cycles,
▶ Demand is fixed,
▶ Every customer has a set of appliances with preferred time windows,
▶ All appliances have power consumption limits,
▶ All appliances are preemptive.
ENERGY PRICING PROBLEM

Assumptions
The smart grid operator has four energy sources:

▶ Electricity bought from leader,
▶ Electricity bought from competitor,
▶ Renewable energy,
▶ Stored energy.

The renewable energy production is known in advance.
Bilevel Model

Exogenous data

- $H$: Set of time slots,
- $K$: Energy cost for the leader for time slot $h$,
- $\bar{p}^h$: Competitor’s price for time slot $h$,
- $N$: Set of customers,
- $A_n$: Set of devices for customer $n$,
- $\beta_{n,a}^\text{max}$: Power limit of appliance $a$ for customer $n$,
- $E_{n,a}$: Demand of customer $n$ for appliance $a$,
- $T_{n,a} = \{T_{n,a}^{\text{first}}, \ldots, T_{n,a}^{\text{last}}\}$: Time window for appliance $a$ of customer $n$,
- $C_{n,a}(h)$: Inconvenience cost for customer $n$ if appliance $a$ is used at time $h$,
- $\lambda_{\text{max}}^h$: Hourly production of renewable energy,
- $S_{\text{min}}, S_{\text{max}}$: Lower and upper bounds for battery capacity,
- $\rho_c$: Charging coefficient.
Bilevel Model

Decision variables of the leader

- \( p^h \): Energy price for time slot \( h \).

Decision variables of the follower

- \( x^h_{(n,a)} \): Energy bought from the leader,
- \( \bar{x}^h_{(n,a)} \): Energy bought from the competitor,
- \( \lambda^h_{(n,a)} \): Energy taken from the renewable energy production,
- \( s^h_{(n,a)} \): Energy taken from the battery,
- \( S^h \): Energy storage state at time \( h \),
- \( \lambda^h_s \): Renewable energy transferred to the battery,
- \( x^h_s \): Energy bought from the leader and transferred to the battery,
- \( \bar{x}^h_s \): Energy bought from the competitor and transferred to the battery.
Bilevel Model: Objective Functions

Leader's objective function:

\[
\max_p \sum_{n \in N} \sum_{a \in A_n} \sum_{h \in T_{n,a}} p^h x^h_{(n,a)} + \sum_{h \in H} \left( p^h x^h_s - K \left( h, x^h_s + \sum_{n \in N} \sum_{a \in A_n} x^h_{(n,a)} \right) \right).
\]

Follower's objective function:

\[
\min_{x, \bar{x}, \lambda, s} \sum_{n \in N} \sum_{a \in A_n} \sum_{h \in T_{n,a}} \left( p^h x^h_{(n,a)} + \bar{p}^h \bar{x}^h_{(n,a)} + C^h_{(n,a)} \left( x^h_{(n,a)} + \bar{x}^h_{(n,a)} + \lambda^h_{(n,a)} + s^h_{(n,a)} \right) \right) \\
+ \sum_{h \in H} \left( p^h x^h_s + \bar{p}^h \bar{x}^h_s \right).
\]
**Bilevel Model: Constraints of the Follower**

\[
\sum_{h \in T_{n,a}} \left( x^h_{(n,a)} + \bar{x}^h_{(n,a)} + \lambda^h_{(n,a)} + s^h_{(n,a)} \right) \geq E_{(n,a)} \quad \forall n \in N, a \in A_n
\]

\[
x^h_{(n,a)} + \bar{x}^h_{(n,a)} + \lambda^h_{(n,a)} + s^h_{(n,a)} \leq \beta_{(n,a)}^{\text{max}} \quad \forall n \in N, a \in A_n, h \in T_{n,a}
\]

\[
\lambda^s_h + \sum_{n \in N} \sum_{a \in A_n} \lambda^h_{(n,a)} \leq \lambda^h_{\text{max}} \quad \forall h \in H
\]

\[
S^{h+1} = S^h - \sum_{n \in N} \sum_{a \in A_n} S^h_{(n,a)} + \rho^c (\lambda^h_s + x^h_s + \bar{x}^h_s) \quad \forall h \in H
\]

\[
\sum_{n \in N} \sum_{a \in A_n} S^h_{(n,a)} \leq S^h \quad \forall h \in H
\]

\[
S_{\text{min}} \leq S^h \leq S_{\text{max}} \quad \forall h \in H.
\]
STOCHASTIC APPROACH

Motivation
Renewable energy production is by nature unpredictable → $\lambda^h_{\text{max}}$ not known in advance.

Properties

- Scenario tree-based approach,

> Every leaf is a scenario,
> Every scenario happens with given probability.
SCENARIO TREES

Impact on the model

- Time separated in time periods (around 3 hours),
- One set of variables per scenario,
- Nonanticipativity constraints,
- Expected values of the objective functions.
**Exact Solution Method**

**Single Level formulation**

- Optimality conditions (primal, dual and complementarity constraints) of the follower,
- Complementary slackness constraints $\rightarrow$ linearized using binary variables,
- Objective function is linearized using the follower’s dual objective function,
- Single level MIP.
BASE EXAMPLE

Four appliances \{1, 2, 3, 4\}:

- Appliance 1, \( \beta_{1}^{\text{max}} = 1, E_1 = 1.5 \),
- Appliance 2, \( \beta_{2}^{\text{max}} = 1, E_2 = 2 \),
- Appliance 3, \( \beta_{3}^{\text{max}} = 1, E_3 = 2.5 \),
- Appliance 4, \( \beta_{4}^{\text{max}} = 1, E_4 = 3 \).
**BASE EXAMPLE**

Two scenarios, similar up to $h = 7$.

![Renewable energy production graph]

Energy storage capacity: $S^h \in [0, 1]$, $\rho^c = 0.9$. 
BASE EXAMPLE

Energy supply costs for the leader, one competitor.
BASE EXAMPLE

Leader’s optimal prices, competitor’s prices and energy supply costs.
**BASE EXAMPLE**

**What we thought:**

- **Anticipated energy consumption of device 1**
  - Energy vs. Time

- **Anticipated energy consumption of device 2**
  - Energy vs. Time
**BASE EXAMPLE**

**What we thought:**

**What happened:**
PARAMETERS OF THE TEST INSTANCES

- 1 customer owning 5, 10 or 20 appliances (500-3000W each),
- 1 to 4 time periods on 6 or 12 hours,
- Energy costs based on SPOT market prices: 40-70€/MWh,
- Competitor’s prices from 0.1 to 0.2 €/kWh,
- Renewable energy production: smartflower™ POP+, 2.31 kWp → 2-3 MWh/year,
- Storage size: 2,3 kWh,
- 3 sizes, 3 starting states
- 5 instances for each parameter setting → 1080 instances.
VSS AND EVPI

Two usual bounds in stochastic programming.

VSS

- Value of stochastic solution.
- Optimal solution on an average scenario.
- 1. Optimal prices on the average scenario.
- 2. Follower’s optimal reaction to these prices $\rightarrow EEV$.
- 3. $VSS = STO - EEV$.

EVPI

- Expected value of perfect information.
- The decision-makers know which scenario will occur.
- 1. Optimal solution for each scenario.
- 2. Expected value on all scenarios $\rightarrow WS$.
- 3. $EVPI = WS - STO$.

Usually, $EEV \leq STO \leq WS$. 
STO-VSS-EVPI
WS

Counter-intuitive, but normal in a bilevel context.
**COMPUTATION TIME**

Time limit : 1000 s.
Larger times on larger instances : 12 hours, 4 time periods (16 scenarios), 20 appliances.
PROSPECTS

What we did

▶ Innovative approach for DSM,
▶ Explicit integration of the customer response into the optimization process of the supplier,
▶ Integration of storage capacities, renewable energy and the related uncertainty,

What we intend to do

▶ Stochastic approach,
  ▶ More tests,
  ▶ Development of heuristics,
▶ Multi-leader approach.
THANK YOU FOR LISTENING
Energy consumption of appliances 3 and 4 in scenarios 1 and 2.
STO-VSS-EVPI

VSS and EVPI

6 hours, 2-16 scenarios
GAPS

Gaps

Gaps minus 3 instances
BATTERY PARAMETERS