Greening multi-tenant data center demand response with parameterized supply function bidding

Niangjun Chen
Xiaoqi Ren, Shaolei Ren, and Adam Wierman
2 stories about energy and data centers

**Typical story:** data centers are energy hogs

**Emerging story:** data centers are valuable resources

**Idea:** use data centers for demand response (DR)

9/26/16
Data centers have great potential for DR

20 MW Data Center with 20% flexibility = 700 kWh fast charging, optimally placed storage [Liu et al 2014]

~$5 million cost!

Current practice: turn on diesel generator upon utility’s request – costly and inefficient!

This talk: Efficient DR in Multi-tenant Data Centers
Multi-tenant (colocation) data centers

Multiple tenants house and manage their own servers independently in shared space.

Data center operator is mainly responsible for facility support (e.g., power supply, cooling).
Multi-tenant (colocation) data centers

Multiple tenants house and manage their own servers independently in shared space.

Data center operator is mainly responsible for facility support (e.g., power supply, cooling).

...of total data center industry electricity usage

- Enterprise: 53%
- Colocation: 37%
- Hyper-scale (e.g. google): 7.8%
Why target **multi-tenant** data center for DR?

Most multi-tenant data centers are in metropolitan areas – Downtown Los Angeles, New York, Silicon Valley, etc.

This is where demand response is **most** needed!

---

**Example:** On July 22, 2011, hundreds of multi-tenant **colocation data centers** participated in emergency demand response and contributed by cutting their electricity usage before a nation-wide blackout occurred in the U.S. and Canada.

--- A. Misra, “Responding Before Electric Emergencies.”
Our contribution: a simple and provably efficient mechanism to incentivize tenants’ reduction

Goal: \[ \min \alpha \cdot y + \sum_i c_i(s_i) \]

s.t. \[ y + \sum_i s_i = \delta \]

Operator’s challenge:
1. No direct control of tenants’ reduction \( s_i \)
2. Tenants’ private cost \( c_i \) unknown

Our proposal: use supply function bidding
Why supply function bidding?

1. VCG type mechanisms are problematic in energy settings among them:
   - tenants required to submit complex bid
   - allocation problem for operator is NP hard
   - price differentiation ...
Why supply function bidding?

1. VCG type mechanisms are problematic in energy settings
   [Zhang et al 2015] [Rothkopf 2007]

2. Supply function bidding is widely used in electricity market
   [Baldick et al 2004] [Day et al 2002] [David and Wen 2000]

3. Prior work on supply function bidding
   [Klemperer and Meyer 1989] [Niu et al 2005]
   [Johari and Tsitsiklis 2011] [Xu et al 2015]

Key difference with our work: we consider operator has a backup supply option

Unconstrained supply function, no performance guarantee
Parameterized supply function, good performance guarantee
A parameterized supply function mechanism

1. Operator announces supply function $s(b, p) = \delta - b/p$
2. Tenant $i$ submits bid $b_i$
3. Operator sets market price $p$ to minimize its own cost (payment to tenants plus diesel cost)
4. DR is exercised
A parameterized supply function mechanism

How does operator set $p$ and $y$?
- $\min_{p,y} p(\delta-y) + ay$ subject to $\sum_i (\delta - b_i/p) + y = \delta$
- equivalent to quadratic minimization problem, have closed form solution
A parameterized supply function mechanism

How does tenant $i$ bid $b_i$?

- **price-taking** \[ \max p \cdot S_i(b_i, p) - c_i(S_i(b_i, p)) \]
- **price-anticipating** \[ \max_{b_i} p(b) \cdot S_i(b_i, p(b)) - c_i(S_i(b_i, p(b))) \]

Operator

Cut energy $\delta$

Diesel energy

$y = \delta - \Sigma s_i$

Utility

Supply bid $b_i$

Tenants

Price $p$

Cut energy by $s_i=\delta - b_i/p$
A parameterized supply function mechanism

Simple: tenant only need to communicate one parameter
Fair: no price differentiation
Cost saving for operator: cost of dispatch decrease compared to diesel only
Equilibrium: always exists and unique
A parameterized supply function mechanism

Applicable to any problem of satisfying an inelastic demand $\delta$ with $N$ suppliers with an (expensive) backup option
Characterizing the equilibrium

**Theorem:** When tenants are **price-taking**, the market equilibrium is unique and characterized by

$$\min_{s, y} \sum_i c_i(s_i) + \frac{\alpha}{2N\delta} (y + (N - 1)\delta)^2$$

subject to

$$\sum_i s_i + y = \delta$$

Due to strategic behavior of operator

9/26/16
Characterizing the equilibrium

**Theorem:** When tenants are price-anticipating, the market equilibrium is unique and characterized by

$$\min_{s, y} \sum_i \hat{c}_i(s_i) + \frac{\alpha}{2N\delta} (y + (N - 1)\delta)^2$$

subject to

$$\sum_i s_i + y = \delta$$

where

$$c_i(s_i) \leq \hat{c}_i(s_i) \leq c_i(s_i) + s_i \alpha/2N$$

Strategic behavior of tenants

Strategic behavior of operator
How good is the equilibrium?

1. What is the social cost?
2. What are tenants’ costs?
3. What is operator’s cost?
4. What is the reduction in diesel usage?

We answer these questions with both theoretical guarantees and trace-based simulations.
What are we comparing to?

**Benchmark:** Centrally controlled social cost minimization (SCM)

\[
\begin{align*}
\min & \quad \alpha \cdot y + \sum_i c_i(s_i) \\
\text{s.t.} & \quad y + \sum_i s_i = \delta
\end{align*}
\]

**Case study:** DR signals issued by PJM on January 7, 2014, due to cold weather.
1. What is the social cost?

**Theorem:** For both price-taking and price-anticipating tenants, 
\[
\text{cost}(\text{ColoDR}) \leq \text{cost}(\text{SCM}) + \frac{\alpha \delta}{N}
\]

Near optimal when \(N\) is small

Vanishing when \(N\) is large, what if \(N\) is small?
2&3. What are tenants’ and operator’s costs?

Theorem: For both price-taking and price-anticipating tenants,

\[ \text{cost}_t(\text{ColoDR}) \leq \text{cost}_t(\text{SCM}) + \frac{2\alpha \delta}{N} \]

\[ \text{cost}_o(\text{ColoDR}) \geq \text{cost}_o(\text{SCM}) - \frac{\alpha \delta}{N} \]

Higher utility for tenants with larger flexibility

<table>
<thead>
<tr>
<th>Net utility ($)</th>
<th>Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>150</td>
<td>6</td>
</tr>
<tr>
<td>100</td>
<td>8</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>4</td>
</tr>
<tr>
<td>250</td>
<td>6</td>
</tr>
<tr>
<td>200</td>
<td>8</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>12</td>
</tr>
</tbody>
</table>

9/26/16

ColoDR(price-taking) ColoDR(price-anticipating) SCM Diesel only
4. What is the reduction in diesel usage?

**Theorem:** For price-taking tenants, \( y^t < y^* + \delta / 2 \)

For price-anticipating tenants, \( y^u \leq y^* + \delta \)

In worst case, ColoDR may use a lot more diesel than optimal.
How good is the equilibrium?

1. Social cost
   \[ \text{cost}(\text{ColoDR}) \leq \text{cost}(\text{SCM}) + \alpha \delta / N \]

2. Tenants’ cost
   \[ \text{cost}_t(\text{ColoDR}) \leq \text{cost}_t(\text{SCM}) + 2\alpha \delta / N \]

3. Operator’s cost
   \[ \text{cost}_o(\text{ColoDR}) \geq \text{cost}_o(\text{SCM}) - \alpha \delta / N \]

4. Diesel reduction
   \[ y^t \leq y^* + \delta / 2 \quad y^a \leq y^* + \delta \]
Key Message

Multi-tenant data center demand response can be “green” by incentivizing tenants’ cooperation
  - Our supply function bidding mechanism achieve this goal with a provably-efficient outcome

\[
\text{Diesel energy } y = \delta - \sum s_i \\
\text{Cut energy } \delta \\
\text{Utility} \\
\text{Supply bid } b_i \\
\text{Operator} \\
\text{Price } p \\
\text{Tenants} \\
\text{Cut energy by } s_i = \delta - b_i / p
\]