Greening Multi-Tenant Data Center Demand Response

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Joint work with Xiaoqi Ren, Shaolei Ren, and Adam Wierman

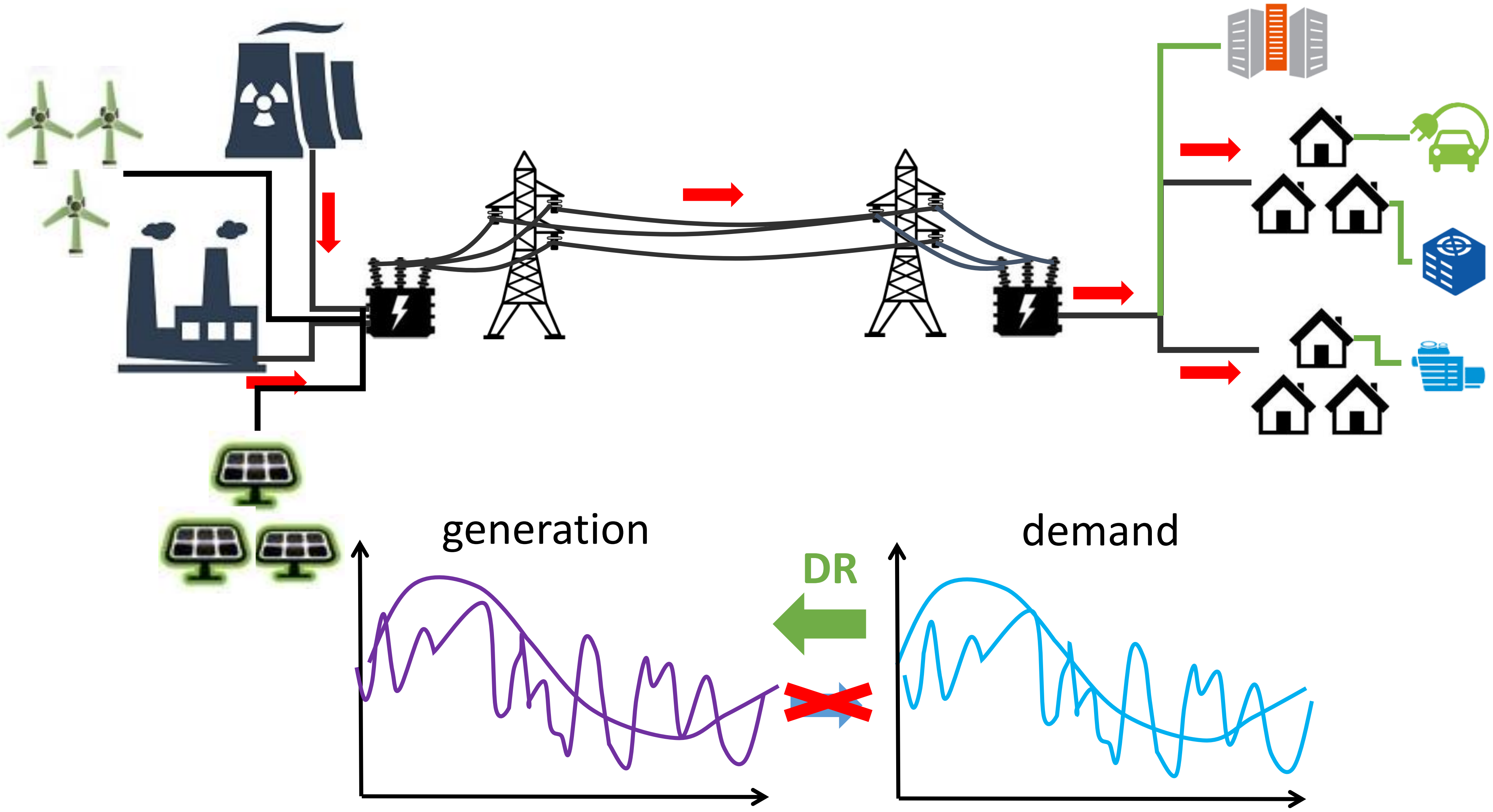
2 stories about energy and data centers

Typical story: data centers are energy hogs

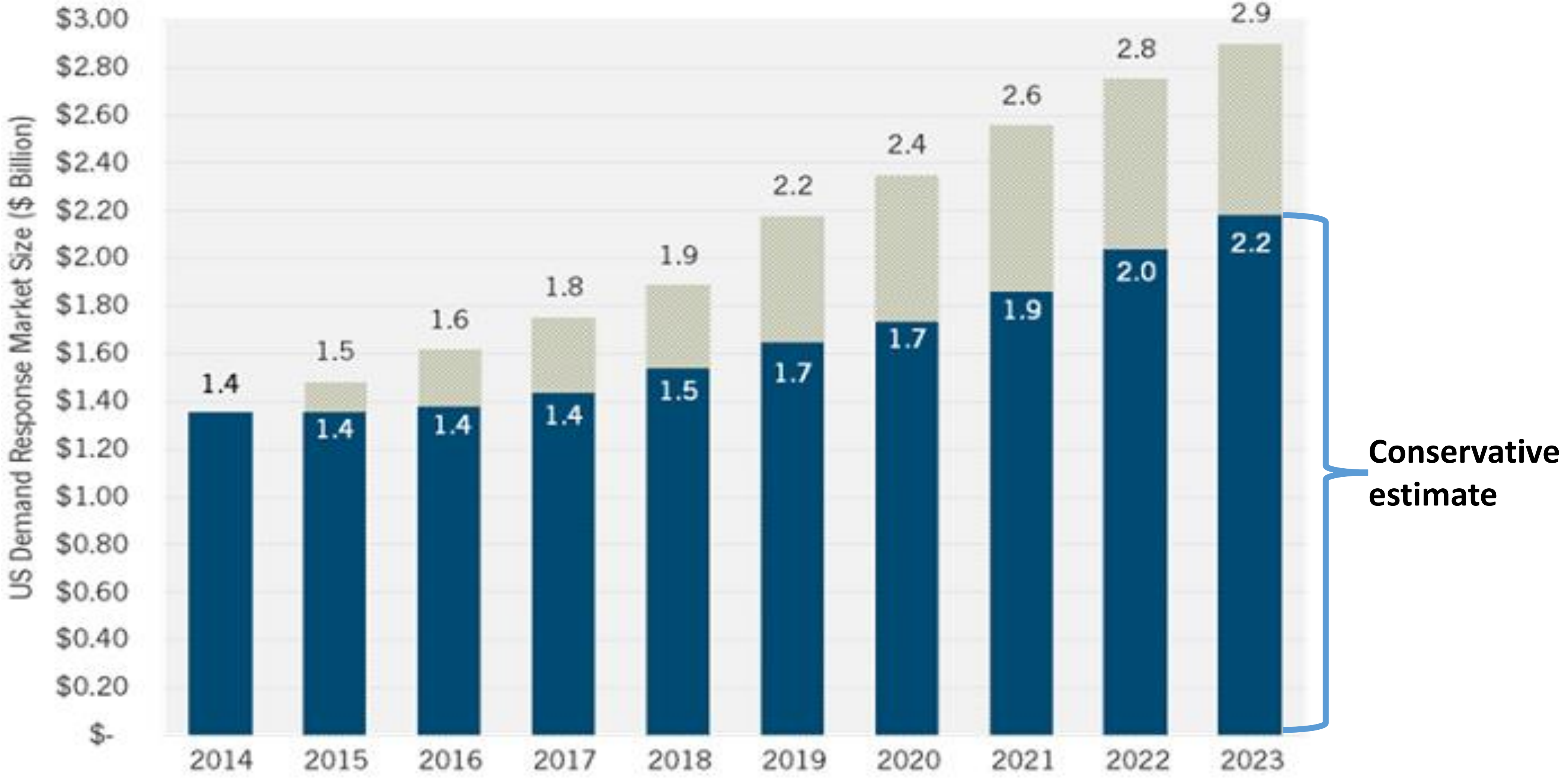

Emerging story: data centers are valuable resources


Idea: use data centers for demand response (DR)

DR is crucial for renewable integration

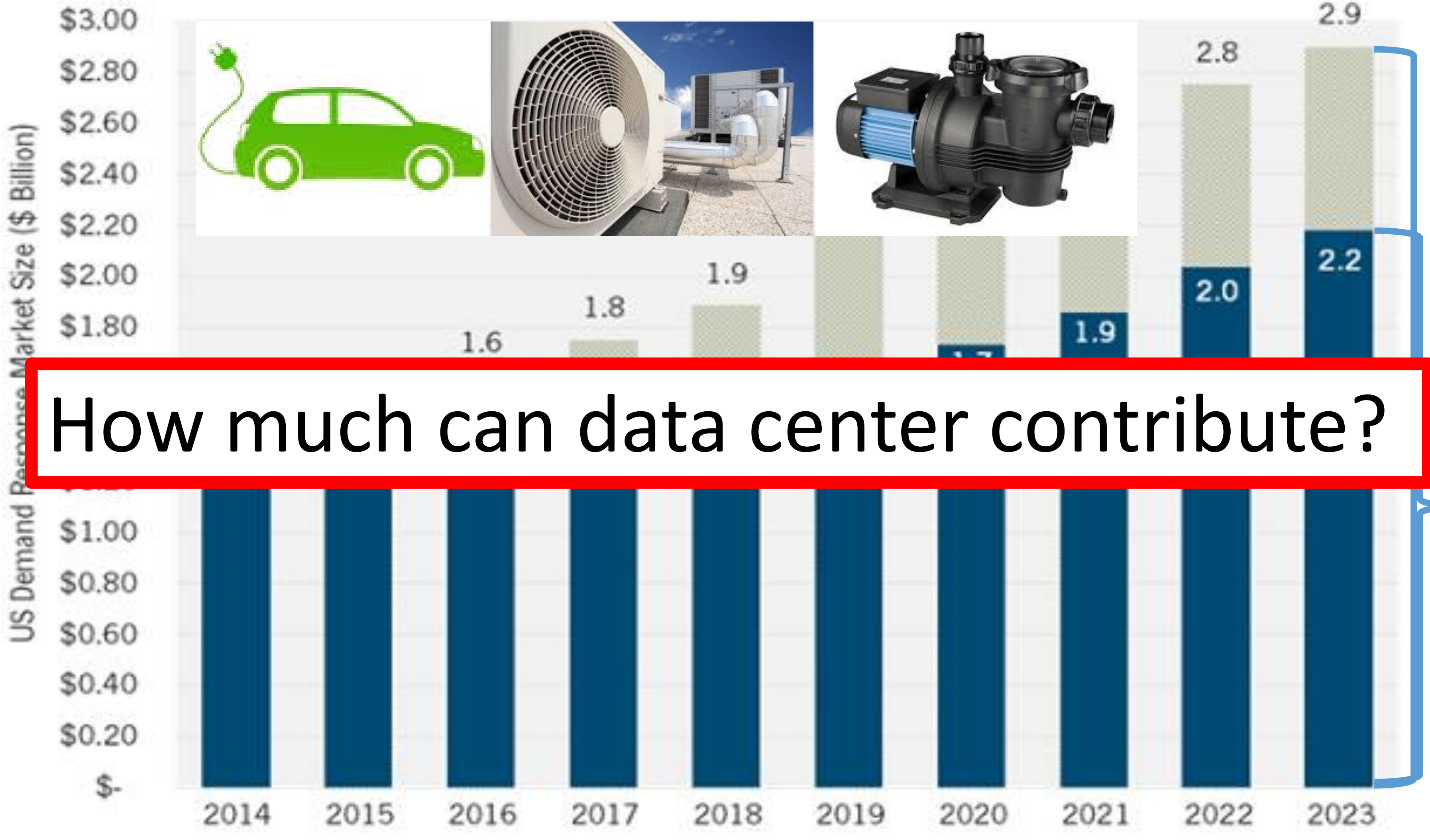


Finding DR resources is challenging



GTM research, “U.S. Demand Response Outlook 2014”

Finding DR resources is challenging



How much can data center contribute?

Aggressive estimate

Conservative estimate

GTM research, “U.S. Demand Response Outlook 2014”

Data centers have great potential for DR

~$5 million cost!

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

However, current participation is still 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

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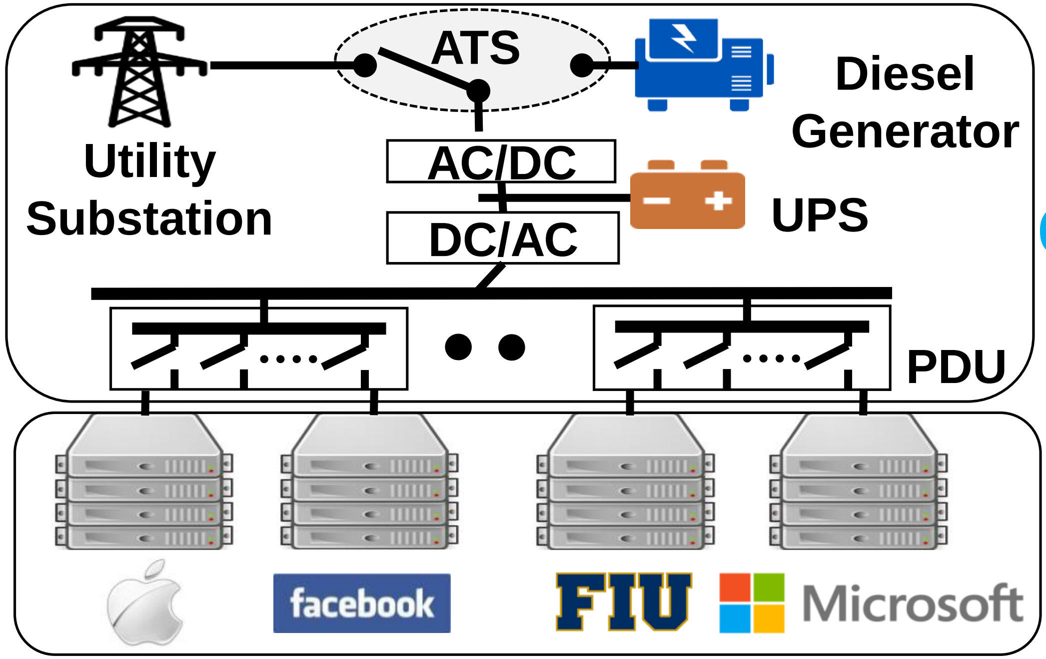
Data center operator is mainly responsible for facility support (e.g., power supply, cooling)



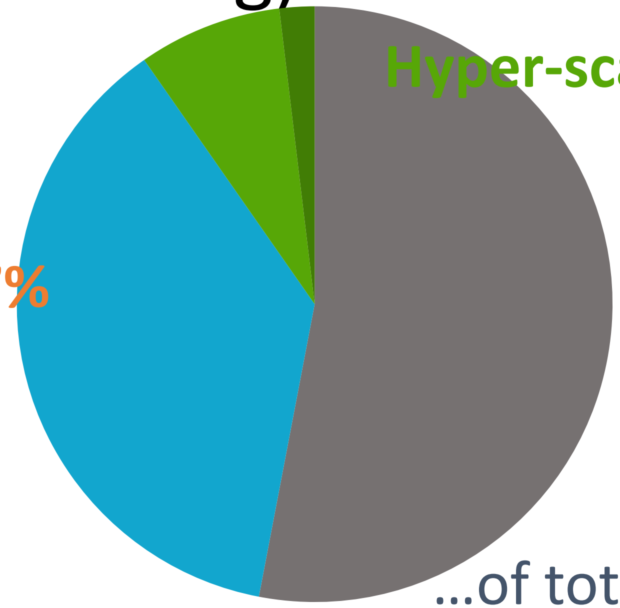
Operator

Tenants

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)



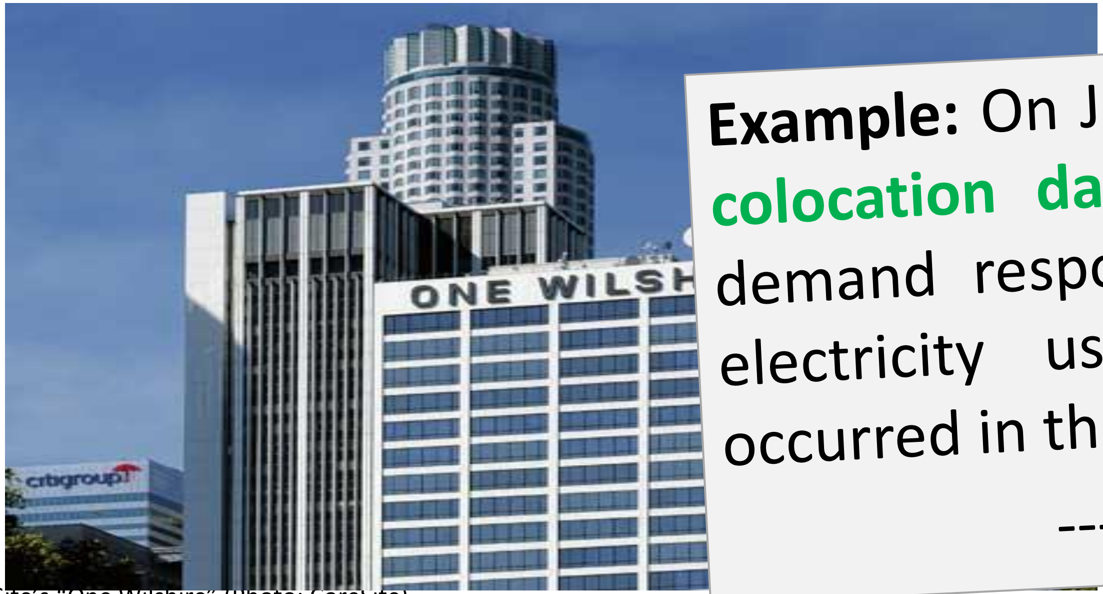
CoreSite's "One Wilshire" (Photo: CoreSite)

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!



CoreSite's "One Wilshire" (Photo: CoreSite)

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.

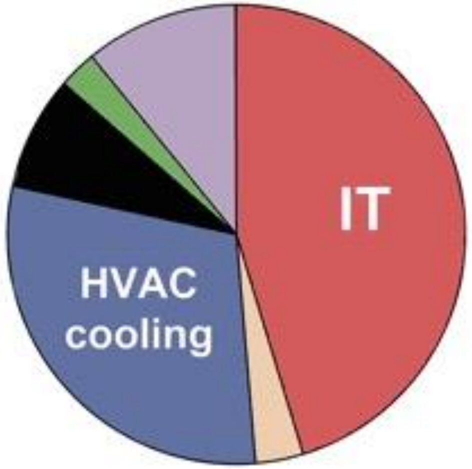
--- A. Misra, "Responding Before Electric Emergencies."

How do multi-tenant data center provide DR?

- Turn on **diesel generator** upon utility's request
  - Costly and environmentally unfriendly

Opportunity:

Tenants typically have great flexibility in energy usage



[LBNL,HP] workload management can save 10-30+% in server energy 10-60min

We should buy energy reduction from tenants!

Goal: $$\min\ \alpha \cdot y + \Sigma_i c_i(s_i)$$

$$\text{s.t. } y + \Sigma_i s_i = \delta$$

y: amount of local generation   **α**: price for diesel

s_i: load reduction of tenant ***i*** c_i: cost of reduction of tenant ***i***

Goal: $\min \ \boxed{\alpha \cdot y} + \boxed{\Sigma_i c_i(s_i)}$

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cost of local generation cost of load reduction

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meets energy reduction target

y: amount of local generation

$\boldsymbol{\alpha}$: price for diesel

$\boldsymbol{s_i}$: load reduction of tenant ***i***

$\boldsymbol{c_i}$: cost of reduction of tenant ***i***

Our contribution: a simple and provably efficient mechanism to incentivize tenants' reduction

Goal: $$\min \ \alpha \cdot y + \Sigma_i c_i(s_i)$$

$$\text{s.t.} \ \ y + \Sigma_i s_i = \delta$$

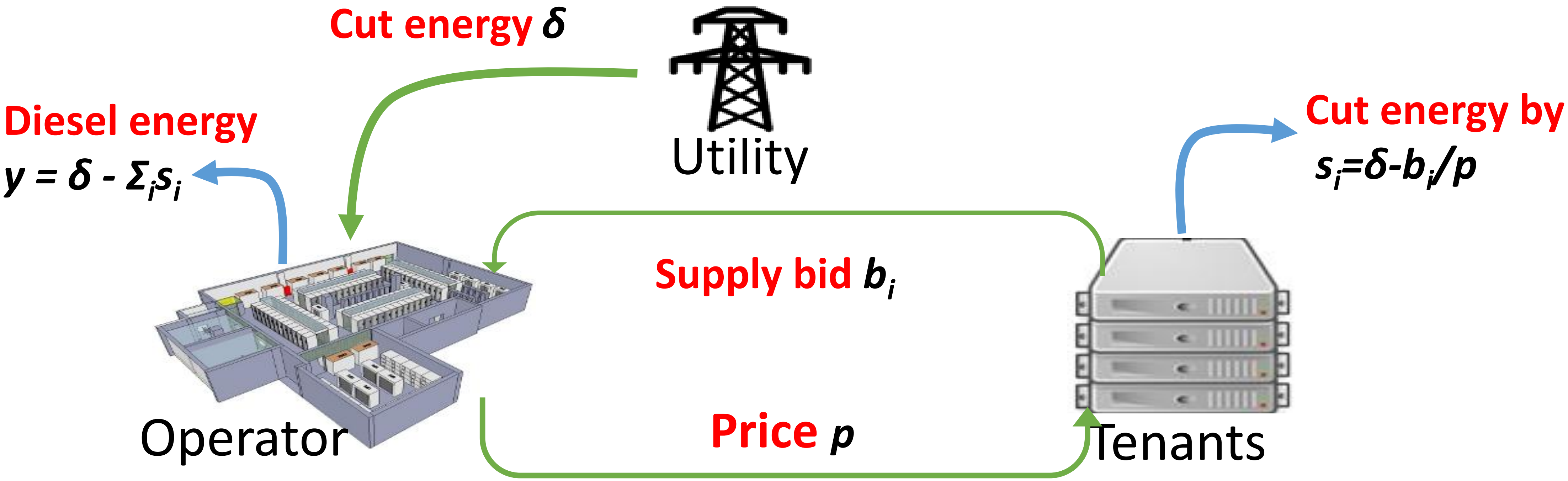
Operator's challenge:

1. No direct control of tenants' reduction s_i
2. Tenants' private cost c_i unknown

y: amount of local generation α: price for diesel

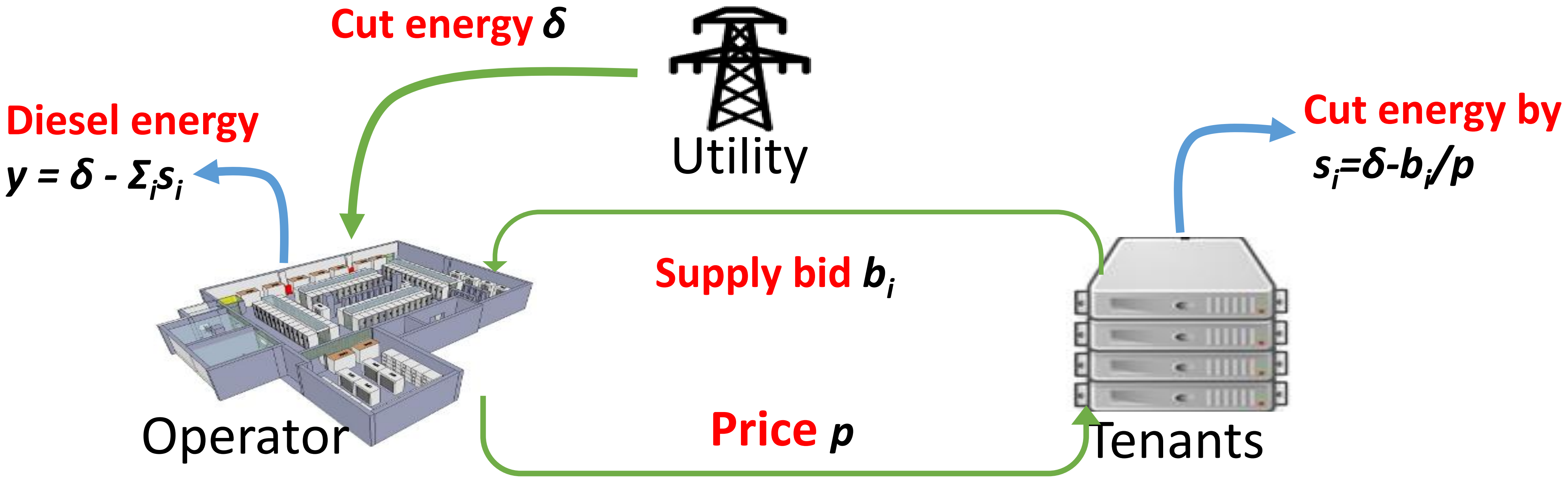
s_i: load reduction of tenant i c_i: cost of reduction of tenant i

ColoDR: a supply function mechanism for DR



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 it own cost (payment to tenants plus diesel cost)
4. DR is exercised

ColoDR: a supply function mechanism for DR



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(more on this later)

Why supply function bidding?

1. VCG type mechanisms are problematic
   [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]

How well does **ColoDR** work?

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 should we compare to?

Benchmark: Centrally controlled social cost minimization (SCM)

$$\min \ \alpha \cdot y + \Sigma_i c_i(s_i)$$

$$\text{s.t. } \ y + \Sigma_i s_i = \delta$$

Tenant behavior for ColoDR

Price-**taking:** Consider the price as is:

$$\max_{b_i} \ p \cdot S_i(b_i, p) - c_i(S_i(b_i, p))$$

Price-**anticipating:** Consider the impact of bidding decisions on the market price:

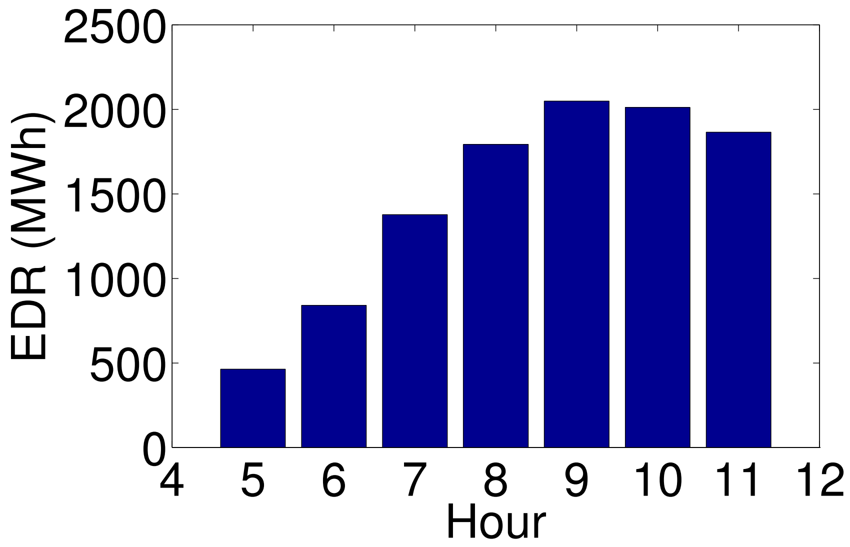
$$\max_{b_i} \ p(\mathbf{b}) \cdot S_i(b_i, p(\mathbf{b})) - c_i(S_i(b_i, p(\mathbf{b})))$$

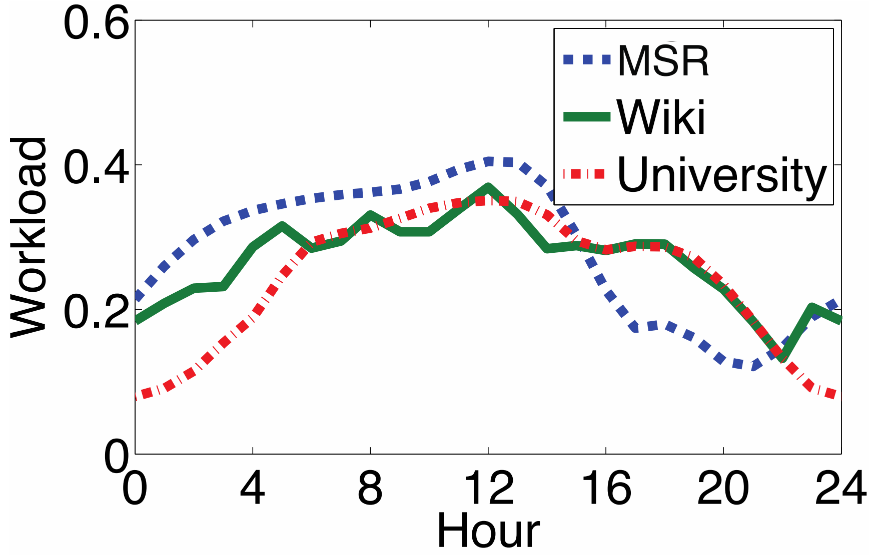
What should we compare to?

Case study

DR signals issued by PJM on January 7, 2014, due to cold weather.

Three different types of workload with different tolerance to delay.

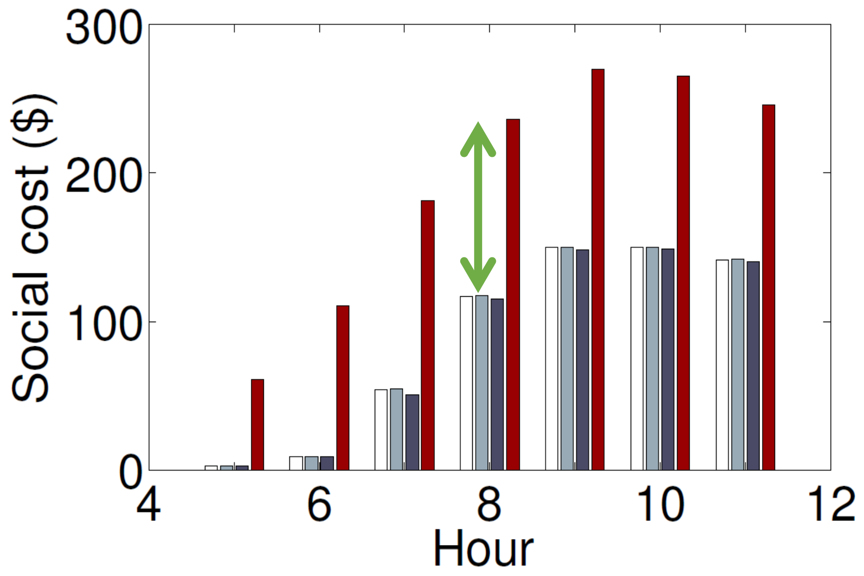


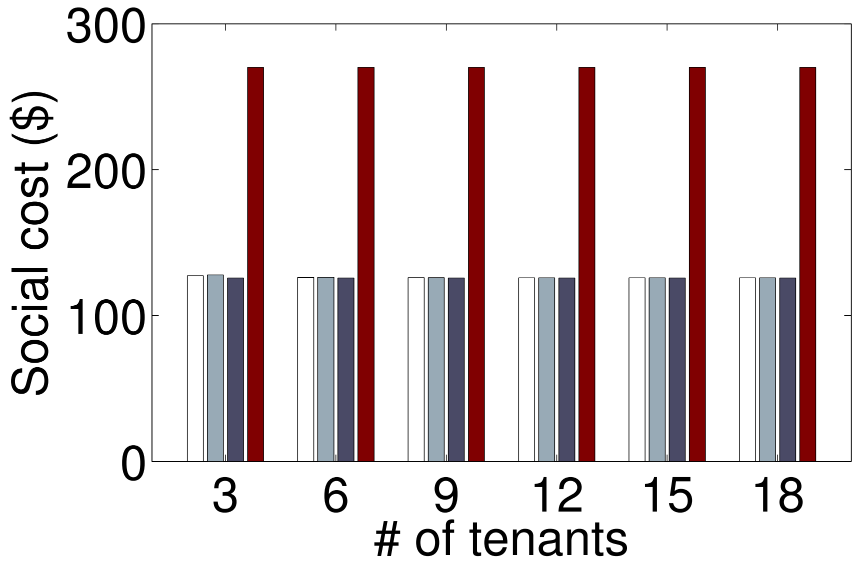


1. What is the social cost?

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

$$\mathrm{cost}(\mathrm{ColoDR}) \le \mathrm{cost}(\mathrm{SCM}) + \alpha\delta/N$$



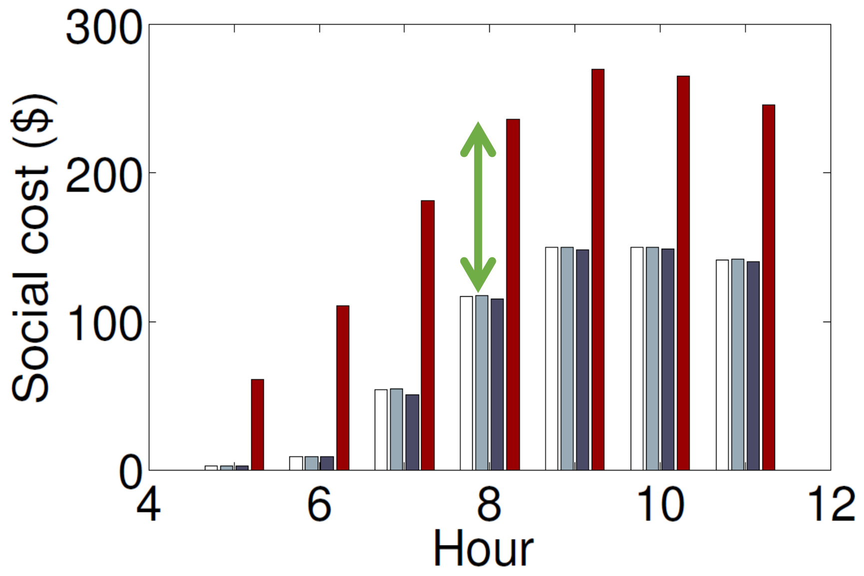


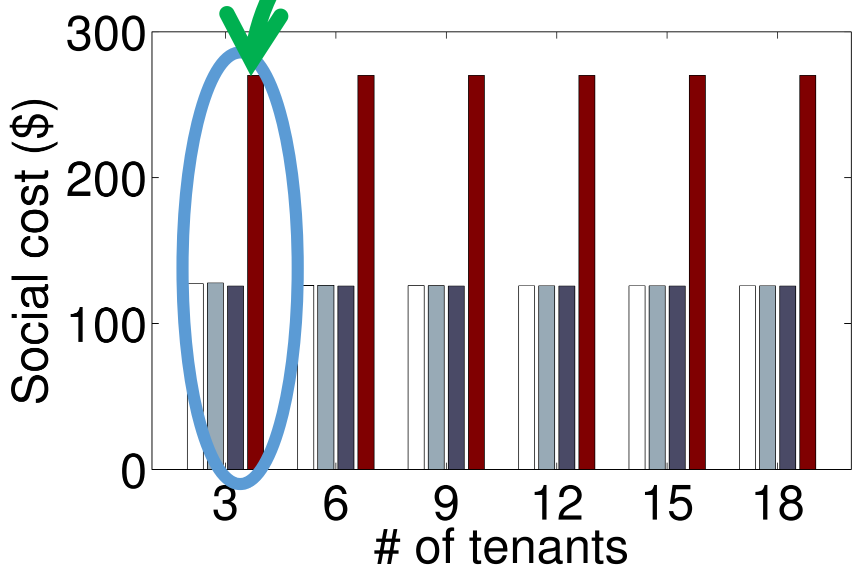
1. What is the social cost?

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

$$\text{cost}(\text{ColoDR}) \leq \text{cost}(\text{SCM}) + \boxed{\alpha\delta/N}$$

Near optimal when N is small





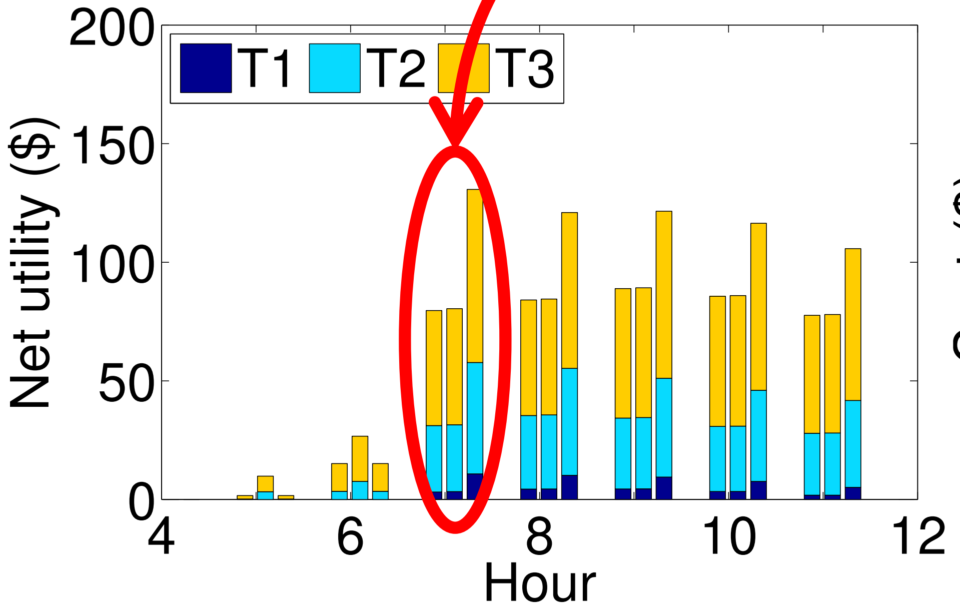
➔ ColoDR(price-taking) ColoDR(price-anticipating) SCM Diesel-only

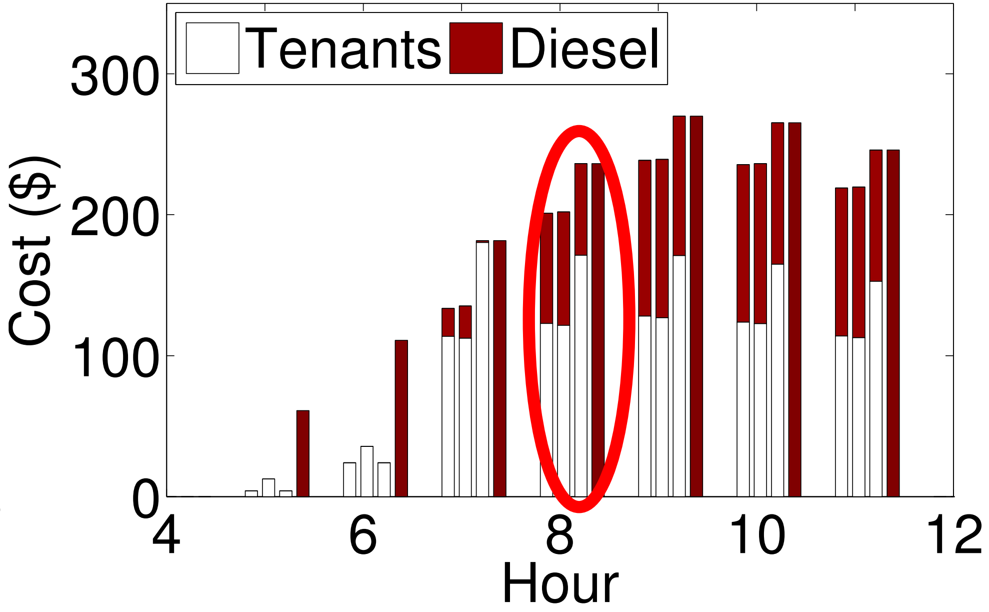
2&3. What are tenants' and operator's costs?

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

$$\mathrm{cost_t(ColoDR)} \leq \mathrm{cost_t(SCM)} + 2\alpha\delta/N$$
$$\mathrm{cost_o(ColoDR)} \geq \mathrm{cost_o(SCM)} - \alpha\delta/N$$

Higher utility for tenants with larger flexibility



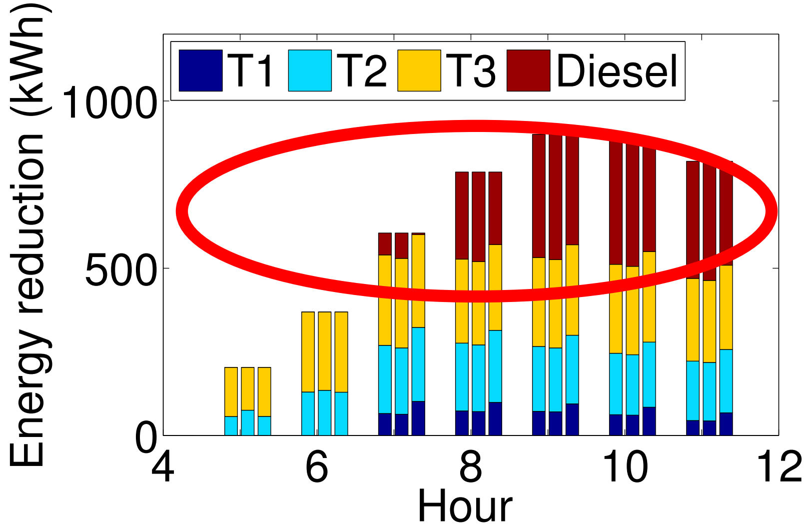


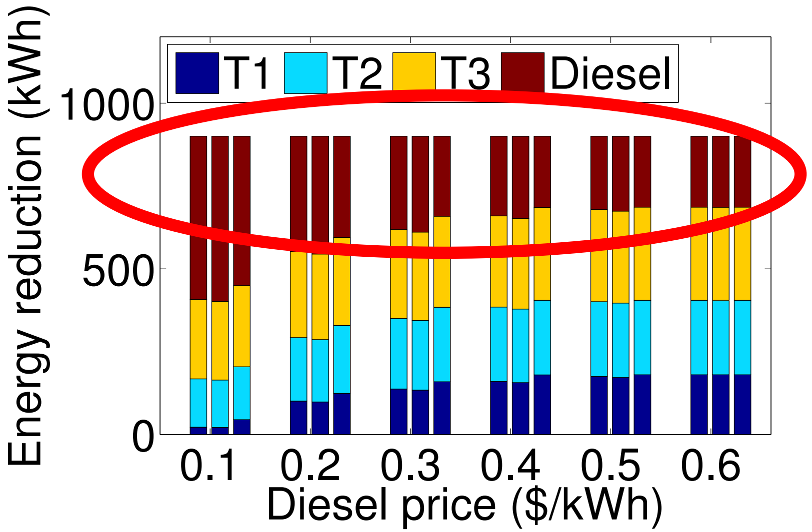
➔	ColoDR(price-taking)	ColoDR(price-anticipating)	SCM	Diesel only

4. What is the reduction in diesel usage?

Theorem: For both **price-taking** tenants, $y^t \le y^* + \delta/2$
for **price-anticipating** tenants, $\boxed{y^a \le y^* + \delta}$

In worst case, ColoDR may use a lot more diesel than optimal





➔ ColoDR(price-taking) ColoDR(price-anticipating) SCM

How well does **ColoDR work**?

1. What is the social cost?

$$\mathrm{cost}(\mathrm{ColoDR}) \leq \mathrm{cost}(\mathrm{SCM}) + \alpha\delta/N$$

2. What is tenants' cost?

$$\mathrm{cost_t}(\mathrm{ColoDR}) \leq \mathrm{cost_t}(\mathrm{SCM}) + 2\alpha\delta/N$$

3. What is operator's profit?

$$\mathrm{cost_o}(\mathrm{ColoDR}) \geq \mathrm{cost_o}(\mathrm{SCM}) - \alpha\delta/N$$

4. What is the reduction in diesel usage?

$$y^t \leq y^* + \delta/2 \qquad\qquad y^a \leq y^* + \delta$$

All these follow from one key characterization lemma

A characterization lemma

Characterize equilibrium as the outcome of an optimization problem

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

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

$$\text{s.t.} \ \ \Sigma_i s_i + y = \delta$$

Due to strategic behavior of operator

A characterization lemma

Characterize equilibrium as the outcome of an optimization problem

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

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

$$\text{s.t. } \Sigma_i s_i + y = \delta$$

Strategic behavior of tenants

Strategic behavior of operator

where

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

Two messages

#1: Multi-tenant data center DR is a billion dollar market

- Turning an energy hog into a social asset!

#2: Multi-tenant data center demand response can be “green” by incentivizing tenants’ cooperation

- Our proposed mechanism based on supply function bidding incentivizes and coordinates tenants’ energy shedding, with a provably-efficient outcome.