A Business Model for Load Control Aggregation to Firm Up Renewable Capacity

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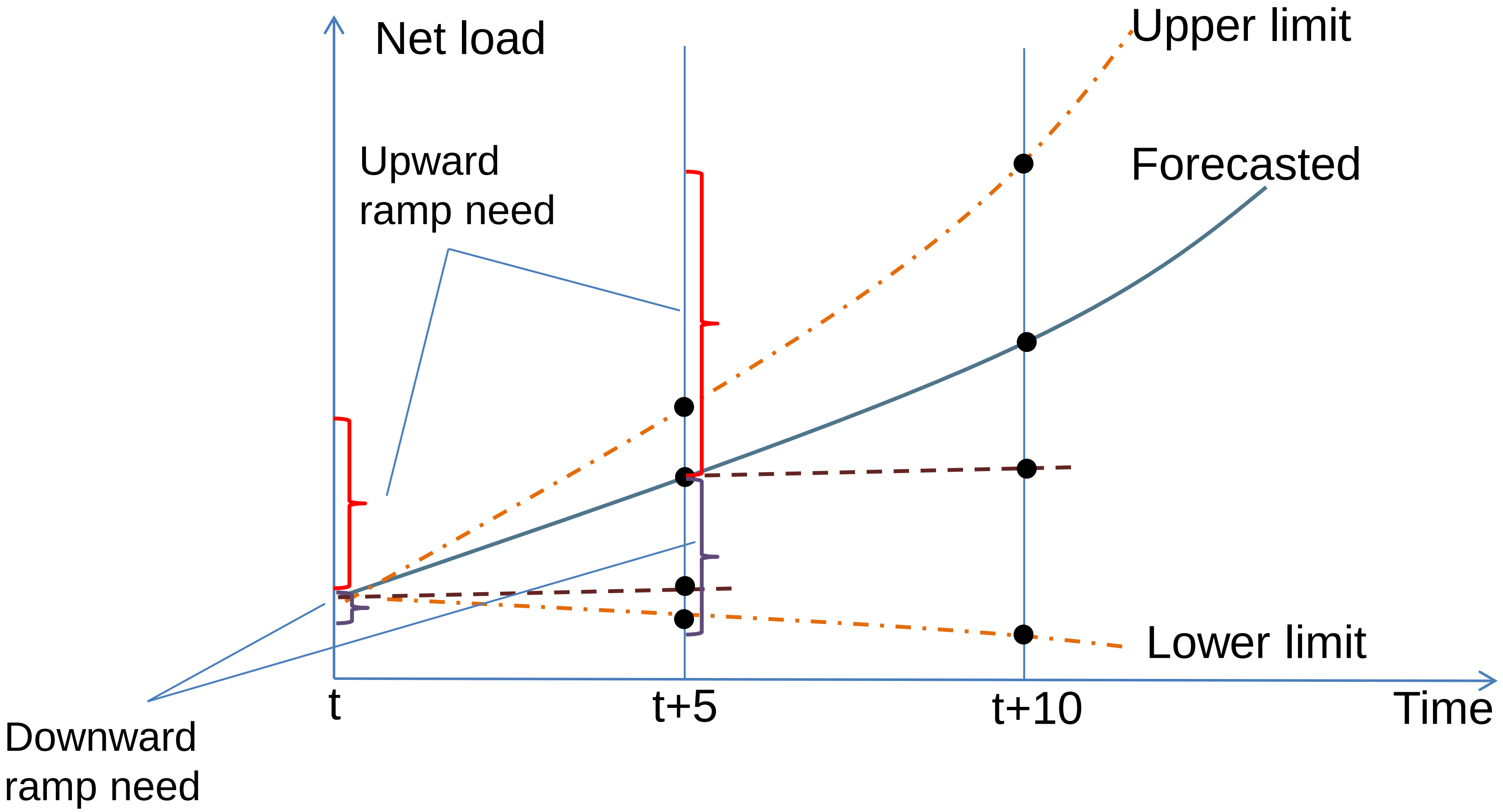
General Observations About Demand Response

- While today’s metering and control technology is cheaper, technology was never a barrier to implementation of demand response
- The focus has been (as now) on demonstration of capability, rather than on developing a business model that will facilitate implementation.
- The key elements to making demand response a reality are:
  - A regulatory framework
  - Institutional structure
  - A sustainable business model that will incentivize customer choice at the retail level and produce valuable products for the wholesale market (ISO)

Economic *Paradigms for Demand Response*

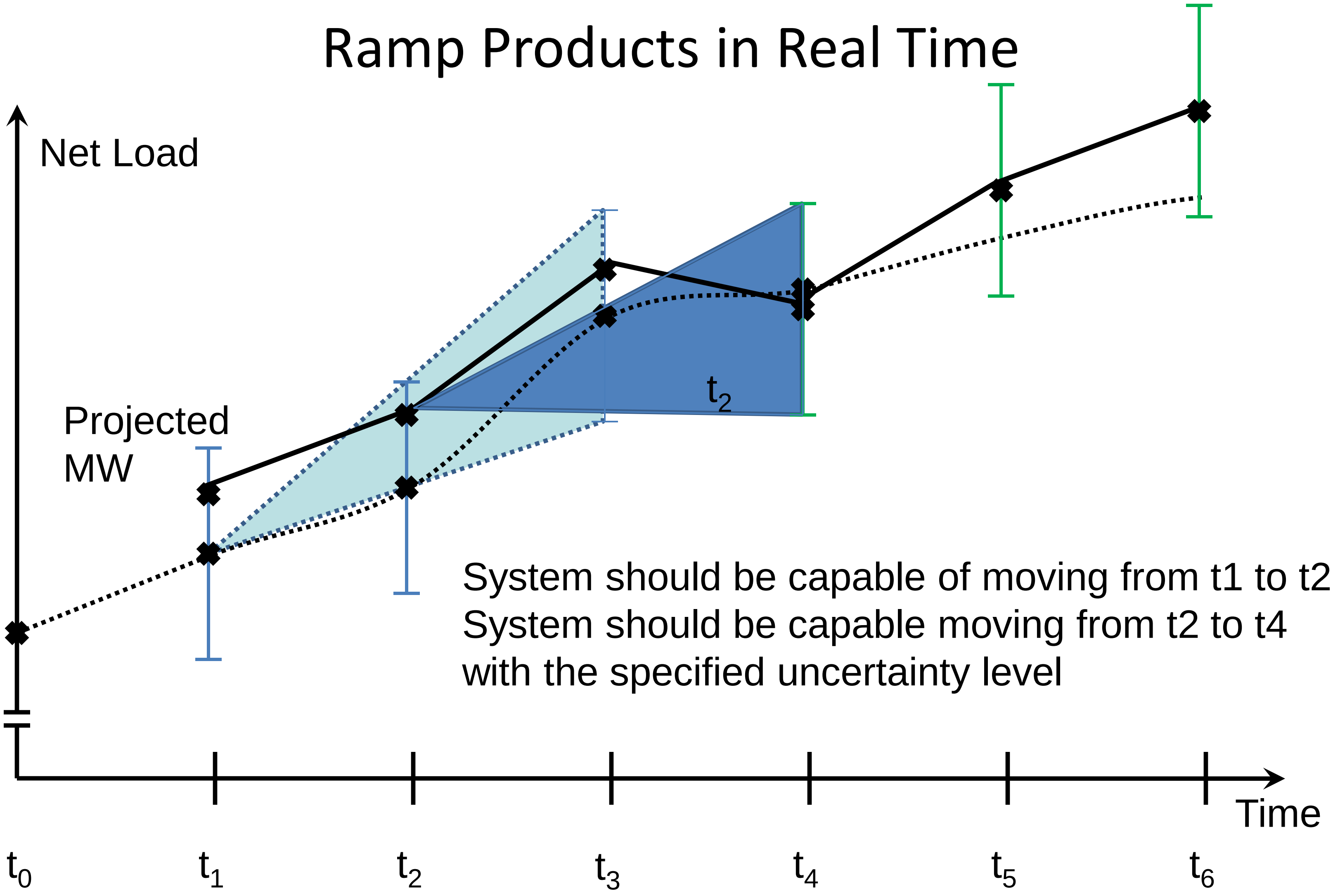
- Provide real time prices to retail customers
  - Economists gold standard
  - Treating electricity as a commodity works well at wholesale level but at retail level treating electricity as a service may be preferable (classic economic debate of price vs. quantity)
  - RT price response can suppress energy price spikes but does not address need for A/S or short term flexible ramping products

Model of flex ramp in multi interval optimization



Ramping constraints will be enforced for every interval in the study horizon

Ramp Products in Real Time



System should be capable of moving from t1 to t2
System should be capable moving from t2 to t4
with the specified uncertainty level

From The CAISO 2014 DMM Report

“While there are many economists that are enthusiastic about DR for all consumers, we are not aware of a reported success of real-time pricing for a big, heterogeneous population area that could serve as a benchmark. Mobilizing retail level demand side flexibility to reduce operating and investment cost in the electricity sector by employing smart grid technologies and market mechanism is still regarded as “work in progress”

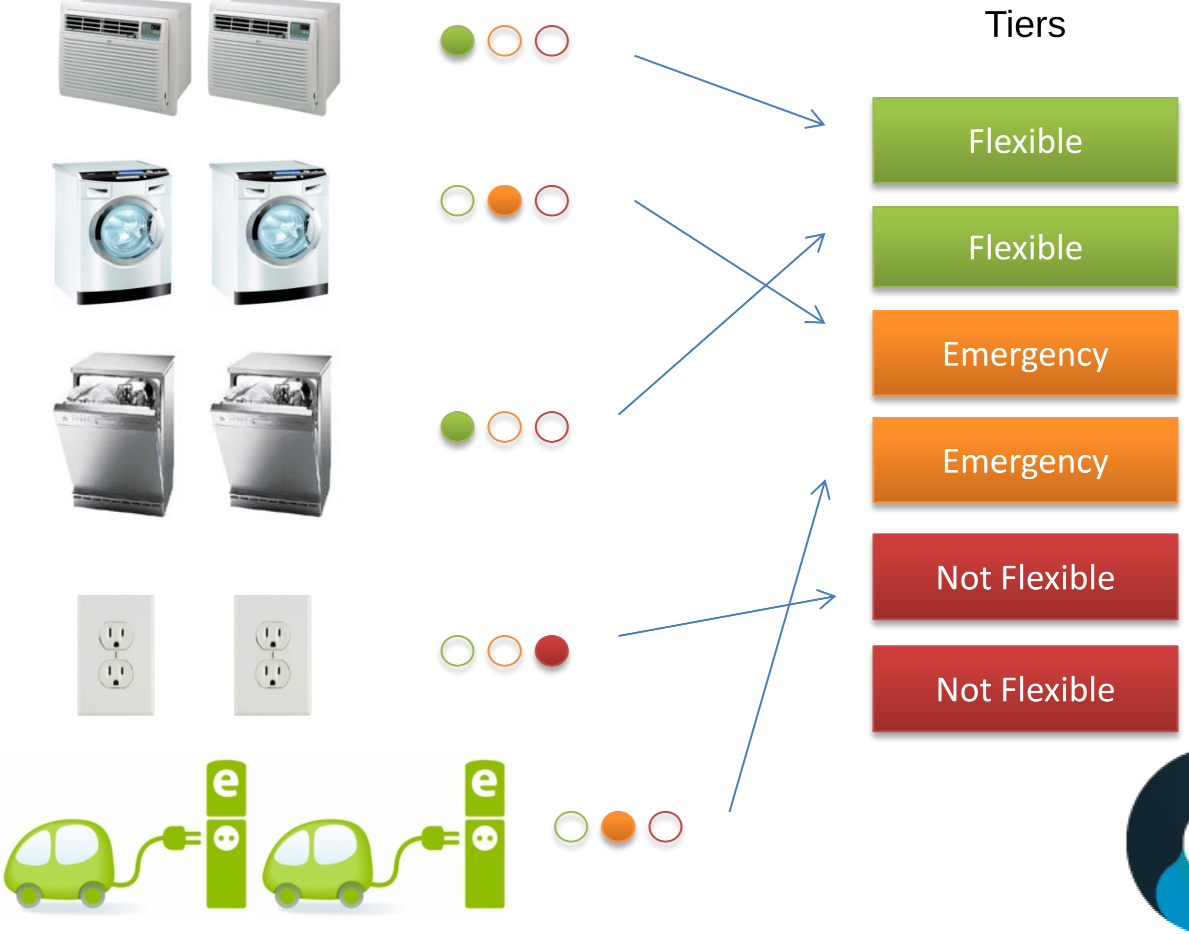
Economic *Paradigms for Demand Response (cont'd)*

- Provide quality differentiated service based on contracted load control options.
  - Quality differentiated service and optional price plans are common in other service industries (air transportation, cell phone, insurance)
  - Customers have experience with choosing between alternative service contracts

The Challenge

- ❑Need Business model and economic paradigm for a utility or third party aggregator to bridge the gap between wholesale commodity market and retail service
- ❑Aggregated retail load control can be bid into the wholesale markets for balance energy, flexible ramping, contingency reserves products or ancillary services.
  - ➢ Load control through direct device control (thrmostats, airconditioners, water heaters, EV battery charge)
    - o Intrusive
    - o Faster response enables higher valued products (e.g. regulation)
  - ➢ Or control of power through the meter with customer self-dynamic control of allocation to devices in the home.

Appliance Control Paradigm



Aggregation Tiers

Flexible

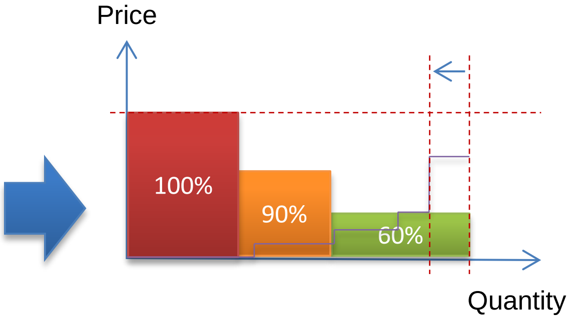
Flexible

Emergency

Emergency

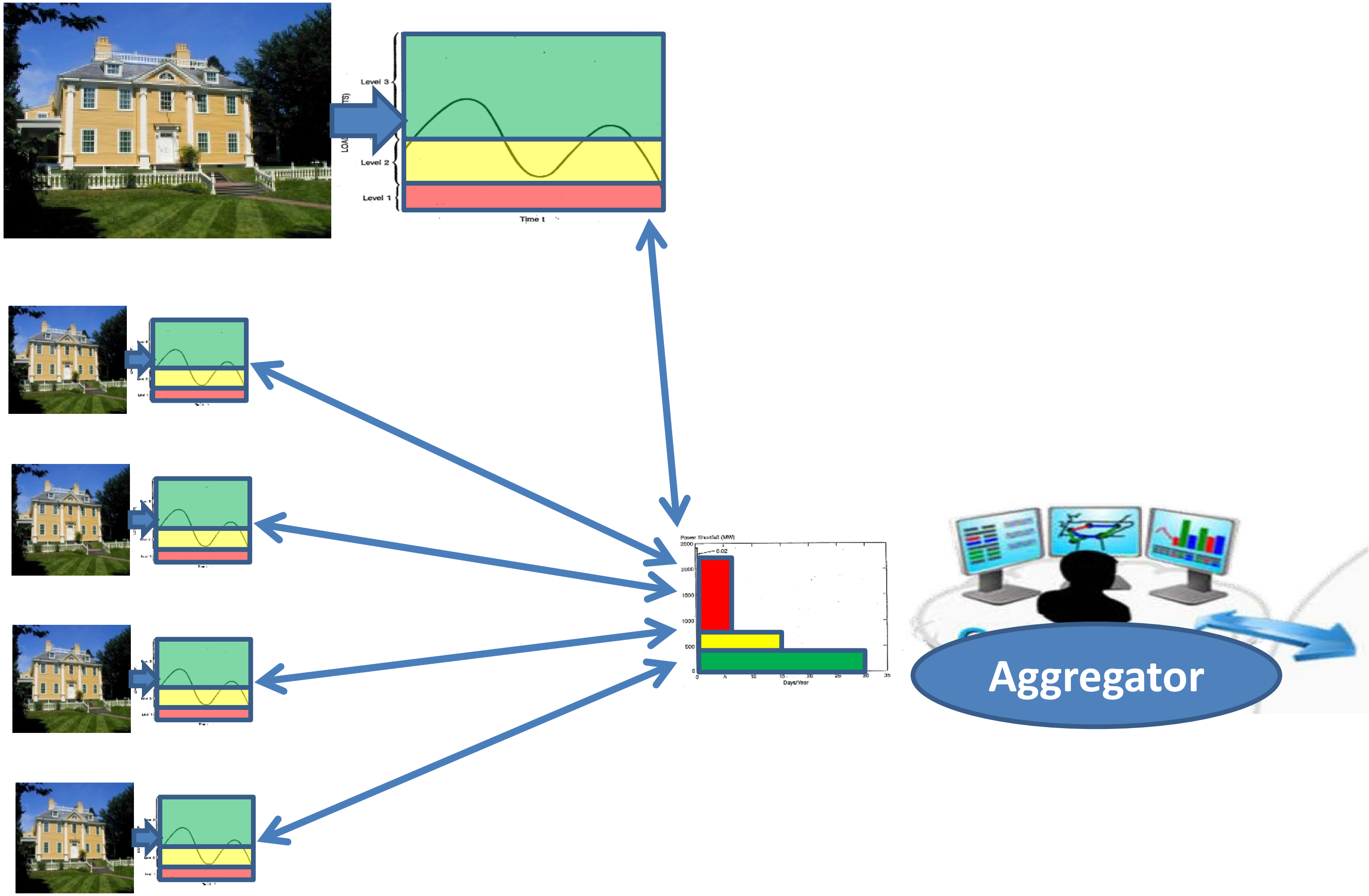
Not Flexible

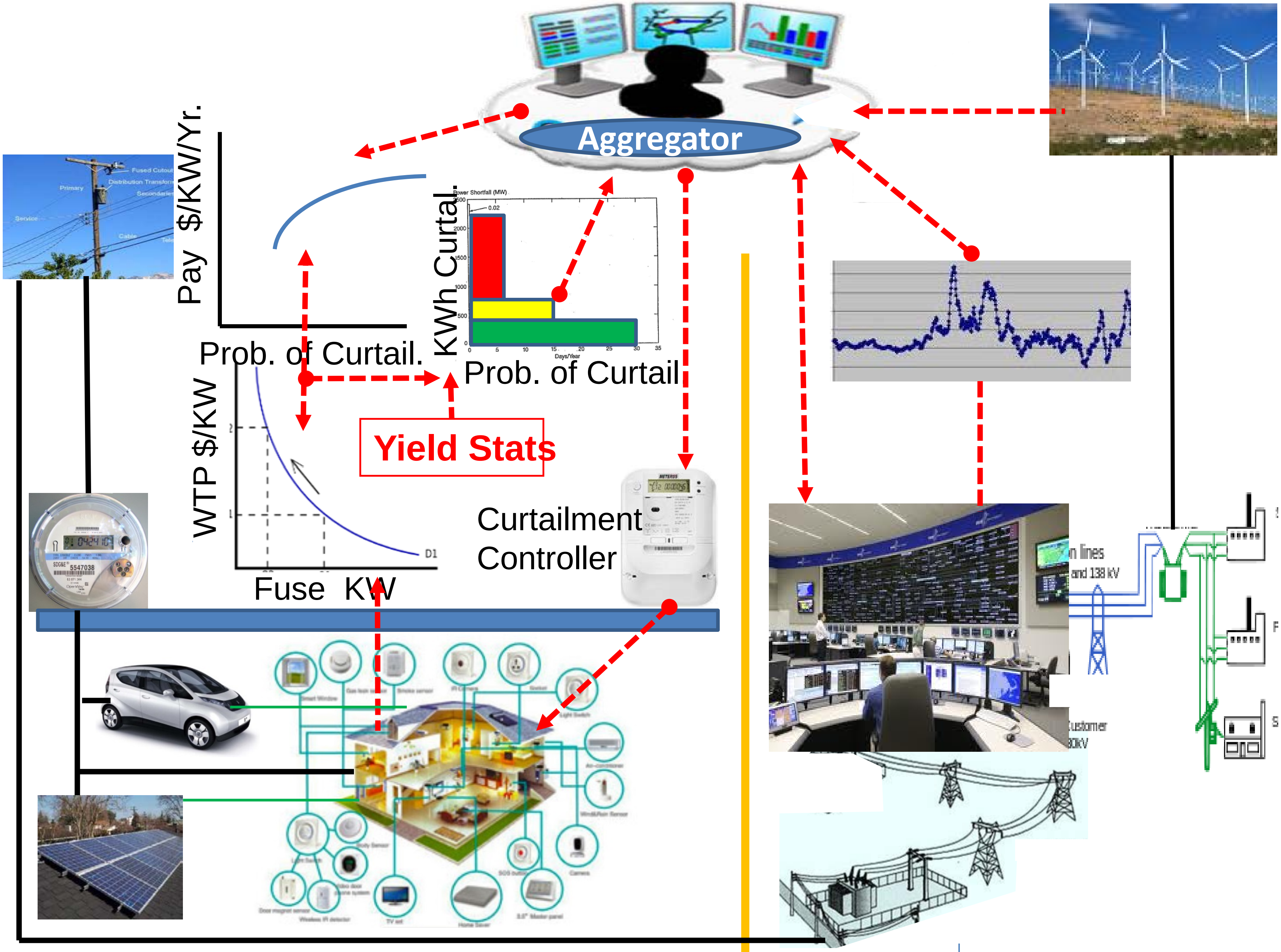
Not Flexible



Fuse Control Paradigm

Stratification of Demand into Service Priorities





Aggregator

Pay $/KW/Yr.

Prob. of Curtail.

KWh Curtal.

Prob. of Curtail

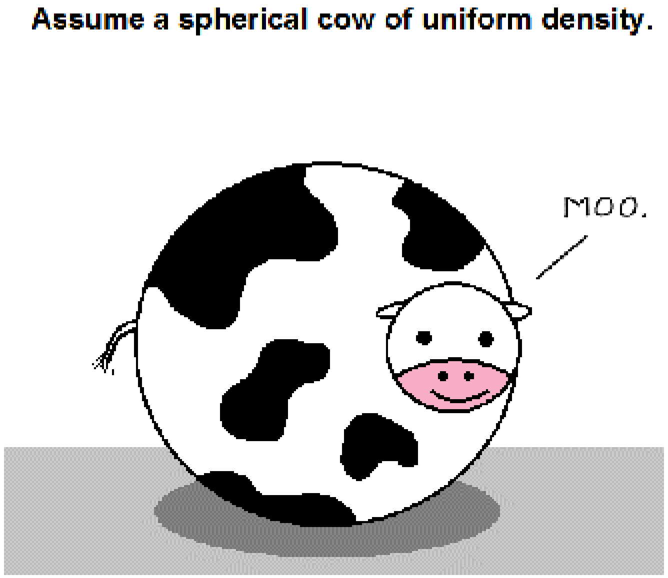
WTP $/KW

Fuse KW

Yield Stats

Curtailment Controller

Regulatory Framework



- Renewable resources must have incentives to firm up their supply.
  - Eliminate feed-in tariffs and require renewables to schedule (at least in the 15 minute market)
  - Enable firmed up renewable resources (bundled with flexible load) to receive capacity payments
- Implement demand charges at retail level which can be adjusted based on curtailment options

Research Agenda

- ❑ Validation of the Fuse Control Paradigm by evaluating efficiency loss due to aggregation and hierarchical control
- ❑ Mechanism design for mobilizing load response
- ❑ Integrated planning model for load control aggregation with firming up of wind supply

- ☐ Validation of the Fuse Control Paradigm by evaluating efficiency loss due to aggregation and hierarchical control
- ☐ Mechanism design for mobilizing load response
- ☐ Develop planning model for load control aggregation and for firming up wind supply

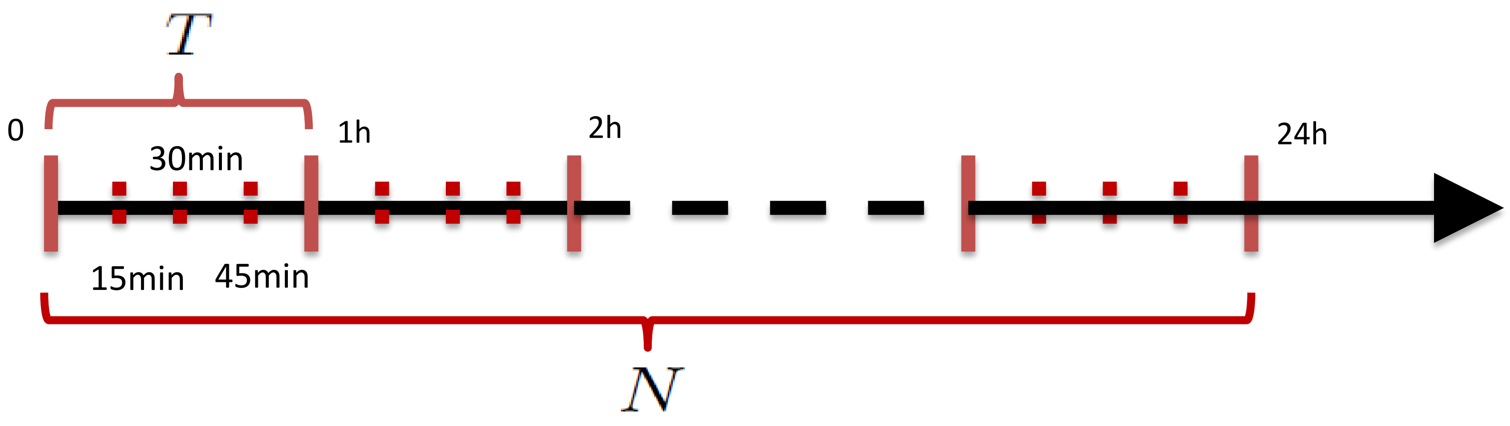
Fuse control problem formulation

Consider $k = 1.\ldots.N$ time intervals

1. Fixed loads: $P_L^j(k),\ j = 1, \ldots, N_L$
2. Photovoltaic power (PV) forecast: $P_{PV}^j(k),\ j = 1, \ldots, N_{PV}$
3. Flexible loads: $P_c^j(k),\ j = 1, \ldots, N_c$
4. Fuse limit: $P_f(i)$ for $i = 1, \ldots, N/T$ (reset every T time intervals)
5. PV forecast error: $\delta^j(k),\ j = 1, \ldots, N_{PV}$ $\delta^j = [\delta^j(1) \ldots \delta^j(N)]$

$$\delta = [\delta^1 \ldots \delta^{N_{PV}}] \in \Delta \sim \mathbb{P}$$

PV forecast error can also capture other net load uncertainties
Uncertainties can be characterized in terms of probability distributions,
Sample scenarios or uncertainty regions



Household allocation problem

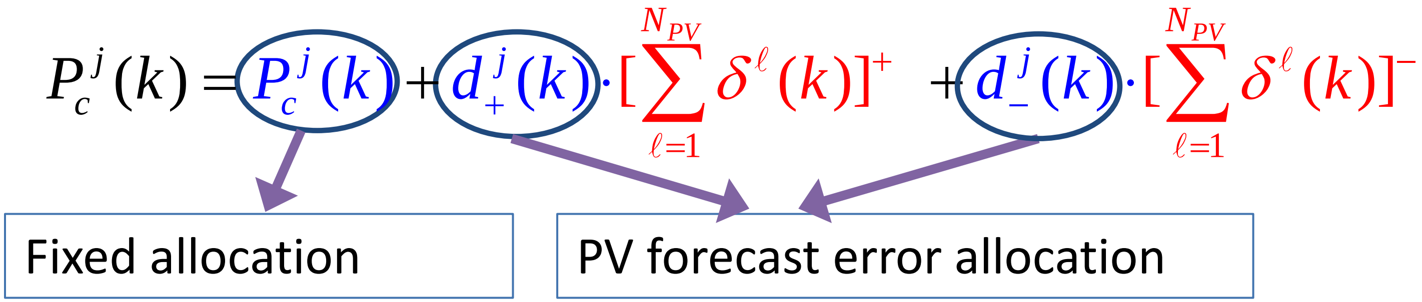
Objective: Minimize expected or worst-case value of total load disutility

(Disutility: Weighted difference of the scheduled value of each load from a baseline profile)

subject to:

- Fuse limit
- Load flexibility margins
- Allocation constraints

Assume affine allocation rule in response to uncertainty



$$P_c^j(k) = P_c^j(k) + d_+^j(k)\cdot\Big[\sum_{\ell=1}^{N_{PV}} \delta^\ell(k)\Big]^+ + d_-^j(k)\cdot\Big[\sum_{\ell=1}^{N_{PV}} \delta^\ell(k)\Big]^-$$

Fixed allocation

PV forecast error allocation

Fuse control problem formulation

- Objective function (a closer look):

$$\sum_{k=1}^{N}\sum_{j=1}^{N_c}\mathcal{R}_{\delta\in\Delta}[U^j(k,\delta)]$$

- $\mathcal{R}_{\delta\in\Delta}\left[\,\cdot\,\right]$ - Risk metric, e.g. expected value, worst-case value

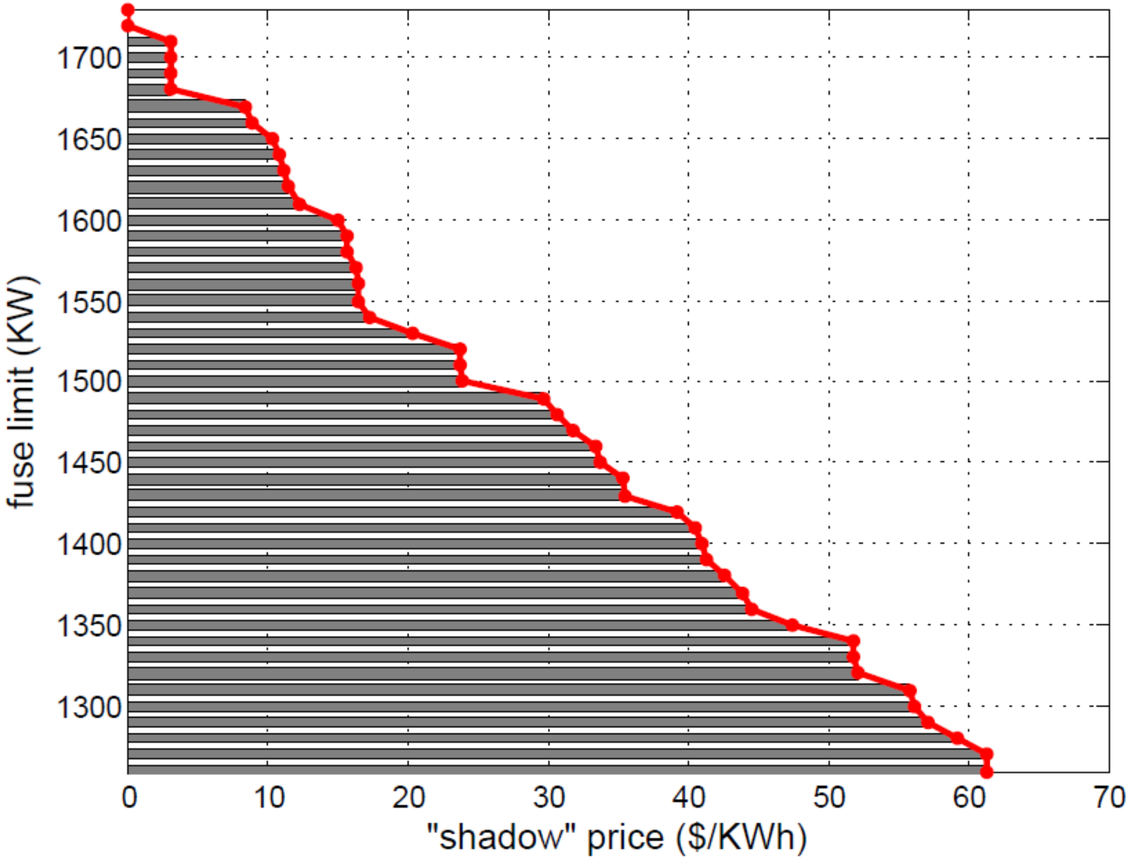
- $U^j(k,\delta)$ - Load disutility, difference from a baseline profile (load can only be curtailed)

$$U^j(k,\delta)=\boxed{\rho^j(k)}\left(P^j_{c,\mathrm{base}}(k)-P^j(k,\delta)\right)$$

Time, load dependant penalty factor

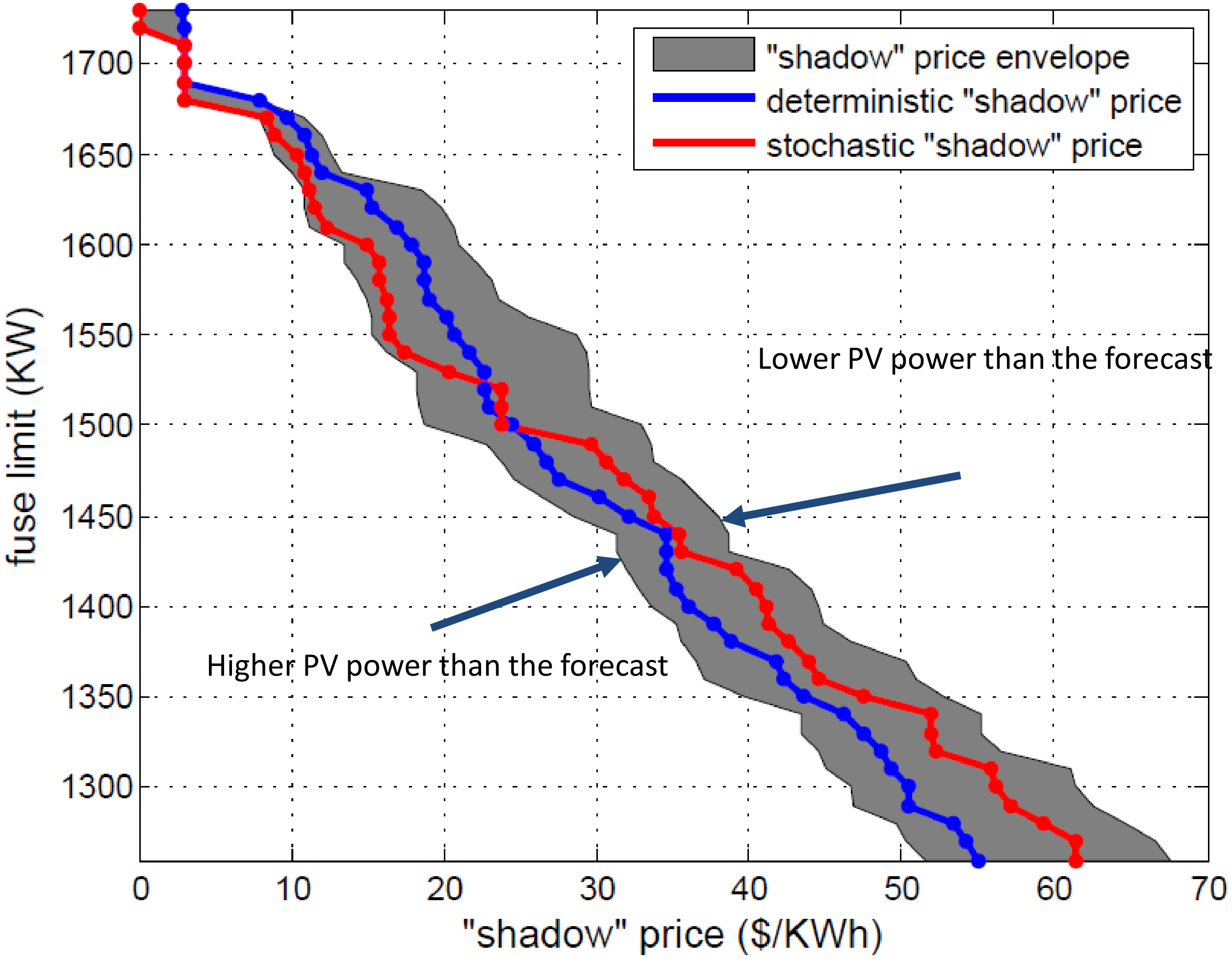
Fuse increment offer curve

For each fuse limit, shadow price is computed based on the two-step averaging procedure



Shadow Price envelope

If we extract sufficiently high # samples, stochastic curve lies inside the envelope with high probability (proof based on duality and randomized optimization)



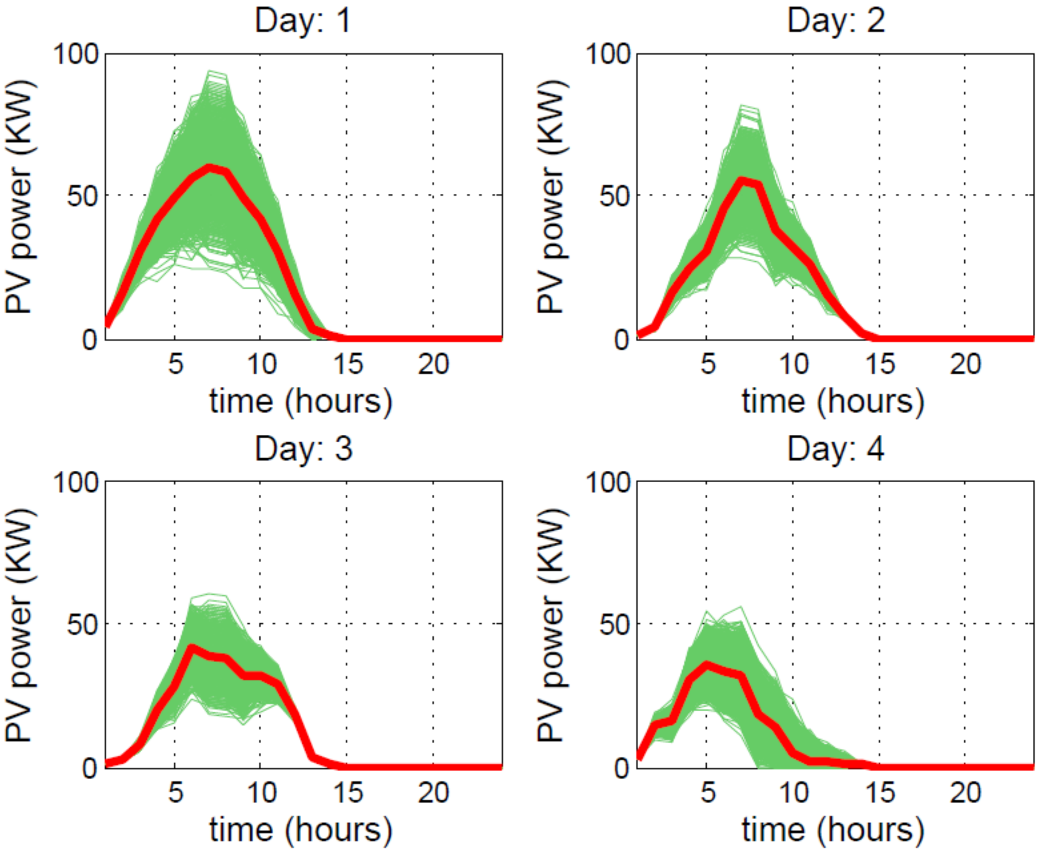
Lower PV power than the forecast

Higher PV power than the forecast

Simulation study

1. PV power profiles for 4 representative days within a month (used to construct average "shadow" prices for the demand curve)

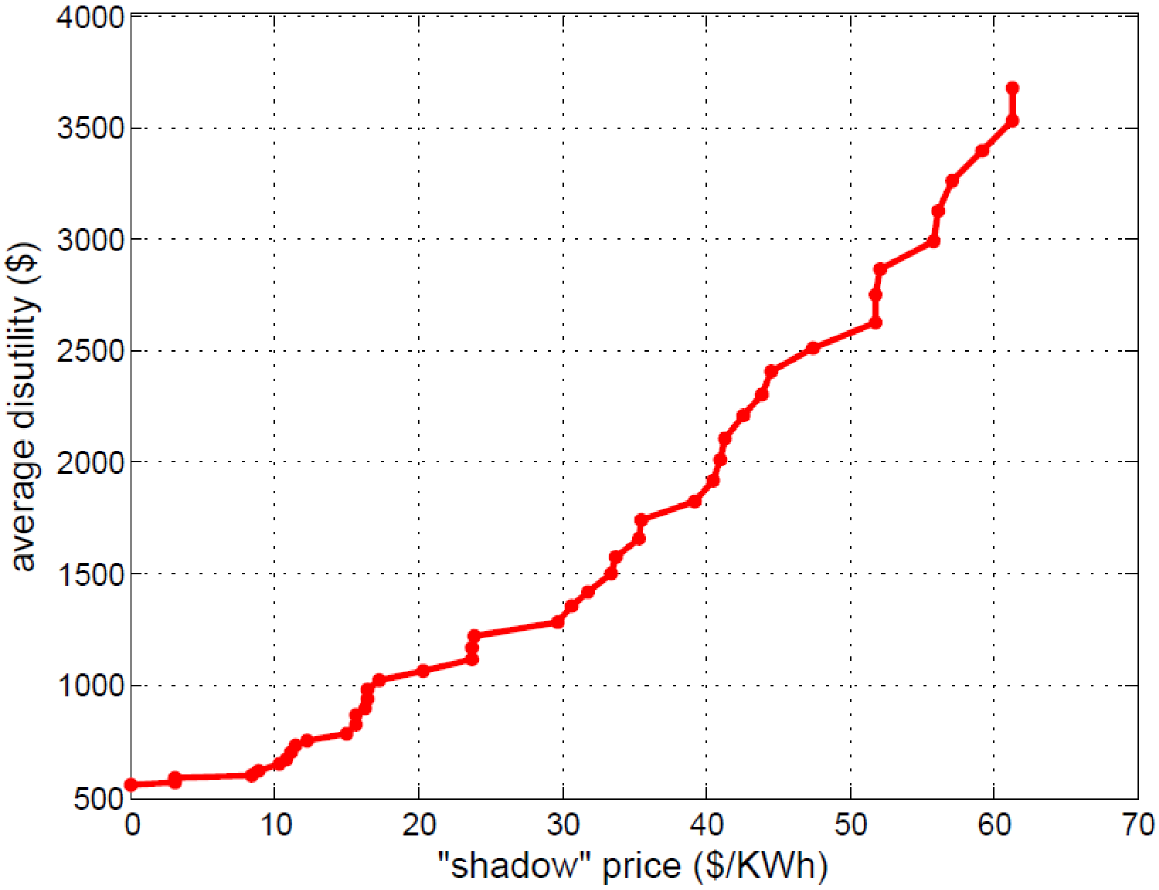
2. Scenarios generated via a discrete time stochastic process driven by Gaussian noise (correlation is taken into account)



Simulation study

For each fuse limit we use demand curve to compute disutility due to load curtailment

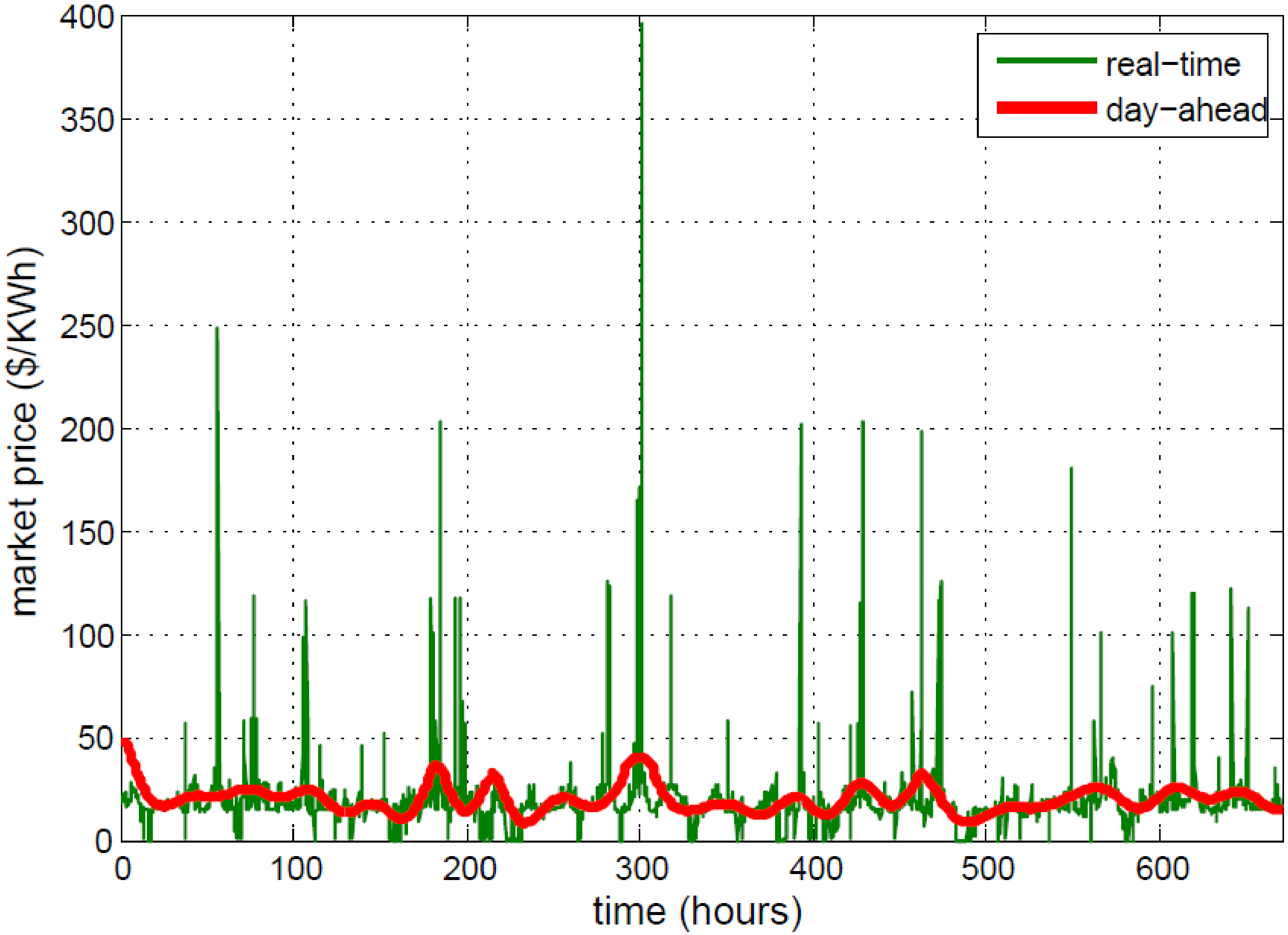
Disutility vs. ‘shadow’ price



Simulation study

1. Compare with a set-up where consumers respond to real-time market prices

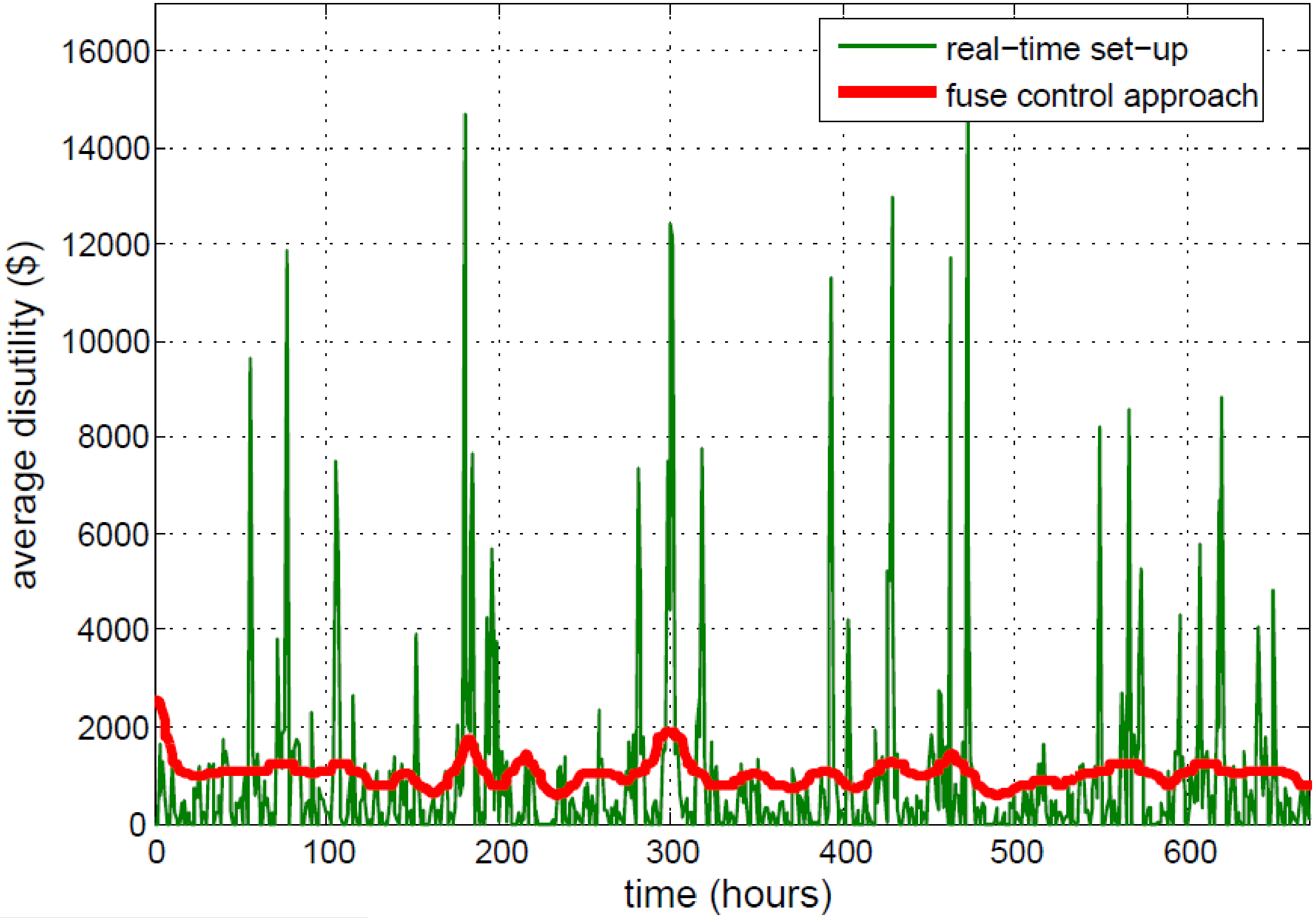
Market price profiles



Simulation study

1. Compare with a set-up where consumers respond to real-time market prices

Disutility

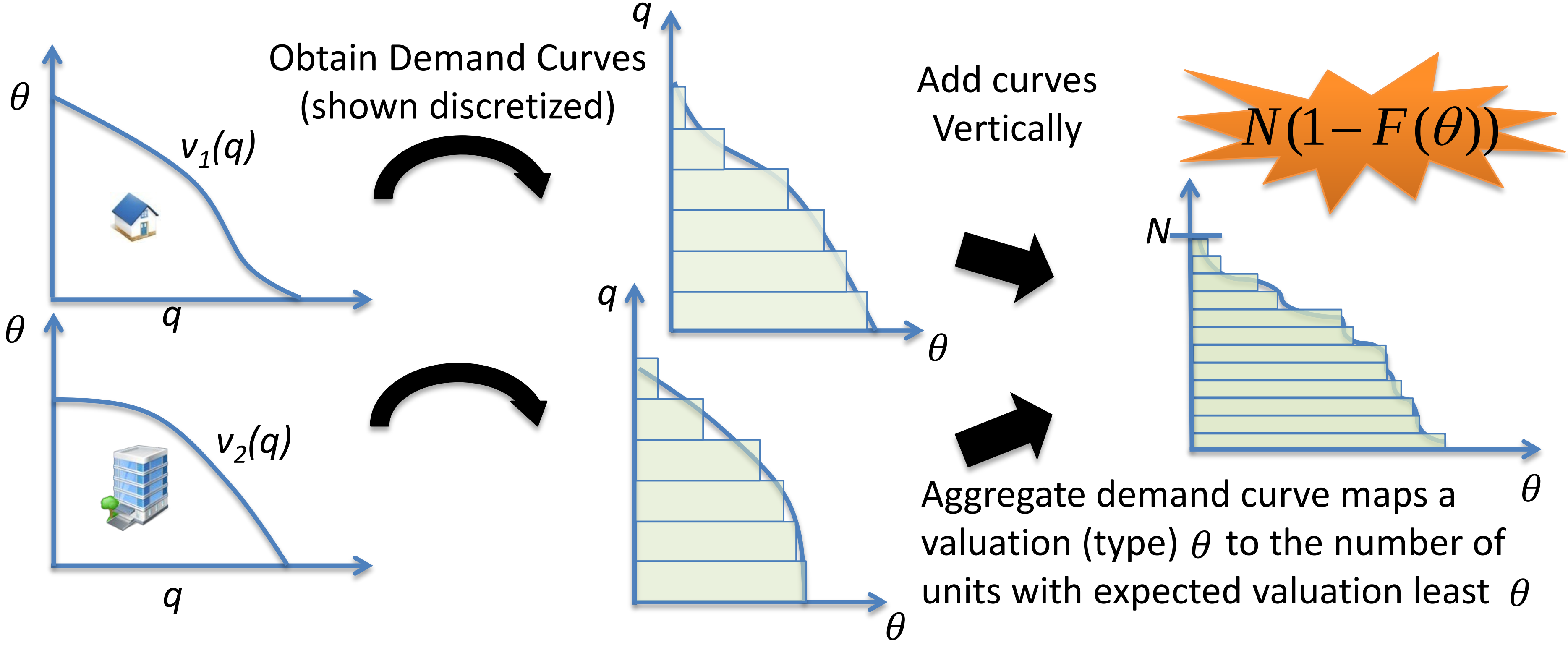


- 14.2 % higher disutility with the fuse control approach (information loss)

- Validation of the Fuse Control Paradigm by evaluating efficiency loss due to aggregation and hierarchical control
- Mechanism design for mobilizing load response
- Integrated planning model for load control aggregation with firming up of wind supply

The Customer Model

DR customers are represented in aggregate as a continuum of demand increments, each with an expected valuation θ (referred to as type). The aggregate demand curve is the CDF of types scaled to total load capacity *N*, $D(\theta) = N(1 - F(\theta))$



Obtain Demand Curves (shown discretized)

Add curves Vertically

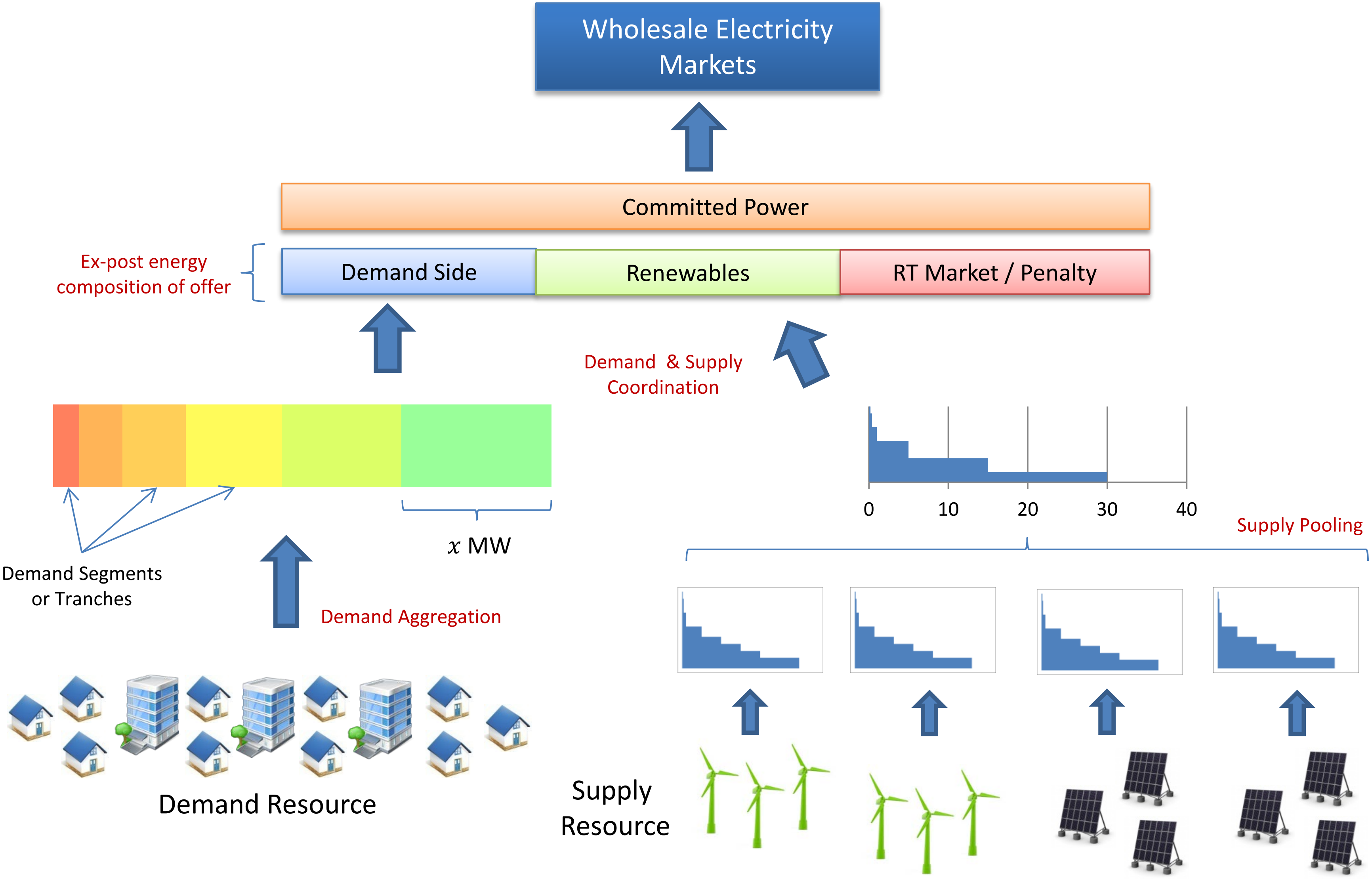
$N(1 - F(\theta))$

Aggregate demand curve maps a valuation (type) θ to the number of units with expected valuation least θ

The "Customer" Model (for each load segment)

- "Customer" values a unit of consumption at θ and faces retail rate p^R
  - ➥"Outside option" utility = $(\theta - p^R)^+$. (forgo contract)
- Pay load segment $t(\theta)$ for the right to curtail this segment with probability $1 - r(\theta)$.
- Customers are risk-neutral:
  - ➥utility with contract = $r(\theta - p^R)^+ + t(\theta)$

The Wholesale Product Offered by the Aggregator



Wholesale Electricity Markets

Committed Power

Ex-post energy composition of offer

Demand Side

Renewables

RT Market / Penalty

Demand & Supply Coordination

x MW

Demand Segments or Tranches

Demand Aggregation

Demand Resource

Supply Pooling

Supply Resource

The Aggregator's Operations

- Aggregator owns a variable energy resource, producing power quantity s with pdf $g(s)$
- Offers a menu of contracts to capacity increments with ex-ante payments that vary with customer self-selected probability of curtailment for each increment and pays
- Commits to supply power quantity *q* in the forward wholesale market contingent on the whole sale price *p*
- After observing variable energy realization, dispatches a scenario-dependent quantity of contracted DR
- Collects a net settlement

$$pq + a\left[DR + s - q\right]^{+} + b\left[DR + s - q\right]^{-}$$

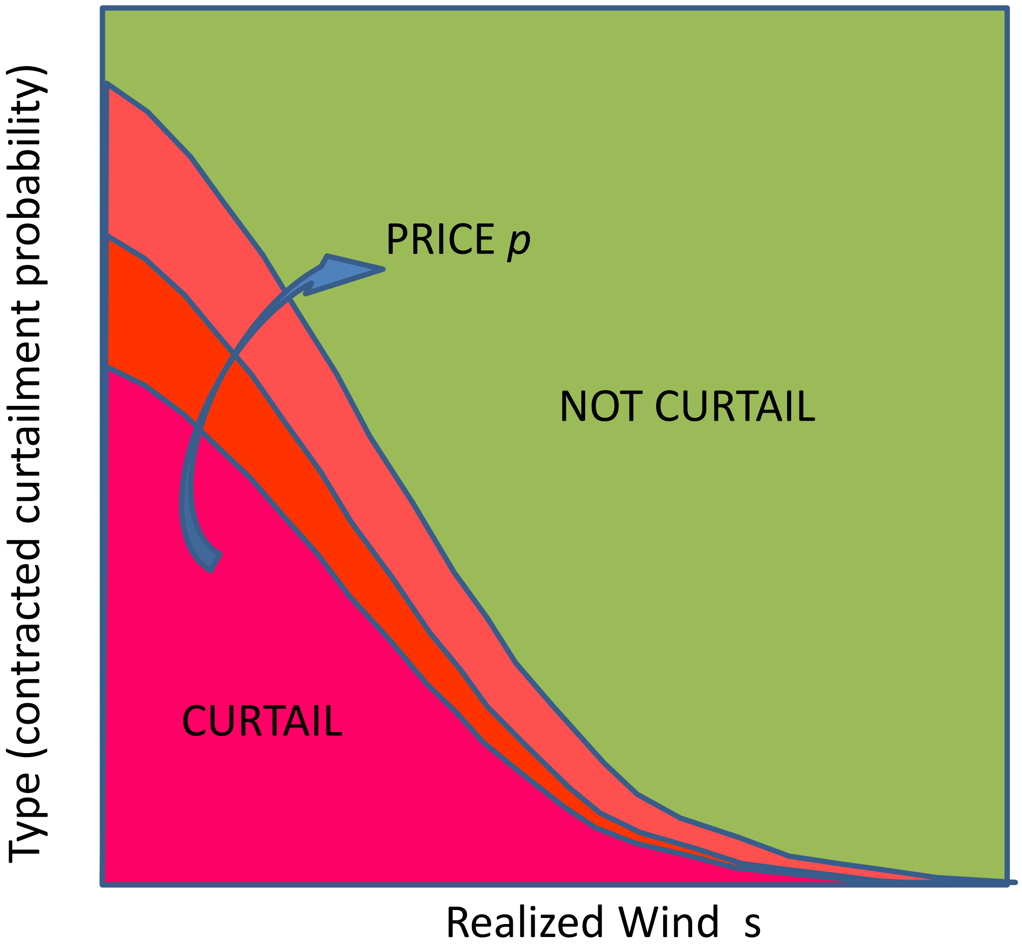
The Aggregator’s Problem

$$\max_{q,DR,T} \bar{J}(q, DR, T)$$

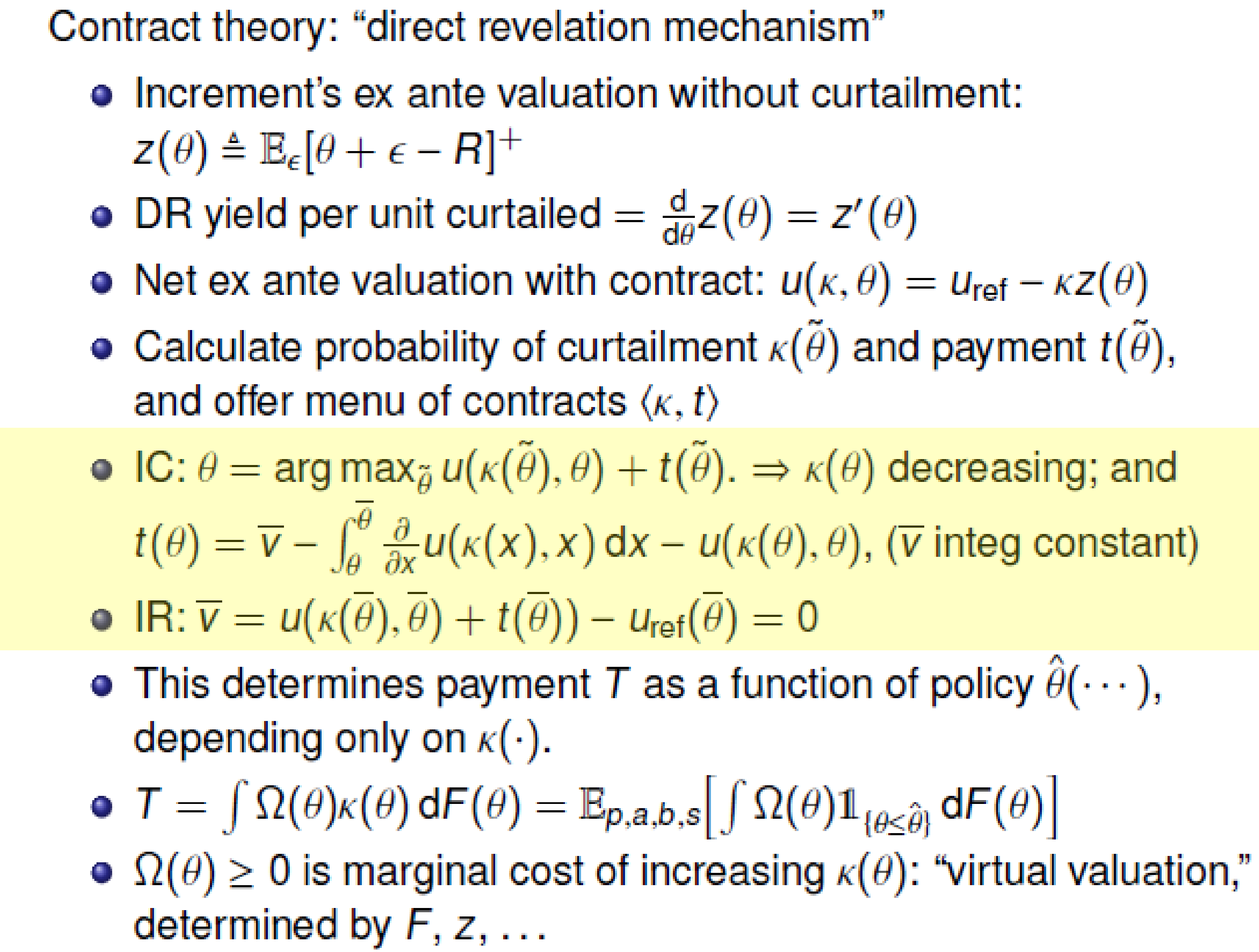
$$= \max_{q,DR,T} \mathbb{E}_{p,a,b,s}\Big[\underset{\underset{\text{Day-ahead revenue}}{\uparrow}}{p}\, q + a(\overbrace{DR + s - q}^{\text{overproduction}})^{+} - b(\overbrace{q - DR - s}^{\text{shortfall}})^{+}\Big] - \underset{\underset{\text{payment to DR}}{\uparrow}}{T}$$

- Random variables
  - p : day ahead (DA) price
  - a : overproduction payment rate
  - b : shortfall penalty rate
  - s : Real time (RT) VER realization, “wind”, $\sim g(\cdot)$
- Control policy variables
  - q : $(p, a, b) \mapsto q(p, a, b) \geq 0$: DA offer quantity
  - DR : $(p, a, b, s) \mapsto DR(p, a, b, s) \geq 0$: DR dispatch quantity
  - T is determined by DR, using contract theory, explained below

DR Curtailment Policy



DR Contract Design



Contract theory: “direct revelation mechanism”

- Increment’s ex ante valuation without curtailment: $z(\theta) \triangleq \mathbb{E}_\epsilon[\theta + \epsilon - R]^+$
- DR yield per unit curtailed $= \frac{\mathrm{d}}{\mathrm{d}\theta} z(\theta) = z'(\theta)$
- Net ex ante valuation with contract: $u(\kappa, \theta) = u_{\mathrm{ref}} - \kappa z(\theta)$
- Calculate probability of curtailment $\kappa(\tilde{\theta})$ and payment $t(\tilde{\theta})$, and offer menu of contracts $\langle \kappa, t \rangle$
- IC: $\theta = \arg\max_{\tilde{\theta}} u(\kappa(\tilde{\theta}), \theta) + t(\tilde{\theta})$. $\Rightarrow \kappa(\theta)$ decreasing; and $t(\theta) = \overline{v} - \int_{\theta}^{\overline{\theta}} \frac{\partial}{\partial x} u(\kappa(x), x)\, \mathrm{d}x - u(\kappa(\theta), \theta)$, ($\overline{v}$ integ constant)
- IR: $\overline{v} = u(\kappa(\overline{\theta}), \overline{\theta}) + t(\overline{\theta})) - u_{\mathrm{ref}}(\overline{\theta}) = 0$
- This determines payment T as a function of policy $\hat{\theta}(\cdots)$, depending only on $\kappa(\cdot)$.
- $T = \int \Omega(\theta)\kappa(\theta)\, \mathrm{d}F(\theta) = \mathbb{E}_{p,a,b,s}\Big[\int \Omega(\theta)\mathbb{1}_{\{\theta \le \hat{\theta}\}}\, \mathrm{d}F(\theta)\Big]$
- $\Omega(\theta) \geq 0$ is marginal cost of increasing $\kappa(\theta)$: “virtual valuation,” determined by F, z, …

Optimizing DR Policy Pointwise

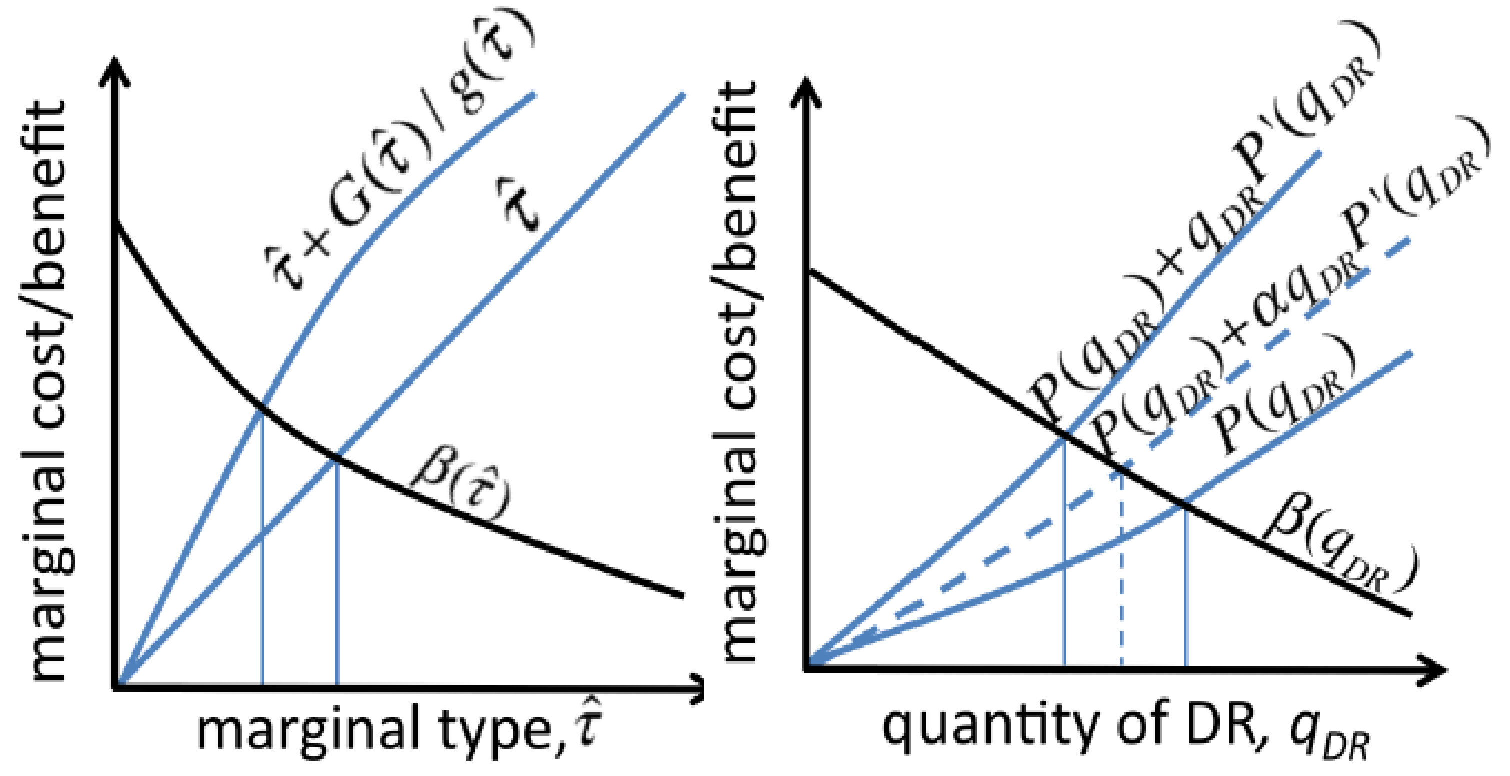
$$\max_{q,\hat{\theta}} \overline{J} = \mathbb{E}_{p,a,b} \max_{q} \mathbb{E}_{s} \max_{\hat{\theta}} [J(p,a,b,s;\hat{\theta}(\cdot),q(\cdot))]$$

- $\Omega(\theta) =$ cost to curtail type θ (contract theory analysis)
- $z'(\theta) =$ the resulting quantity of DR from a unit mass of type θ
- $MC(\theta) \triangleq \Omega(\theta)/z'(\theta)$: marginal cost per unit DR yield
- $DR(s) \triangleq \int z'(\theta)\mathbb{1}_{\theta \leq \hat{\theta}(p,a,b,s)}\, dF(\theta)$, DR production
- First order condition for $\hat{\theta}^*$ given a, b, s, and q: $0 \in \partial J(\hat{\theta}^*)$, $\Leftrightarrow$

$$MC(\hat{\theta}^*) = \begin{cases} a & \text{if } DR(s) + s > q \quad \text{(overproduction)} \\ b & \text{if } DR(s) + s < q \quad \text{(underproduction)} \end{cases}$$

and $DR(s) + s = q \Leftrightarrow MC(DR^{-1}(s)) \in [a,b]$: zero imbalance, if marginal cost of required DR is between the imbalance prices

Contingent Optimal DR Procurement (Monopsony/Olinopsony solution)



(a) Optimization of marginal type. (b) Optimization of DR quantity.

Putting it all Together

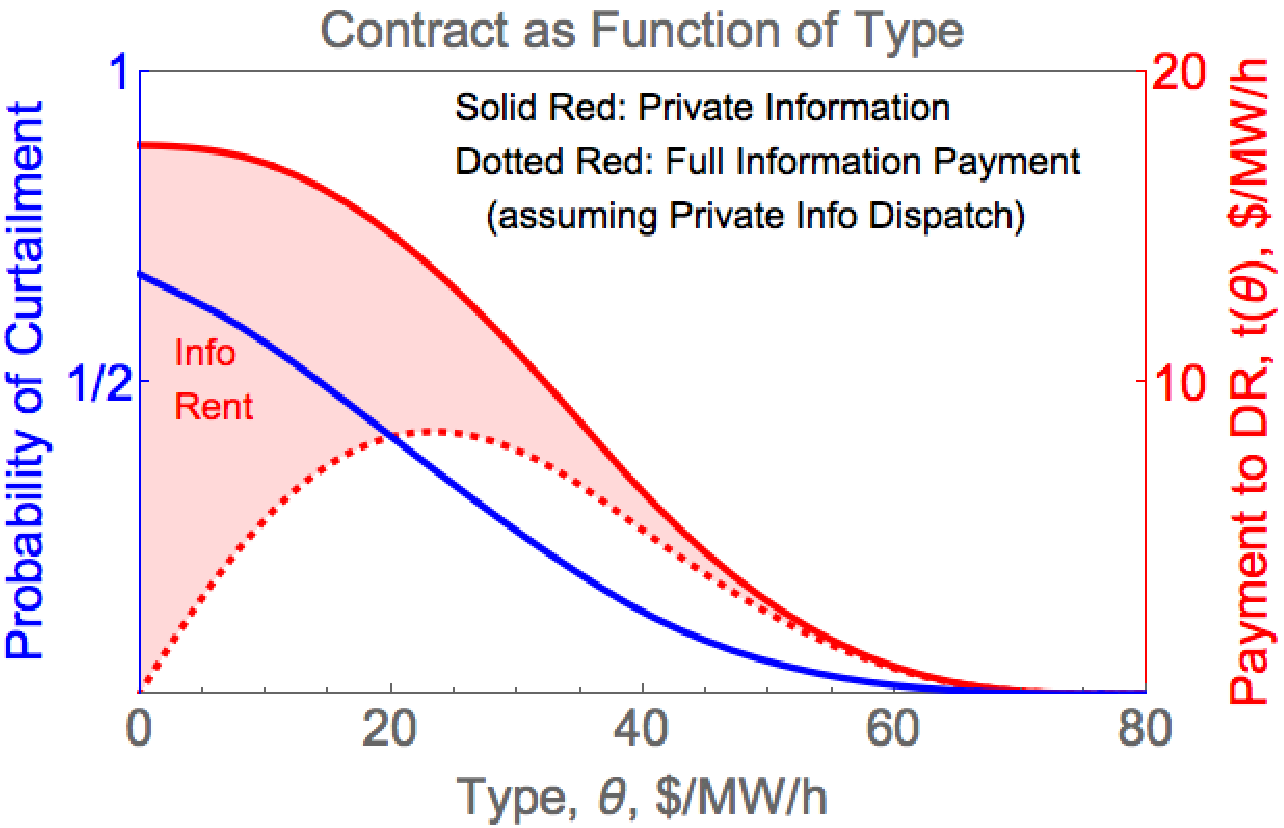
1. Aggregator determines curtailment policy in each (p, a, b, s), given q: $\mathrm{MC}(\hat{\theta}^*) = \mathrm{MB}(\hat{\theta}^*)$
2. For each (p, a, b) choose q^* so that the $\mathbb{E}[\mathrm{MC}(\hat{\theta}^*)]$ above $= p$
3. $q : (p, a, b) \mapsto q(p, a, b)$ is a supply surface: contingent offer policy
4. Taking expectation over (p, a, b, s), these elements determine $\kappa(\theta) = \mathbb{E}[\Pr\{\theta \leq \hat{\theta}^*\}]$, which determines $t(\theta)$
5. Evaluating $\big(\kappa(\theta), t(\theta)\big)$ for each $\theta \in [\underline{\theta}, \overline{\theta}]$, we get the explicit menu ("indirect mechanism"), mapping κ's to t's

Simple Example

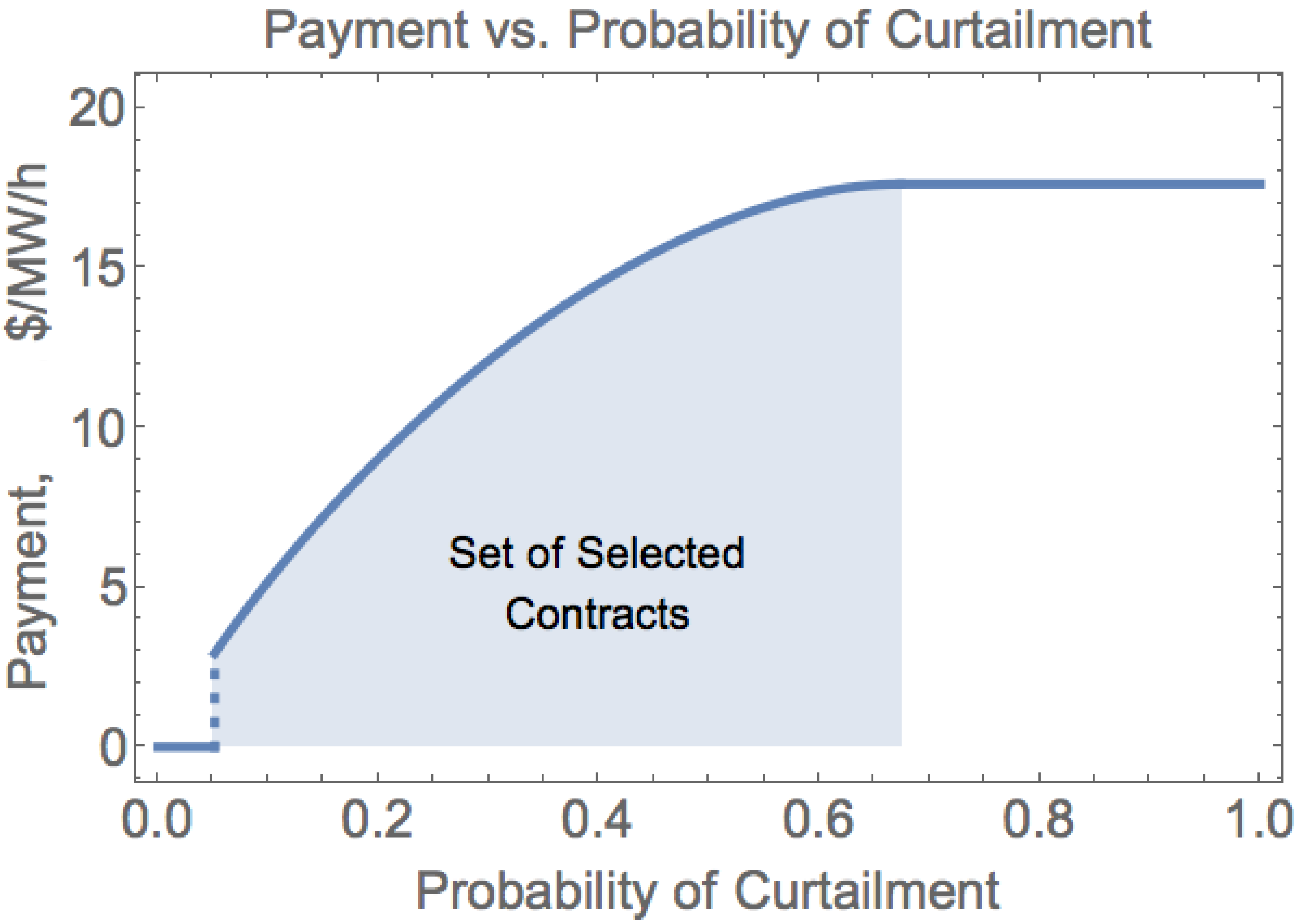
$$
\begin{aligned}
&\overline{s} = 100 \text{ MW} \\
&R = \$30/\text{MW} \quad \text{(generation component of the retail price)} \\
&N = D(R) = 100 \text{ MW} \quad \text{(aggregate demand at } R = \$30\text{)} \\
&\eta(R) = 0.3 \quad \text{(elasticity at } R = \$30\text{)}\,.
\end{aligned}
$$

$$
\begin{aligned}
&p \sim \text{Uniform}[10, 100] \\
&a = (1 - \delta)p \\
&b = (1 + \delta)p \\
&\delta \sim \text{Uniform}[0.1, 0.9]\,.
\end{aligned}
$$

Target Contract Terms as Function of Type

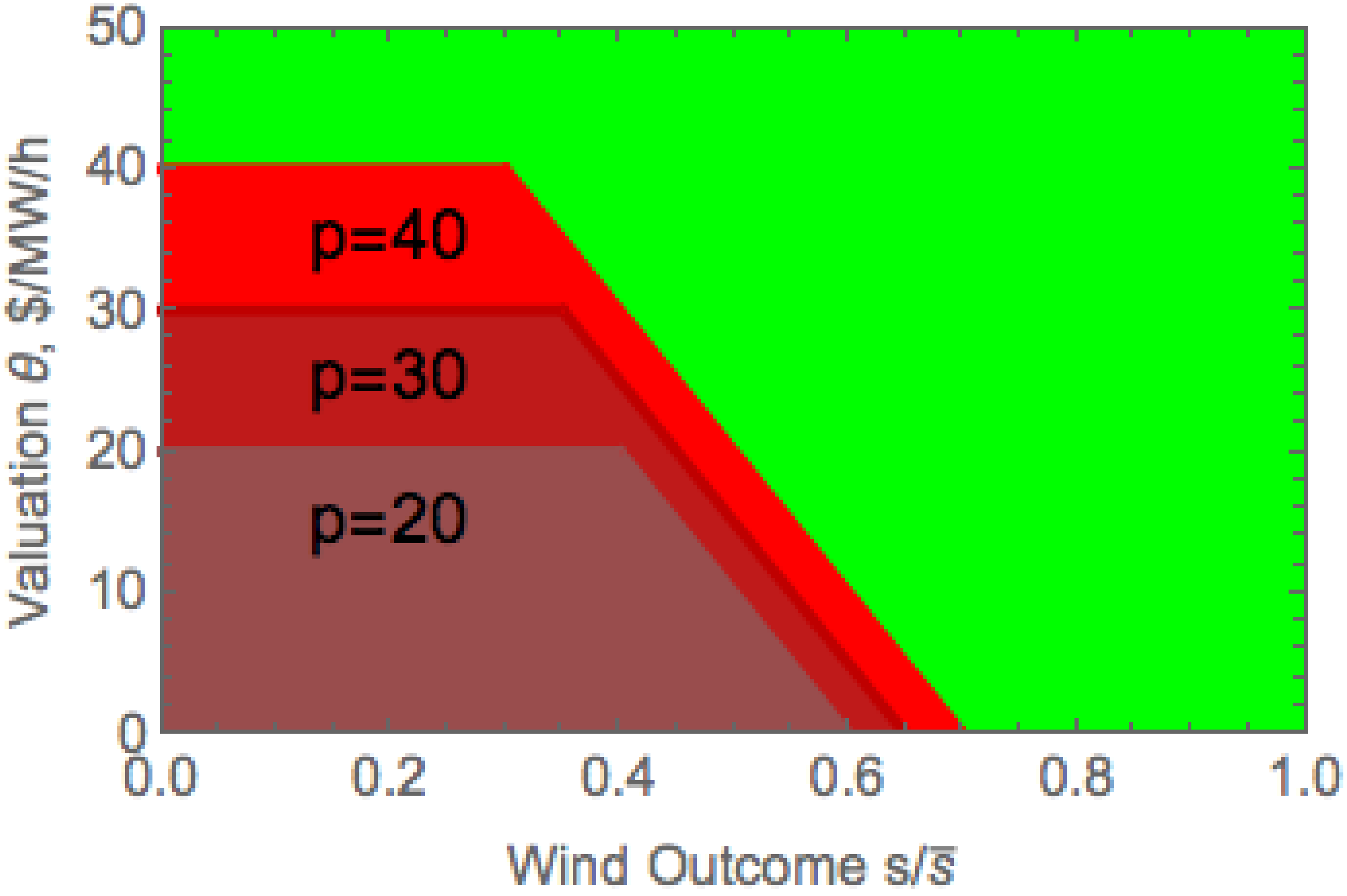


Payment to DR as Function of Curtailment Probability

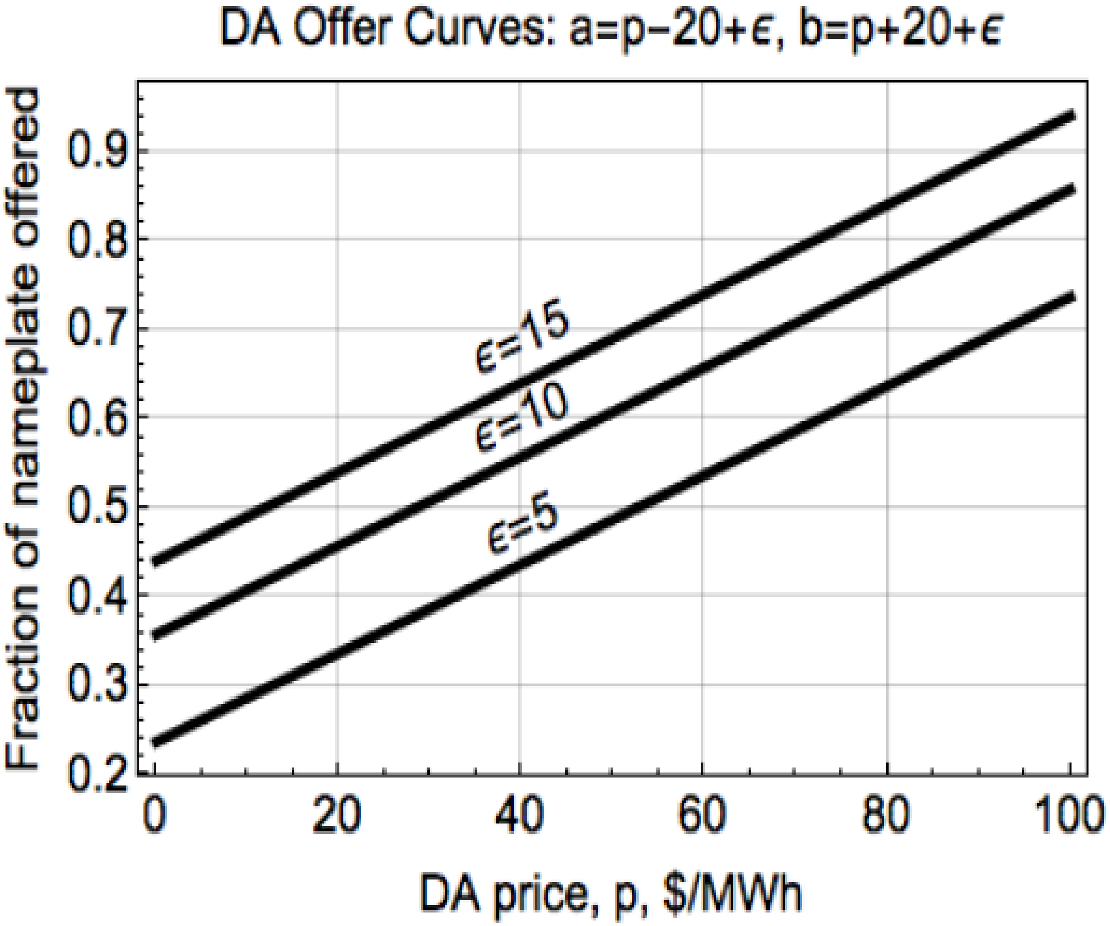


Optimal Curtailment Policy

(for *a=0, b=2p*)



Supply Functions



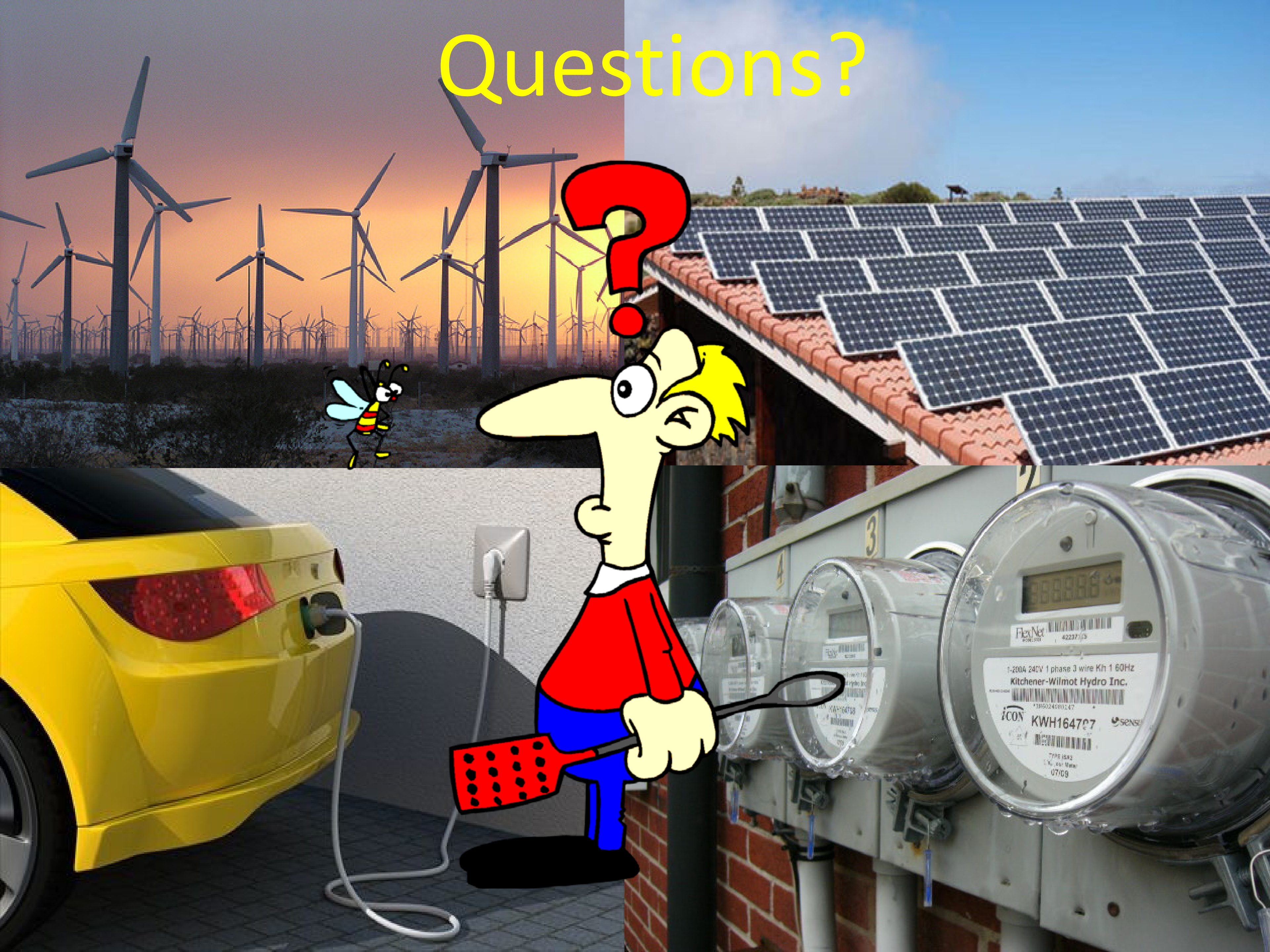
PUBLICATIONS & PRESENTATIONS

- Oren Shmuel S., “A Historical Perspective and Business Model for Load Response Aggregation Based on Priority Service”, Proceedings of the 46th HICSS Conference, Maui, Hawaii January 7-10, pp 2206-2214, 2013.
- Margellos, Kostas and Shmuel Oren, “Capacity Controlled Demand Side Management: A Stochastic Pricing Analysis”, IEEE PES Transactions, Vol 31, No 1, (2016) pp 706-717.
- Margellos Kostas and Shmuel Oren, “A Fuse Control Paradigm for Demand Side Management: Formulation and Stochastic Pricing Analysis”, Proceedings of the American Control Conference , Chicago, Ill, July 1-3, 2015.
- Campaign Clay and Shmuel Oren, “Firming Renewable Power with Demand Response: An End to End Aggregator Business Model”, To appear in Journal of Regulatory Economics, (Published online May 2016)

PRESENTATIONS

- IEEE, PES GM, Invited Panelist, “A Business Model for Residential Load Control Aggregation”, Harbor Bay, MD, July 27-31, 2014.
- EPFL Conference on Demand Response, Plenary “A Historical Perspective and Business Model for Load Control Aggregation”, Lausanne, Switzerland September 10, 2015.
- KIT Institute for Industrial Production, Chair of Energy Economics, Invited Lecture, “A business Model for Load Response Aggregation to Firm up Renewable Resources”, Karlsruhe, Germany, November 11, 2015.
- Rutgers 35 Eastern Conference, Invited Talk, “Firming Renewable Power with Demand Response: An End to End Aggregator Business Model”, (with Clay Campaign), Shawnee, PA, May 11-13, 2016.

Questions?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1-200A 240V 1 phase 3 wire Kh 1 60Hz
Kitchener-Wilmot Hydro Inc.
KWH164727
SENSUS
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