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

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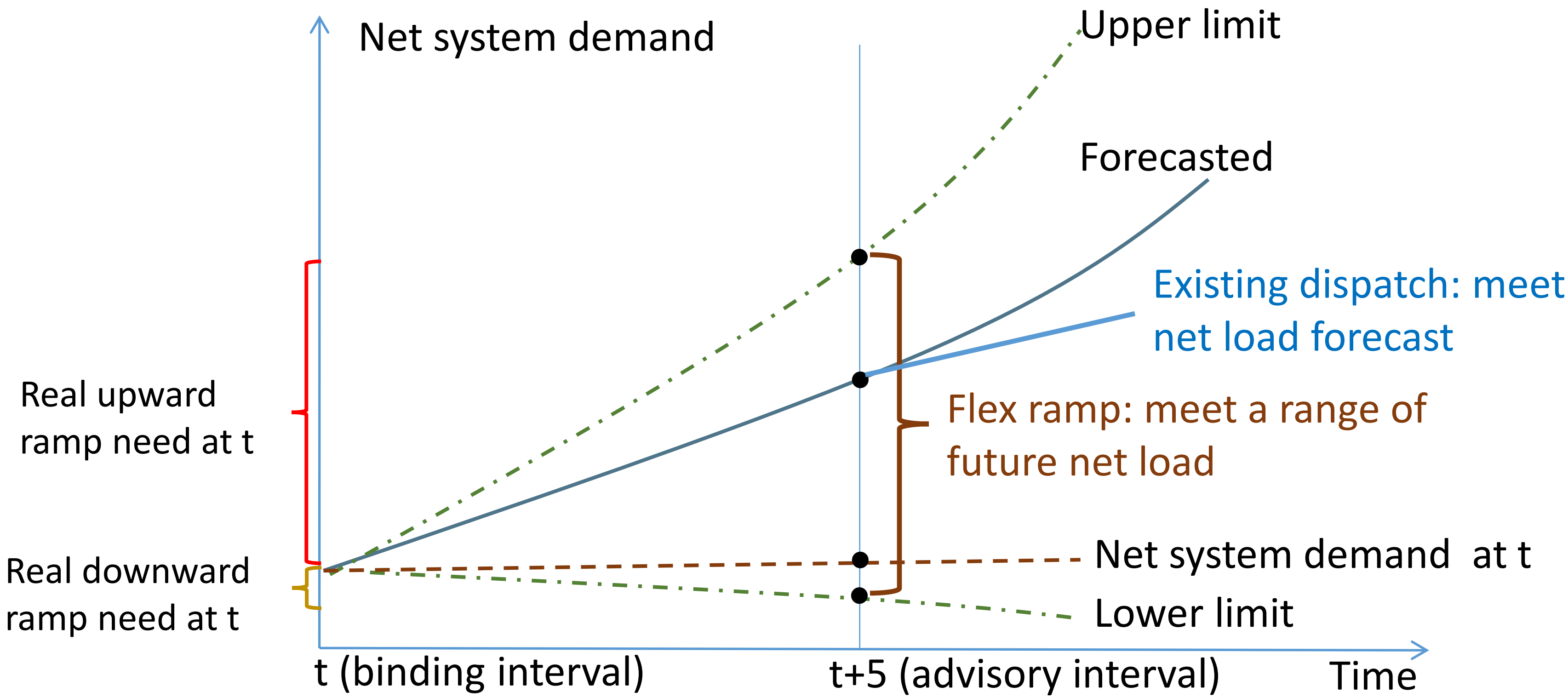
Economic *Paradigms for Demand Response*

- 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 multi-interval look ahead needs such as short term flexible ramping products or other A/S that are co-optimized with energy. ☹

Ramping need



Ramping need:

Potential net load change from interval t to interval t+5
(net system demand t+5 – net system demand t)

Source: California ISO

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

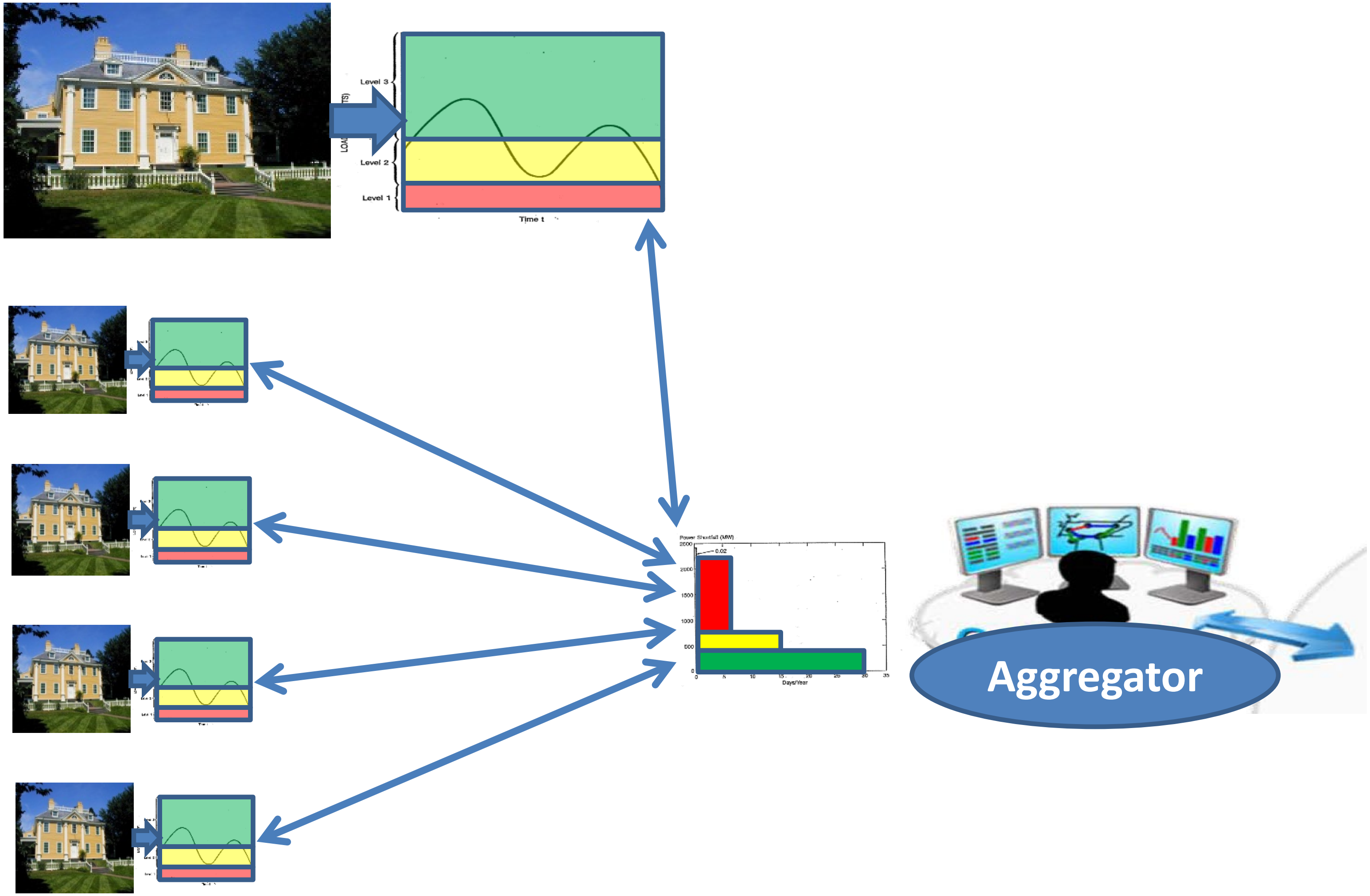
- Provide quality differentiated service based on contracted load control options.
  - Quality differentiated service and optional price plans are common in other service industries (air transportation, cell phone, insurance)☺
  - Customers have experience with choosing between alternative service contracts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

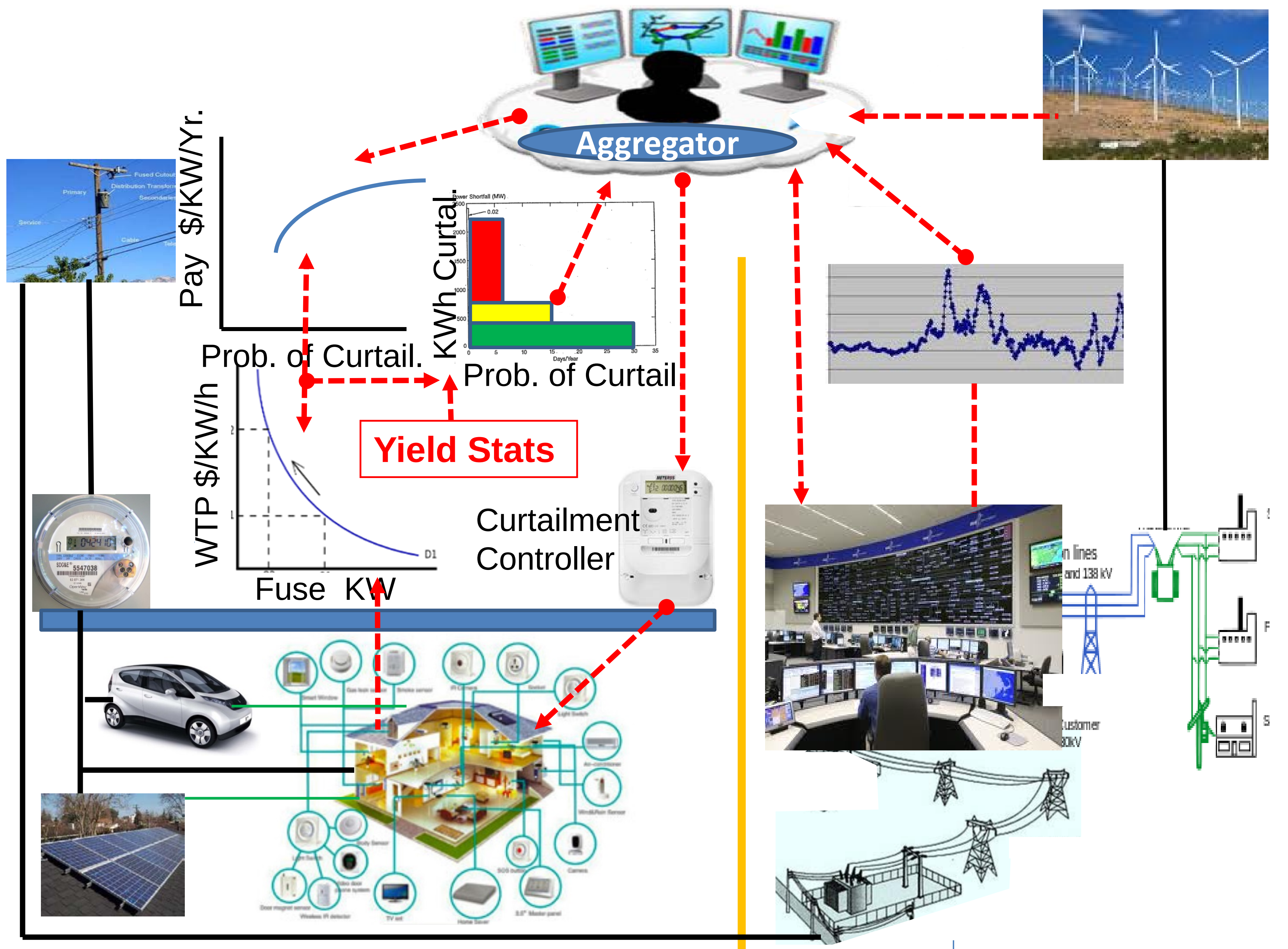
The Challenge

- ❑ 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 (thermostats, air conditioners, water heaters, EV battery charger)
    - o Intrusive ☹
    - o Faster response enables higher valued products (e.g. regulation) ☺
  - ➢ Or control of power capacity through the meter with customer dynamic self-control of allocation to devices behind the meter.

Fuse Control Paradigm

Stratification of Demand into Service Priorities

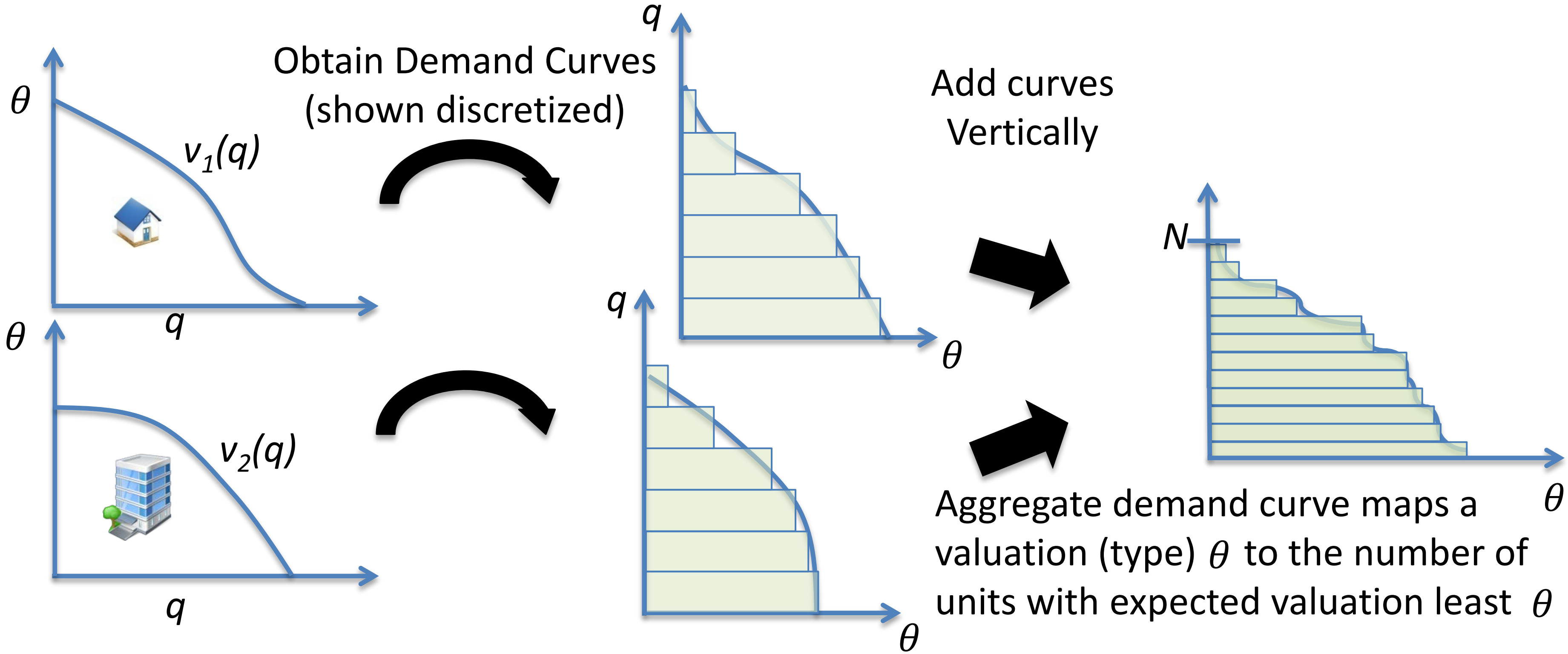




Aggregator
Pay $/KW/Yr.
Prob. of Curtail.
KWh Curtal.
Prob. of Curtail
WTP $/KW/h
Fuse KW
D1
Yield Stats
Curtailment
Controller
Power Shortfall (MW)
Days/Year
Primary
Fused Cutout
Distribution Transformer
Secondaries
Service
Cable

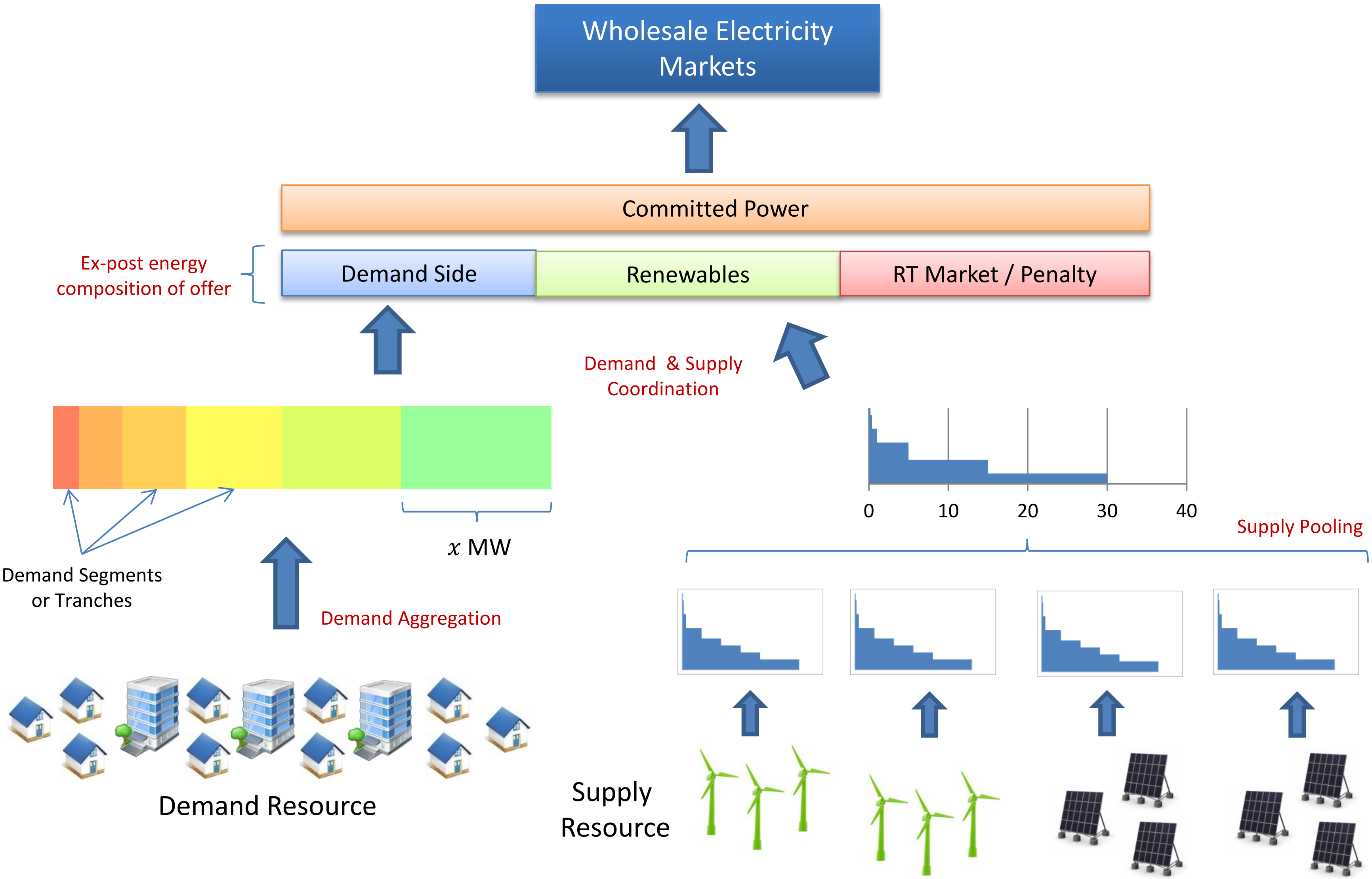
The Customer Model

DR customers are represented in aggregate as a continuum of demand increments identified by a type parameter θ reflecting expected utility of consumption. The aggregate demand curve (for capacity) can be interpreted as the CDF of types scaled to total load capacity.   .



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

The Wholesale Product Offered by the Aggregator

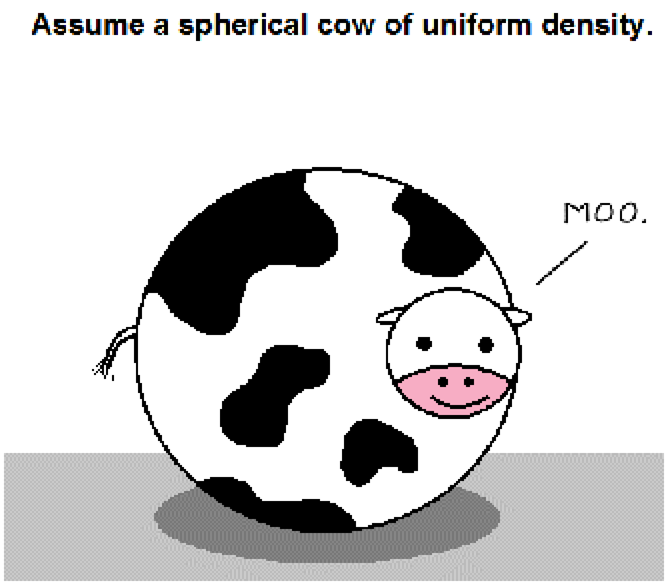


The Aggregator's Operations

- 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

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

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

* Margellos, Kostas and Shmuel Oren, "Capacity Controlled Demand Side Management: A Stochastic Pricing Analysis", To appear in *IEEE PES Transactions*

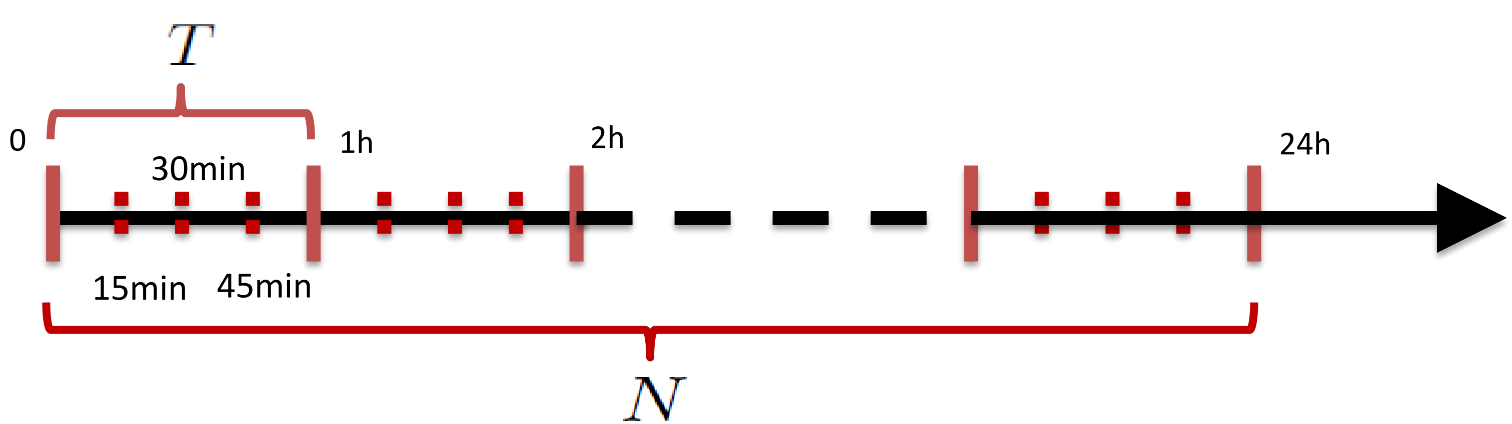
Fuse control problem formulation

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

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

Fixed allocation

PV forecast error allocation

Fuse control problem formulation … in math

$$\min_{\left\{\left\{P_c^j(k),\ d_+^j(k),\ d_-^j(k)\right\}_{j=1}^{N_c}\right\}_{k=1}^{N}} \sum_{k=1}^{N}\sum_{j=1}^{N_c}\mathcal{R}_{\delta\in\Delta}[U^j(k,\delta)]$$

subject to:

Fuse limit

$$\sum_{k=iT-T+1}^{iT}\left[\sum_{j=1}^{N_L}P_L^j(k)-\sum_{j=1}^{N_{PV}}\left(P_{PV}^j(k)+\delta^j(k)\right)+\sum_{j=1}^{N_c}P^j(k,\delta)\right]\le P_f(i),\ \boxed{\forall\delta\in\Delta}$$

$$\alpha^j(k)P_{c,\text{base}}^j(k)\le P^j(k,\delta)\le P_{c,\text{base}}^j(k),\ \boxed{\forall\delta\in\Delta}$$

$$\sum_{j=1}^{N_c}d_+^j(k)=1,\ \ \sum_{j=1}^{N_c}d_-^j(k)=1,\ \ d_+^j(k),d_-^j(k)\ge 0$$

Semi-infinite constraints

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

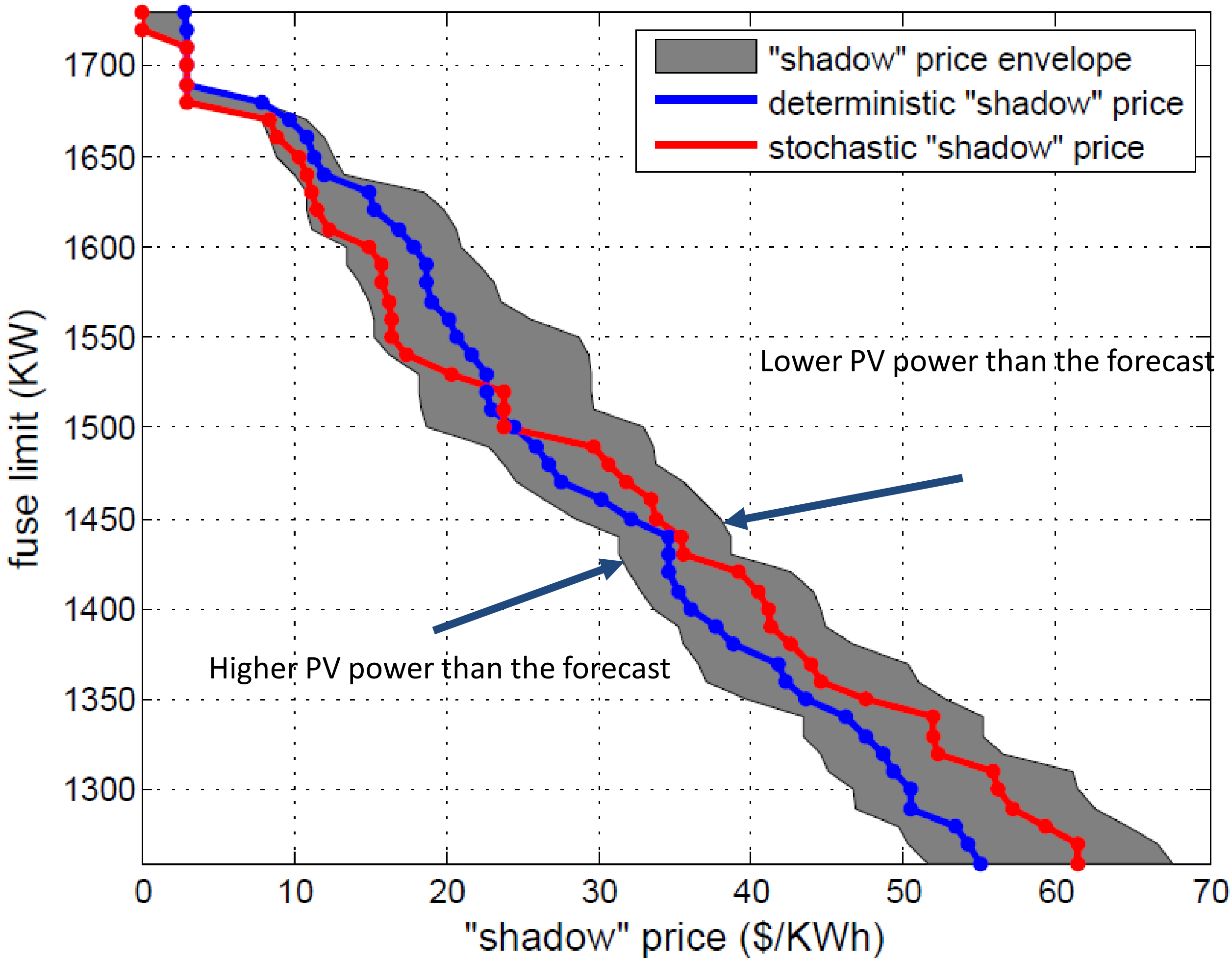
- $U^j(k,\delta)$ - Load disutility, difference from a baseline profile (load can only be curtailed)

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

Time, load dependant penalty factor

Shadow Price envelope

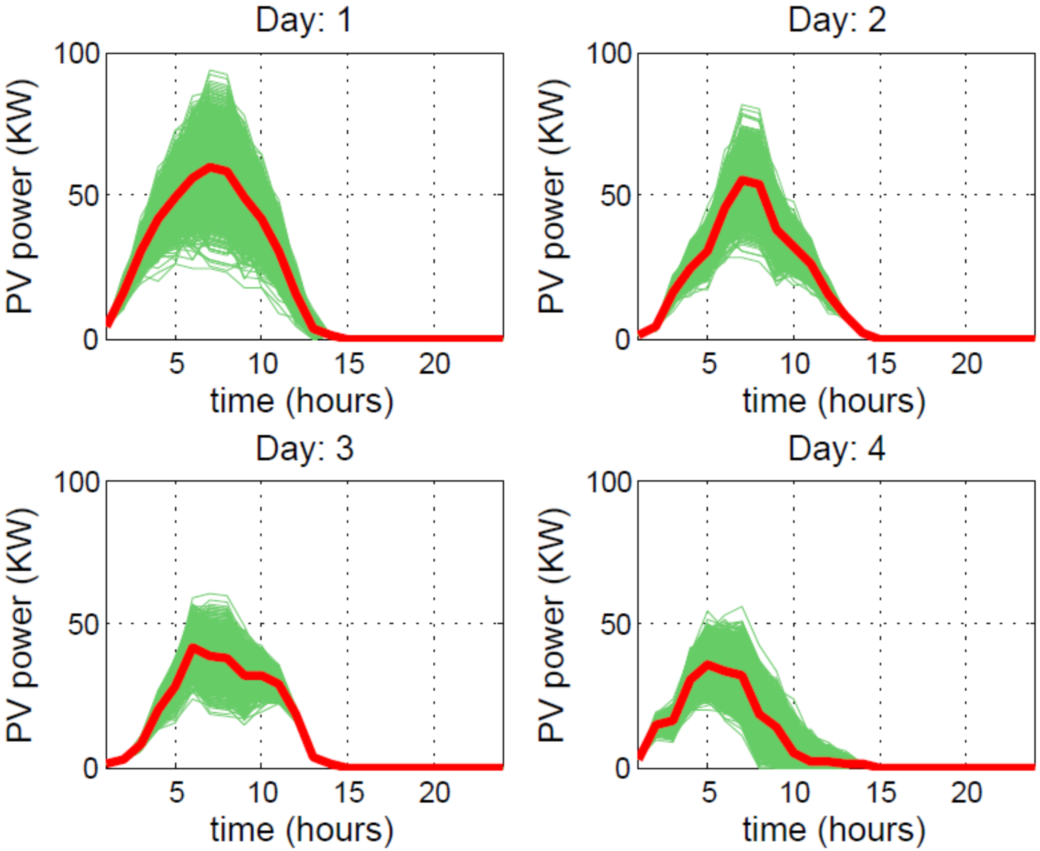
If we extract sufficiently high # samples, stochastic curve lies inside the envelope with high probability (proof based on duality and randomized optimization)



Simulation study

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

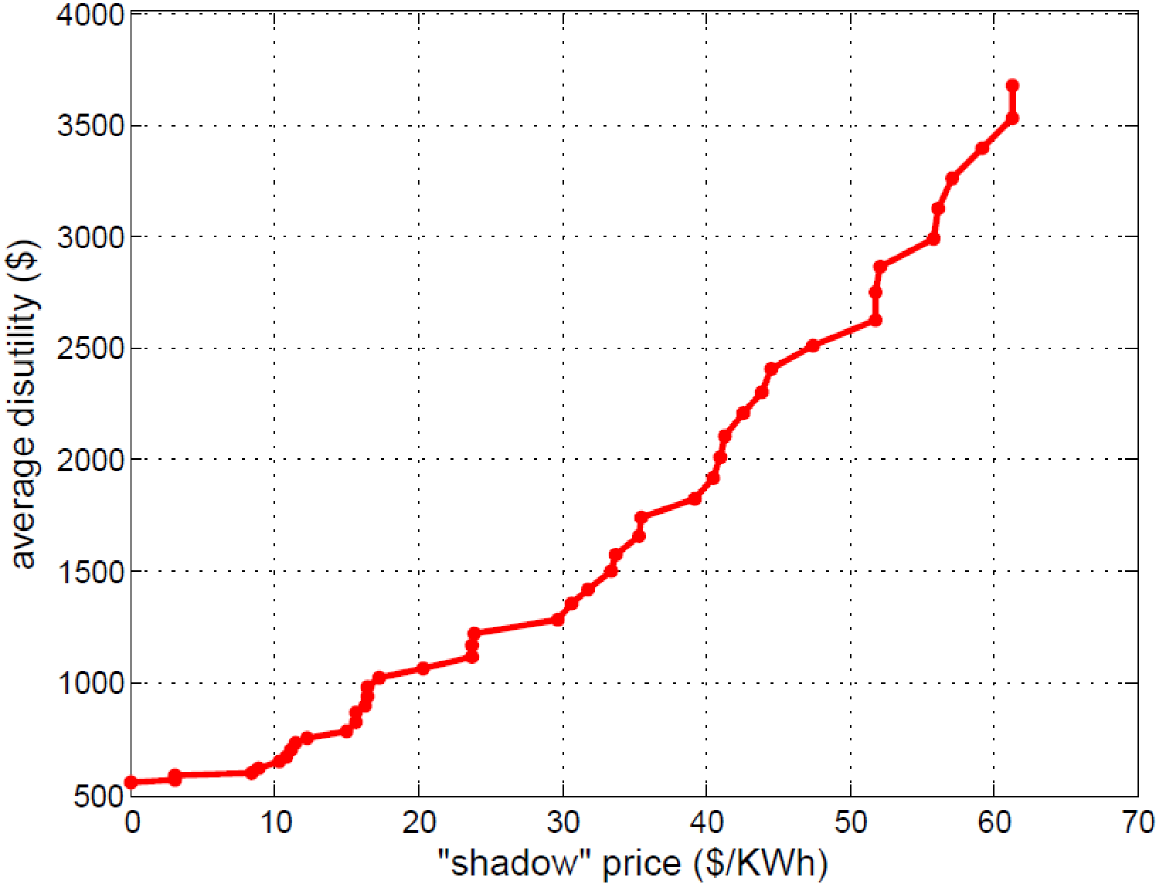
2. Scenarios generated via a discrete time stochastic process driven by Gaussian noise (correlation is taken into account)



Simulation study

For each fuse limit we use demand curve to compute disutility due to load curtailment (Convexity results from behind the meter optimization)

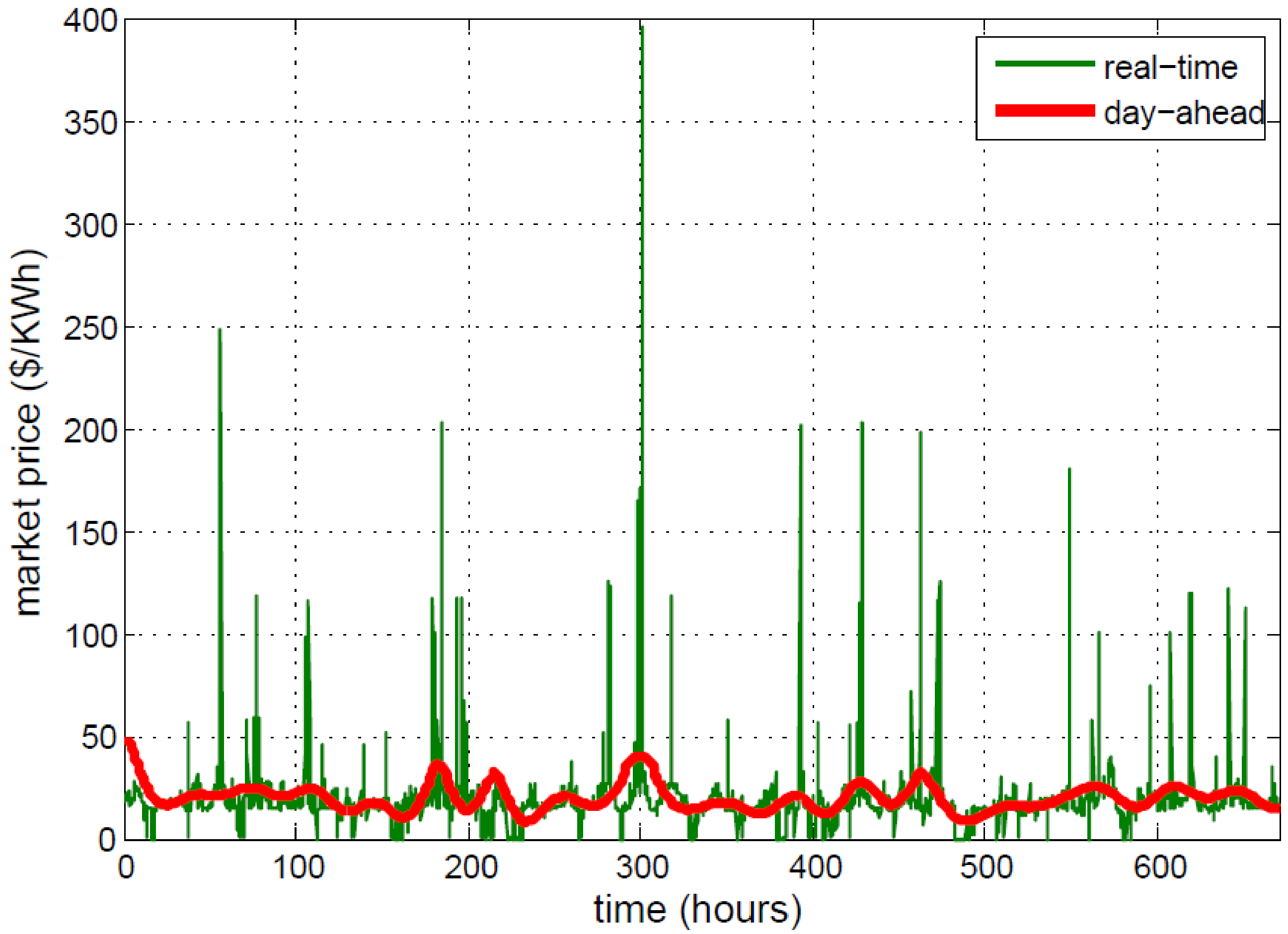
Disutility vs. 'shadow' price



Simulation study

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

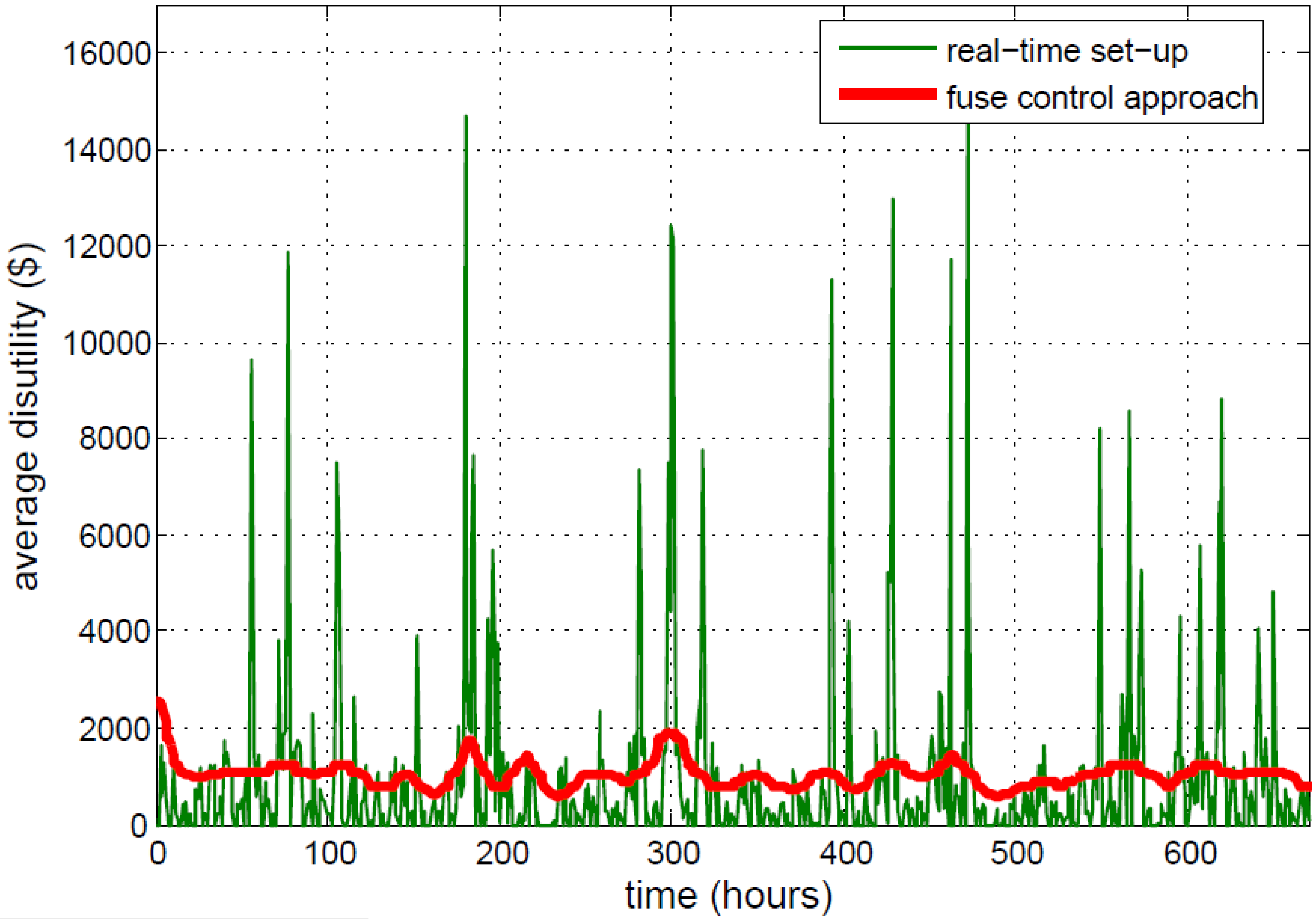
Market price profiles



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 Aggregator's Problem

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

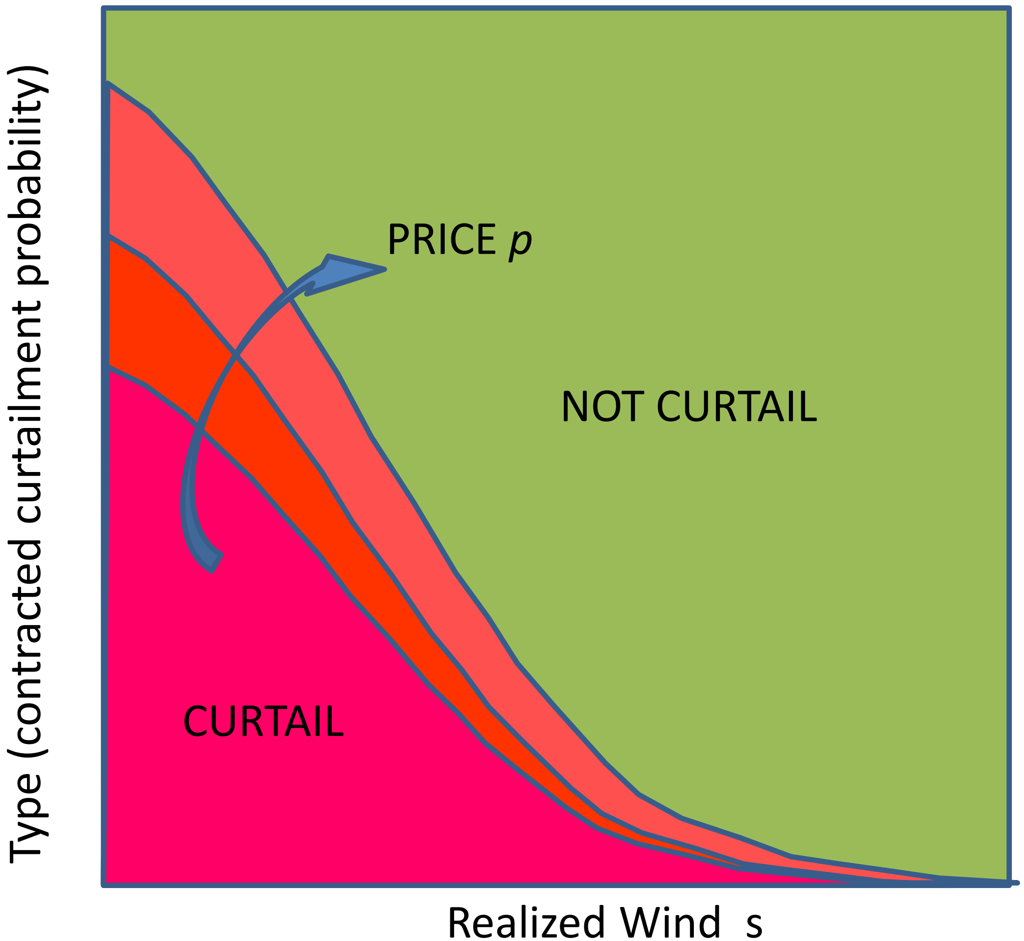
$$= \max_{q,DR,T} \mathbb{E}_{p,a,b,s}\Big[\underset{\uparrow}{p}\, q + a(\overbrace{DR + s - q}^{\text{overproduction}})^{+} - b(\overbrace{q - DR - s}^{\text{shortfall}})^{+}\Big] - \underset{\uparrow}{T}$$

Day-ahead revenue

payment to DR

- 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: $u(\kappa, \theta) = u_{\text{ref}} - \kappa z(\theta)$
- 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: $\overline{v} = u(\kappa(\overline{\theta}), \overline{\theta}) + t(\overline{\theta})) - u_{\text{ref}}(\overline{\theta}) = 0$
- This determines payment T as a function of policy $\hat{\theta}(\cdots)$, depending only on $\kappa(\cdot)$.
- $T = \int \Omega(\theta)\kappa(\theta)\,\mathrm{d}F(\theta) = \mathbb{E}_{p,a,b,s}\left[\int \Omega(\theta)\mathbb{1}_{\{\theta \le \hat{\theta}\}}\,\mathrm{d}F(\theta)\right]$
- $\Omega(\theta) \ge 0$ is marginal cost of increasing $\kappa(\theta)$: "virtual valuation," determined by F, z, ...

Optimizing DR Policy Pointwise

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

- $\Omega(\theta)$ = 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: $0 \in \partial J(\hat{\theta}^*)$, $\Leftrightarrow$

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

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

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

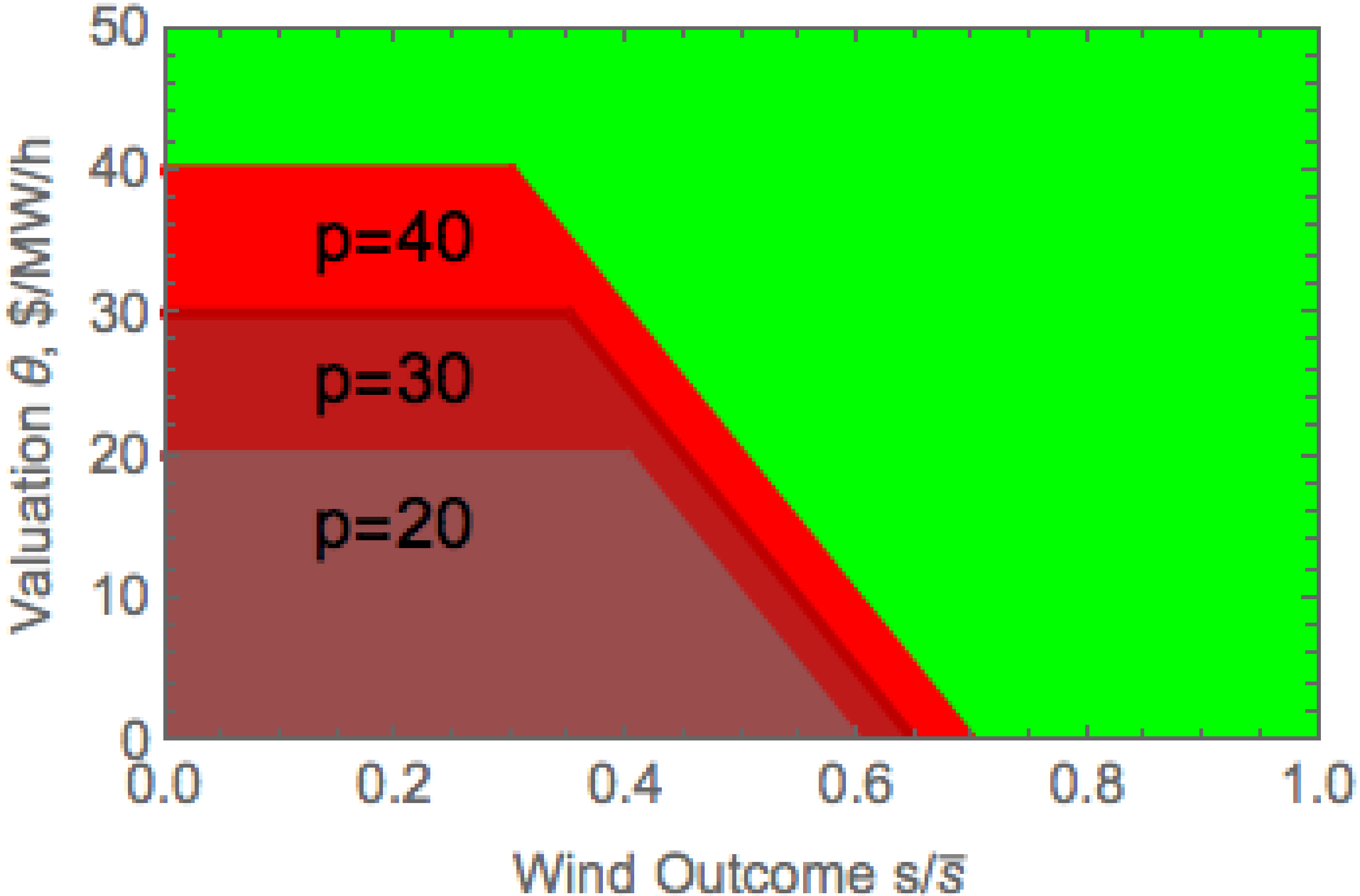
- $\mathbf{s} \sim \text{Unif}[0, \bar{s}], \theta \sim \text{Unif}[\underline{\theta}, \bar{\theta}]$, no valuation shocks

$p \sim \text{Unif}[10, 60],\ a = 0,\ b \sim \text{Unif}[2\sqrt{p/v},\ 2(1-\sqrt{1-pv})/v]$

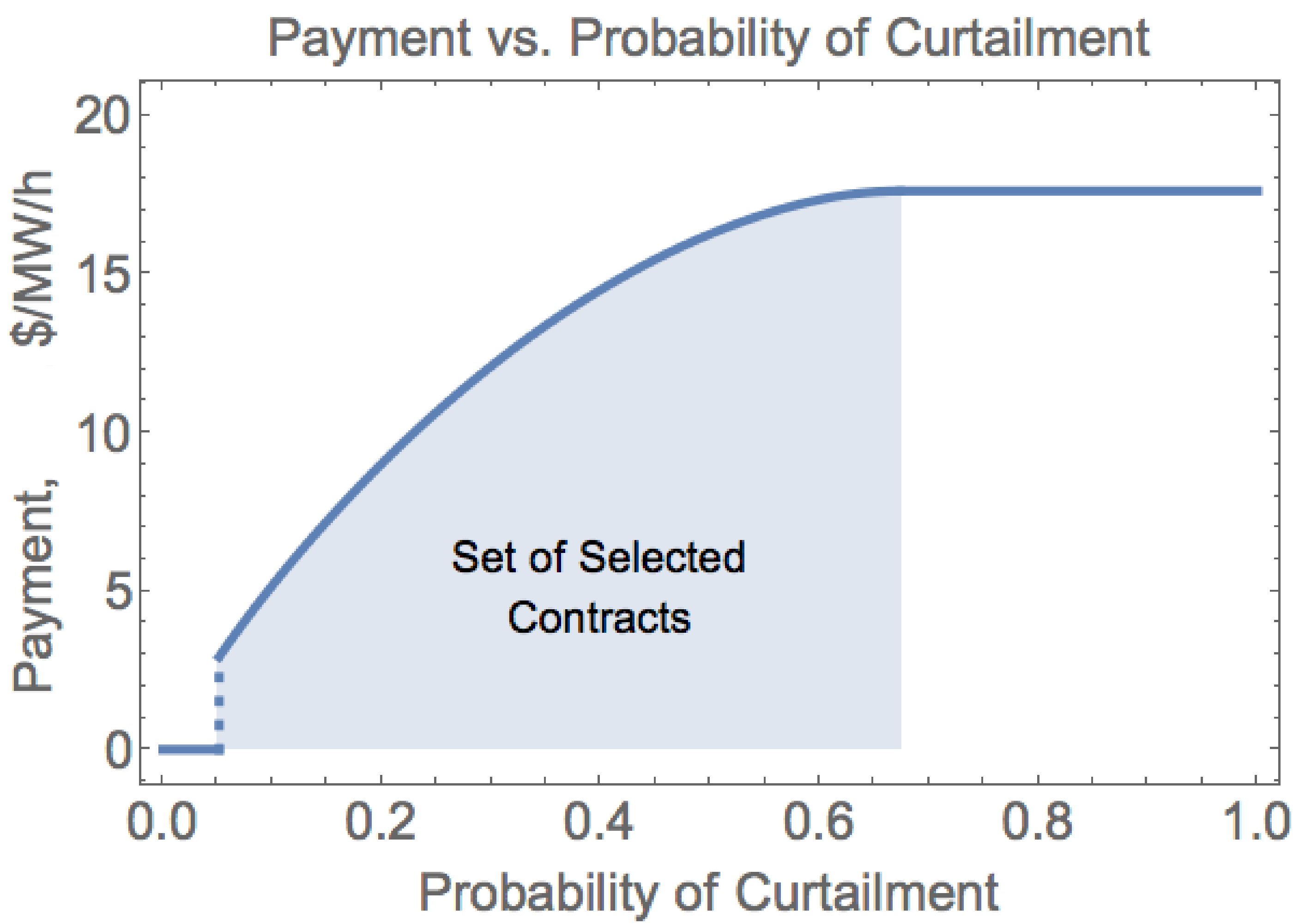
- Retail rate *R*= $\underline{\theta}$, lowest type.
- $v \triangleq N / \left(\bar{s}(\bar{\theta} - \underline{\theta})\right) = 0.1$ = MW of DR, per 1\$ range, per unit nameplate capacity.
- *v*=.01 derived from *s* = 100 MW, *N* = 100 MW, valuation range $(\bar{\theta} - \underline{\theta}) = 100\,\$/MW/h$
- Write problem in terms of decision variable $\gamma \triangleq q/\bar{s}$.

Optimal Curtailment Policy

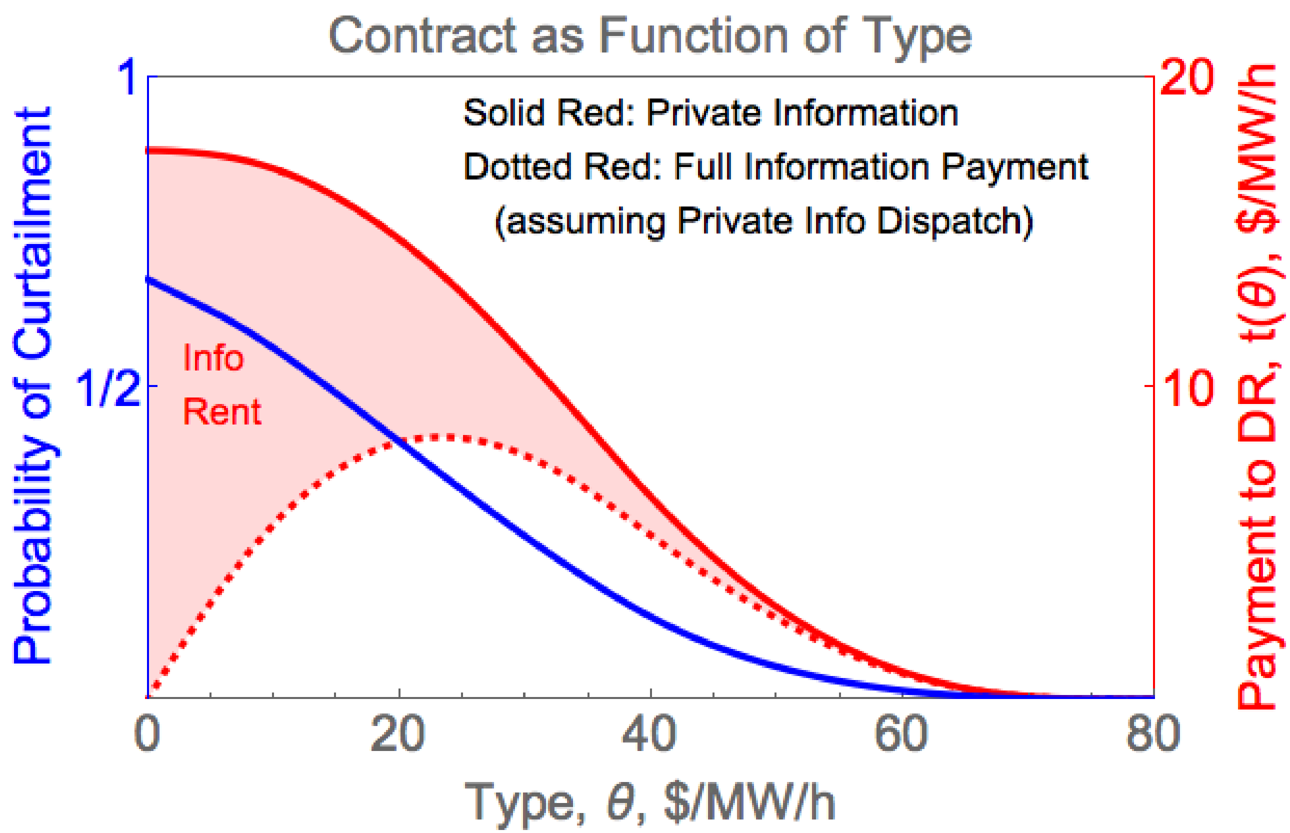
(for *a=0, b=2p*)



Payment to DR as Function of Curtailment Probability

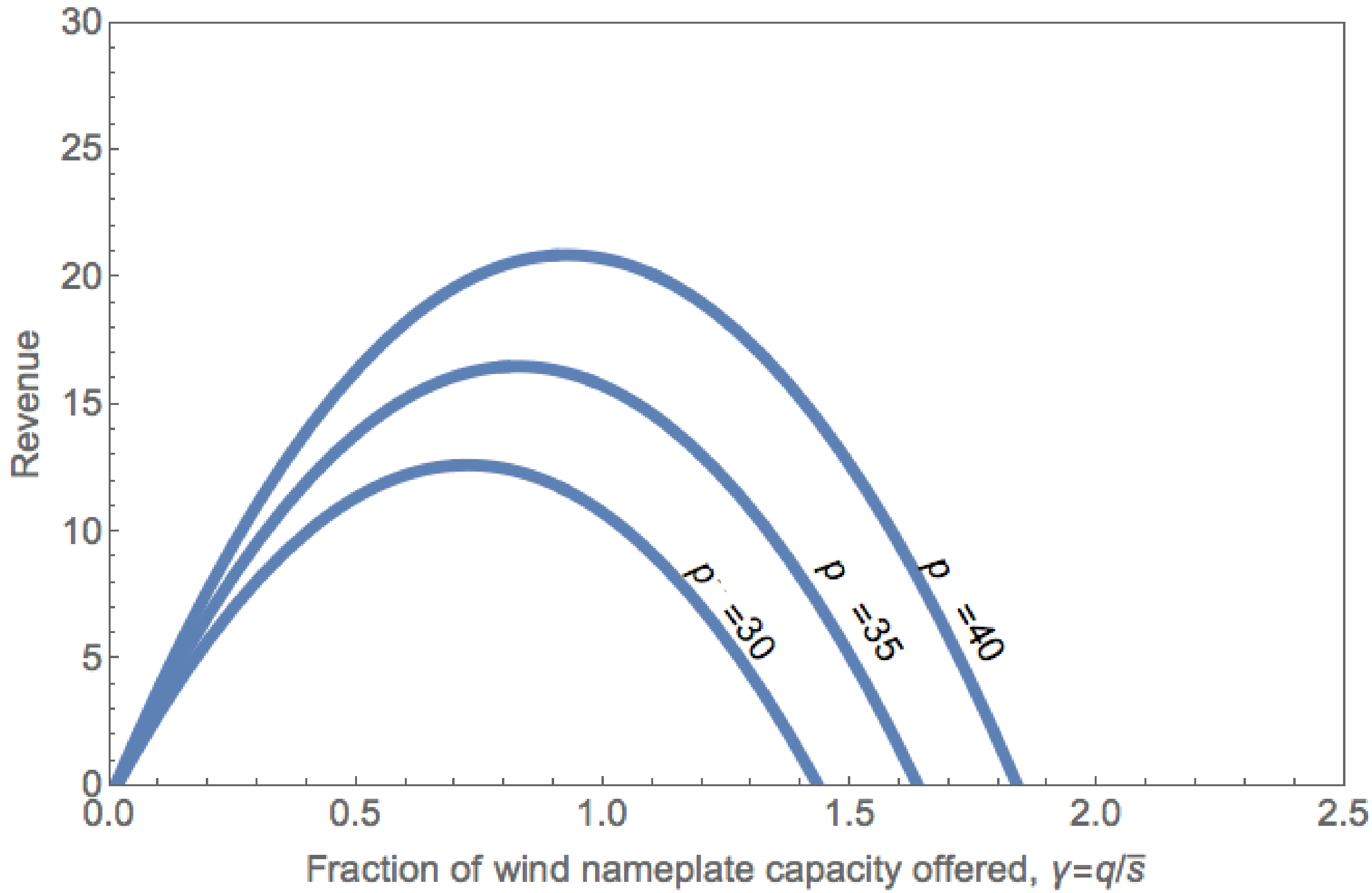


Target Contract Terms as Function of Type

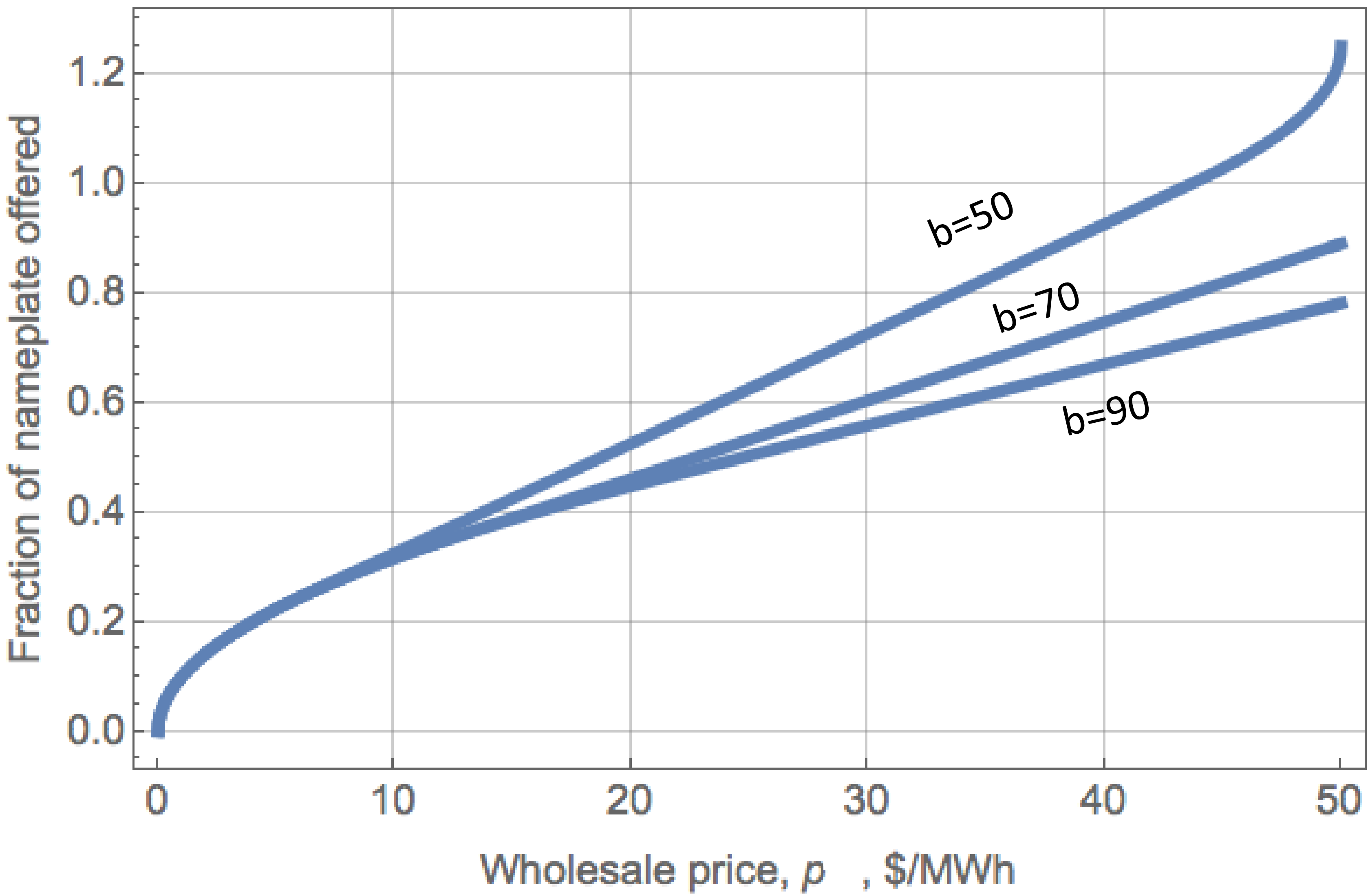


Profit Curves

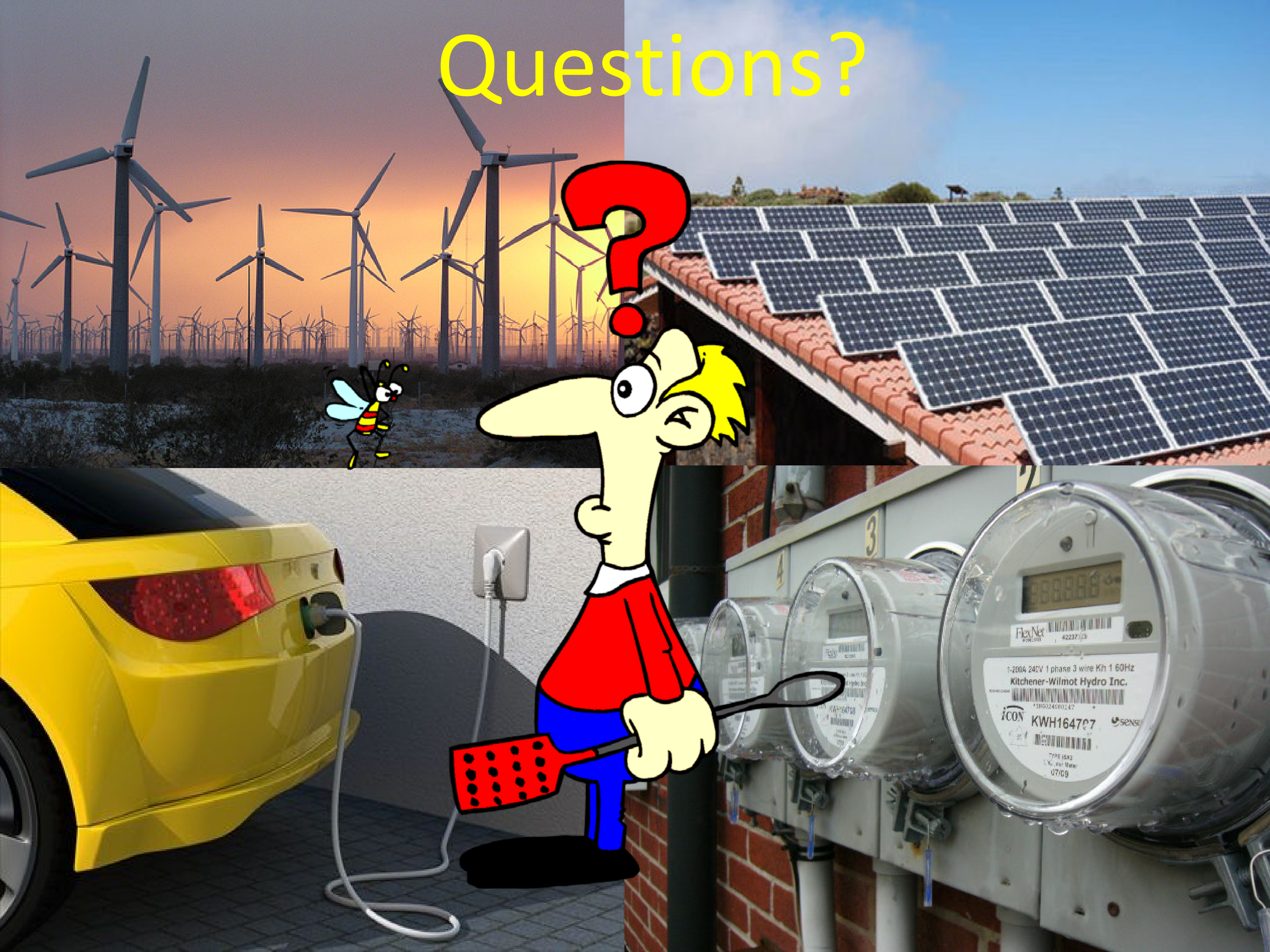
(*a=0, b=50*)



Supply Functions



Questions?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1-200A 240V 1 phase 3 wire Kh 1 60Hz
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