Real-Time Pricing and Demand Response

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Agenda for Today

- Why Dynamic Pricing?
- Key Characteristics of Demand Response Programs
- Fundamental Nature of Demand Response
- Advantages of Real-Time Pricing
- Extending RTP with a Double-Auction Retail Market
- Results from a Field Experiment
- Challenges in Designing RTP Rates
- Implications for Smart Grid Communications Architecture
- Extending RTP to Engage Demand for Ancillary Services

Why Dynamic Pricing?

The Arguments for Dynamic Retail Pricing

- Unlock the potential for demand response (DR) to save capital and operational costs – <u>and empower consumers</u>
- Better match of retail rates to cost of service creates transparency, unleashes DR (and distributed generation & storage)
- FERC suggests ~20% DR capacity is achievable
- Historically, DR used to manage system peak load
- <u>Additional benefits can potentially be obtained</u>:
  - Mitigate wholesale market price spikes
  - Respond to LMPs (locational marginal prices)
  - Manage distribution system capacity & constraints
  - Provide ancillary services cheaper & faster than power plants
  - Assist integration of intermittent renewables (ancillary services, ramping)
  - Enhance reliability for grid operators with fast response
  - Manage charging of electric vehicles

What are the Benefits at Stake?

- Generation capacity *(marginal cost)* ~$800/kW
- Transmission capacity *(avg. avoided cost)* ~$150/kW
- Distribution capacity *(avg. avoided cost)* ~$250/kW
- Wholesale market prices / production costs (avg) ~$70/MWh
- Spinning reserve costs *(avg)* ~$10/MWh
- Regulation costs *(avg)* ~$20/MWh
- Reliability ???
- Renewables integration ???
- Electric vehicle integration ???

Key Characteristics of Demand Response Program Designs

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Curtailment-Based DR Programs

- Interruptible loads – primarily industrial, large commercial
  - Incentive typically discount for electricity
  - Phone-call/pager based
  - Participants tend drop out if called upon (too often, sometimes at all)
  - Typically used only in emergencies
  - May count as spinning reserve
- Direct load control (DLC) – payment for utility control of load, primarily residential AC & HW, some C&I also
  - Incentive typically fixed payment per year or peak month (i.e. $50/mo)
  - Direct control is nice (from utility perspective) – get all you can!
  - Duty-cycling: best to reduce each home's <u>measured</u> duty cycle
  - Thermostat setback programs: more direct, known impact

Price-Based DR Programs

- Pricing programs – voluntary, preserve customer choice
  - Designed to make DR participation nearly universal
    - More response, less impact on any individual
  - Rates designed to be revenue neutral for average customer shape
  - Can engage other end uses; best if desired response is automated
  - TOU – fixed, time-of-day block pricing – no peak signal
  - CPP – critical peak prices, typically ~15 days/yr, 6 hours/day (max)
  - RTP – real-time pricing – fully flexible, utilizes DR for multiple purposes to provide maximum value (requires automation)
  - *Note: retail price signals can be fully regulated*

Curtailment-Based DR Programs (cont.)

- Peak-time rebates (PTR) – payment for “actual” load reduced
  - Load reduction ≡ Baseline load – Actual load
  - $/kW per hour offer can be dynamic, real-time
  - Incentive = $\sum_t$ Load reduction(t) * $/KW offer(t)
  - Consumer-friendly & PUC-friendly
    - customer remains on existing tariff (e.g., flat rate); no ratemaking
    - voluntary, opt-in characteristics like pricing programs
    - no revenue-recovery or customer bill risk from market volatility risk
  - Has many of the properties of RTP, except requires a baseline
  - Later in this presentation, you will see how PTR-like incentives can supplement RTP

Infrastructure Requirements Increase with Sophistication of DR Program

- Key question: Are the additional benefits worth the marginal costs?

Infrastructure Required*	Program Type					
	DLC	TOU	CPP	PTR	RTP	RTP Double Auction
Rate design		Y	Y		Y	Y
AMI & backhaul		Y	Y	Y	Y	Y
DR network: low-bandwidth, 1-way	Y		Y	Y		
low-bandwidth, 2-way	(p)					
high-bandwidth, 1-way				(p)	Y	
high-bandwidth, 2-way						Y
Pricing engine (software)				Y	Y	Y
Billing engine		Y	Y	Y	Y	Y
Load switch	Y		(p)			
Programmable thermostat	(p)	(p)				
Smart thermostat/controls	(p)		(p)	(p)	Y	Y
Smart appliances				(p)	(p)	(p)

* Compared to Interruptible program with baseline phone/pager system & PUC incentive approval

(p) = preferred – higher participation and/or benefits

The Fundamental Nature of Demand Response

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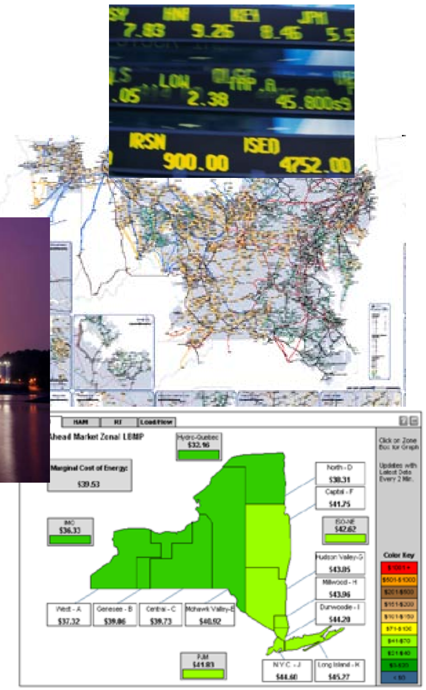
GridLAB-D: A Unique Tool for Designing Smart Grids

Unifies models of the key elements of a smart grid:

Power Systems

Loads

Markets



- ✓ Smart grid analyses
  - field projects
  - technologies
  - control strategies
  - cost/benefits
- ✓ Time scale: sec. to years
- ✓ Open source
- ✓ Contributions from
  - government
  - industry
  - academia
- ✓ Vendors can add or extract own modules

- ➢ GridLAB-D is a DOE-funded, open–source, time-series simulation of all aspects of operating a smart grid from the substation level down to loads in unprecedented detail
- ➢ Simultaneously solves:
  - 3-phase, unbalanced power flow in distribution systems, explicit control strategies
  - end use load physics, voltage-dependency, behavior & control in 1000s of bldgs.
  - double-auction retail supply/demand markets

Thermostat with a Simple Economic Response to Price *(Cooling Example)*

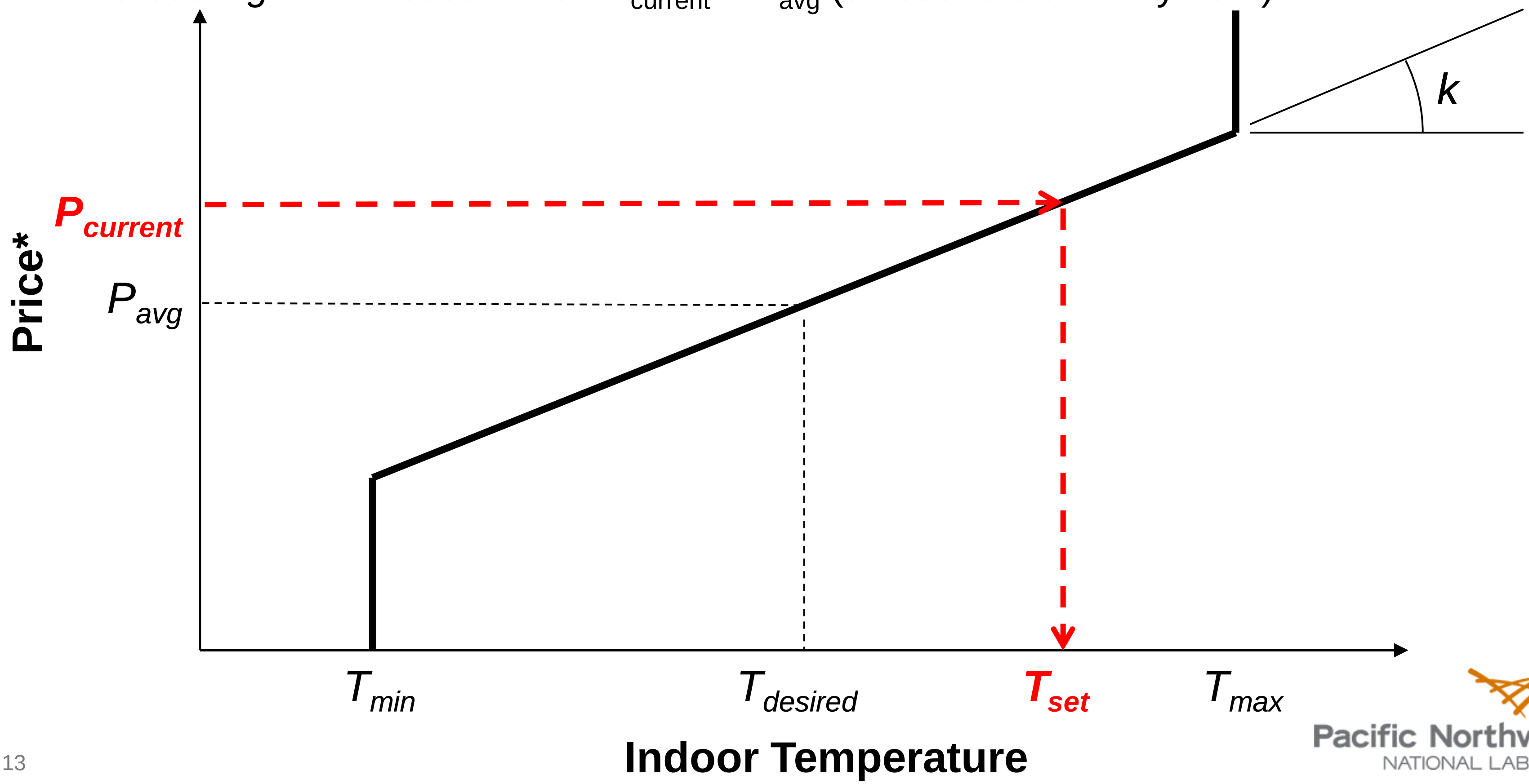
User sets: $T_{desired}$ and *comfort vs. savings* (on thermostat, by time & day-of-week)

These imply: T_{max}, T_{min}, k (price response parameters); $T_{set} = T_{desired}$ @ avg. price

*Price** is expressed as <u>std. deviation from mean</u> (over period of days to a year)

Tstat setpoint: automatically adjusts to current price ($P_{current}$)

Pre-cooling: will occur when $P_{current} < P_{avg}$ (unless forbidden by user)



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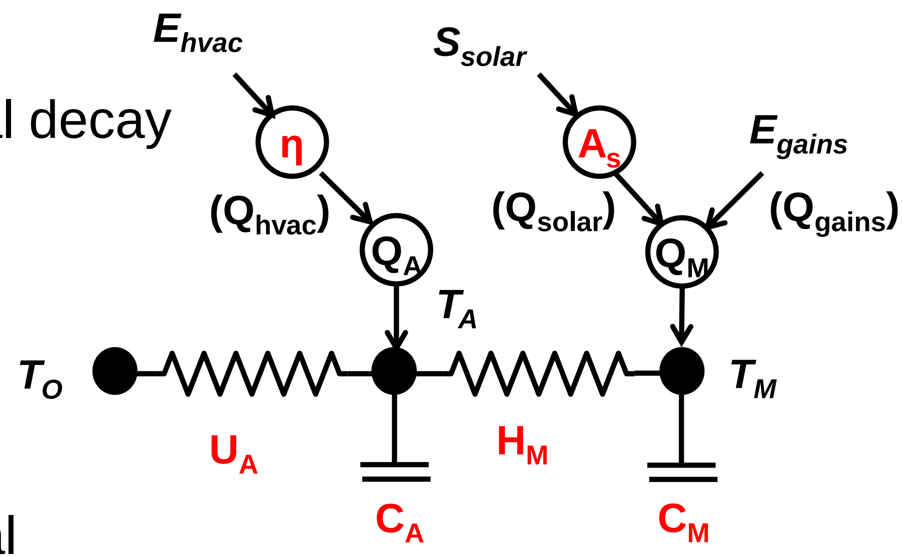
Equivalent Thermal Parameters (ETP) Circuit Used by GridLAB-D to Model HVAC Loads

- Two-node lumped-parameter model
- Over-damped DC circuit – exponential decay
- Simple enough for direct analytic solution & fast computation
- Complex enough to capture building load shapes
- Accounts for weather, building thermal properties, solar & internal gains, thermostat settings



- $Q_a + Q_m$ is heat added by HVAC system + internal (appliances) + solar
  - Internal gains driven by time-of-day, day-of-week schedule
  - Solar gains from weather & window properties
- Air conditioner & heat pump capacity & COP functions of outdoor temp.

$$Q_{HVAC\text{-}electric} = Capacity_{Thermal}(T_O) / COP(T_O)$$

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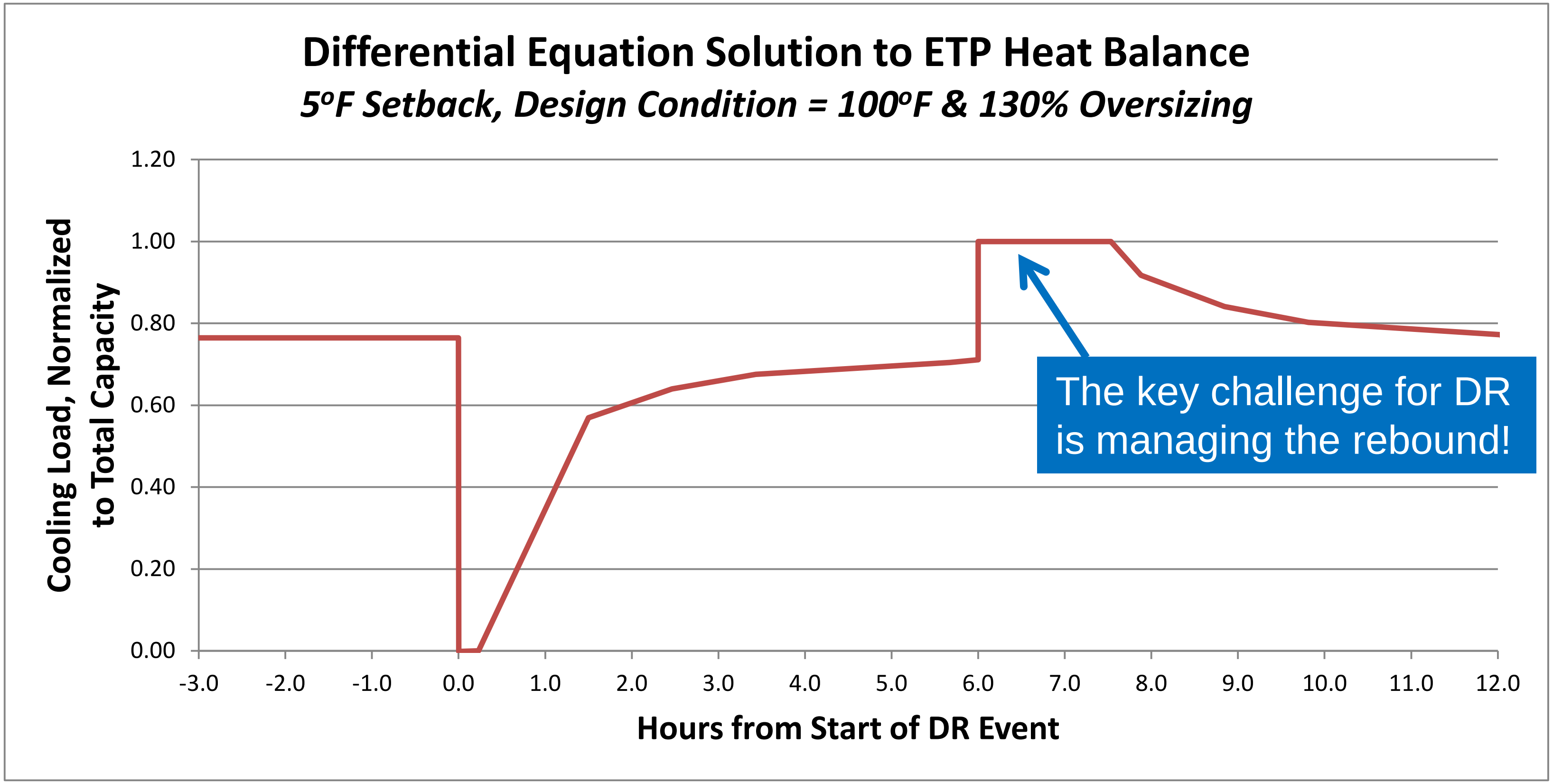
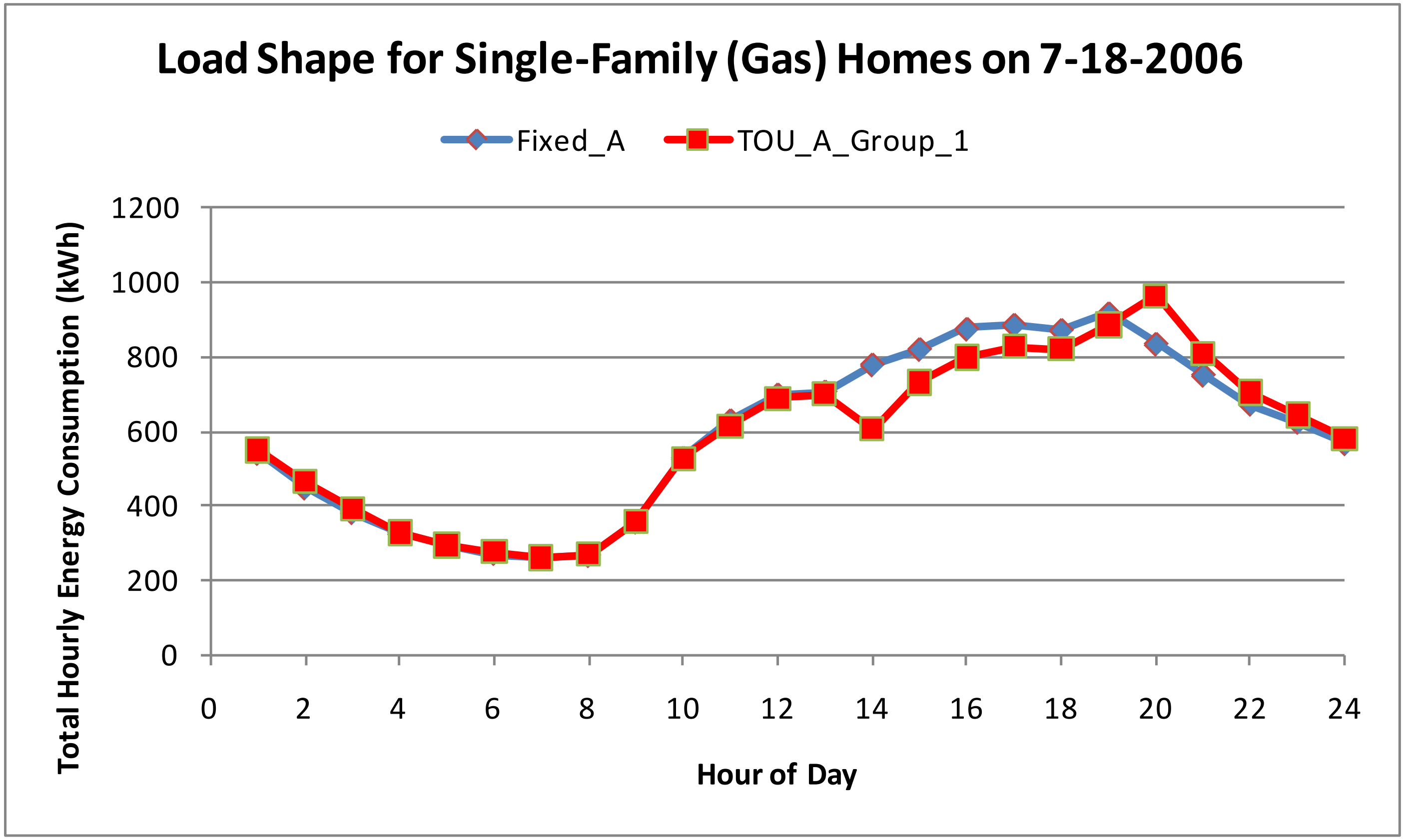
Typical Solution to Demand Response



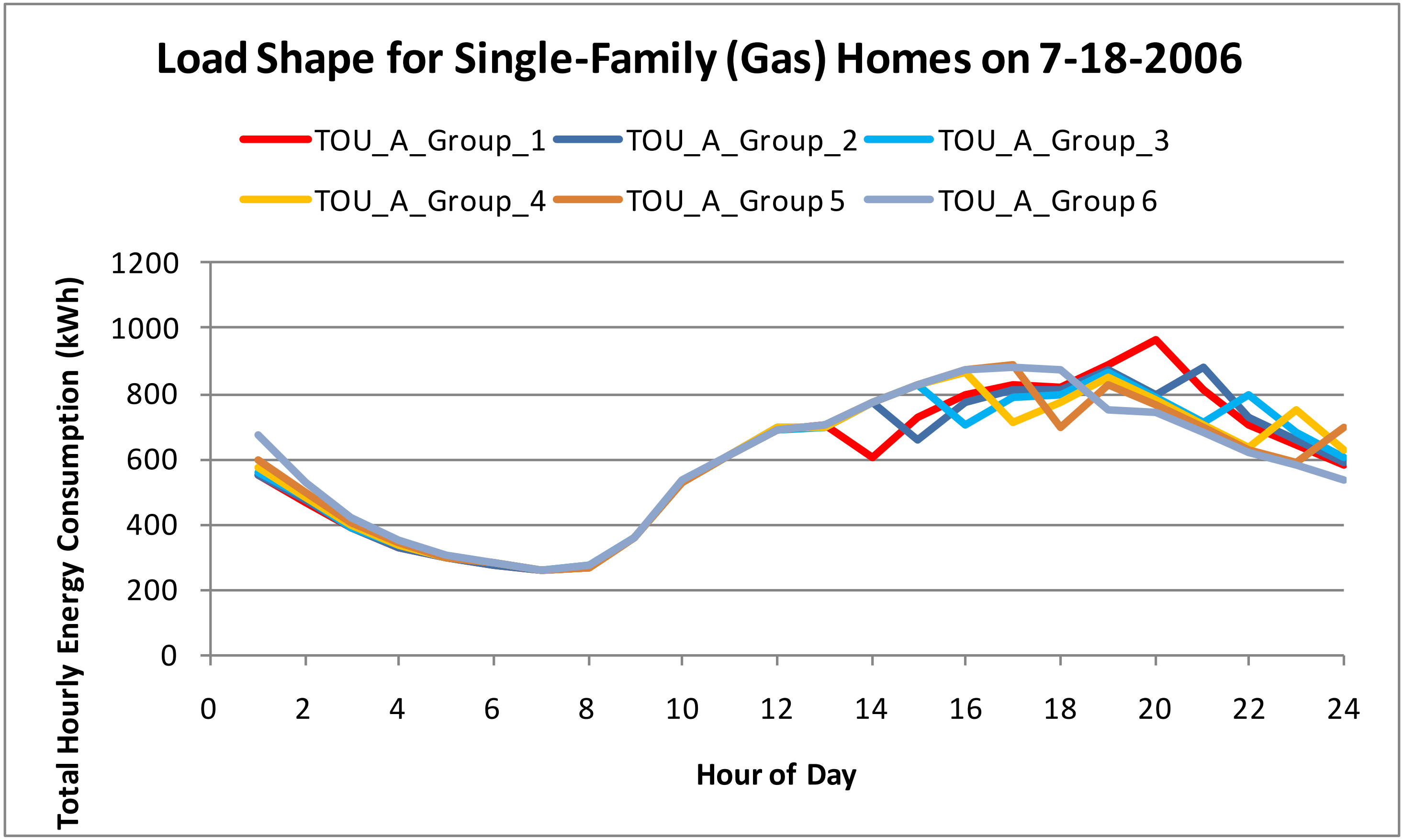
- Initially AC = 0 (~20 min)
- Rises to ~80% of initial load (~1 hr), ~93% at steady-state
- Cooldown load at full capacity (~1/2 hr) – <u>“rebound” effect</u>
- Ongoing cooldown to 125% of initial load (~1 hr)

Simple CPP Does Not Manage Capacity Well



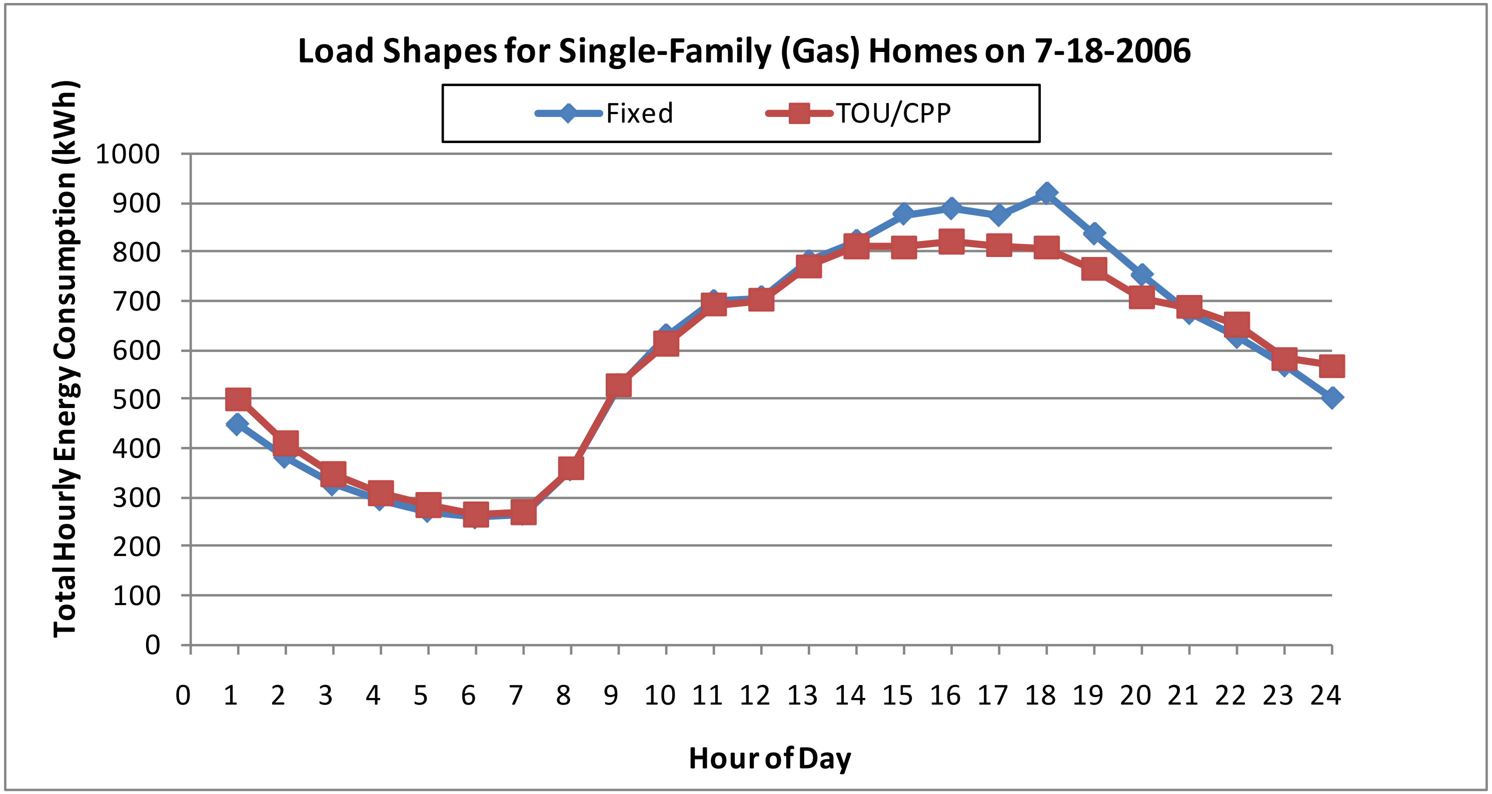
- Limited by lack of response after first hour
- Rebound effect after CPP results in new, even higher peak

Re-Formulation of CPP – Staggered Start Times



- Divide customers into groups, randomly every day
- Stagger start time for each group by 1 hour

Demand Response from Staggered CPP Groups



- Staggered start times for CPP flattens peak load reduction
- 11.5% load reduction on peak day
- Unequal weights for 5 groups

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Summer Peak Load Reductions (2.4ºF Avg. Response)

- Single-family homes dominate results (16% reduction)
- Mobile-homes & multi-family also contribute, but at relatively high cost due to lower loads
- Sm/med commercial contributes (a low % reduction) but also at high cost
- All appear competitive with cost of a coal plant (~$2000/kW), but marginally against a simple-cycle turbine peak load plant (~$800/kW)

Customer Type	N	Peak Demand	Peak Demand Reduction		Existing Customers		New Customers	
					Installed Cost	Cost per kW	Installed Cost	Cost per kW
		(kW)	(%)	(kW/ea.)	($/ea.)	($/kW)	($/ea.)	($/kW)
Residential	23,318	79,120	15.7%	0.53	$441	$825	$135	$253
SFg	10,532	36,280	15.6%	0.54	$415	$773	$135	$251
MHg	3,511	9,762	11.5%	0.32	$415	$1,302	$135	$424
MFe	2,358	6,189	14.8%	0.39	$480	$1,237	$135	$348
Sfe	5,188	21,491	17.3%	0.71	$480	$672	$135	$189
MHe	1,729	5,397	11.4%	0.36	$480	$1,347	$135	$379
Commercial	1,903	24,843	5.3%	0.69	$916	$1,329	$385	$559
COg	951	14,575	5.1%	0.78	$1,210	$1,542	$525	$669
CRg	951	10,268	5.1%	0.55	$622	$1,123	$245	$442
All	25,221	103,963	13.9%	0.57	$477	$834	$178	$311

- Costs for hardware & installation only (AMI, thermostats, HW controllers)
- Network, recruiting, customer service, business systems software not included

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Winter Peak Load Reductions (2.4°F Avg. Response)

- Single-family with electric heat homes dominate results (24% reduction)
- Mobile-homes with electric heat homes also contribute (11% reduction)
- These compete well against power plant costs
- Gas-heated homes contribute only if they have electric water heat
- No contribution from gas-heated commercial
- Multi-family appears to be poor investment

Customer Type	N	Peak Demand	Peak Demand Reduction		Existing Customers		New Customers	
					Installed Cost	Cost per kW	Installed Cost	Cost per kW
		(kW)	(%)	(kW/ea.)	($/ea.)	($/kW)	($/ea.)	($/kW)
Residential	23,318	116,281	15.1%	0.75	$441	$585	$161	$213
SFg	10,532	23,351	2.0%	0.04	$415	$9,241	$135	$3,006
MHg	3,511	5,071	0.0%	0.00	$415	-	$135	-
MFe	2,358	13,514	1.9%	0.11	$480	$4,495	$200	$1,873
Sfe	5,188	55,181	24.1%	2.57	$480	$187	$200	$78
MHe	1,729	19,163	11.2%	1.24	$480	$386	$200	$161
Commercial	1,903	25,118	0.0%	0.00	916	-	$385	-
COg	951	15,690	0.0%	0.00	$1,210	-	$525	-
CRg	951	9,427	0.0%	0.00	$622	-	$245	-
All	25,221	141,398	12.8%	0.72	$477	$665	$178	$248

Advantages of Real-Time Pricing

Why Real-Time Pricing?

- Limitations of CPP
  - Need to stagger start times adds complexity, uncertainty
  - Peak load on highest non-CPP can be new peak, reduces benefit
  - Price spikes & peak loads generally not coincident
  - Cannot be localized for distribution, or used for fast response
- Price-based & PTR advantages are similar in many ways
  - Maintain customer sense of control, engage more customers
  - Higher fidelity to true cost of service/net revenue can be obtained
  - Tap all the value streams, required for business case?
    - wholesale + peak capacity
    - distribution (prices must be localized)
    - Ancillary services (prices must be highly temporal)
- RTP dodges the baseline problem faced by PTR

Extending RTP with a Double-Auction Retail Congestion Market

Transactive Control: A Closed-Loop Control Scheme for Managing Capacity

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Cooling Thermostat with an Economic Response to a *Double-Auction Retail Congestion Market*

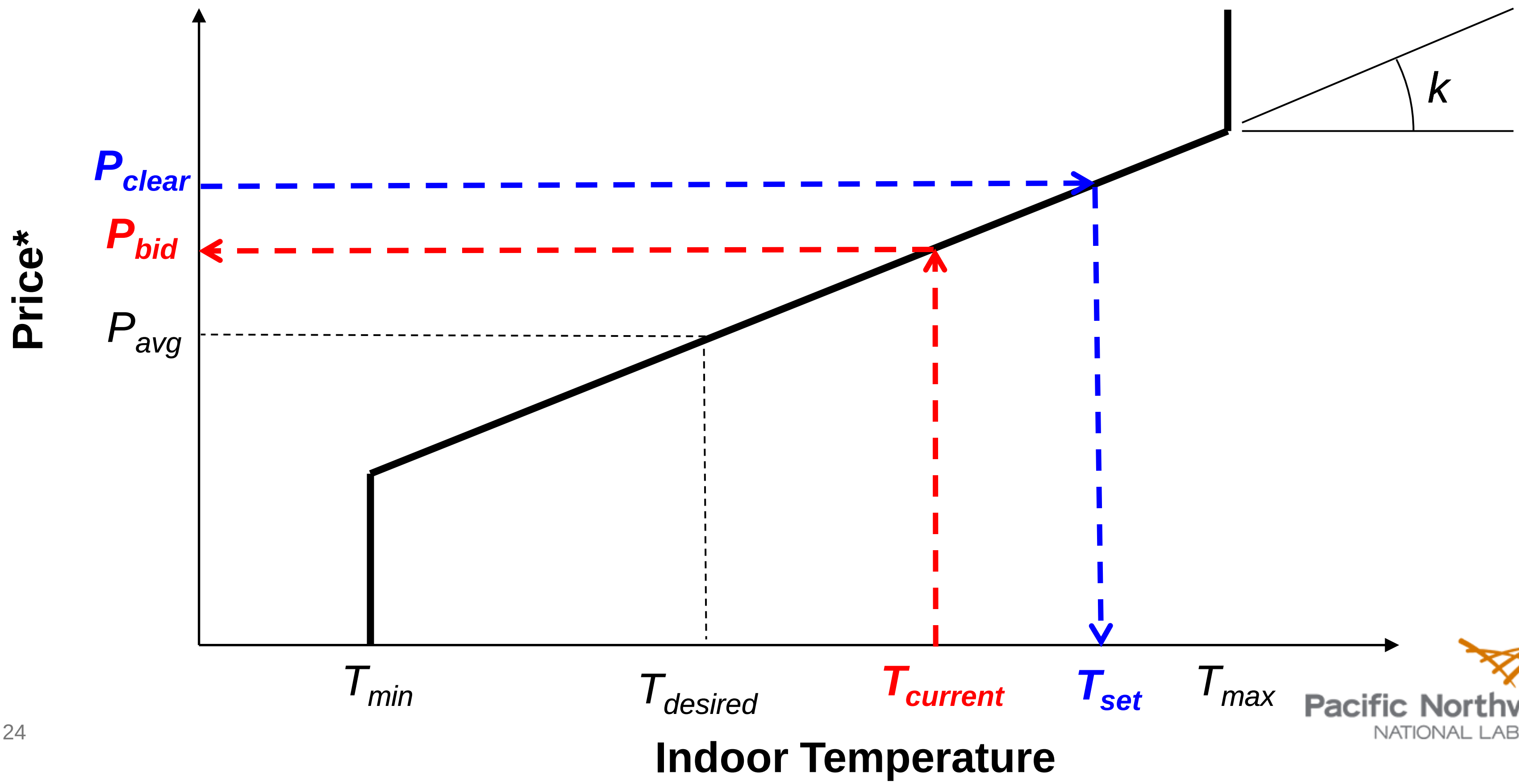
Tstat: bids quantity (power of AC) & price at which AC will "run" based on $T_{current}$

Market: sorts bids & quantities, clearing price set to manage quantity to any capacity limit

Tstat: adjusts setpoint to reflect clearing price

Manages variable demand to maintain desired load, maximizes total comfort of participants

Two-way communication is required



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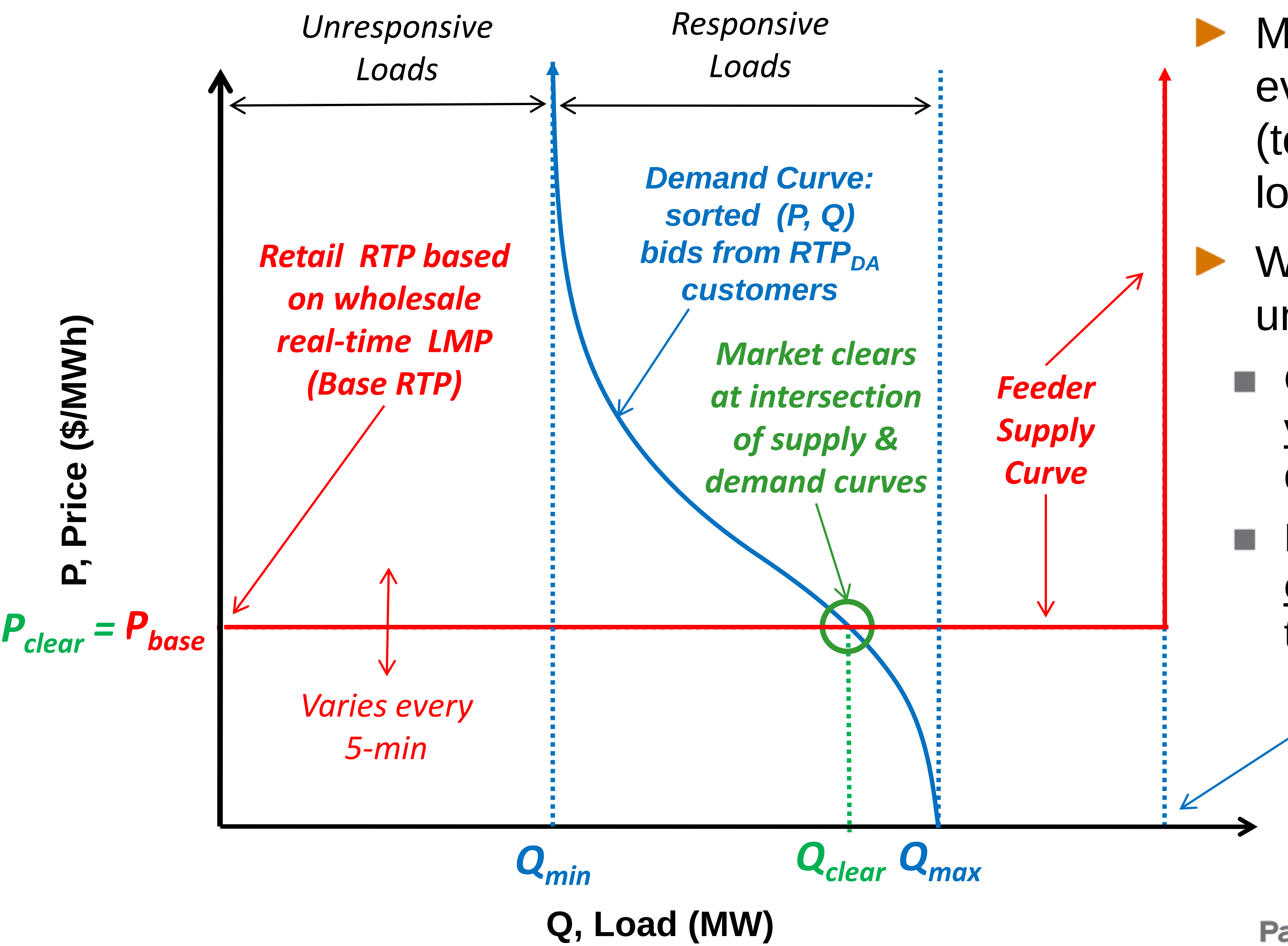
RTP Double Auction Market – *Uncongested Conditions*



- Market clears every 5-min (to ~match AC load cycle)
- When uncongested:
  - Quantity (Q_{clear}) varies with demand curve
  - Price (P_{clear}) is constant, equal to *Base RTP*

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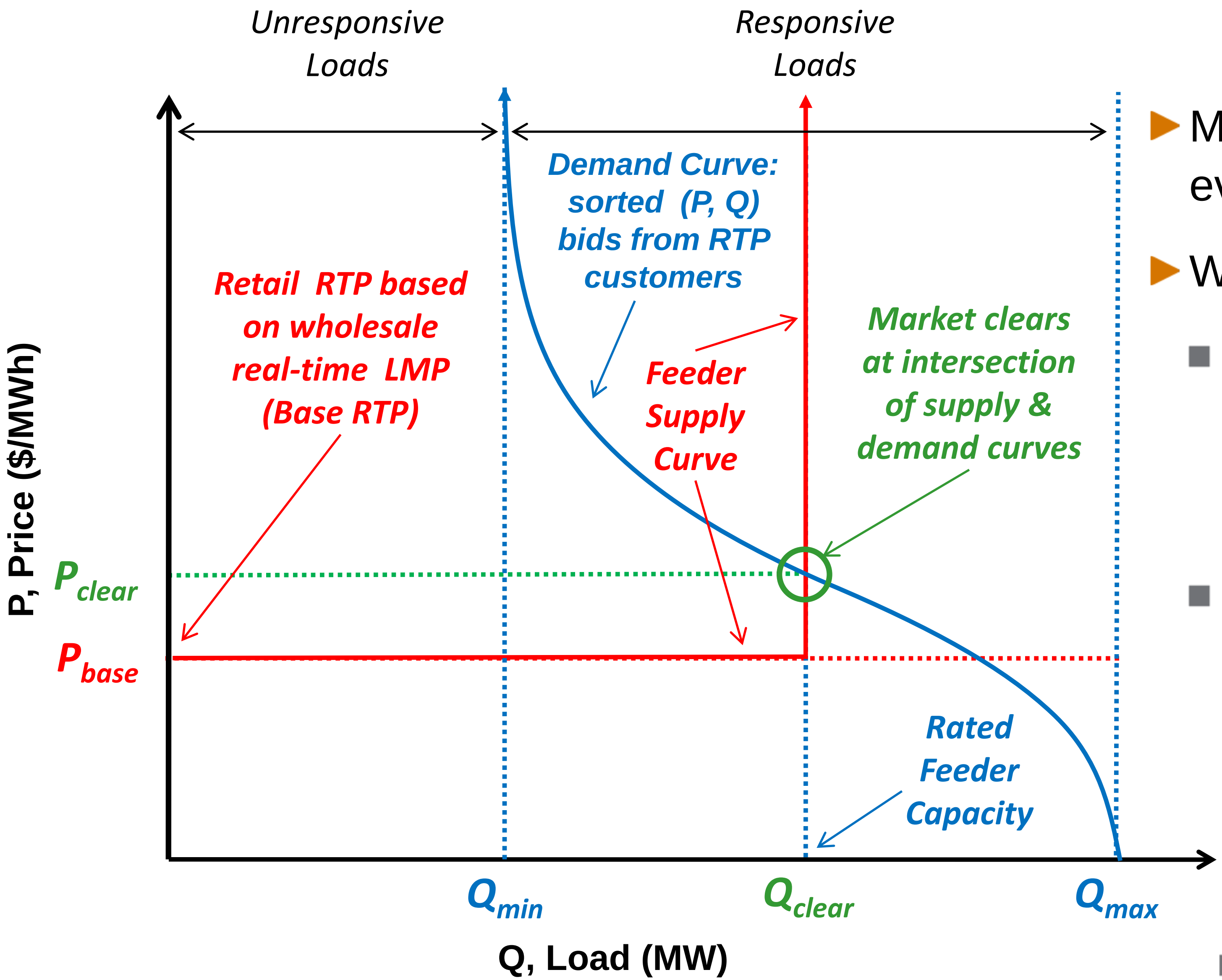
RTP Double Auction Market – *Distribution Congestion*



- Market clears every 5-min
- When congested:
  - Quantity (Q_{clear}) is <u>constant</u> at rated feeder capacity
  - Price (P_{clear}) <u>varies</u> to keep load at rated capacity

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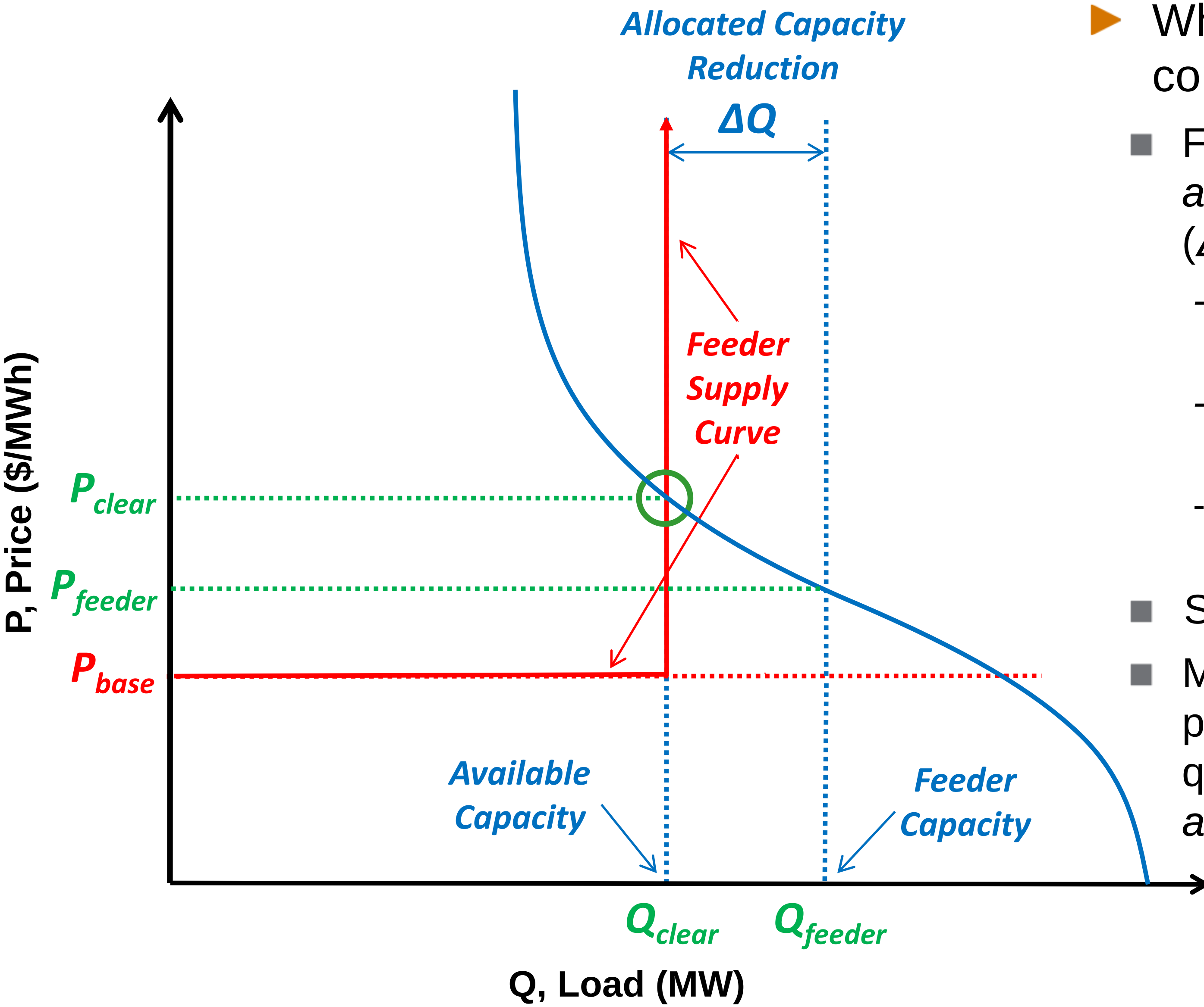
RTP Double Auction Market – *Local Allocation of System Congestion*



- When system-level congestion occurs:
  - Feeder is *allocated a capacity reduction* (*ΔQ*) based on:
    - required reduction of current system load
    - no. feeder customers on RTP_{DA} rate
    - cleared feeder load *(Q_{feeder})*
  - Supply curve adjusted
  - Market clears at higher price (P_{clear}) to keep quantity (Q_{clear}) at *available capacity*

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Results from a Field Experiment with Transactive Control

Engaging Customers and Technical Performance

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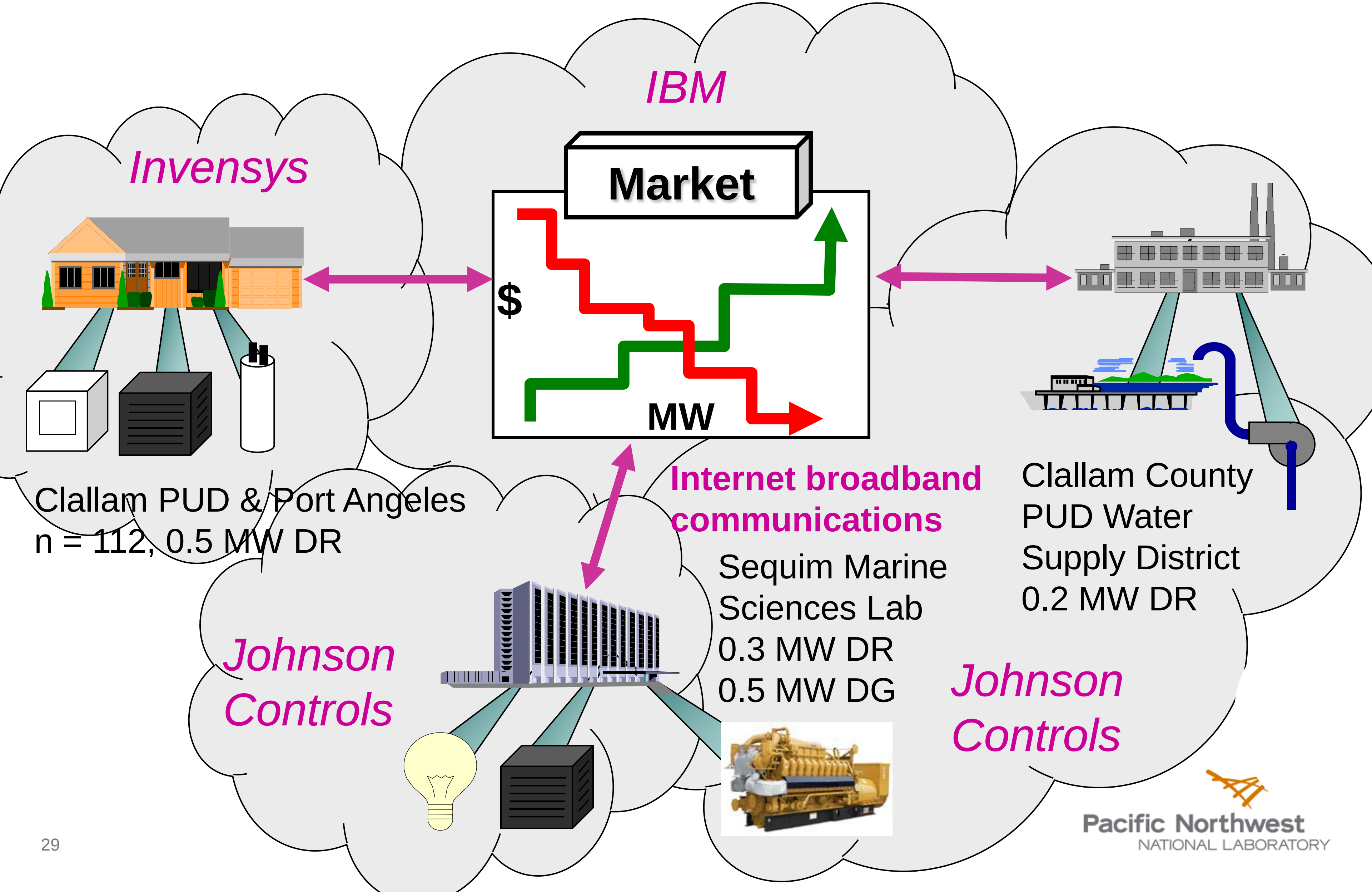
Olympic Peninsula Demonstration



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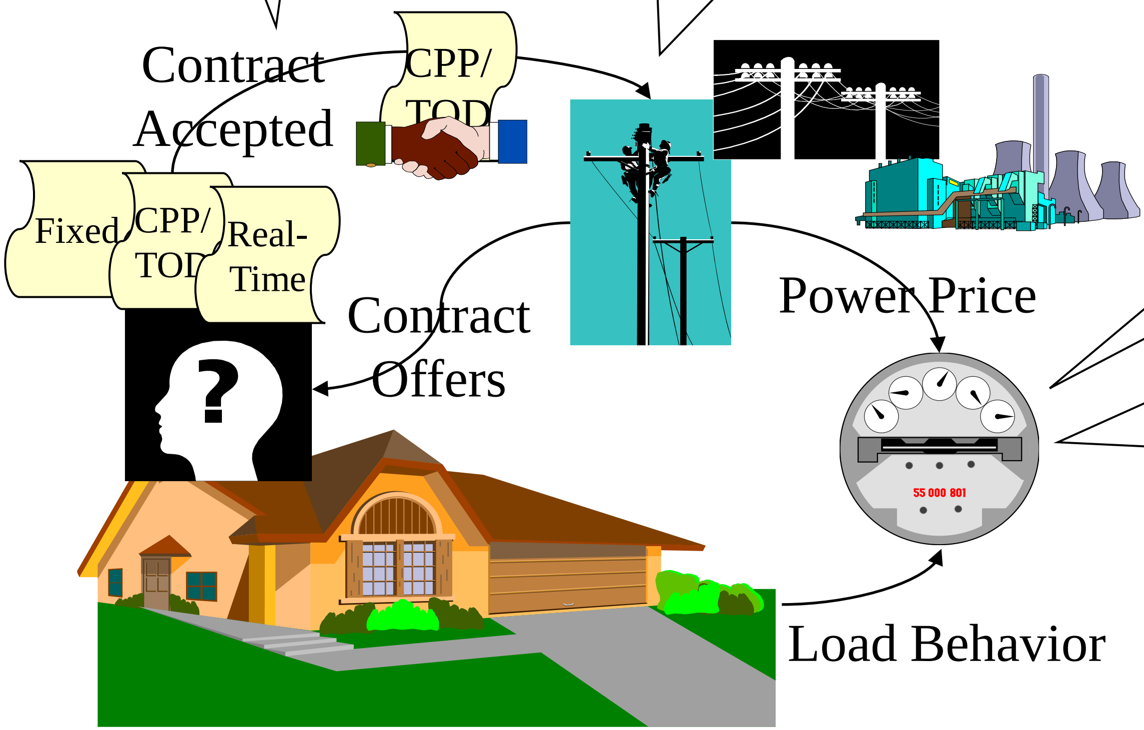
Testing Market-based Customer Incentives

Customer contract choice

Virtual distribution feeder (in software) as if all resources co-located on a single feeder



Real-time (5-min.) market clearing – real cash deposits & shadow billing

Demand response equipment to automate response based on customer preferences

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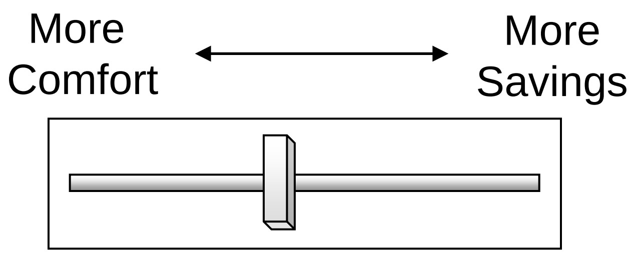
Olympic Peninsula Demo: Key Findings (1)

Customers can be recruited, retained, and will respond to *dynamic pricing* schemes **if they are offered**:

- Opportunity for significant savings (~10% was suggested)
- A “no-lose” proposition compared to a fixed rate
- Control over how much they choose to respond, with which end uses, and a 24-hour override
  - prevents fatigue: reduced participation if called upon too often
- Technology that automates their desired level of response
- A simple, intuitive, semantic interface to automate their response



Translates to control parameters:

K, T_{max}, T_{min} (see *Thermostat slide*)

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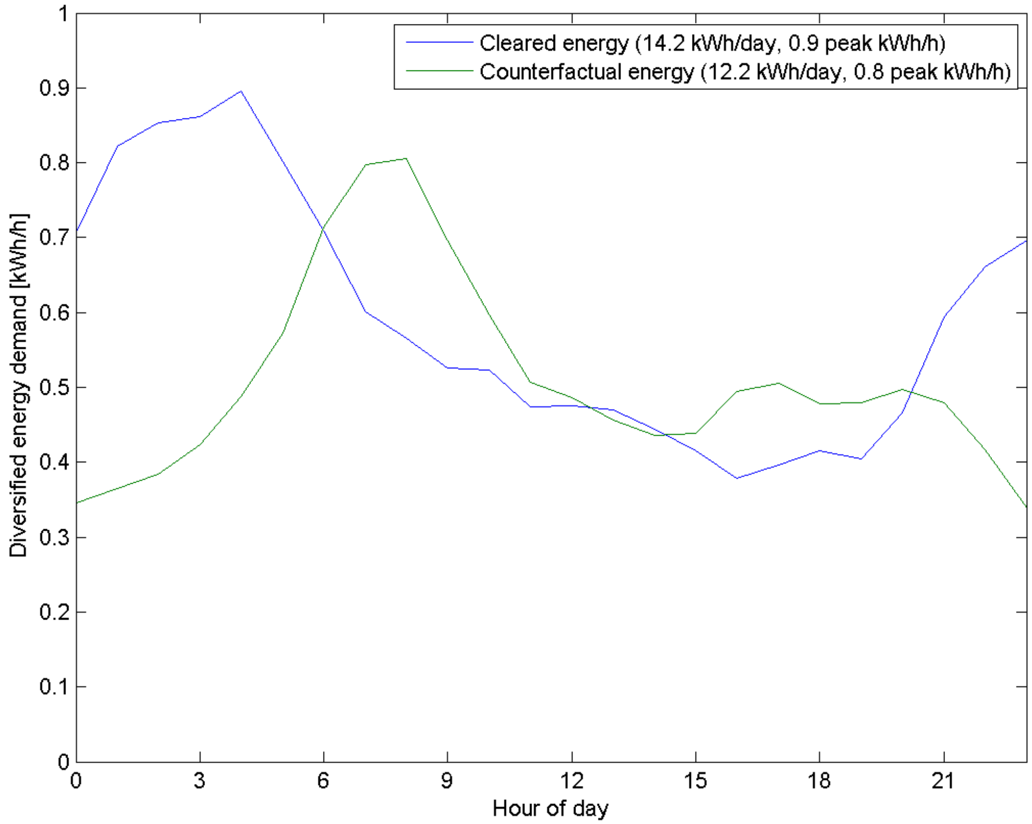
Olympic Peninsula Demo: Key Findings (2)

Significant demand response was obtained:

- 15% reduction of peak load
- Up to 50% reduction in total load for several days in a row during shoulder periods
- Response to wholesale prices + transmission congestion + distribution congestion
- Able to cap net demand at an arbitrary level to manage local distribution constraint
- Short-term response capability could provide regulation, other ancillary services adds significant value at very low impact and low cost)
- Same signals integrated commercial & institutional loads, distributed resources (backup generators)

Load Shifting Results for RTP Customers



- Winter peak load shifted by pre-heating
- Resulting new peak load at 3 AM is non-coincident with system peak at 7 AM
- Illustrates key finding that a portfolio of contract types may be optimal – i.e., we don't want to just create a new peak

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Larger Demos of RTP-Double Auction Underway

- AEP's gridSmart™ stimulus funded demonstration project
  - ~1,000 residential customers will be recruited
  - RTP/double-auction rate design (tariff) approved by Ohio PUC
  - Technical performance & customer engagement to be compared with other DR program types (DLC, TOU, CPP, etc.)
  - Software engine for market operation, HEM-based thermostat bidding, & billing under construction
- Pacific Northwest Smart Grid Demonstration
  - Extending transactive control to link generation, transmission, & distribution nodes in hierarchical architecture
  - Monetizes operational objectives from generation to end-use (e.g., integration of wind)
  - Addressing interoperability & cyber-security issues

www.aeopohio.com/save/demoproject *www.pnwsmartgrid.org*

Challenges in Designing RTP Rates

Revenue Neutrality & Market Volatility

- RTP rate designed to be *revenue neutral* prior to any load shift:
  - Annual revenue (RTP-double auction) = Annual revenue (fixed rate)
  - Population-weighted loads from class load research sample
  - 37 months of historical hourly LMPs
  - I.e., for a customer with avg. annual energy & load shape (& no load shift)

    there is *no change in annual electric bill*

- Form of tariff: Bill $= \sum_t \{ \text{A LMP(t) Scalar}_m + \text{B} \} \text{ kWh(t)} + \text{C}$
  - Lower B, C → higher A, & higher dynamic range in RTP
    - increases savings opportunity for customers
    - A > 1 → volatility in net revenue wrto. LMP
    - $Scalar_m$ ≡ monthly LMP market price adjustment, reduces revenue & bill volatility

$$Scalar_m = \frac{\text{(Baseline 37-month average LMP)}}{\text{(Previous 3-month average LMP)}}$$

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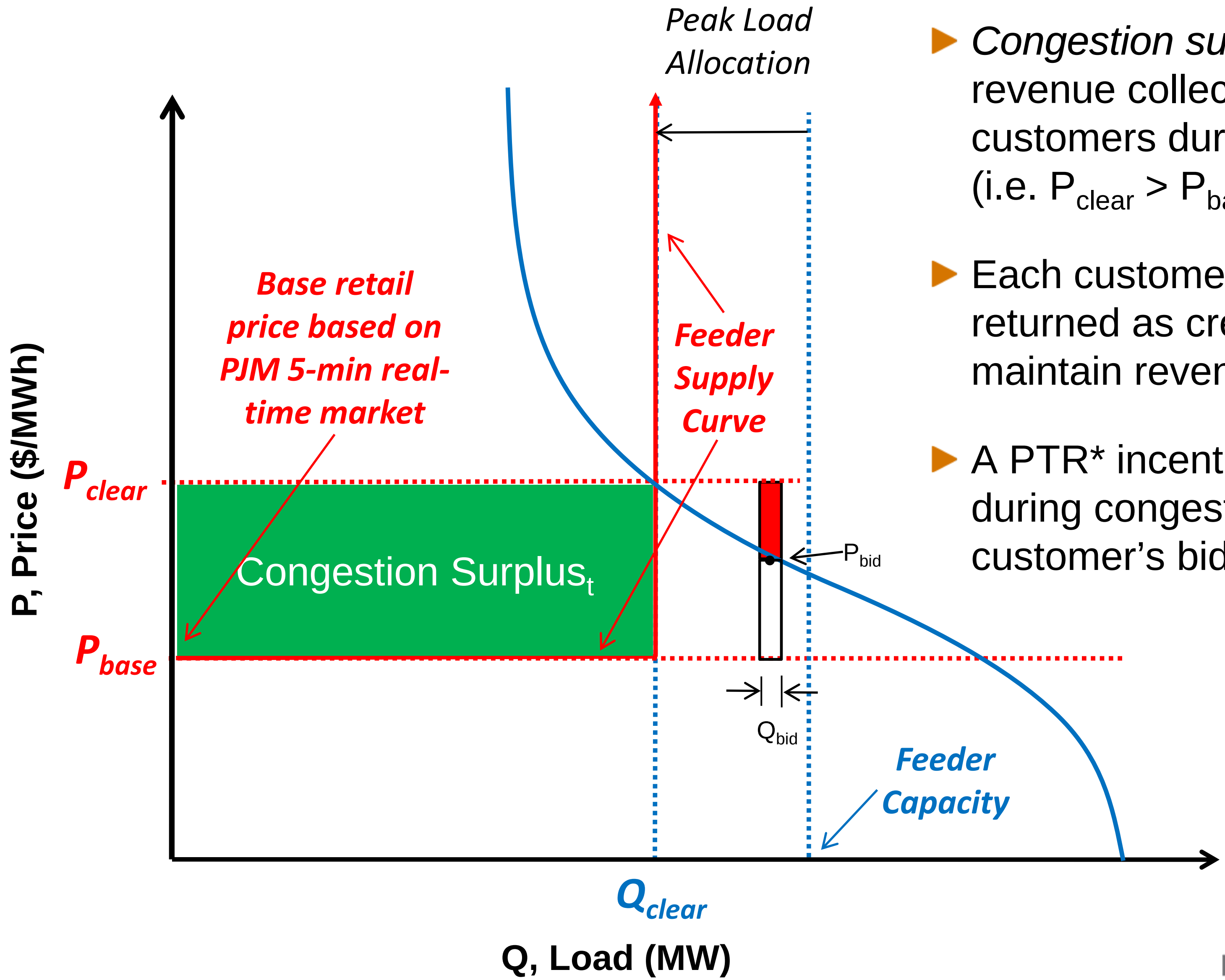
What about the Congestion Surplus?



- *Congestion surplus* is extra revenue collected from RTP_{DA} customers during congestion (i.e. $P_{clear} > P_{base}$)
- Each customer's surplus returned as credit on bill to maintain revenue neutrality
- A PTR* incentive is offered during congestion, based on customer's bid history

* peak time rebate

Why Rebate the Congestion Surplus?

- RTP rate was designed to be revenue neutral without congestion
  - customers who don't respond to congestion prices need to be reimbursed
  - customers who do respond deserve a reward, not a penalty
- Customers on congested feeders will be subject to higher prices than peers on uncongested feeders
  - if the *congestion surplus* is not returned, they are inherently penalized, even if trying to help by being responsive

Why Not Build Congestion Events into the Rate?

- Number of congested days & hours is uncertain
- RTPs during congestion are not known a priori
- Both depend on the interaction of
  - weather in any given year
  - % of peak load reduction targeted
  - responsiveness of RTP customers
- Different prices for different feeders implies …

different rate design for each feeder???

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Ensuring Adequate Customer Incentives

- Potential reduction in bill is customer's incentive to shift to RTP rate, and be responsive
- Despite *revenue neutral* rate, an individual customer with a "bad" load shape could see a bill increase
- *Hold harmless* provision guarantees a customer pays the lesser of RTP & fixed rate bills (1st year only?)
- All ratepayers benefit from
  - deferred generation & T&D capacity
  - mitigation of high market prices
  - potential future sales to spinning reserve markets
  - net the DR deployment cost
- Hence, it's all about the business case:

$$\sum \text{Benefits} \overset{?}{\geq} \text{Incentives} + \text{Deployment Costs}$$

Implications for Smart Grid Communications Architecture

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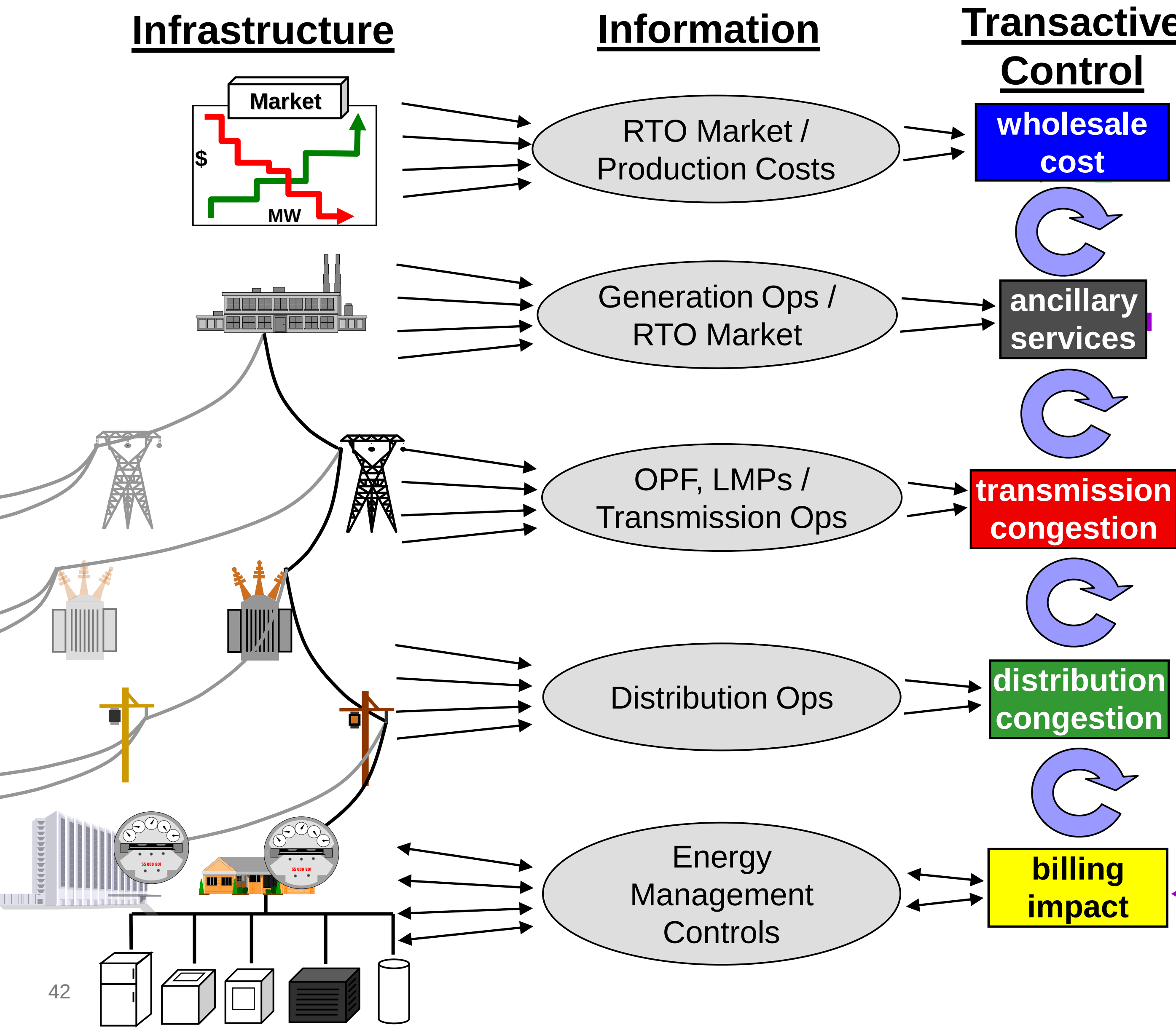
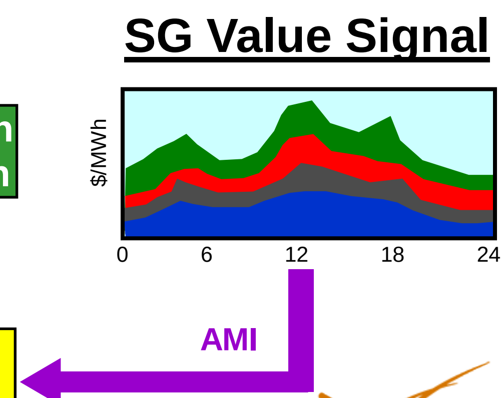
Two-Way, Hierarchical, Transactive Architecture Localizes and Balances Values & Prices



Information for each layer of value signal is <u>entirely local</u>

Honoring <u>natural domains</u> keeps the smart grid simple:

- protocols/standards are mostly quantity, cost, and time (“*KISS*”)
- honoring “need-to-know” enhances cyber security



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Extending RTP to Engage Demand for Ancillary Services

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Potential for Demand Response to Help Manage Large Infusion of Renewables

Regulation: one or more fast-responding power plants continually throttle to match normal fluctuations in load

- Highest cost generation in markets (ties up capacity, zero net energy sales, wear & tear, fuel consumption)
- Fluctuations in solar & wind output exacerbate need for regulation, increase systems cost for renewables at high penetrations