Fast, Scalable Demand-Shaping with ColorPower

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ColorPower in a Nutshell:

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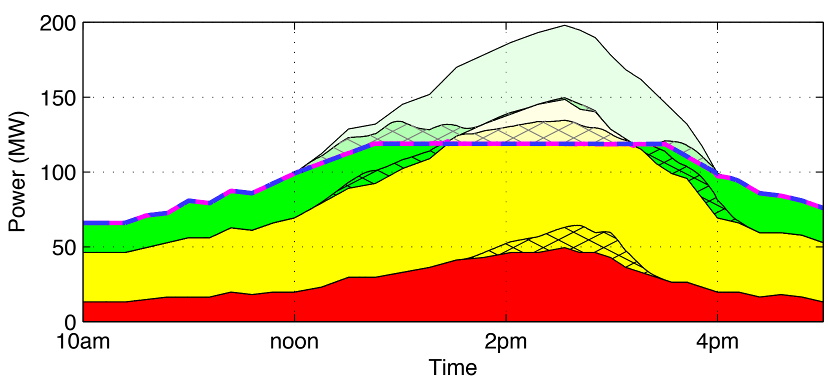
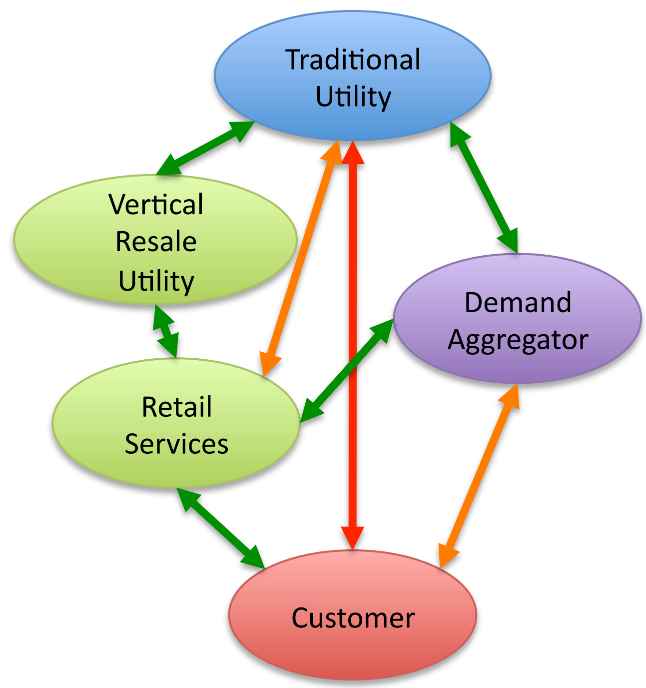
Energy service tiers…

… allow scalable distributed demand management…



… bringing disruptive change to the energy industry.



Talk Outline

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- **Energy Flexibility Tiers**
- The ColorPower algorithm
- Implications and Impact

The Demand Challenge

- Future retail utilities must be able to effectively manage *demand fulfillment at the margin*
  - Defer consumption
  - Pull forward consumption
  - Cancel uneconomic consumption (in customers' best interest!)

- Problem: inadequate coordination between the grid and end user devices

Economists vs. Customers

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Microeconomics View

- Customers can be modeled as rational marginal demand functions for a commodity
- Customers can be modeled as virtual power plants
- Customers need to be sent price signals to modify their behavior

Customer View

- I do not have a marginal demand for power, I want reliable service
- I am not a virtual power plant
- I don’t want price volatility risk or to do laundry at midnight

Retail Power Is a Service

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- Not a hot concert ticket
- Not a basket of commodity electrons

- Customers prefer to buy power as a service, not a commodity
  - Just like many other service industries

The service sector has largely abandoned congestion pricing as a way to manage demand peaking

Paradigms for Peak Demand Control

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Industry	Process / Technology
Various (e.g. manufacturing)	"First Come First Serve" / Backlog Queue
Hospitals	"Most Urgent First" / Waiting Room
Road Transportation	"Alternating Access" / Traffic Light
General Digital Communications	"Best Effort Transport" / TCP/IP
Cellular	Automatic Protocol / CDMA
Cable Networking	Automatic Protocol / DOCSIS
DSL	Automatic Protocol / ATM
Electric Power - Today	Free-for All / Circuit Breaker
Electric Power – Future Consensus	Real-time Auction / Smart Grid

Technology As Auction Enabler

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HOW MUCH IS THIS POWER WORTH TO YOU NOW?

HOW ABOUT NOW?

HOW ABOUT NOW?

SORRY YOU WERE JUST OUTBID BY R1CH_P0WRHAWG

YOUR POWER HAS MOVED TO A PLACE WHERE IT IS MORE APPRECIATED

[POWER OFF]

THE GOOD NEWS IS YOU HAVE NOW SAVED 26 OPEN SODA CANS WORTH OF CO2 EMISSIONS

Energy efficiency or clever trading?

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FrigidTrader 3000

- Aggressive risk/reward tradeoff!
- Detects and avoids hedge-fund price-manipulation strategies!
- Free trading strategy upgrades!
- Icemaker upgrade available

Retail Price Volatility: Be Careful What You Wish For

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Price Signal

PEANUTS ARE VERY EXPENSIVE RIGHT NOW

WIDE-SCALE PRICE VOLATILITY:

GOOD FOR SPECULATORS
BAD FOR CONGESTION CONTROL

CATASTROPHIC FOR SYSTEM RELIABILITY

WE'LL PAY YOU TO TAKE THESE PEANUTS AWAY

Smart Appliance/EV Stampedes

Core problem: price is overloaded

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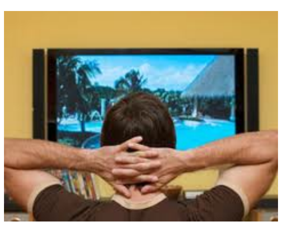
- Too many stakeholders, not enough leverage:
  - Customer preferences
  - Customer impact
  - Procurement of supply
  - Operations reliability
  - Regulatory policy
  - Shareholders and financial traders

Alternative: *less* information

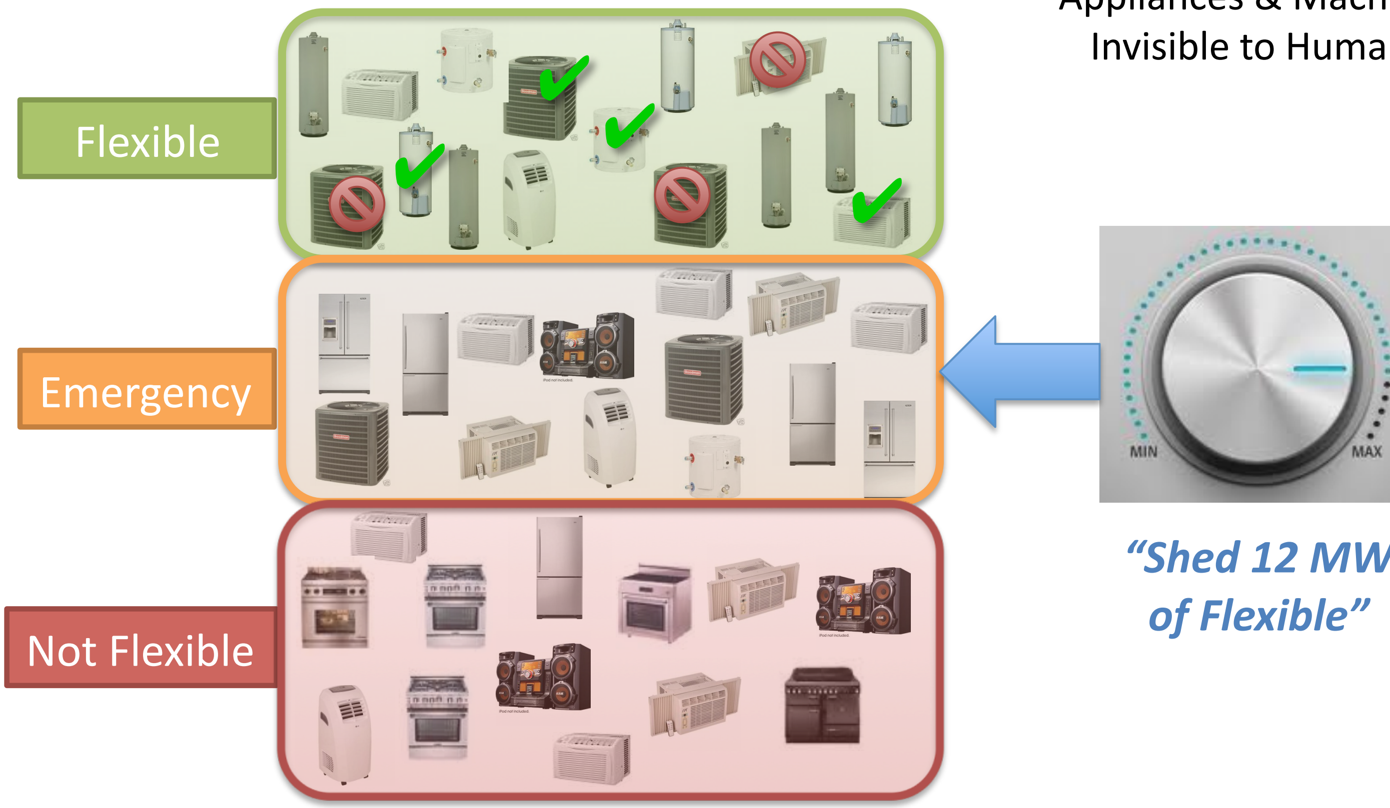
ColorPower: Tiered Energy Priority

Humans:
Always In Control
Privacy Respected



ColorPower Appliance Priorities

1. Obey Your Humans' Preferences
2. Donate Flexibility to Power Grid



Smart Grid:
Coordinates Orderly Power Access For Flexible Appliances & Machines
Invisible to Humans

"Shed 12 MW of Flexible"

Self-Identification of Demand Flexibility

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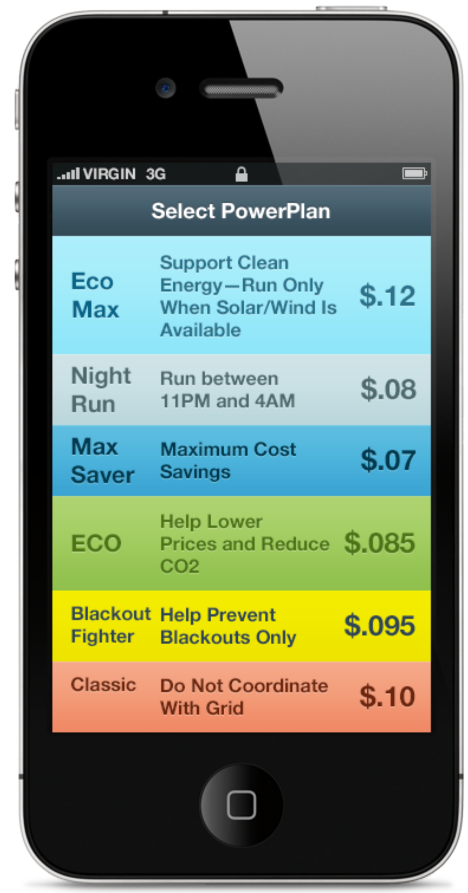

Leaf Button:
On = Flexible

Green = Price Sensitive
Yellow = Reliability Responsive
Red = Opt Out

Cloud Software
With More Options

From Flexibility to Priority Tiers

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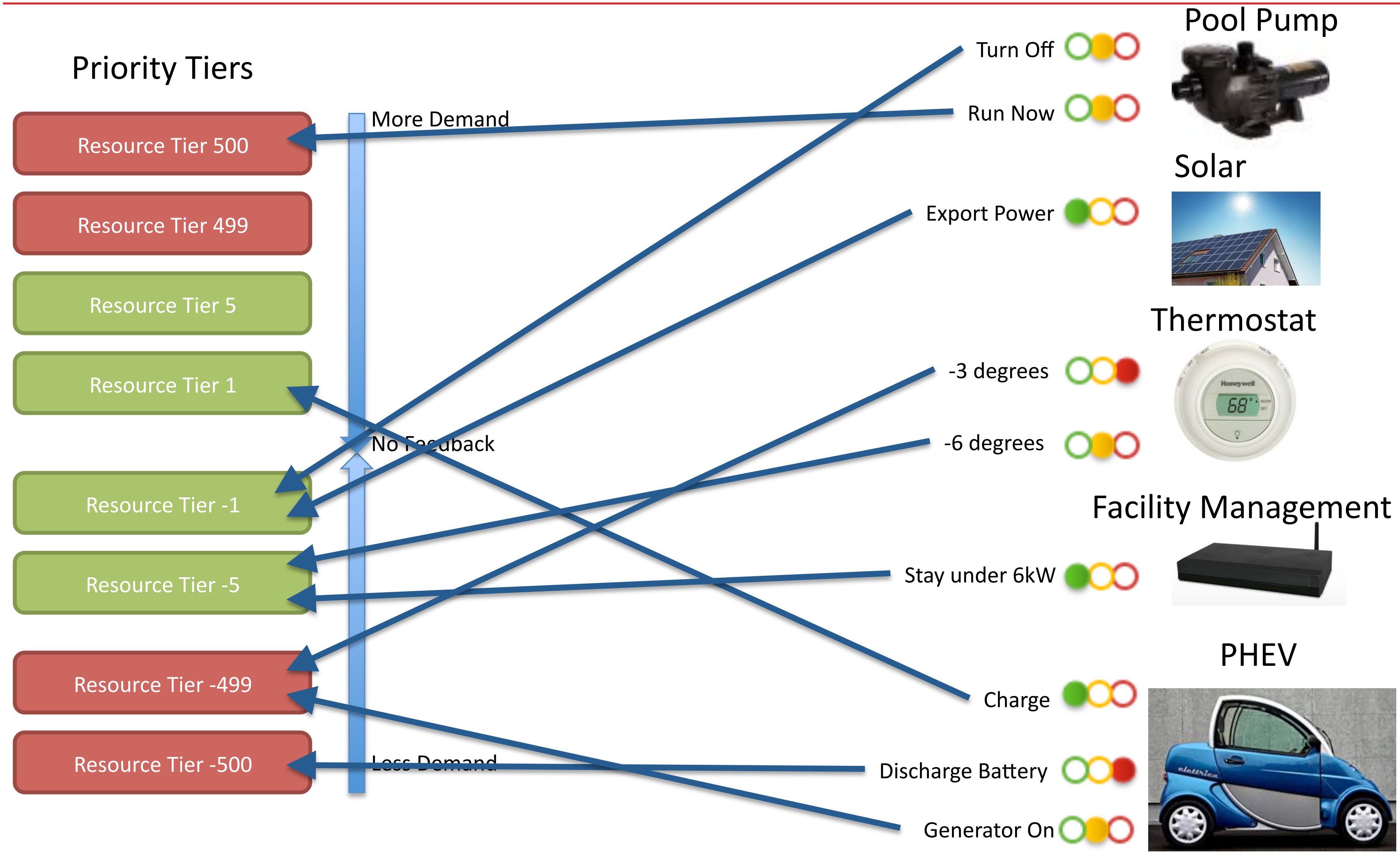
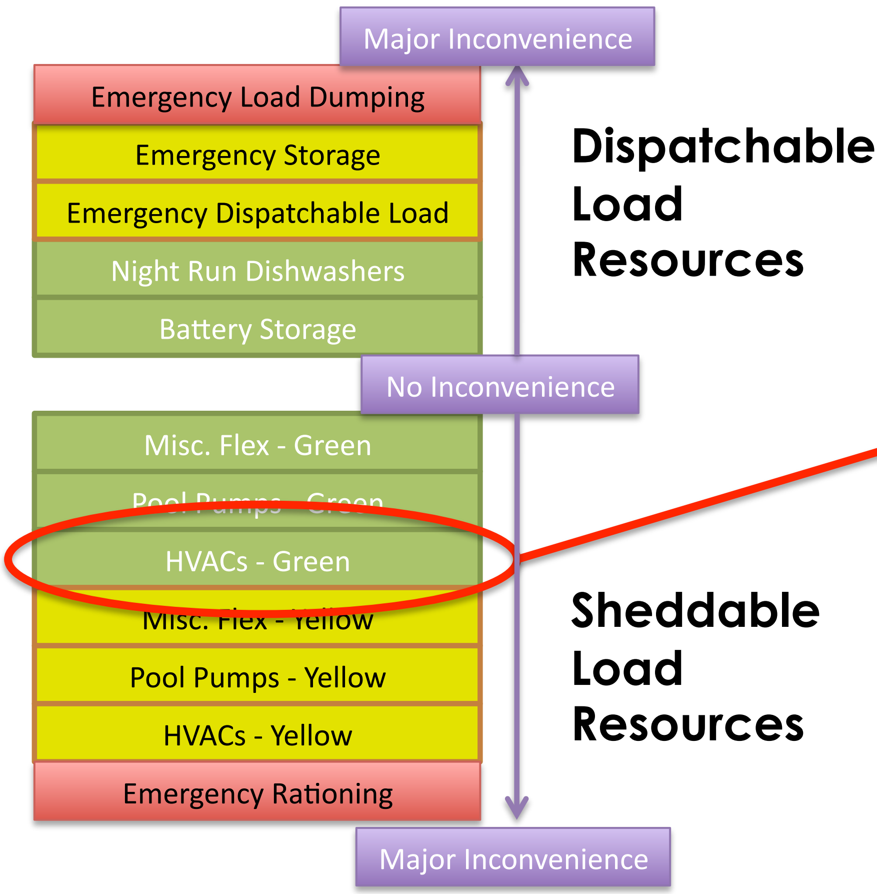


Default Tier Assignment Via Color/Device Type

Tiered Aggregations



HVACs – Green Service Levels

- Max Curtailment: 60%
- Min Cycle Power Timeslice: 10 min
- Max Cycle Downtime: 20 min
- Max Ramp Rate: 200kW/min

Outline

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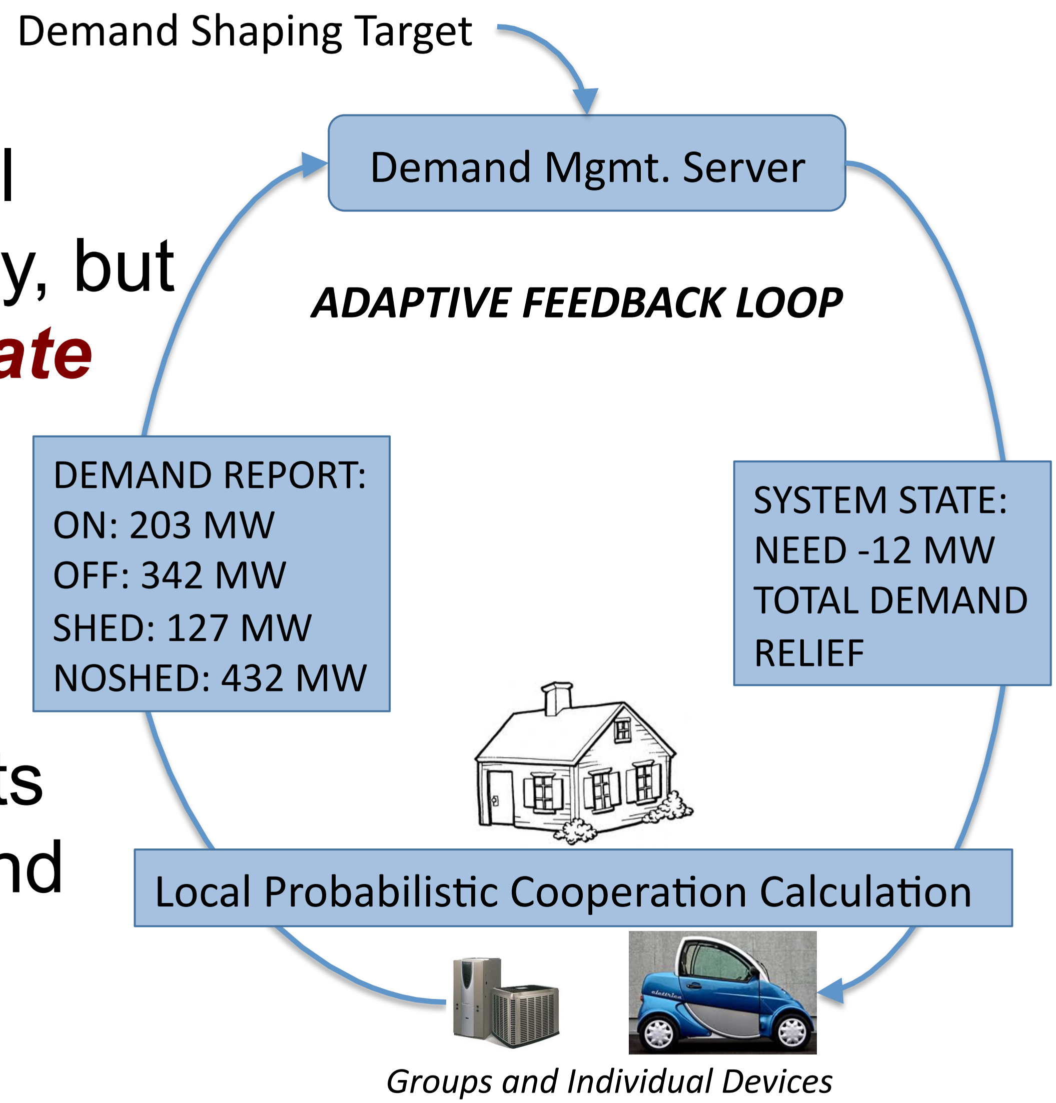
- Energy Flexibility Tiers
- The ColorPower algorithm
  - **Control Architecture**
  - ColorPower Algorithm
  - Validation in Simulation
- Implications and Impact

[Beal, Berliner, & Hunter, SASO'12; Ranade & Beal, SASO'10]

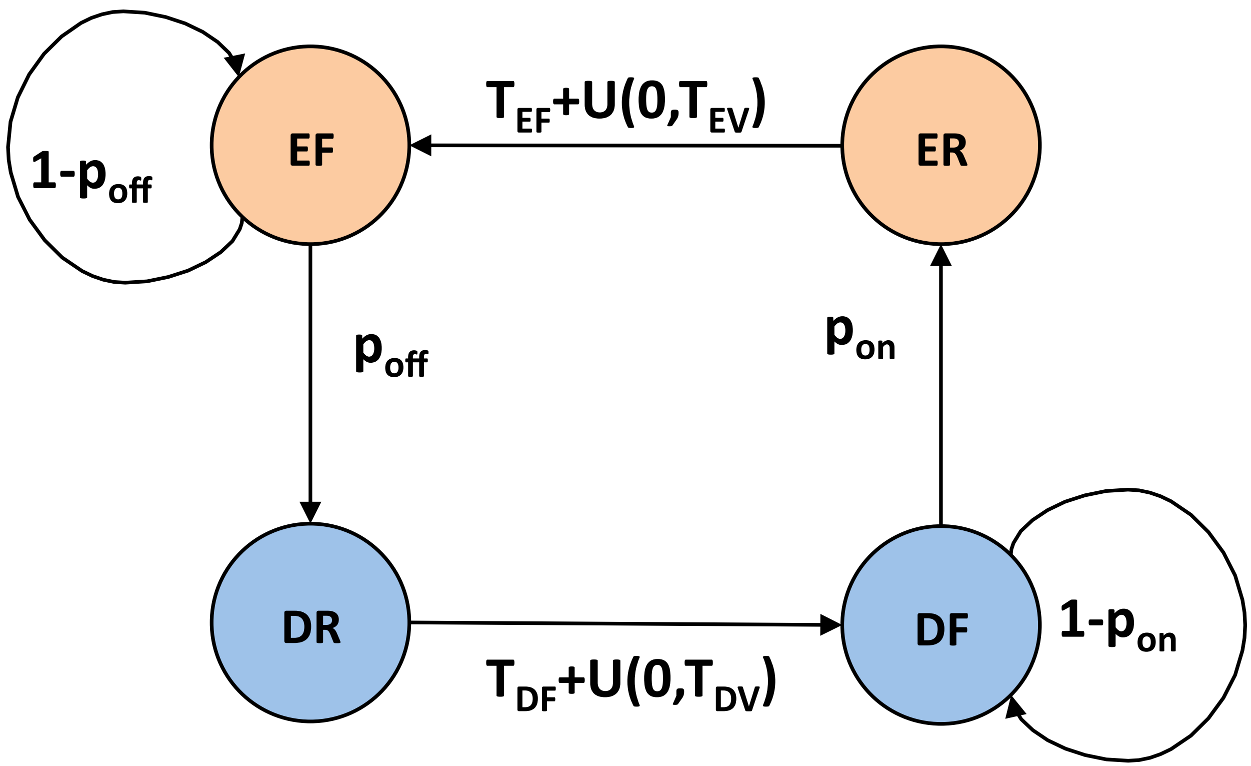
Basic ColorPower Architecture

- Groups and Individual Devices Act Randomly, but ***Precisely in Aggregate***

- Feedback loop recruits resources until demand target satisfied

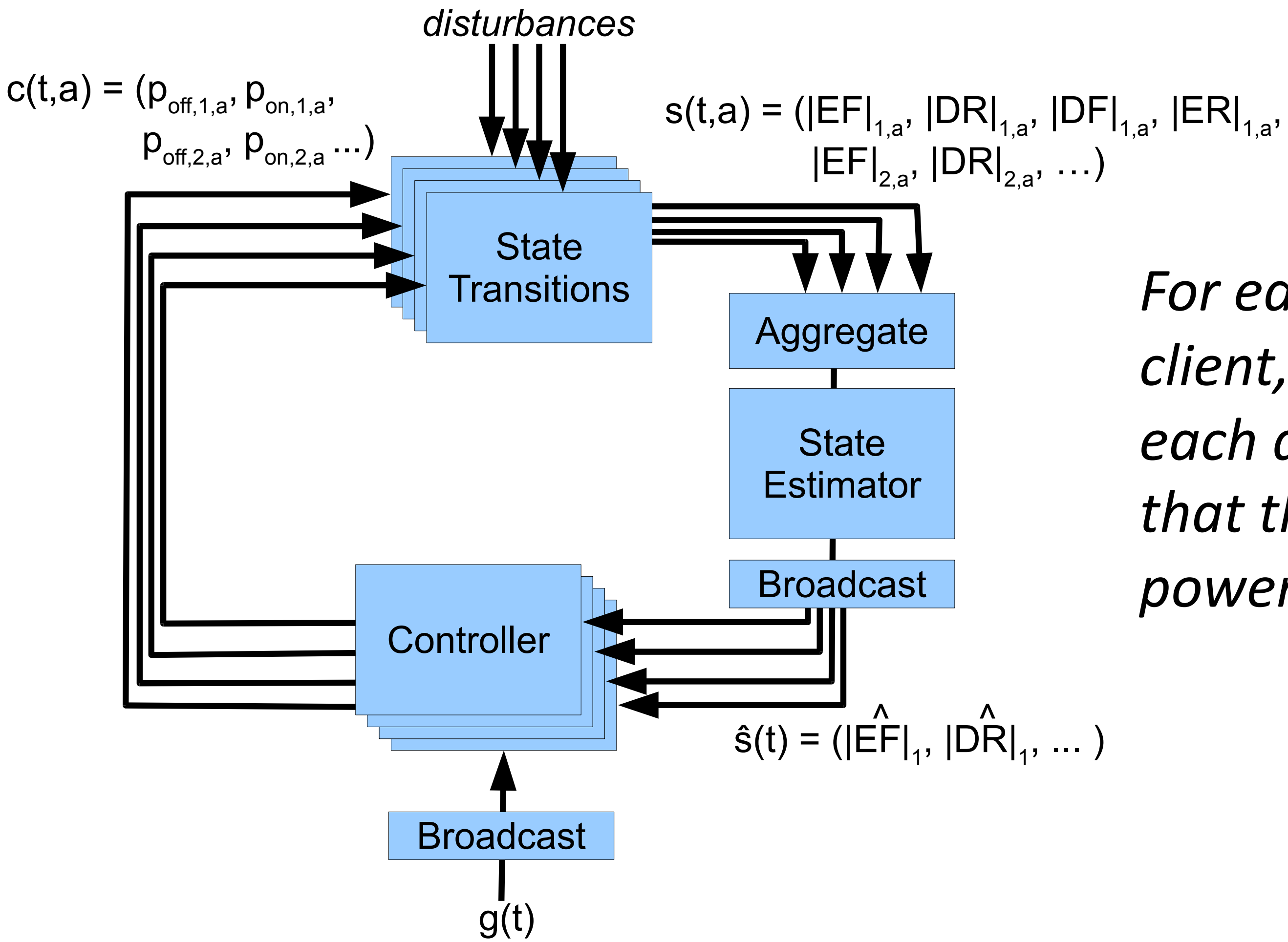


ColorPower State Transitions



- (E)nabled vs. (D)isabled
- (R)efractory vs. (F)lexible

Formal Control Problem



For each ColorPower client, set p_{on}, p_{off} for each device group, such that the total enabled power in s(t) tracks g(t)

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ColorPower 2.0 Algorithm: Intuition

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- Flexibility accumulates as Refractory devices finish their timeouts.
- Allocate flexibility budget in order of importance:
  1. Goal tracking & hard priority constraints
  2. Soft priority
  3. Cycling devices to ensure fairness
  4. Maintaining flexibility reserves for future needs

Constraints

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- Goal tracking: *shape power demand*

$$g(t) = \sum_i |EF_i| + |ER_i|$$

- Color priority: *respect user preferences*

$$|EF_i| + |ER_i| = \begin{cases} D_i - D_{i+1} & \text{if } D_i \leq g(t) \\ g(t) - D_{i+1} & \text{if } D_{i+1} \leq g(t) < D_i \\ 0 & \text{otherwise} \end{cases}$$

$$D_i = \sum_{j \geq i} |EF_j| + |ER_j| + |DF_j| + |DR_j|$$

- Fairness: *no devices are favored*

$$\forall_{a,a'} c(t,a) = c(t,a')$$

- Cycling: *don't keep the same devices off*

$$(|EF_i| > 0) \cap (|DF_i| > 0) \implies (p_{on,a,i} > 0) \cap (p_{off,a,i} > 0)$$

ColorPower 2.0 Algorithm: Equations

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Boundary color *b*: $D_{b+1} \leq g(t) < D_b$

Allocation 1: Goal Tracking

Correction Goal:

$$C^g = \alpha \cdot (g(t) - \sum_i |\hat{EF_i}| + |\hat{ER_i}|)$$

Downward shift:

$$\Delta_i^{g-} = \begin{cases} 0 & \text{if } C^g \geq 0 \text{ or } i > b \\ |\hat{EF_i}| & \text{else if } \sum_{j \leq i} |\hat{EF_j}| \leq |C^g| \\ |C^g| - \sum_{j<i} |\hat{EF_j}| & \text{else if } \sum_{j<i} |\hat{EF_j}| < |C^g| \\ 0 & \text{otherwise} \end{cases}$$

Upward is converse

Allocation 2: Color Priority

$$|\hat{EF_i}|' = |\hat{EF_i}| - \Delta_i^{g-} \quad |\hat{DF_i}|' = |\hat{DF_i}| - \Delta_i^{g+}$$

Downward shift:

$$\Delta_i^{p-} = \begin{cases} 0 & \text{if } i \geq b \text{ or } \sum_{j \leq i} |\hat{EF_j}|' > |DF_b|' \\ |\hat{EF_i}|' & \text{else if } \sum_{j \leq i} |\hat{EF_j}|' \leq |DF_b|' \\ |DF_b|' - \sum_{j<i} |\hat{EF_j}|' & \text{else if } \sum_{j<i} |\hat{EF_j}|' < |DF_b|' \end{cases}$$

Upward is converse

Allocation 3: Cycling

$$|\hat{EF_b}|'' = |\hat{EF_b}| - \Delta_i^{g-} - \Delta_i^{p-}$$

and similar for other states

Reserve fraction *f*:

$$\frac{|EF_b|}{|ER_b|} \geq f \text{ and } \frac{|DF_b|}{|DR_b|} \geq f$$

$$r(t) = (D_b - g(t))/(g(t) - D_{b+1})$$

$$p_{on,ss} = \frac{1}{f \cdot T_D}$$

$$p_{off,ss} = \frac{1}{\frac{1}{r(t)}(f+1)T_D - T_E}$$

when enabled domainates, else converse

$$\Delta_b^{c-} = \Delta_b^{c+} = \min(p_{off,ss} \cdot |EF_b|'', p_{on,ss} \cdot |\hat{DF_b}|'')$$

Computing p_{on} and p_{off}

$$p_{off,i,a} = \frac{\Delta_i^{g-} + \Delta_i^{p-} + \Delta_i^{c-}}{|EF_i|}$$

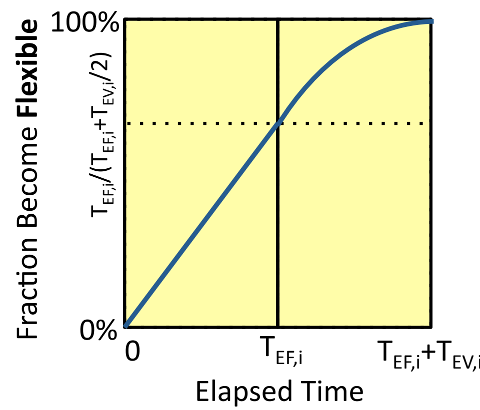
$$p_{on,i,a} = \frac{\Delta_i^{g+} + \Delta_i^{p+} + \Delta_i^{c+}}{|DF_i|}$$

Analysis

- Convergence:
  - Sufficient Flexibility: $\epsilon = (1-\alpha)^{r_c} \cdot \Delta, \text{ where } r_c = \dfrac{\log \epsilon - \log \Delta}{\log(1-\alpha)}$
  - Insufficient Flexibility:

Quadratic: $r_c = T_{EF,b} + \sqrt{\dfrac{\Delta - F - R'}{R - R'}} \cdot T_{EV,b}$

Linear: $r_c = \dfrac{\Delta - F}{R'} \cdot T_{EF,b}$



- Quiescence: (conservative)

Priority constraint: $r_p = \max(T_{DF,b'} + T_{DV,b'}, T_{EF,b} + T_{EV,b})$

Total: $r_q = r_c + r_p + 2(T_{DF,b'} + T_{DV,b'}/2 + T_{EF,b'} + T_{EV,b'}/2)$

- Ramp Tolerance: $\Delta_r^- = |EF| \cdot p_{off,ss}$ and $\Delta_r^+ = |DF| \cdot p_{on,ss}$

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  - **Analysis & Simulation**
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Control Example: Hot Summer Day

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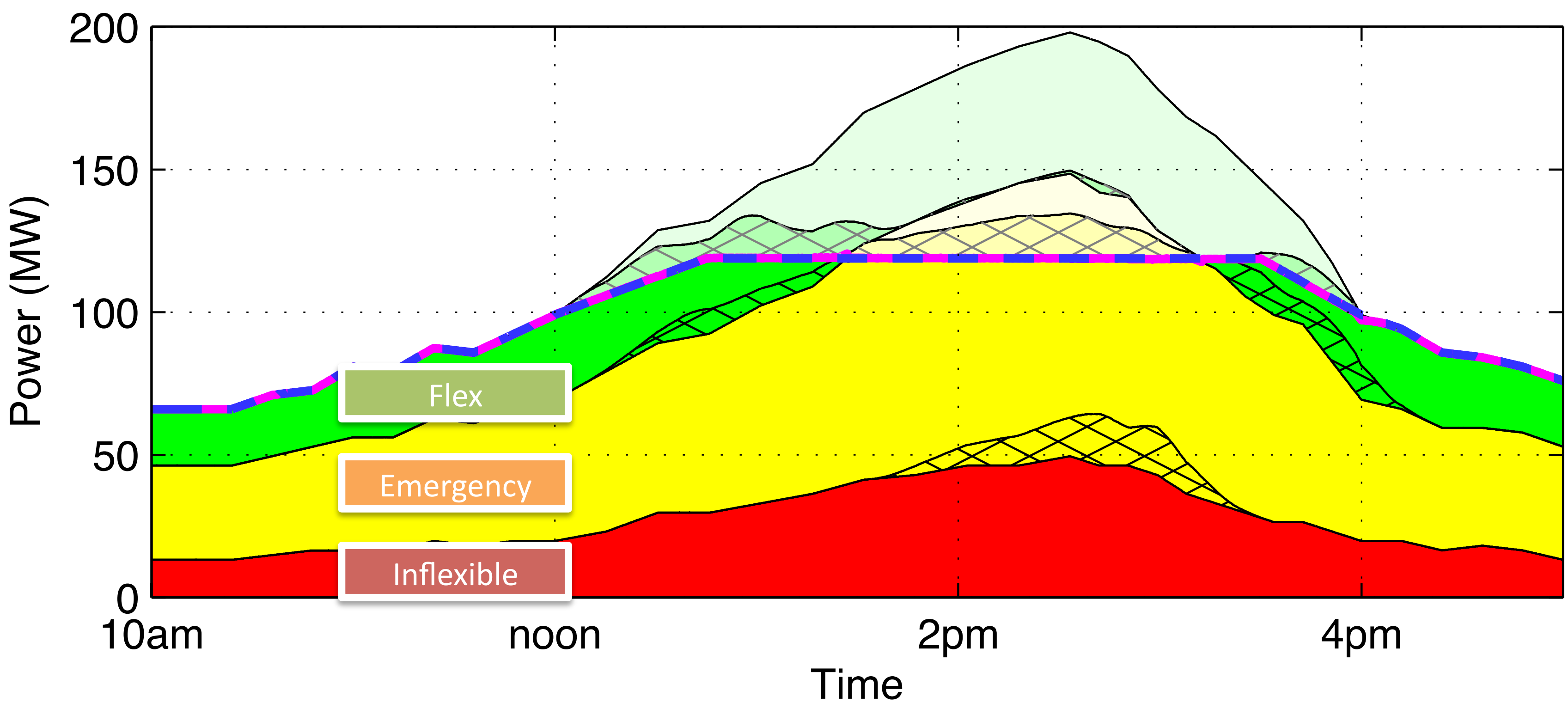
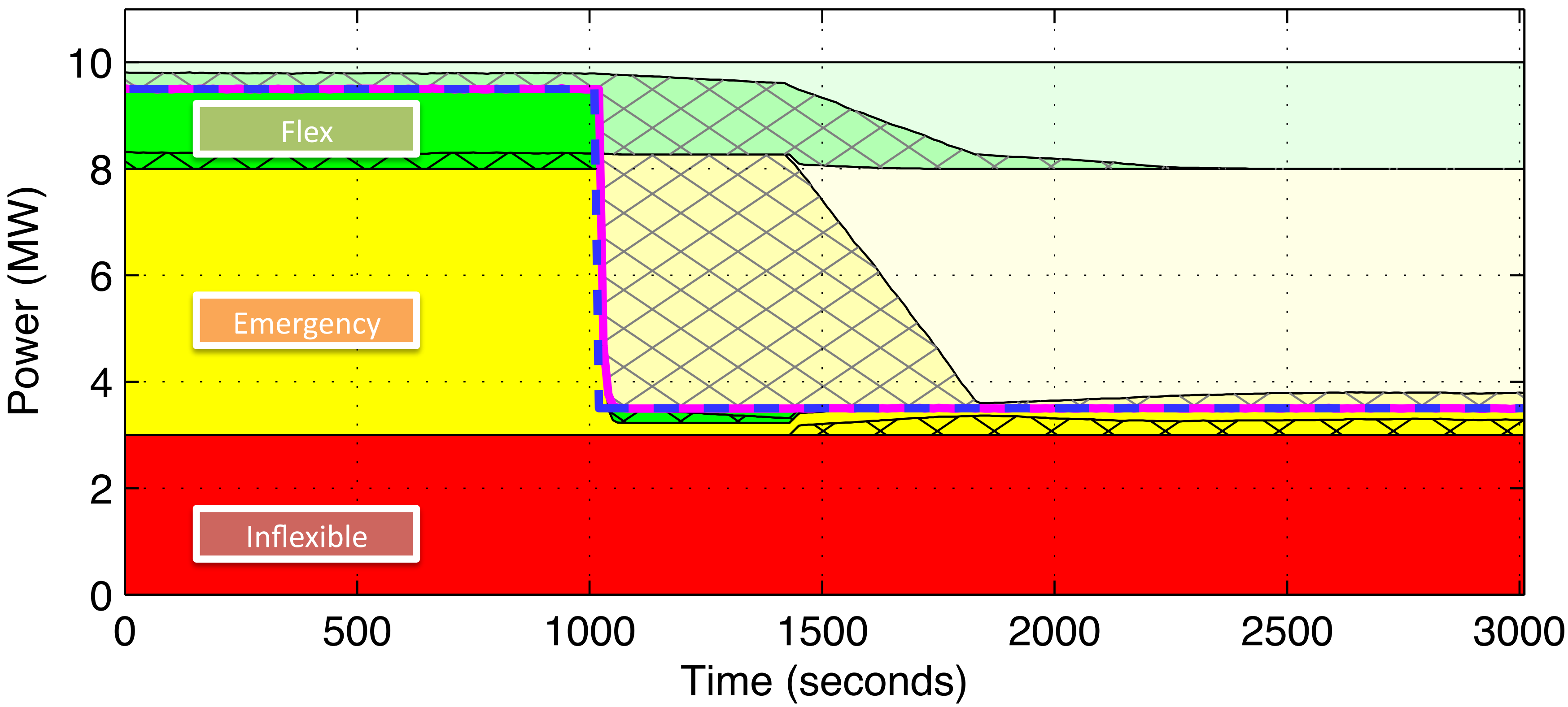


Control Example: Emergency Response



Simulation Base Configuration

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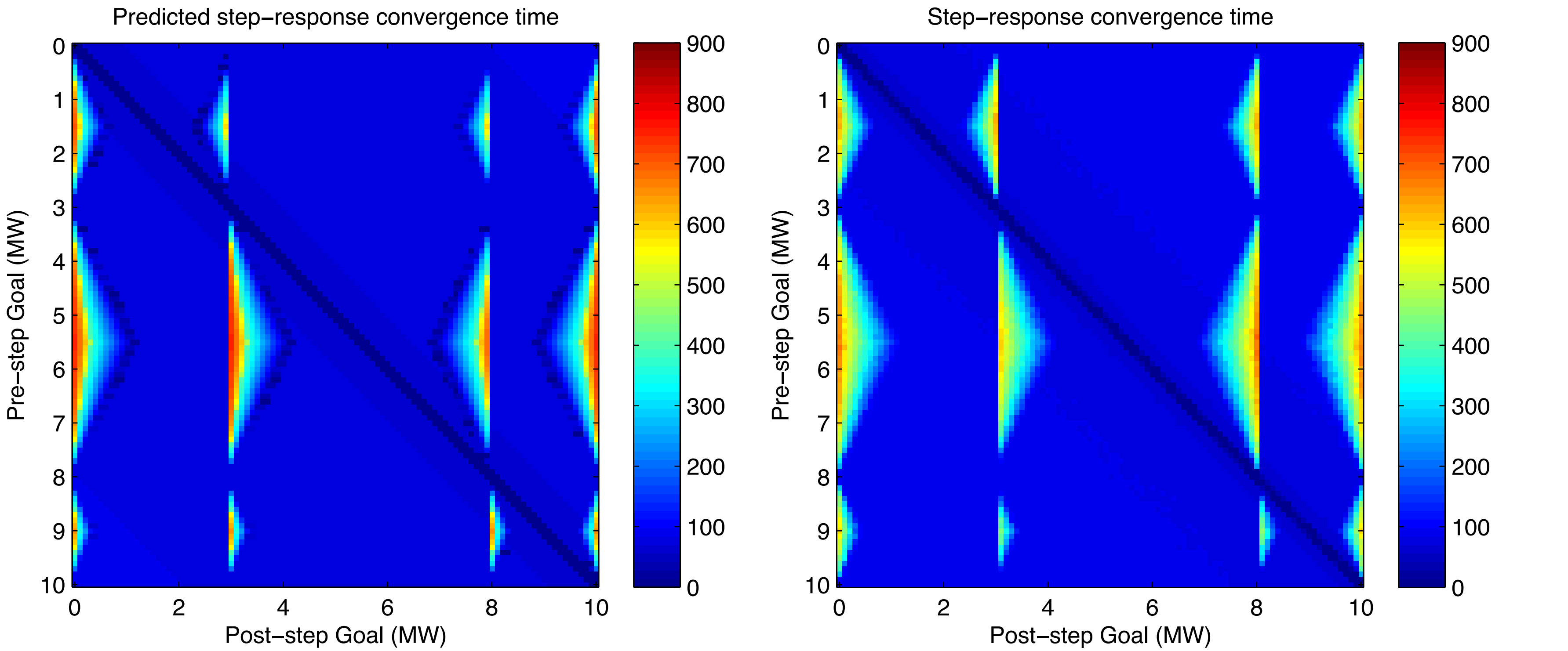
- 10,000 clients, each controlling a 1KW device
- Coloring: 20% green, 50% yellow, 30% red
- Measurement error: 0.1%
- 10 second rounds
- Refractory time: U[400,800] seconds
- Flexible reserve ratio: 1:1
- Attempted correction/round: 80%

Simulation Studies: Convergence

Predicted **Measured**



Excellent agreement

Simulation Studies: Quiescence

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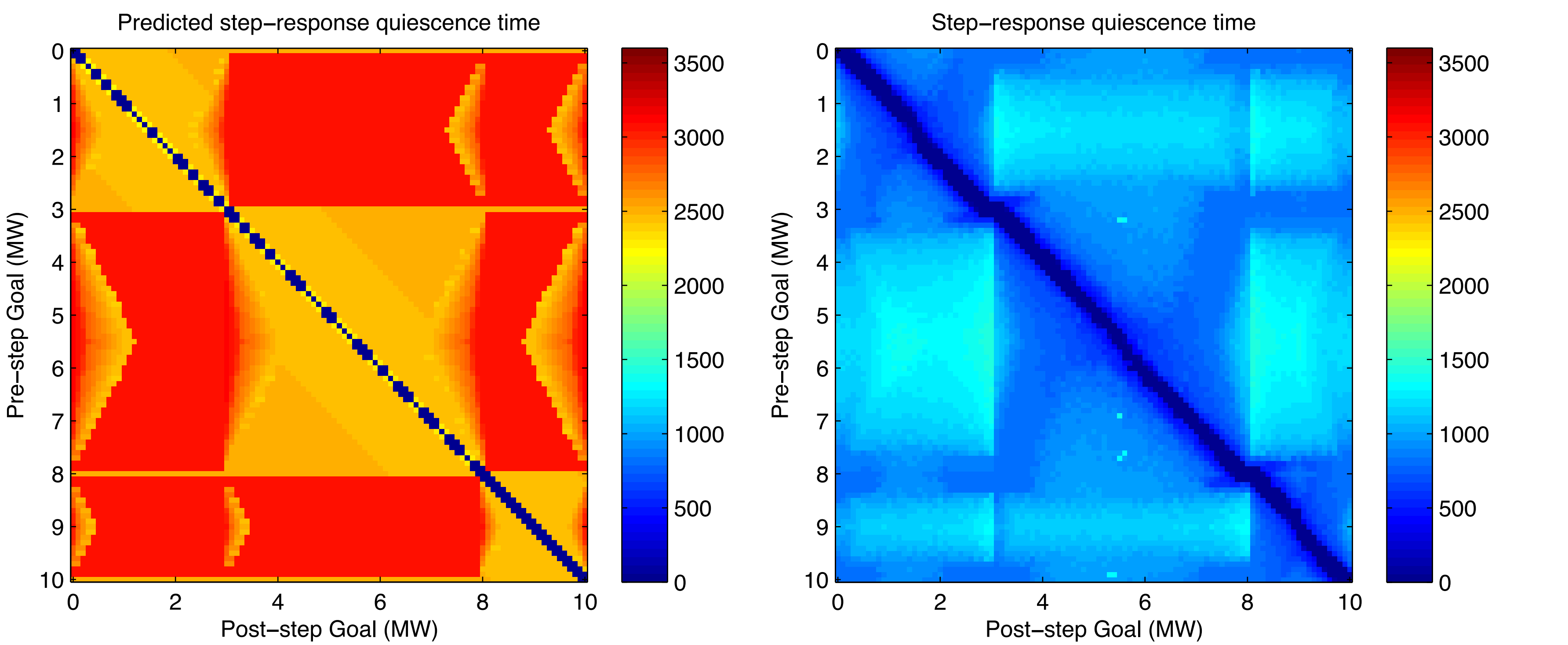
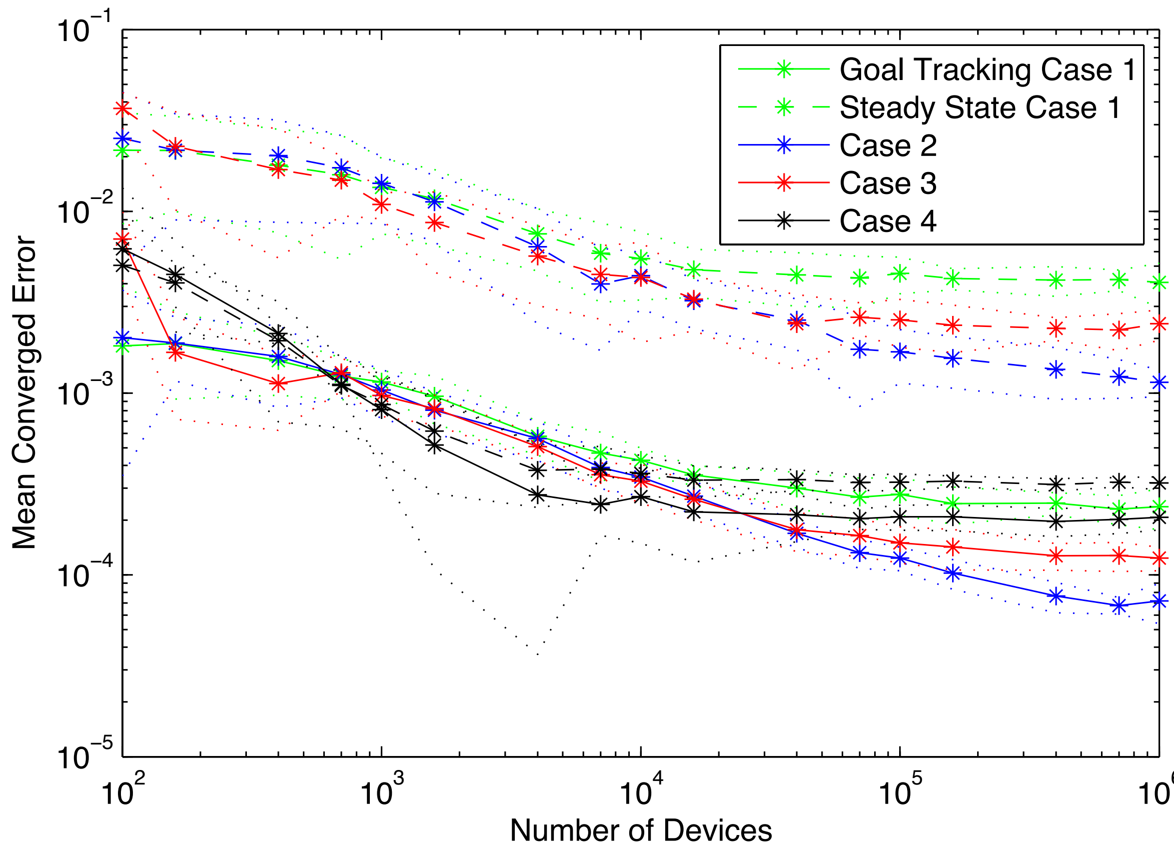
Predicted | **Measured**



Much better than conservative estimate

Simulation Studies: Scaling



More devices = better accuracy

Simulation Studies: Heterogeny & Error

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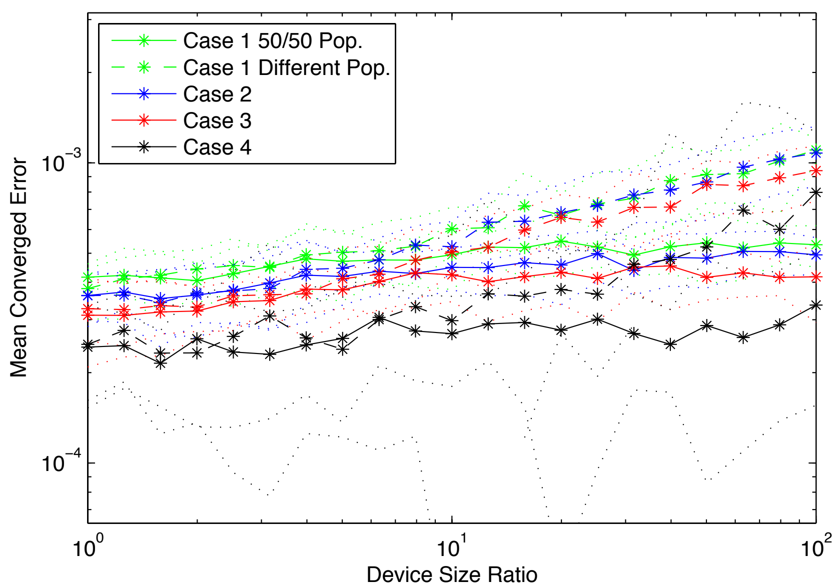
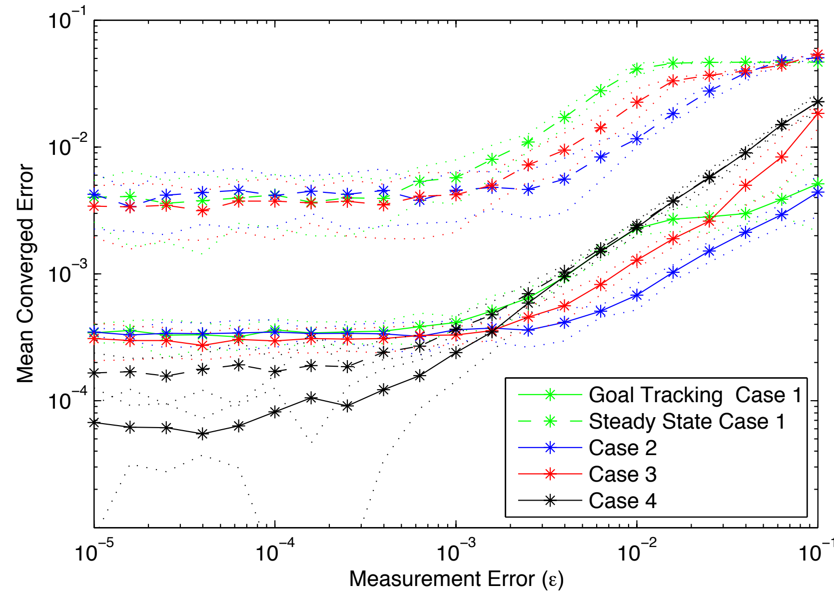
Heterogeneous Devices



Estimation Error



Robust to error and differences in devices

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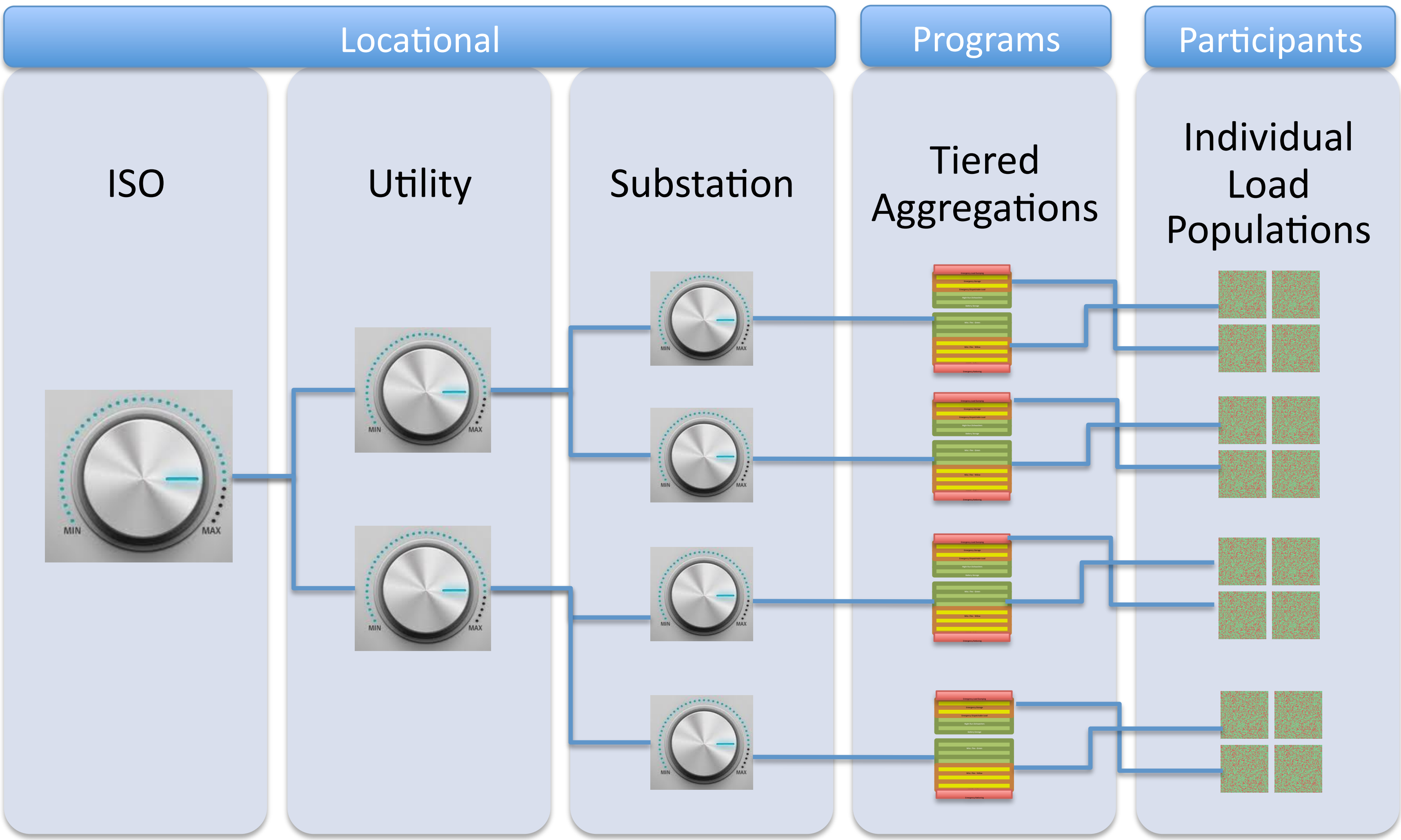
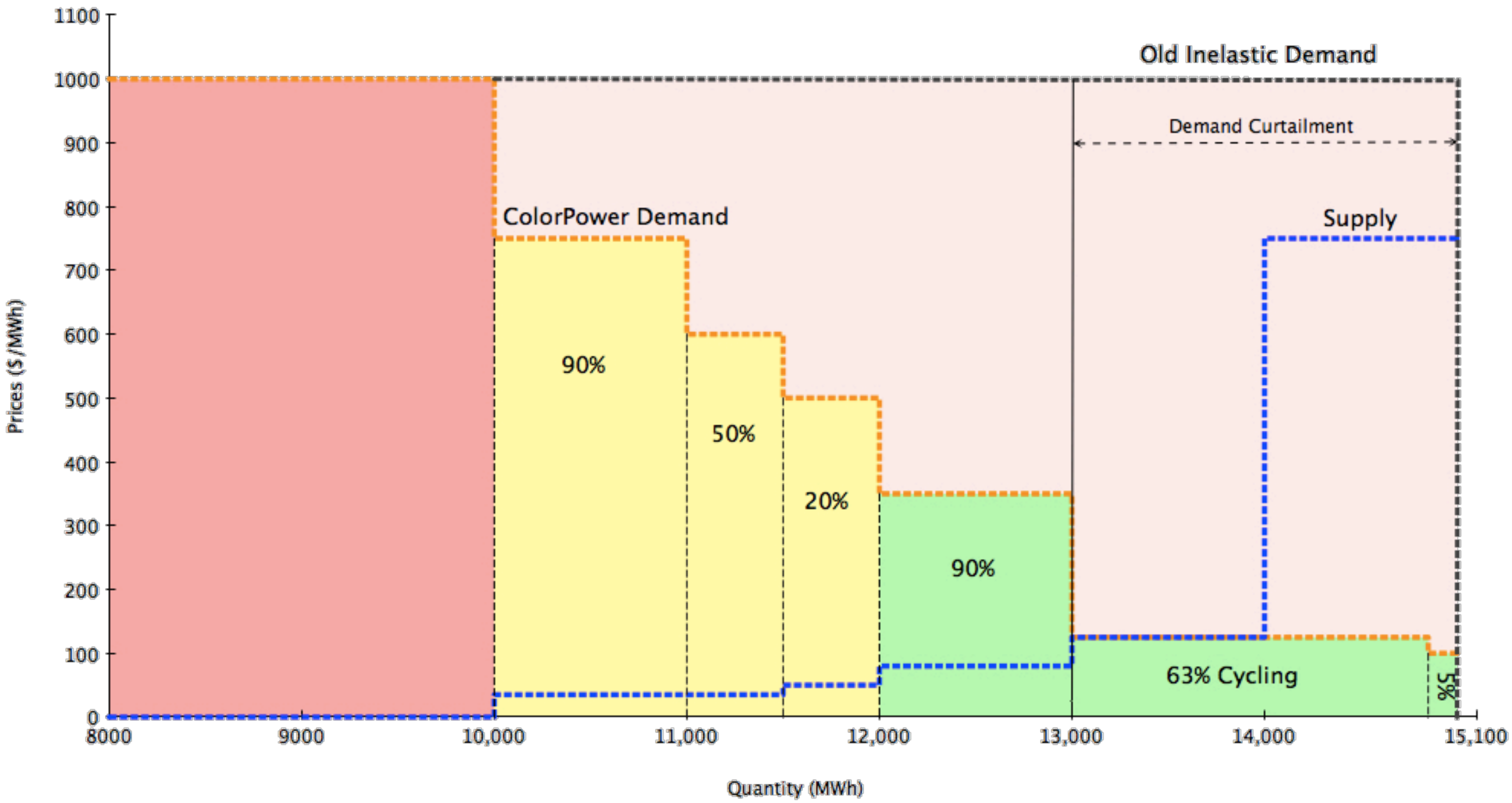
Locational x Program Control



Demand Signals To Markets



*Price signals **to consumers** from markets?*
*ColorPower can send demand signals **from consumers** to markets.*

Disruptive Business Models

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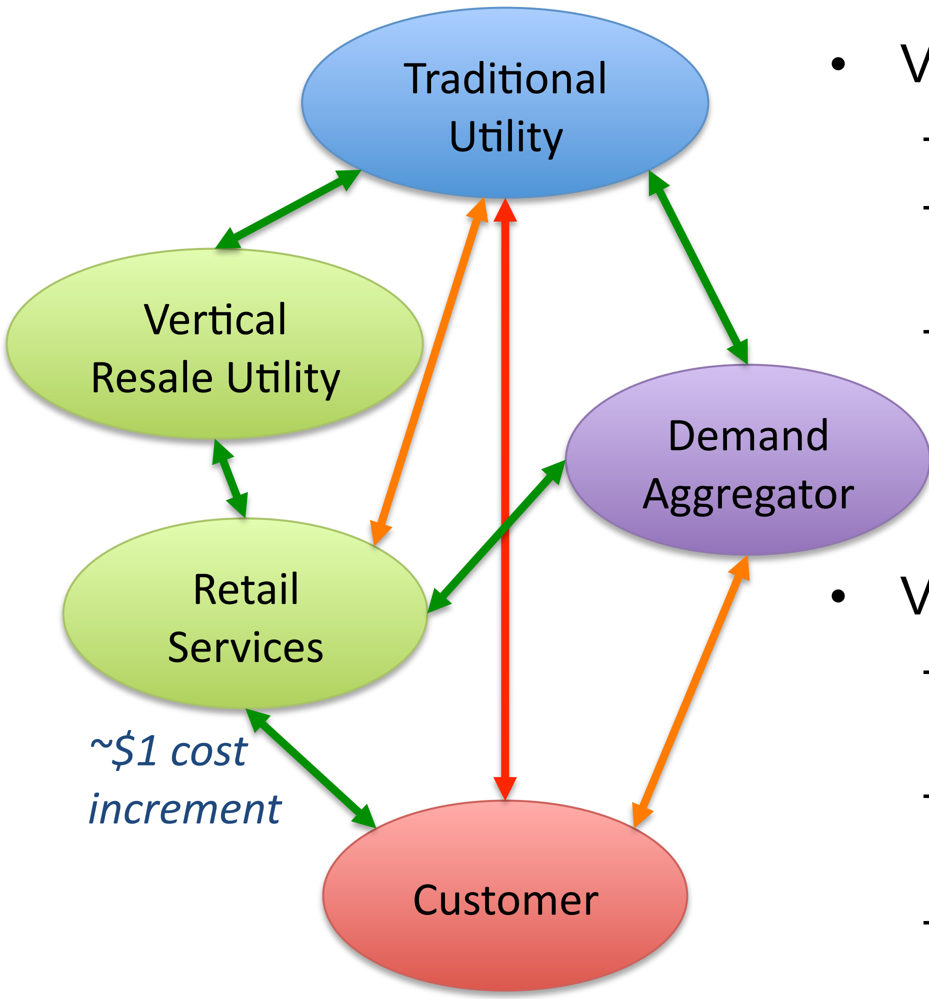

- Value-added services for appliances:
  - ColorPower = 21st Century EnergyStar?
  - Deployment as a side-effect of normal replacement cycles
  - Demand shaping capacity sold directly or contracted to 3rd party managers
- Vertical utilities:
  - Manufacturer / retailer assumes energy risk for a small premium
  - "Air conditioner with brownout protection plan"
  - "Pool pump with a lifetime energy supply"

ColorPower enablers: cheap hardware & networking, ability to bundle at organization boundaries

Contributions

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- Energy flexibility tiers allow separation of demand management concerns
- ColorPower algorithm allows fast, robust, and precise control of thousands to millions of devices.
- ColorPower is pragmatically deployable, and allows disruptive new energy business models.

Next Steps & Collaboration Opportunities

- Small-scale deployment (starting shortly)
- Standardization
- Improved integration with other grid systems
- Adaptation of base principles to other grid control problems?

Acknowledgements

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colorpower

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