Precise Mass-Markets Energy Demand Management Through Stochastic Distributed Computing for a Sustainable Energy Future

ESIF Workshop on

Frontiers in Distributed Optimization and Control of Sustainable Power Systems

January 27-28, 2016 ◆ Golden, Colorado

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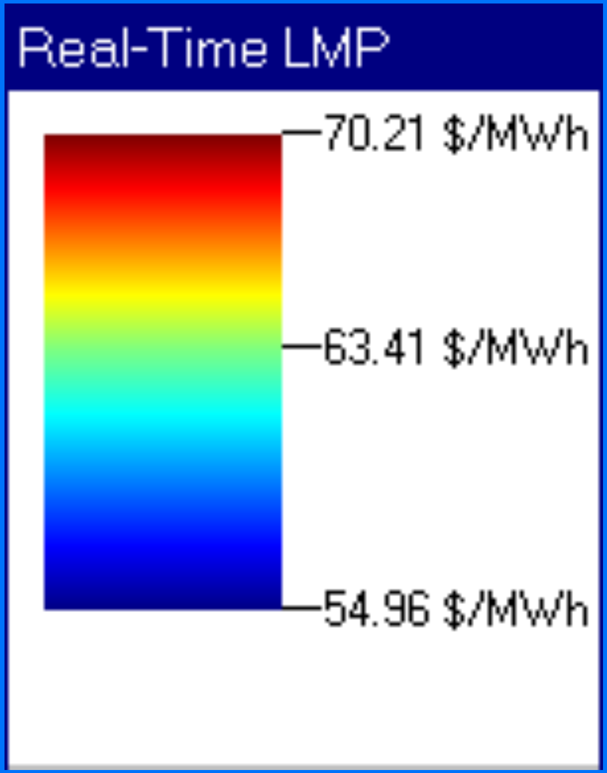
Outline

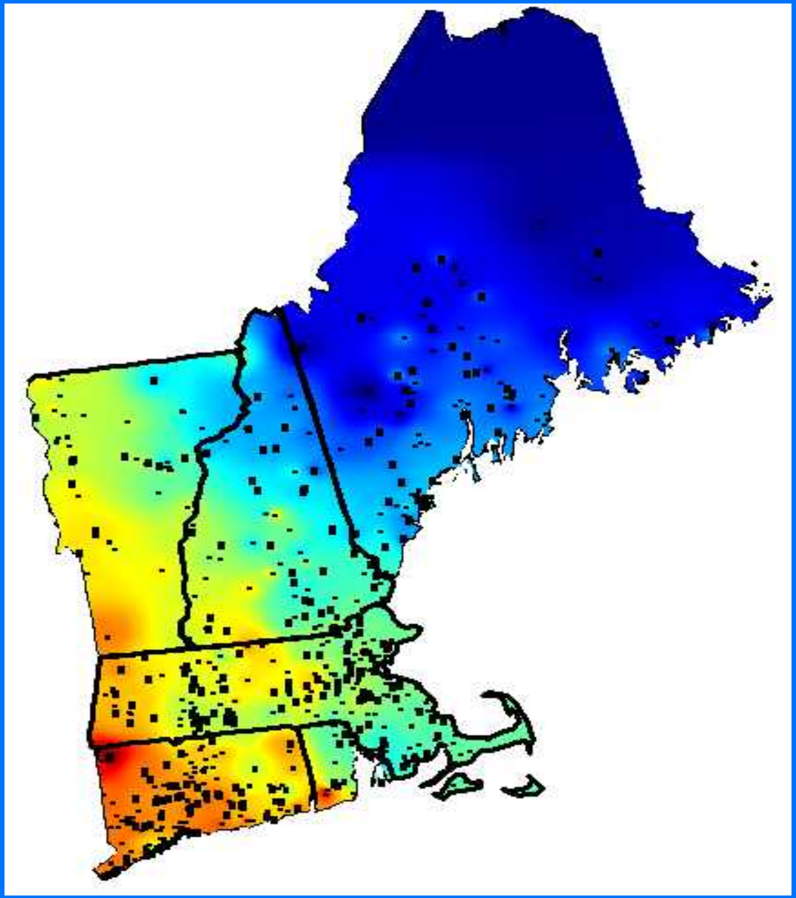
- Overview & Challenges of Current Energy Market Models
- Overview & Current DR Programs
- Key Challenges of a DR New Approach
- High Level Process of the DR New Approach
- Formal Control Problem & Control Design Issues
- The Energy Demand Cloud & Proposed Business Model
- Simulation Results
- Integration of DSOs and ISOs
- Conclusions

Current Energy Market Models

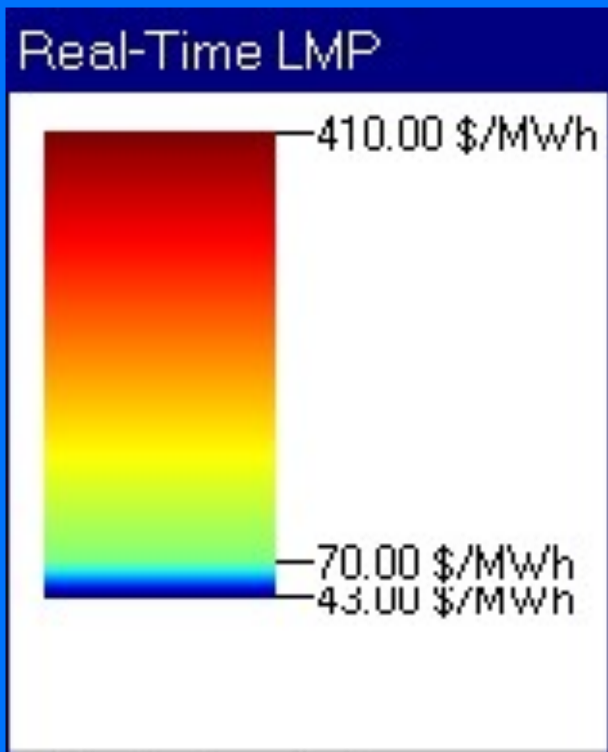
- Various markets for energy (pools, exchanges, bilateral markets, hybrid markets, etc.)
- Various markets for Ancillary Services (sequential markets, Unit Commitment-based integrated markets, long-term contracts, etc.)
- Various markets for transmission (System Operators, Transcos, Zonal Pricing, Nodal Pricing, etc.)

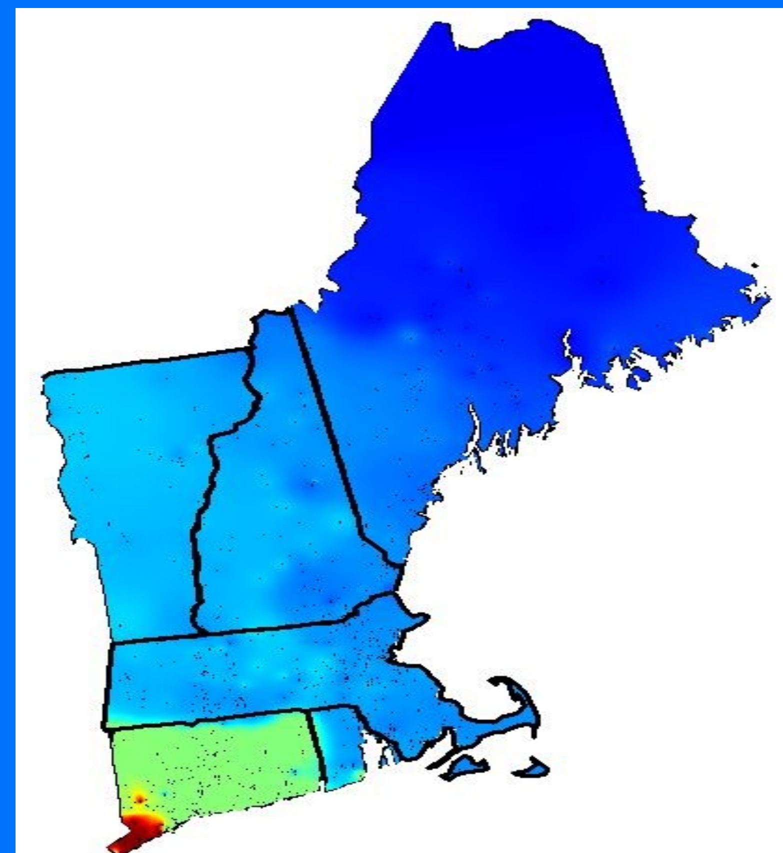
Locational Marginal Prices in Nodal Markets





Extreme Congestion





Basic Market Design Elements

- Forward Market, Mitigation and Reliability Process
- Transmission & Ancillary Services Markets
- Real-Time Markets
- Financial Transmission Rights (FTRs)
- Capacity Markets
- Virtual Trading Markets

Current Market Challenges

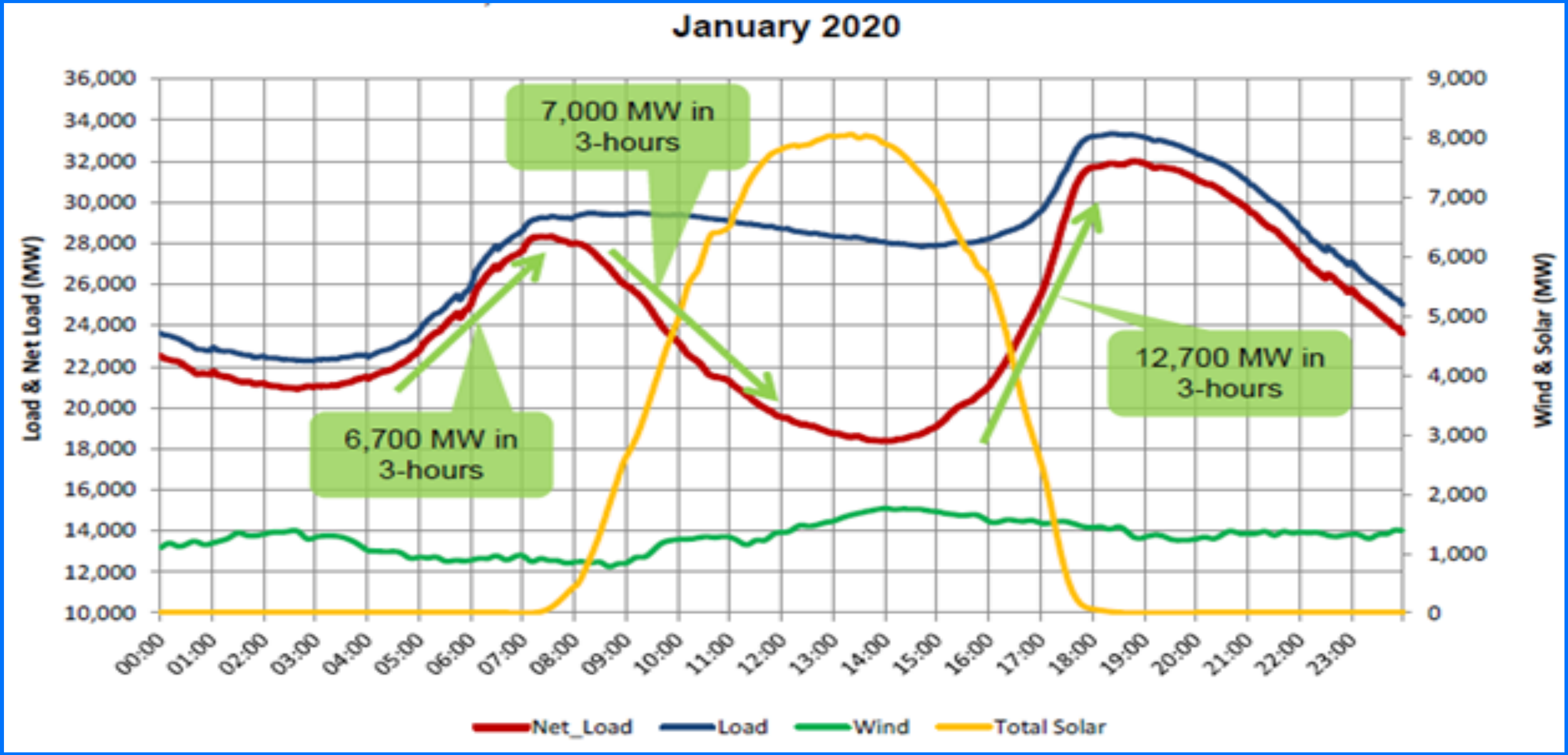
- Co-optimize Markets and Reliability (Co-optimize Energy, AS, Transmission & Reliability products)
- Develop Functional Capacity Markets
- Develop Transmission Markets and Policies for Transmission Investments
- Develop Market Mechanisms to Manage High Penetration of Renewable Energy Sources (RES)
- Integrate DSOs and DERs and ISOs
- Develop innovative technologies for increased reliability and efficiency (DERs, EVs, sensors, communications infrastructure, control equipment, intelligent management systems, etc.)
- Data Communications, Cyber security and Information Privacy Challenges (hacking of the IoTs, the cloud and the smartphones)

Next Generation Energy Market Solutions

- Change the Energy Market architecture – design a market that properly values flexibility and capacity
- Develop a price for Carbon – the current EU ETS system is not working
- Develop new Power Market products
- Invest on flexible generation, like gas power plants
- Implement smart grid technologies and invest on the Internet of Things (IoT) in the power sector
- Develop new Demand Response models and technologies
- Develop and integrate into the power grid storage technologies and other Distributed Energy Resources

Renewable Integration Challenges

California will need 13 GW ramping in 3 Hrs by 2020



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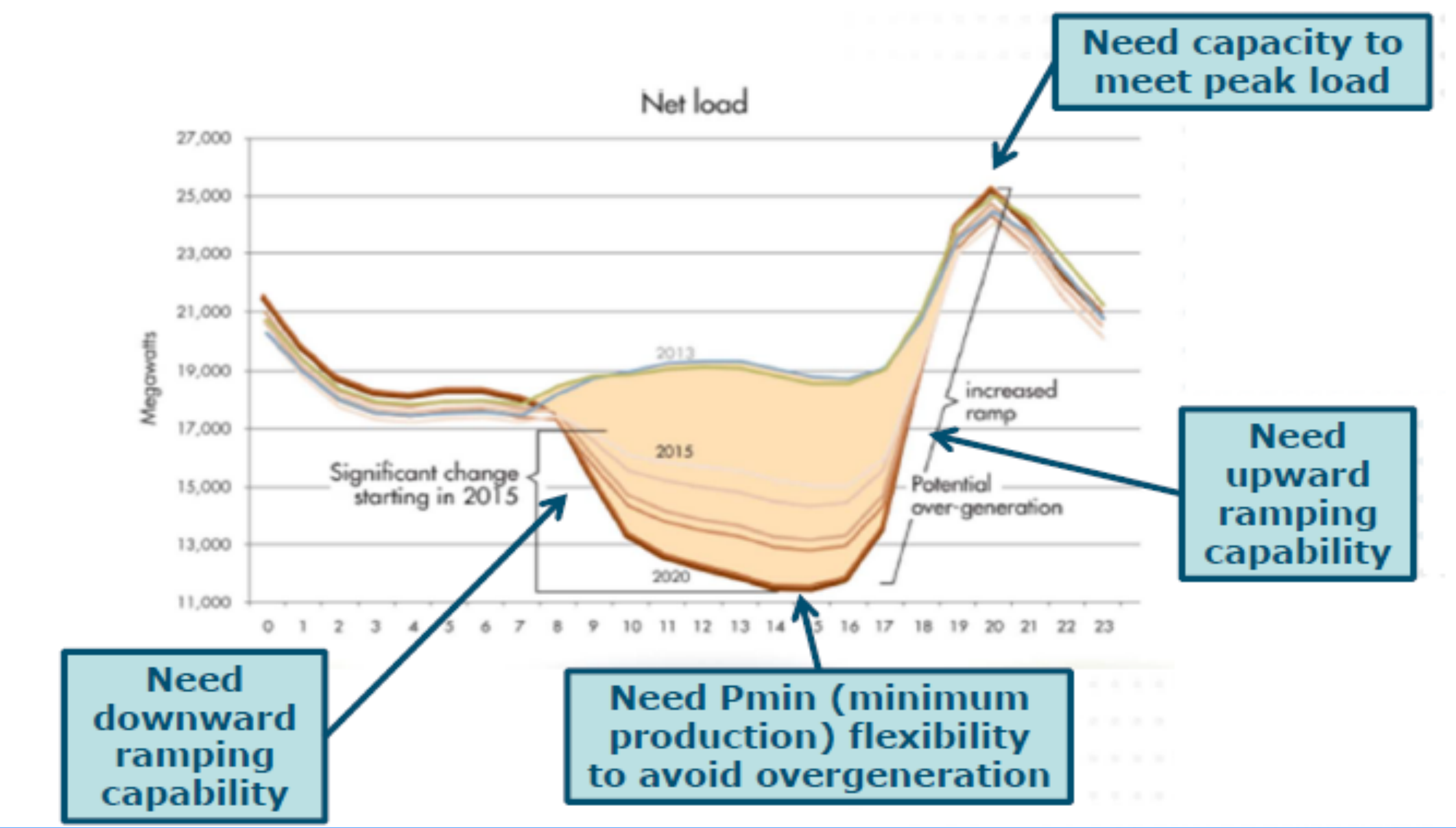
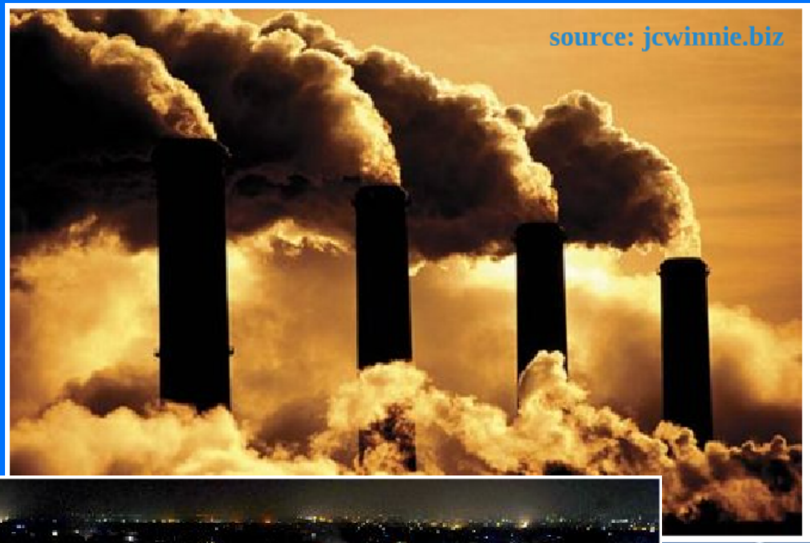
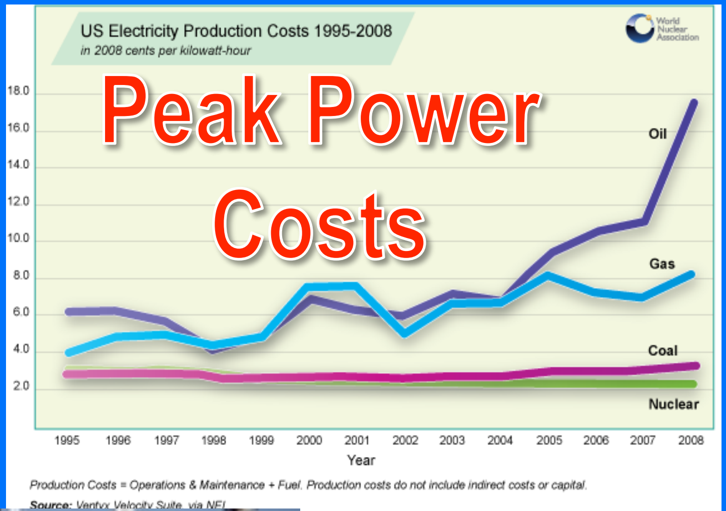
Potential Flexibility Challenges: Anatomy of a 'Duck'



Distributed Power Demand Response; Why DR is Important





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Then, Where is the problem?
(The Era of Coercion Should Come to an End)

- Current DR programs are based on command and control approaches; programs are grouped in 4 groups:
- Customers submit their appliances to direct utility on/off load control
- Customers are exposed to price volatility—a concept called "prices-to-devices"; this is the "holy grail" today for activating DR in wholesale organized markets
- DR aggregators pay people for remote shutoff options; growth has stalled because customers see no other value than trading inconvenience for cash
- Finally, some programs rely on advanced analytics to predict customer behavior and drive messaging and pricing; they try to outguess what customers will do instead of asking them for their preferences

Electricity Markets

No Price-Sensitive Demand -> Inefficiency Everyone Pays For

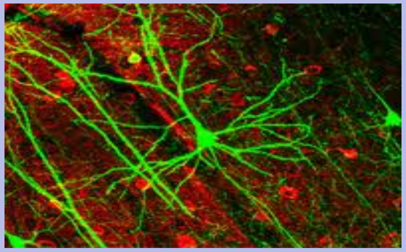
Key DR Challenges

- Scalability:
  - Safe, reliable coordinated response from millions of devices in < 2-4 minutes
- Consumer interface:
  - High benefit, low “annoyance factor”
  - Eliciting useful information (preferences)
  - Privacy concerns (detailed data and devices should remain private) – This means computations should be performed on consumer aggregates)
- Deployability:
  - Technology alignment with market & regulatory structure
  - Market fragmentation across grid & in home
- Fairness

Algorithm Inspiration: NATURE

Natural Self-Organizing Systems


Bacteria Colonies


Neural Networks


Social Insects


Flocks & Schools

- Original algorithm was developed at MIT for biological systems
- Implemented a distributed computed based stochastic control algorithm
- Developed the algorithm for energy devices
- Analysis of devices results in constraints similar to generator constraints, such as minimum up time constraints, minimum down time constraints, etc.

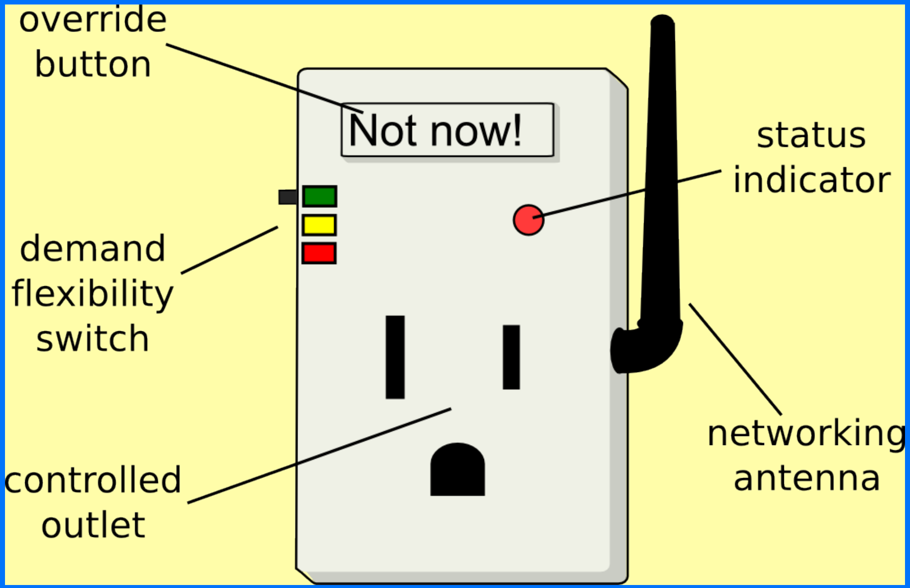
Capturing User Requirements

Anytime Flexible

Peak Power

Emergencies Only

Uncontrolled



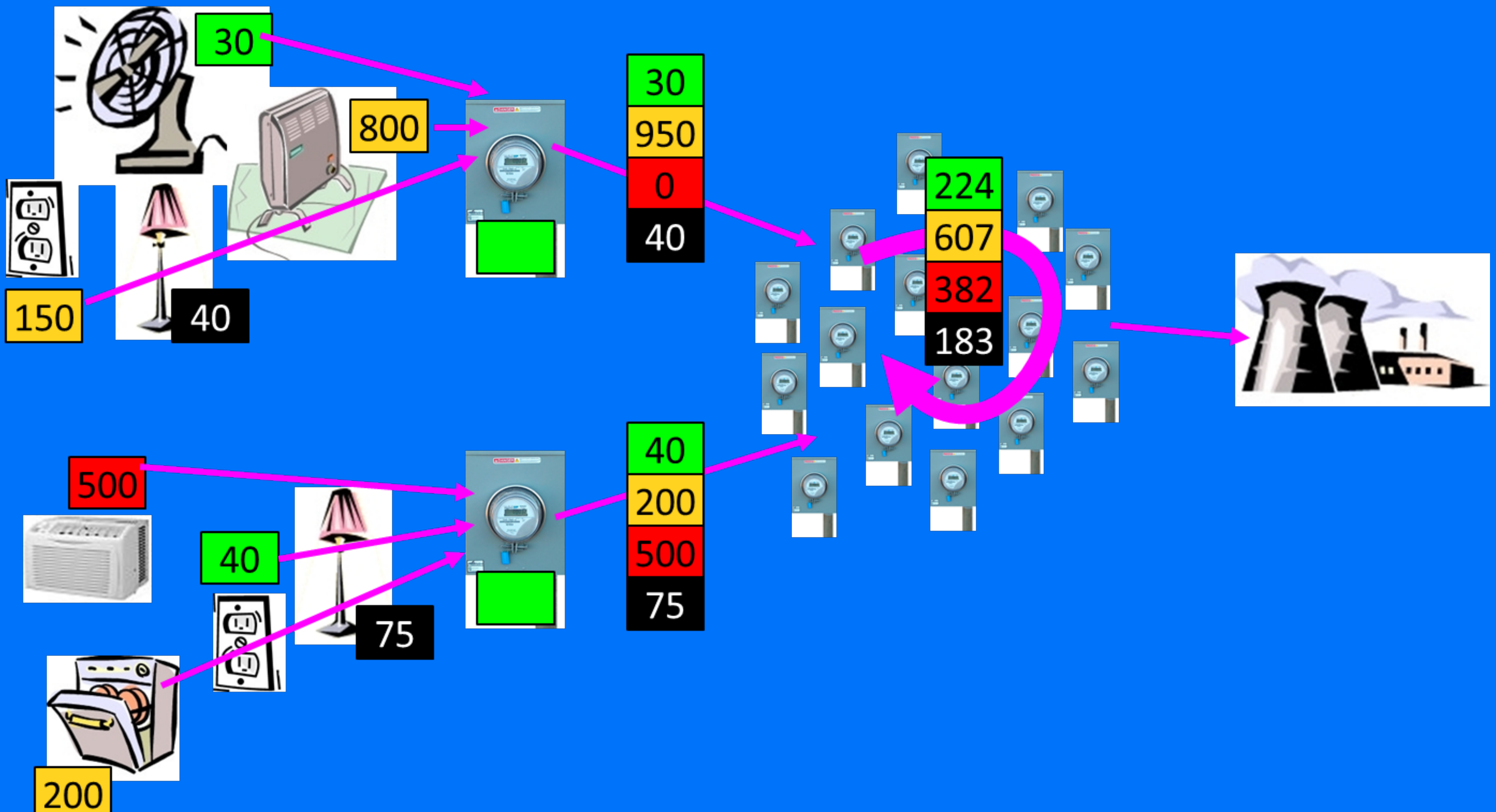
Qualitative
Energy Flexibility

Smart plugs, new appliances,
home automation, …

High Level DR Process

- DR agent (say customer's meter) aggregates device flexibility information which is further aggregated across a network
- This forms a model of the overall system flexibility
- This system flexibility, along with a demand shaping target provided by the Utility or the Aggregator, is redistributed to every device in the system
- The devices then execute a distributed control algorithm (like flipping weighted coins) to determine if they respond or not

Distributed Creation of the Aggregate Model

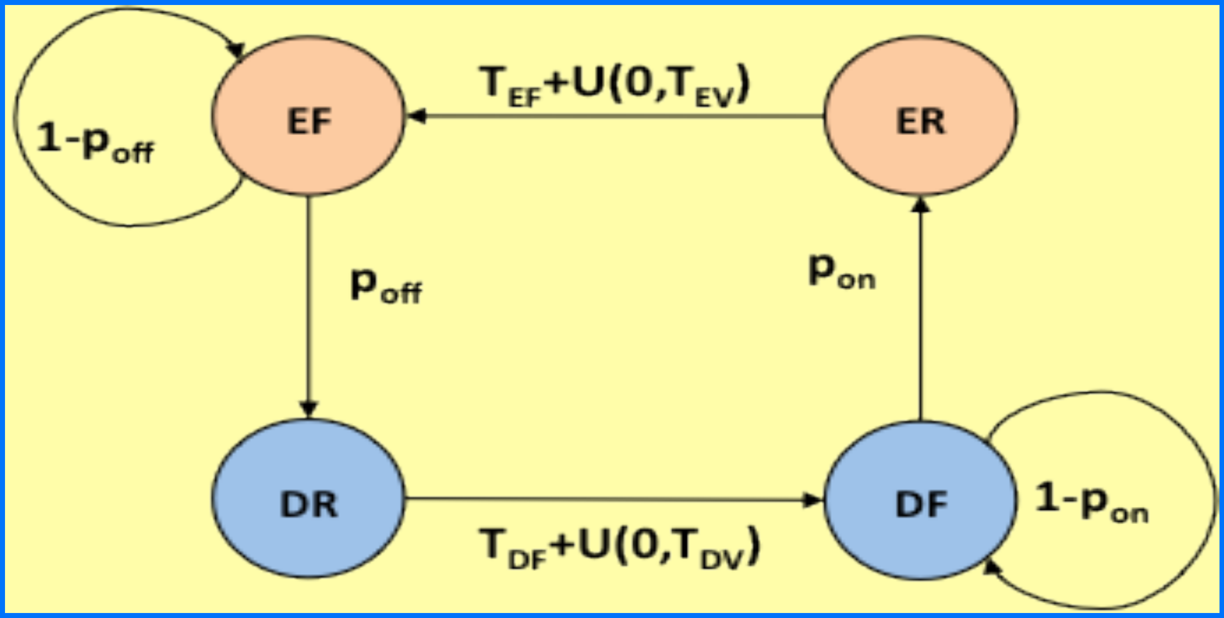


Proposed DR Principles

- Challenge: fast, private, robust, non-intrusive
- Approach: randomized distributed control
  - Aggregate flexibility information to shared model
  - Disseminate control signals
  - Local decision; coin-flip for fractional color
  - Weight for availability, over-damped control

Control problem: long timeouts on state changes

Proposed DR State Transitions

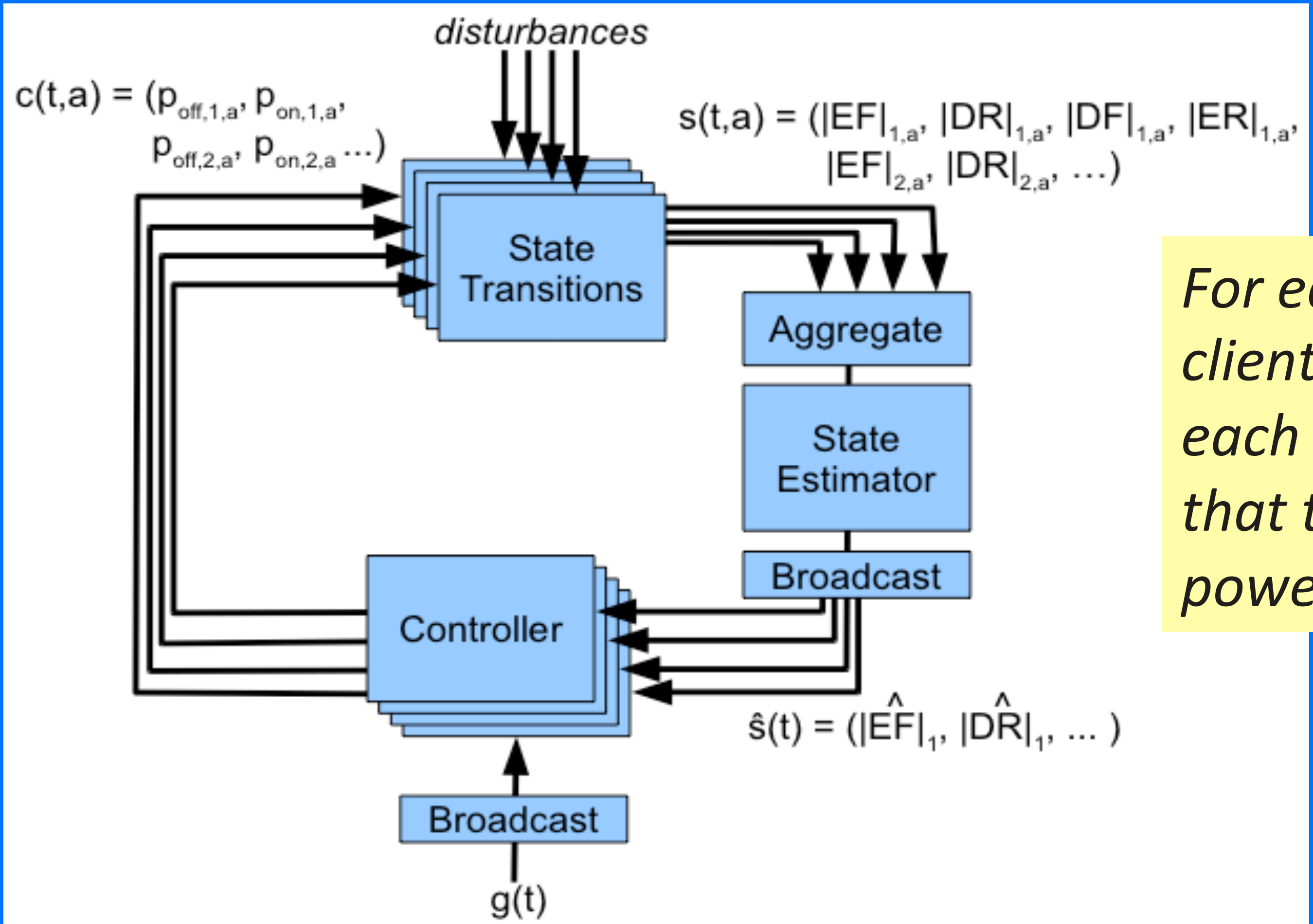


- Within each color, each device: (E)nabled vs. (D)isabled
- (R)efractory (it cannot switch states) vs. (F)lexible (eligible to switch)

Proposed DR State Transitions

- The evolution of each device is modeled like a modified Markov process
- In each round devices in state EF randomly switch off to state DR
- Once in DR device waits for certain rounds before transitions to state DF; the waiting time is a fixed number PLUS a uniform random addition to feather the distribution (so not many devices switch states at once)
- The other two distributions are complementary

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)

Formal Control Problem

- The control problem is to set the transition probabilities such that the total Enabled Demand tracks the target as closely as possible, subject to the constraints
- Device with lower numbered colors are shut off first
- If a color has devices that are Enabled and Disabled, then every device is equally likely to be disabled
- No device is unfairly burdened by its initial bad luck in becoming Disabled

Additional Important Constraints

- **1. Goal tracking:** *shape power demand*

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

- (Sum of Enabled Demand over all colors i is equal to the goal)
- **2. Color priority:** *respect user preferences*

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

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

- Demand D_i is the demand for the ith color and above
- Devices are Enabled from the highest color down until the goal is reached

Additional Important Constraints

- **3. Fairness:** *no devices are favored*

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

- Meaning that the control state is identical for every agent
- **4. Cycling:** *don't keep the same devices off*

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

- This means that as long as there are both Enabled and Disabled devices , some of them should be changing from Enabled to Disabled to vice versa

Controller Design Issues

- It is possible that not all constraints can be satisfied; some of them are more important than others
- Customer preferences are the most important ones
- Goal tracking is the second most important
- Least important is the Cycling constraint
- The Fairness constraint is the easiest to satisfy (simply the same stochastic algorithm on all clients is executed)
- We view the controller as having a "budget" of flexibility to spend with each color offering up to $|EF|_l$ of potential reduction in demand

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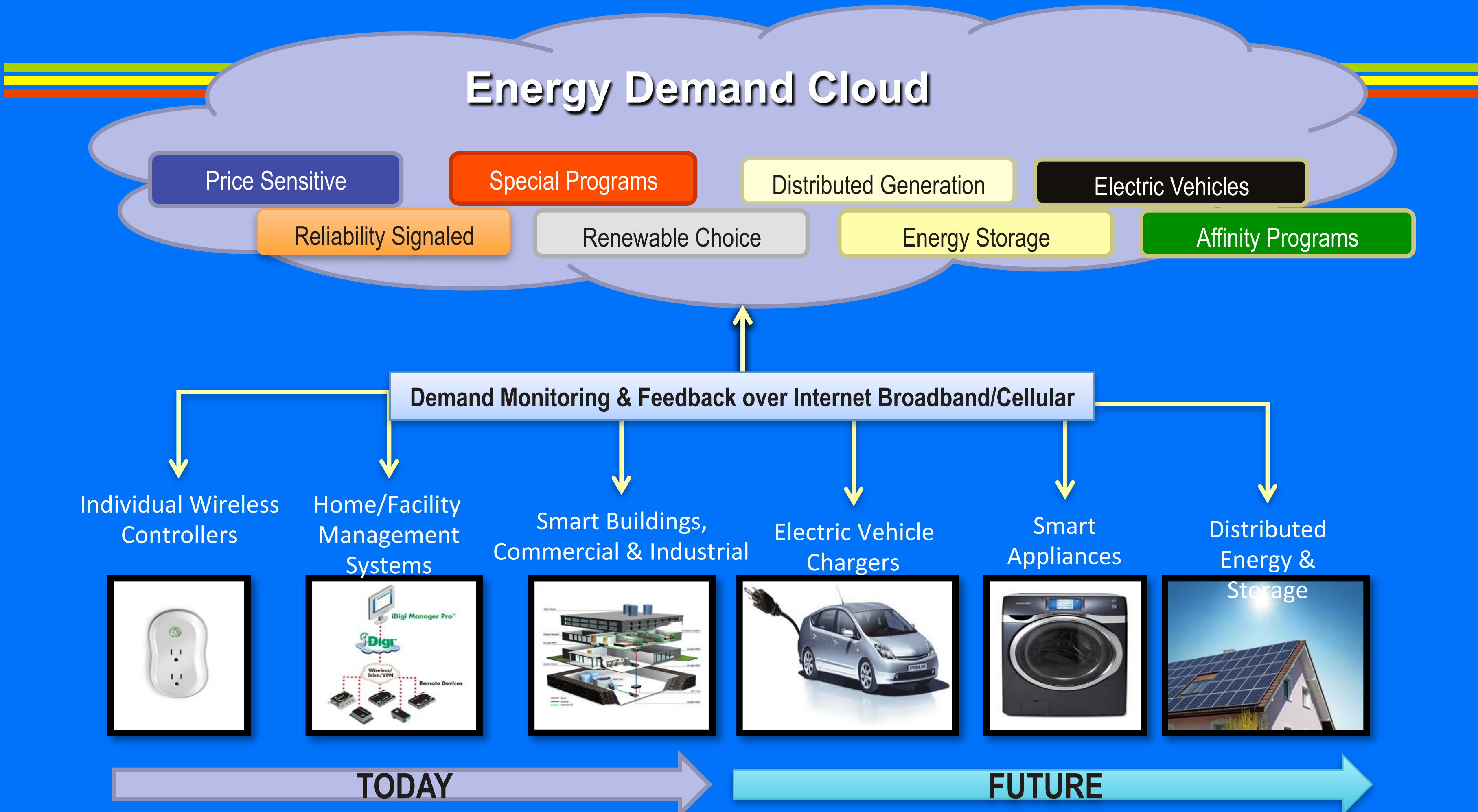
Controller Design Issues

- Flexibility builds up as Refractory devices finish their time outs and move to the Flexible state
- The controller is formulated as a cascade of priorities of how to spend the "Flexibility budget" indicated by the state s(t)
- As the controller considers each constraint in turn, it allocates flexibility to satisfy that constraint (as much as possible)
- Then it attempts to satisfy the rest of the constraints with whatever flexibility remains unallocated
- Any unallocated flexibility is allowed to accumulate as a reserve improving future controllability

Energy Demand Cloud



DR client is ~10kb—virtually any embedded device can run it

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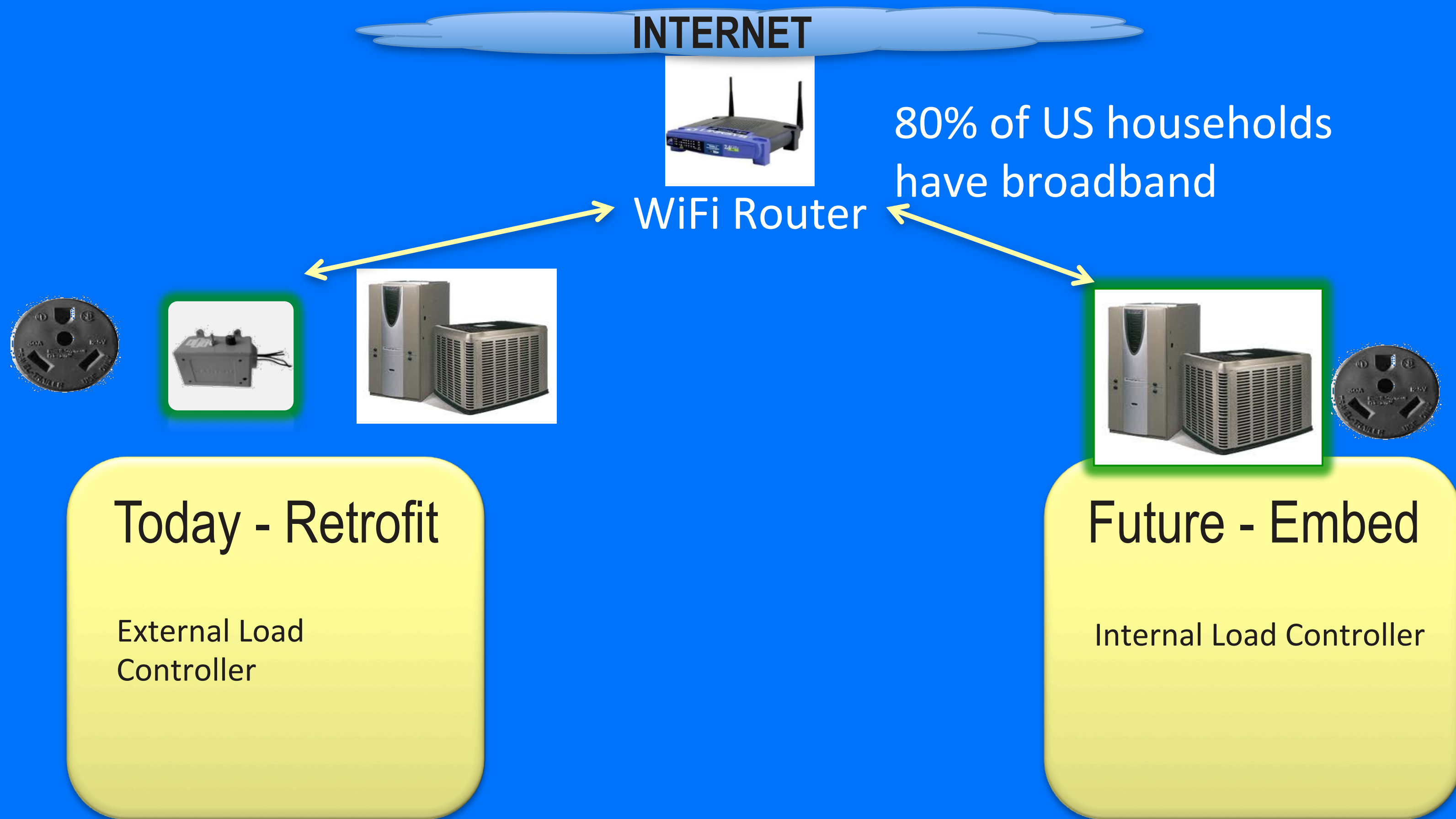
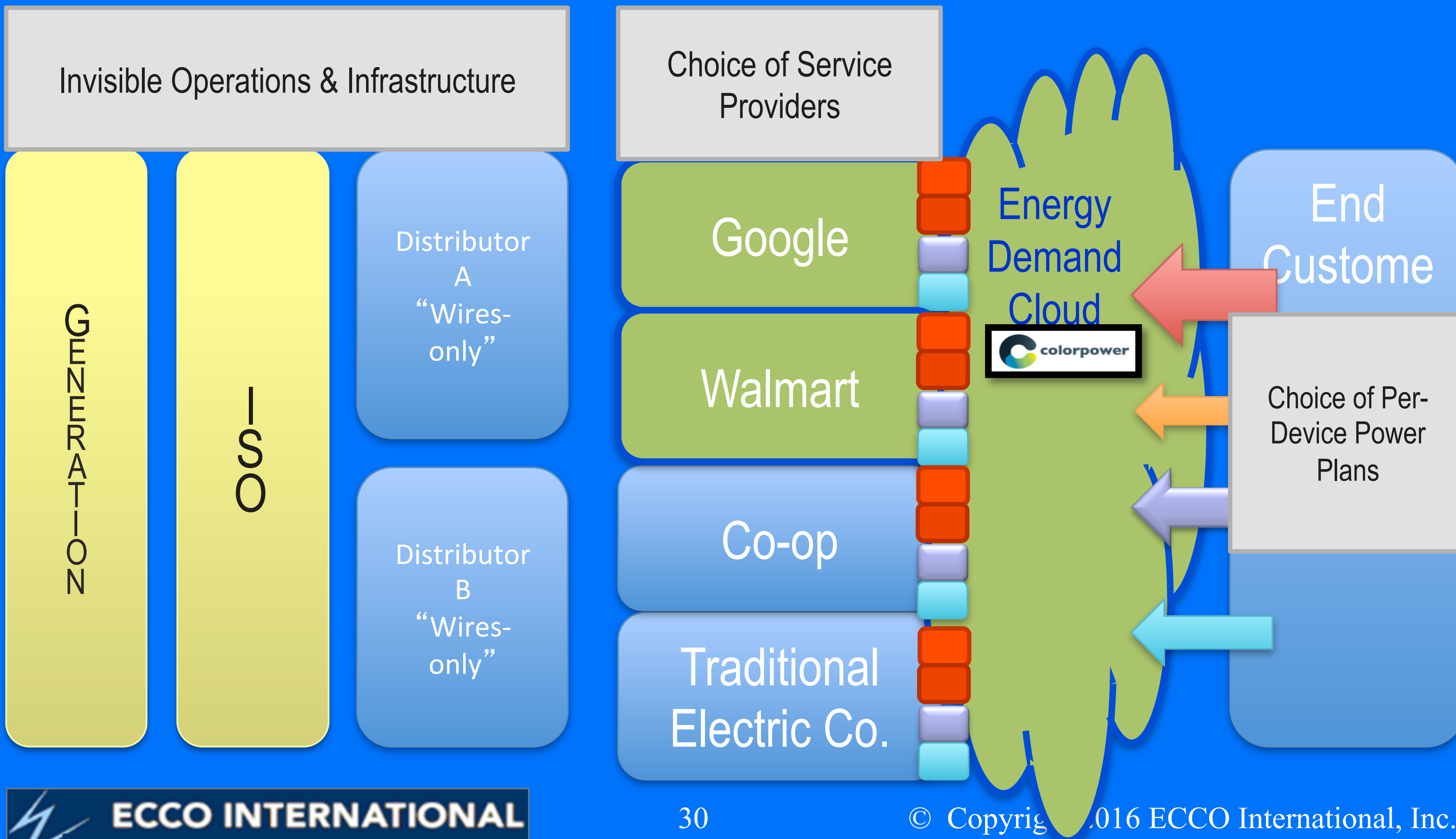
DR Software in Devices



The Telecom – Like Retail Model for the Energy Business



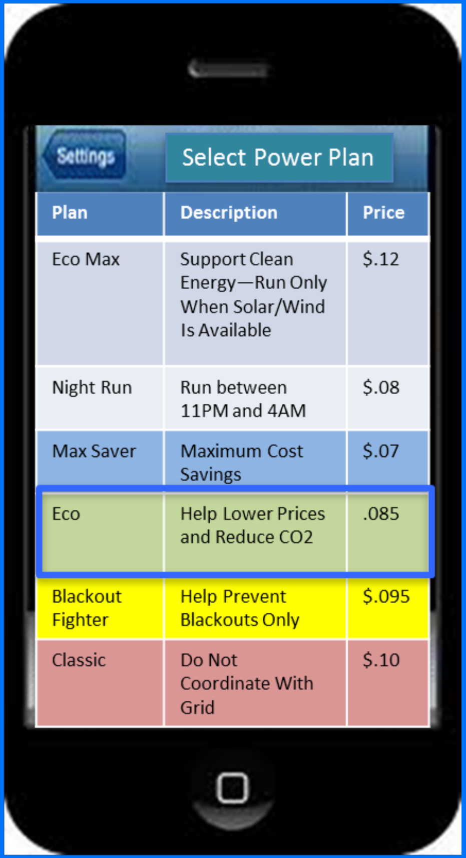
The Proposed Technology Creates Smart Energy Options

Do I want my pool pump to run at night?

Do I just want maximum price savings?

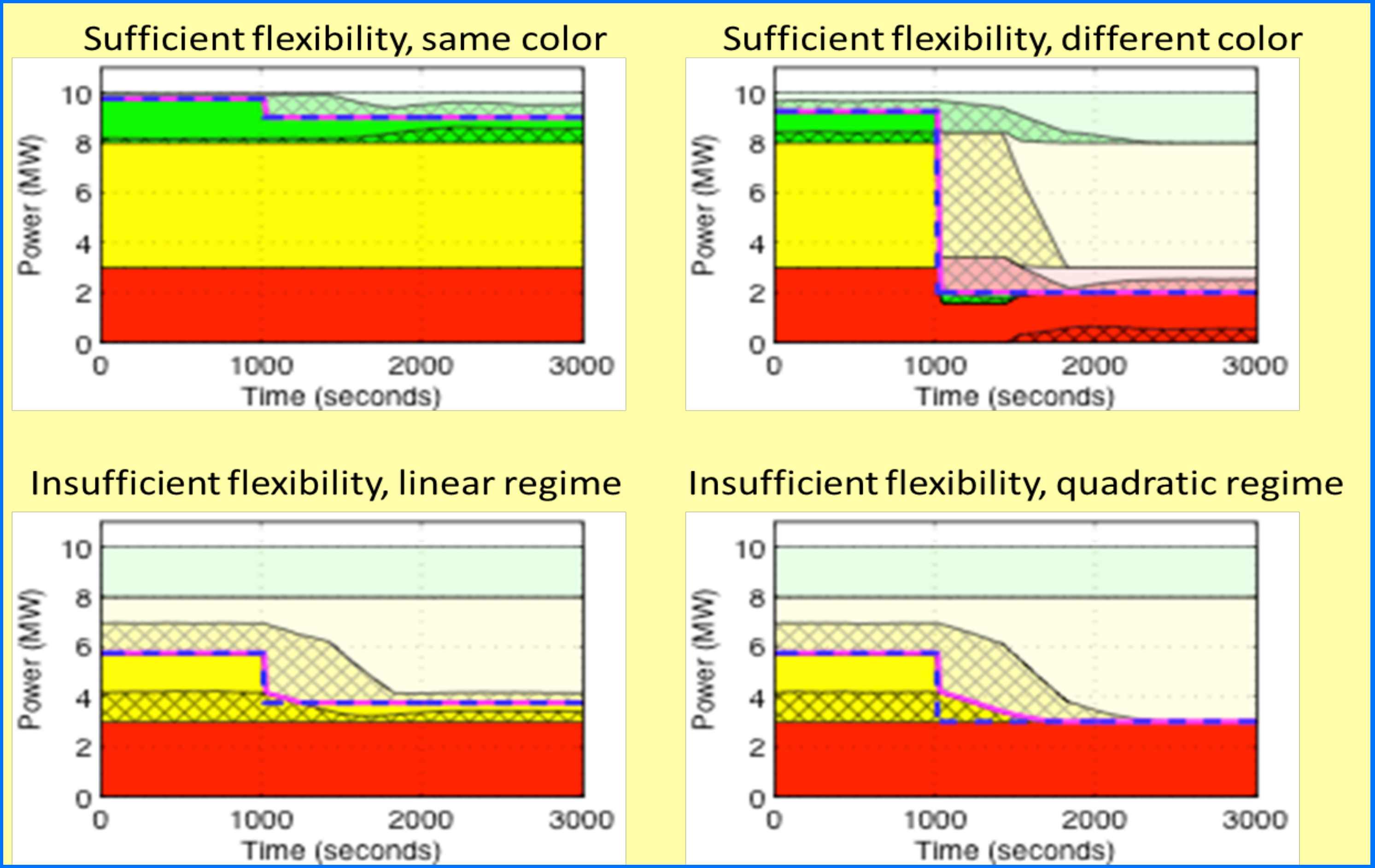
Should I run it only with renewable energy?

Maybe I don't want to coordinate it with the power grid at all today.

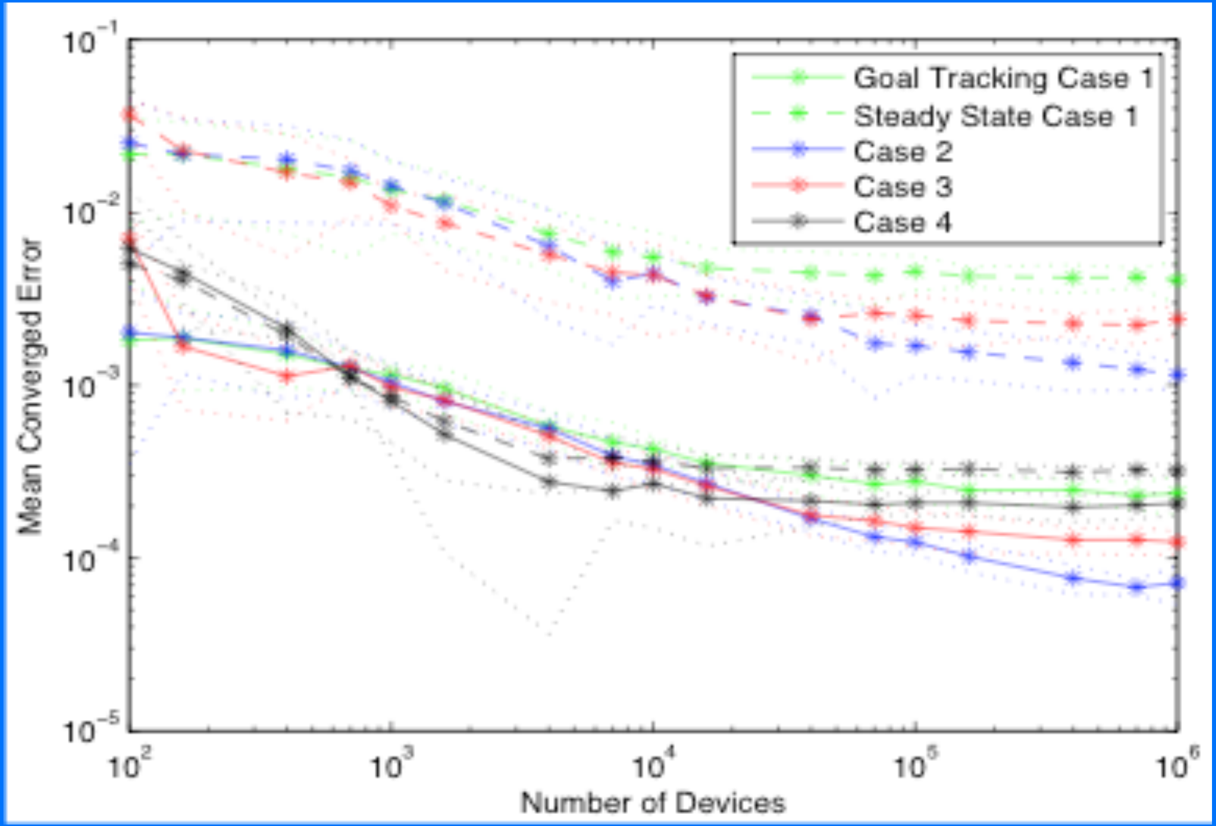


Plan	Description	Price
Eco Max	Support Clean Energy—Run Only When Solar/Wind Is Available	$.12
Night Run	Run between 11PM and 4AM	$.08
Max Saver	Maximum Cost Savings	$.07
Eco	Help Lower Prices and Reduce CO2	.085
Blackout Fighter	Help Prevent Blackouts Only	$.095
Classic	Do Not Coordinate With Grid	$.10

Examples of Control



Simulation Studies: Scaling



More devices = better accuracy

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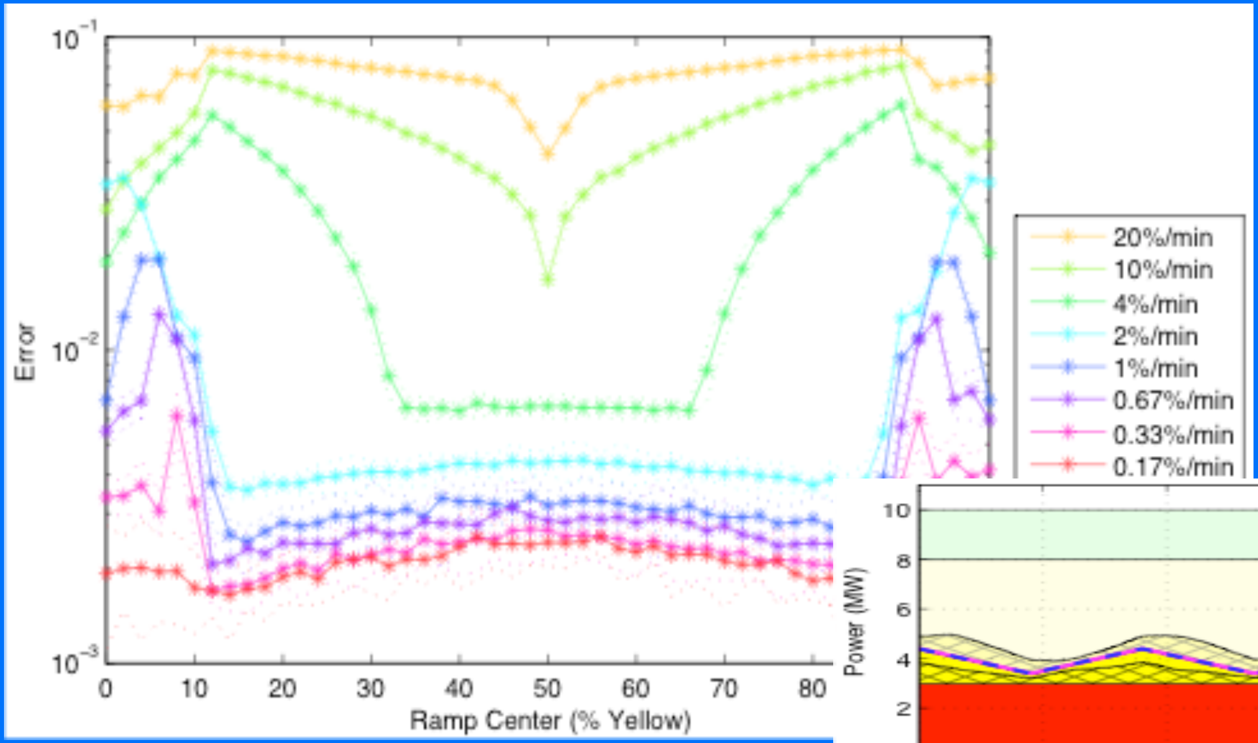
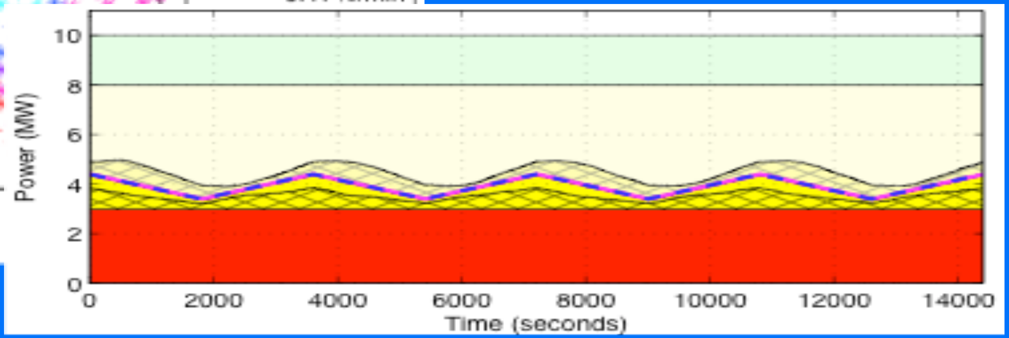
Simulation Studies: Ramp Response

Results



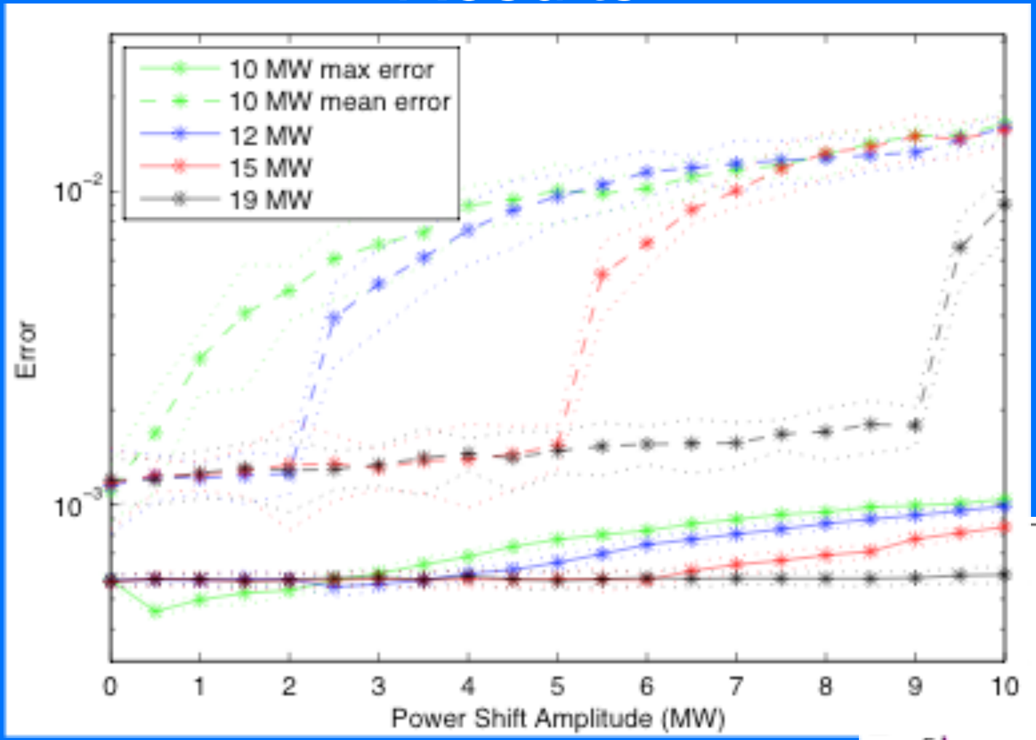
Good behavior unless fairly steep or close to hard bounds

Example



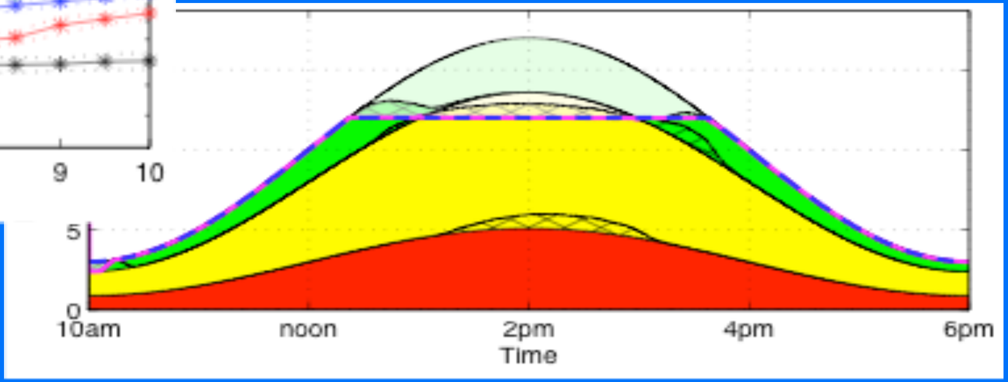
Simulation Studies: Peak Shaving

Results

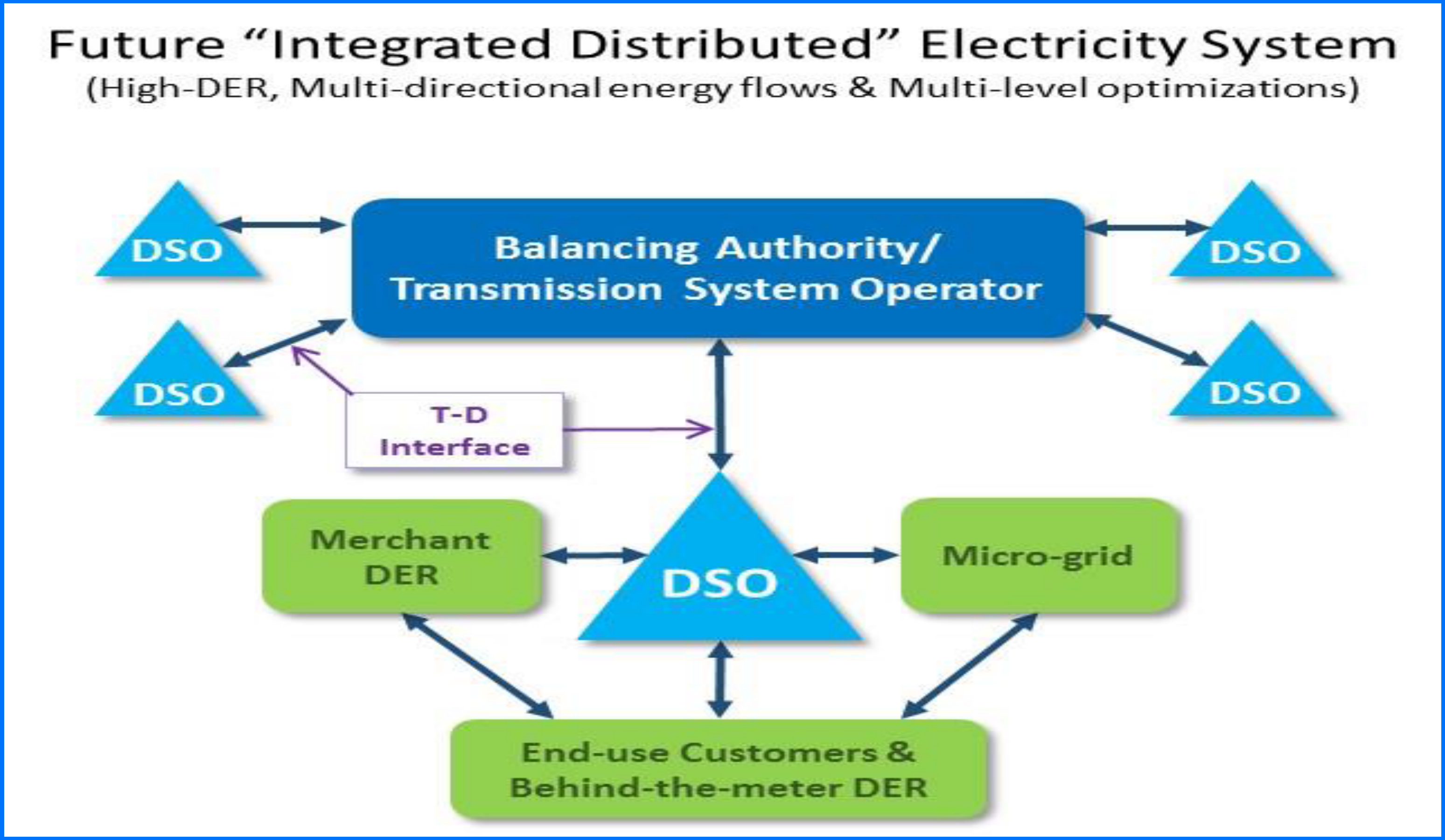


Small tracking errors only while crossing color boundaries

Example



Integrated Distributed Electricity System



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Markets & Power System Operations DR, PV, PEV aggregation and Wind/Solar integration

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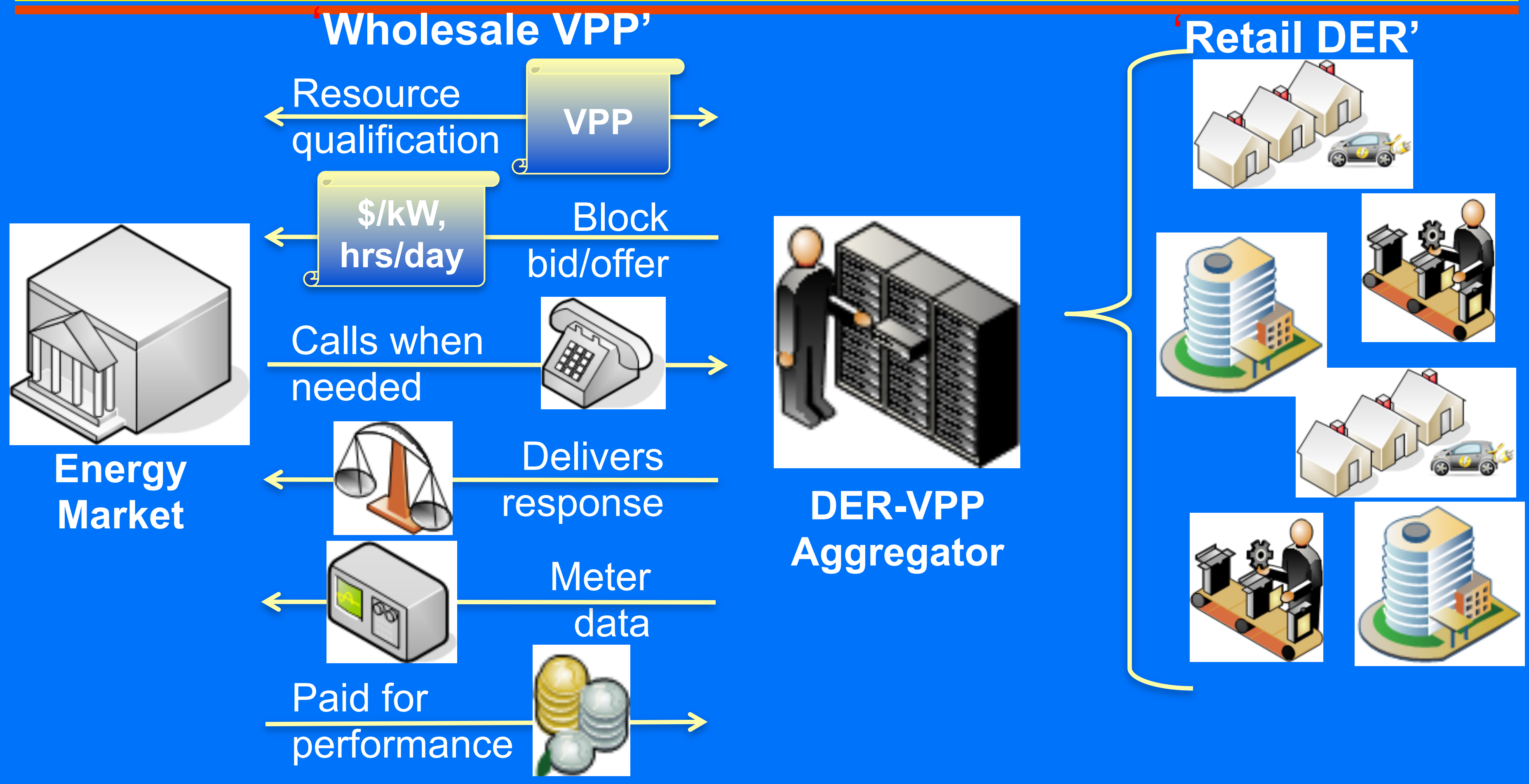
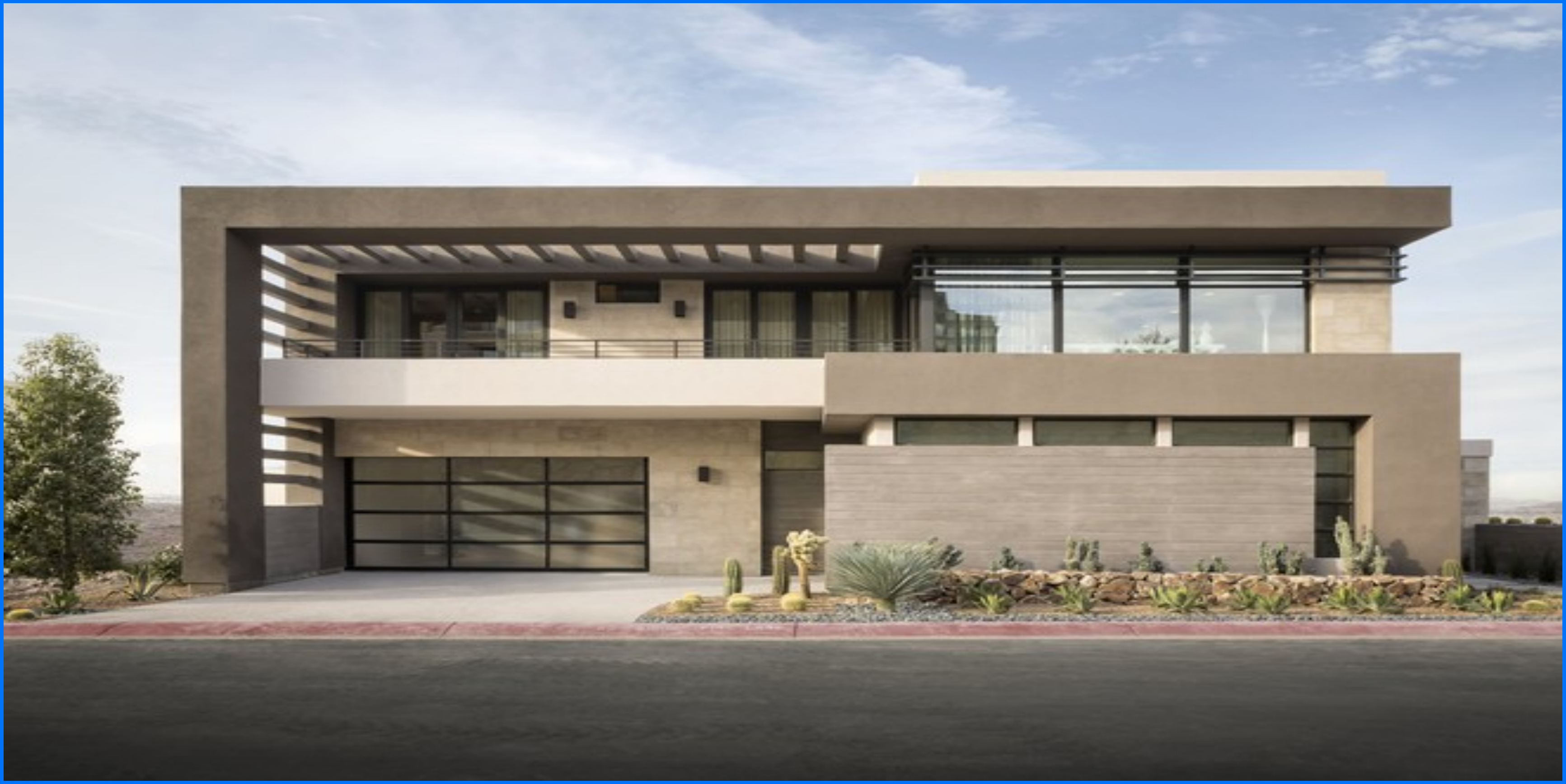
DER Aggregators and Virtual Power Plants
Aggregators hide some of this complexity via VPP abstraction



In the Past Utilities Sold Energy, in the Future will sell Energy Insurance
New Electric Company: Your Home



Conclusions

- DR can play a key role in addressing current energy market challenges
- Current DR programs are not successful
- The new proposed technology is based on a distributed computing based stochastic control algorithm allows fast, accurate and robust control of thousands to millions of devices
- Performance can be accurately predicted from stochastic model analysis
- Performance is robust against fluctuations, errors, and variation between devices
- We are in the process of commercializing the technology