Is Statistical Thermodynamics Helpful in Understanding Smart Grid Behavior?

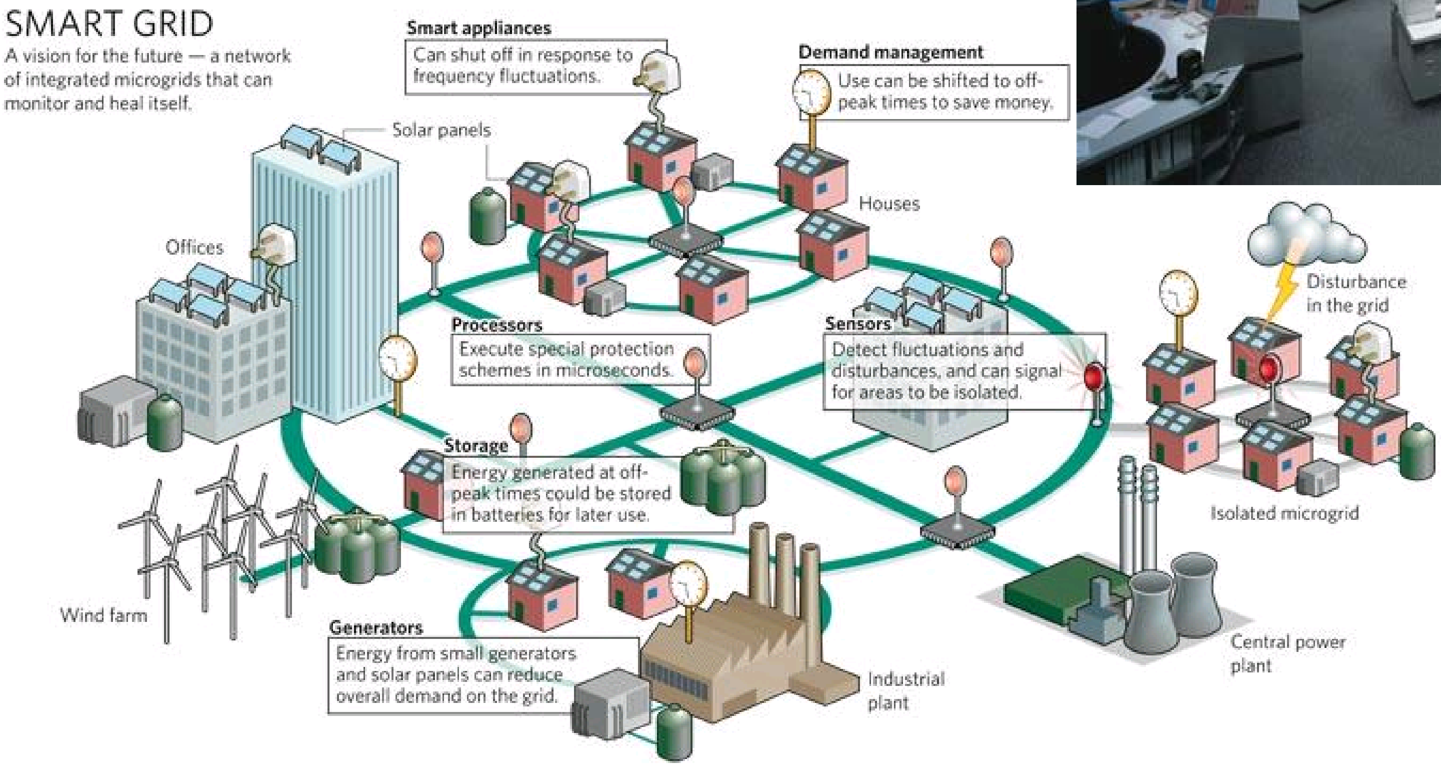
David P. Chassin

LANL CNLS Seminar

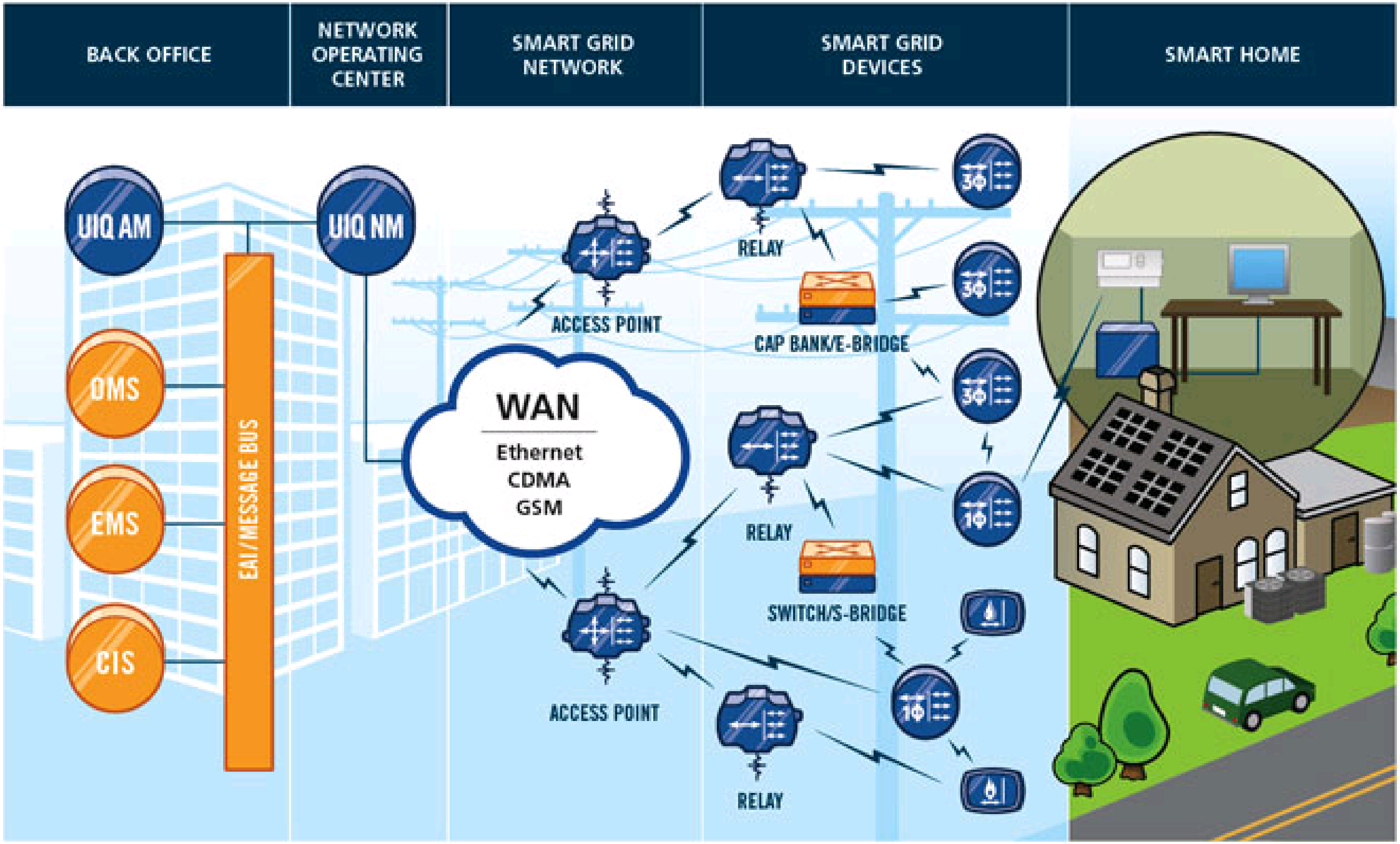
January 12, 2010

Pacific Northwest
NATIONAL LABORATORY

Power Markets and Smart Grids



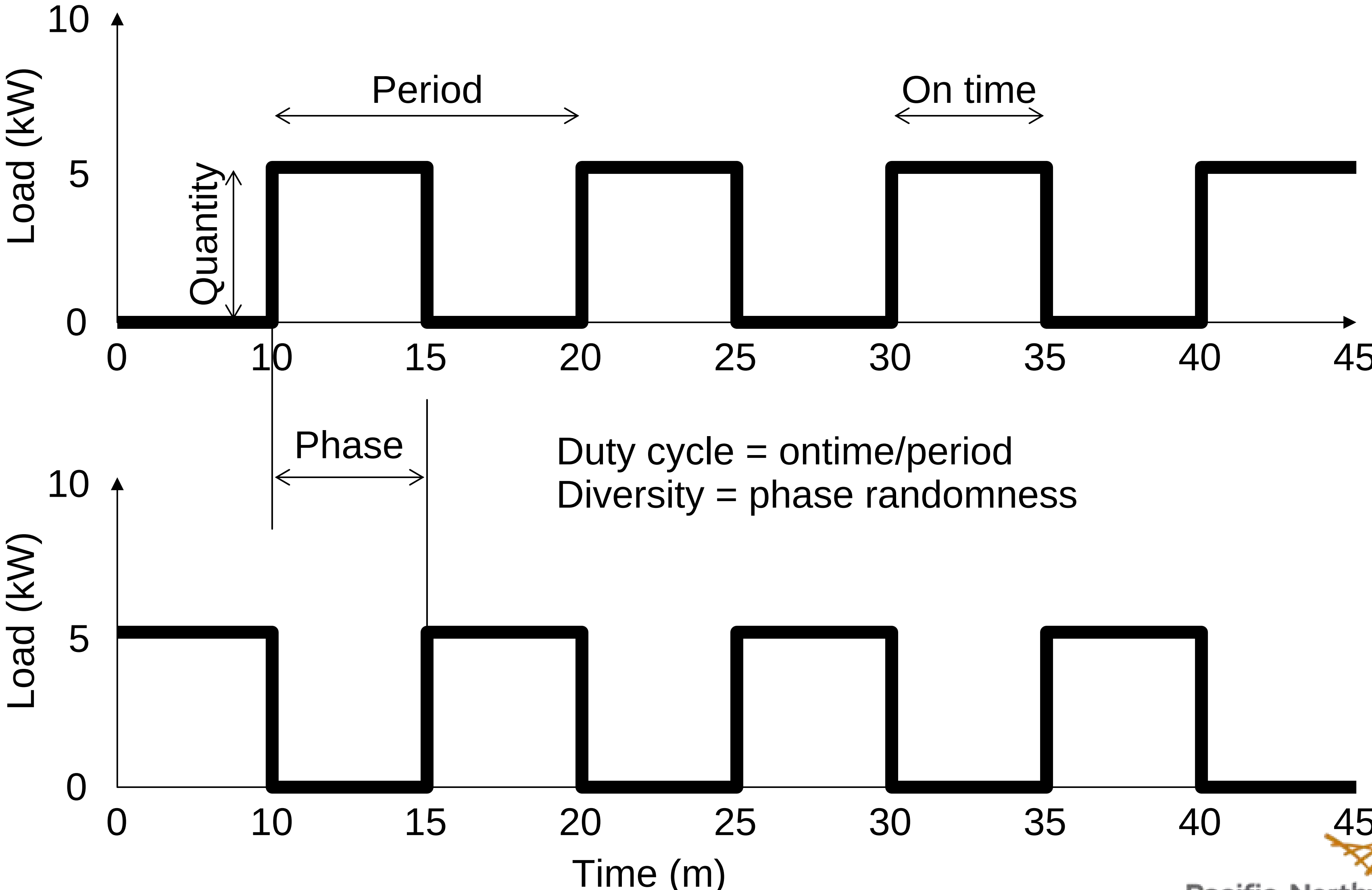
Smart Grid:
Build Data Lines, Not Power Lines



R&D Objectives of Smart Grid Demos

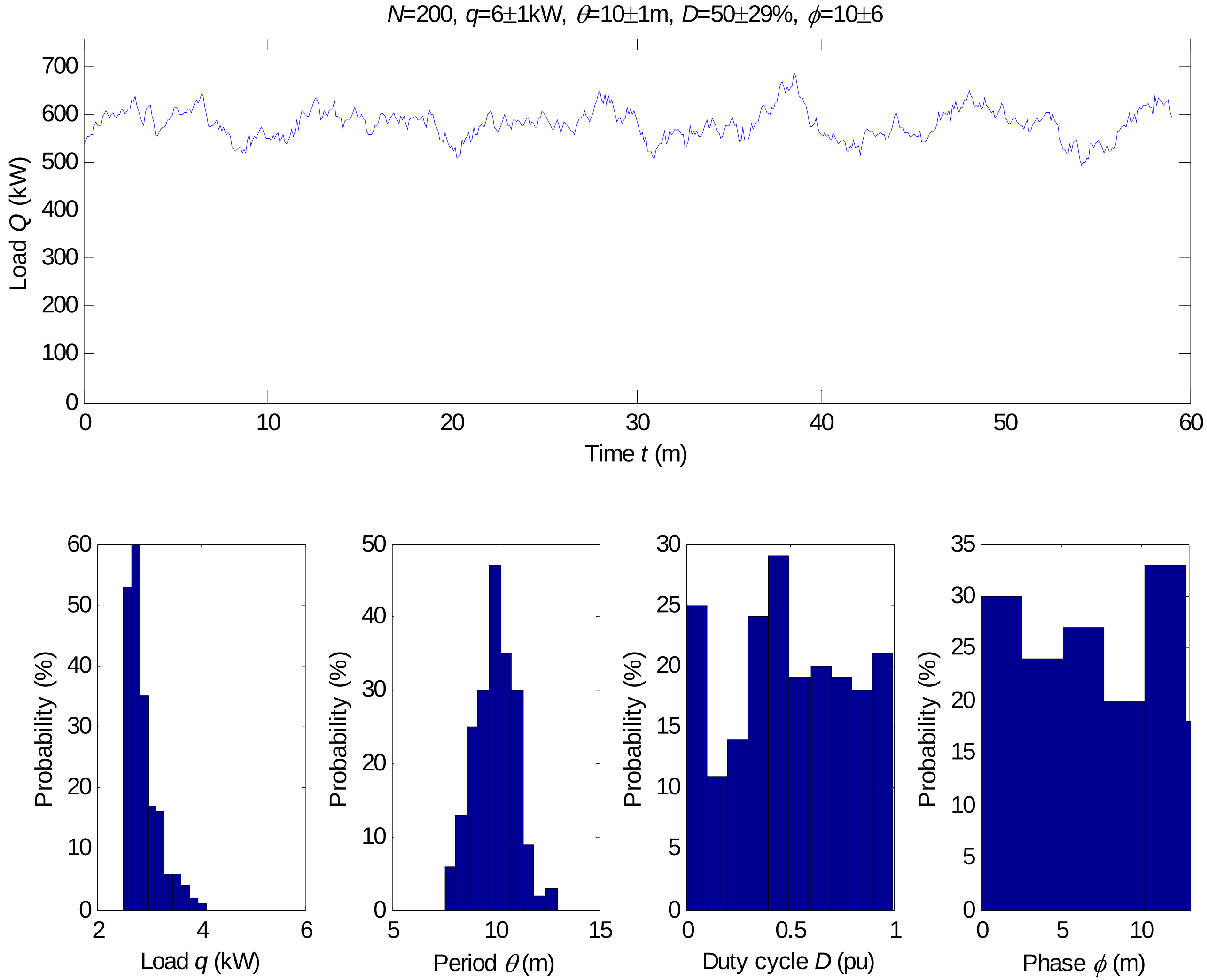
- Engaging loads
  - Understand how loads behave in Smart Grid world
  - Provide new kinds of control strategies
- Enhancing utility business model
  - Study how new virtual assets can be used effectively
  - Producing business cases for Smart Grid programs
- Extending market-like processes into distribution
  - Demonstrate real-time price controls
  - Produce control strategies for "prices to devices"
- Understanding how it all works
  - Examine aggregate system behaviors (stability, etc.)
  - Identify aggregate models of system and control

Thermostatic/periodic loads



Duty cycle = ontime/period
Diversity = phase randomness

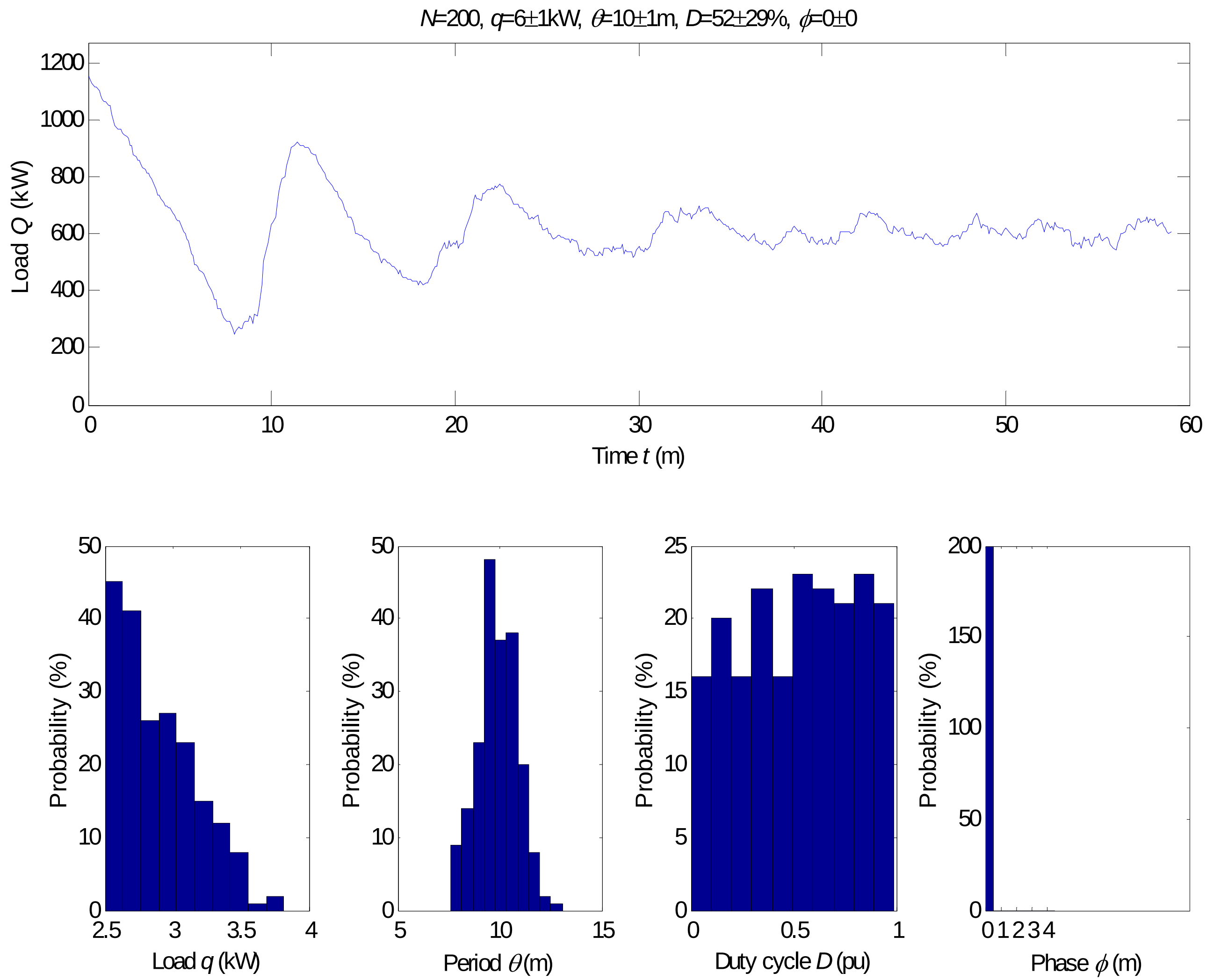
Diversity masks cyclic behavior



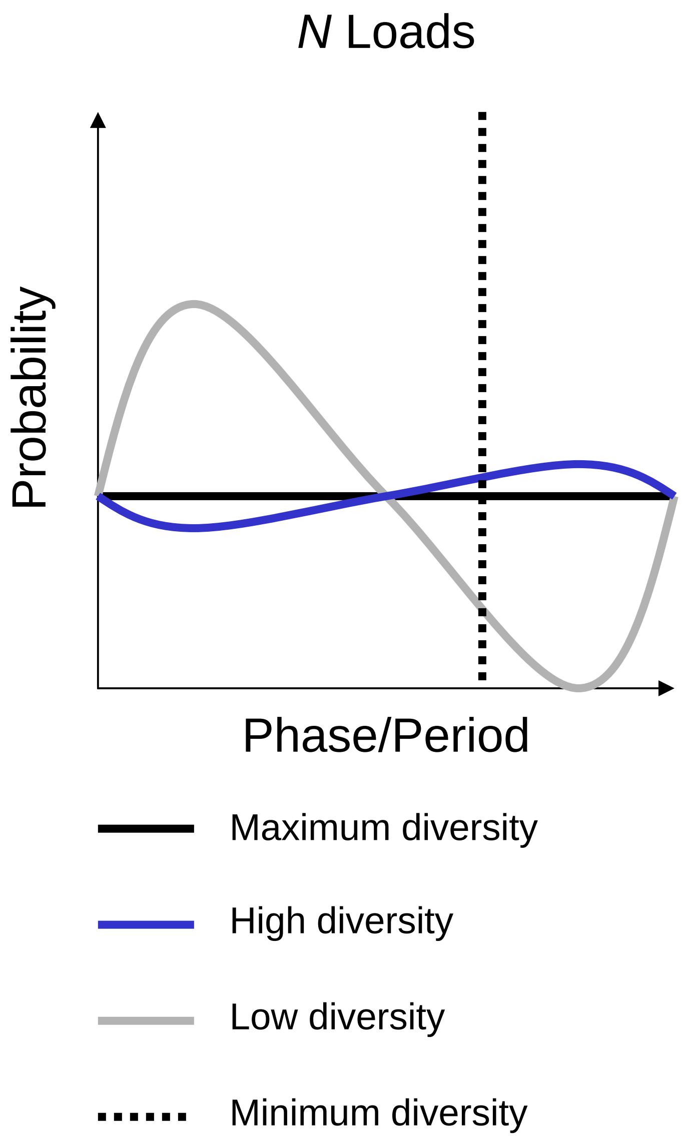
Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

Diversity can be defeated but always returns

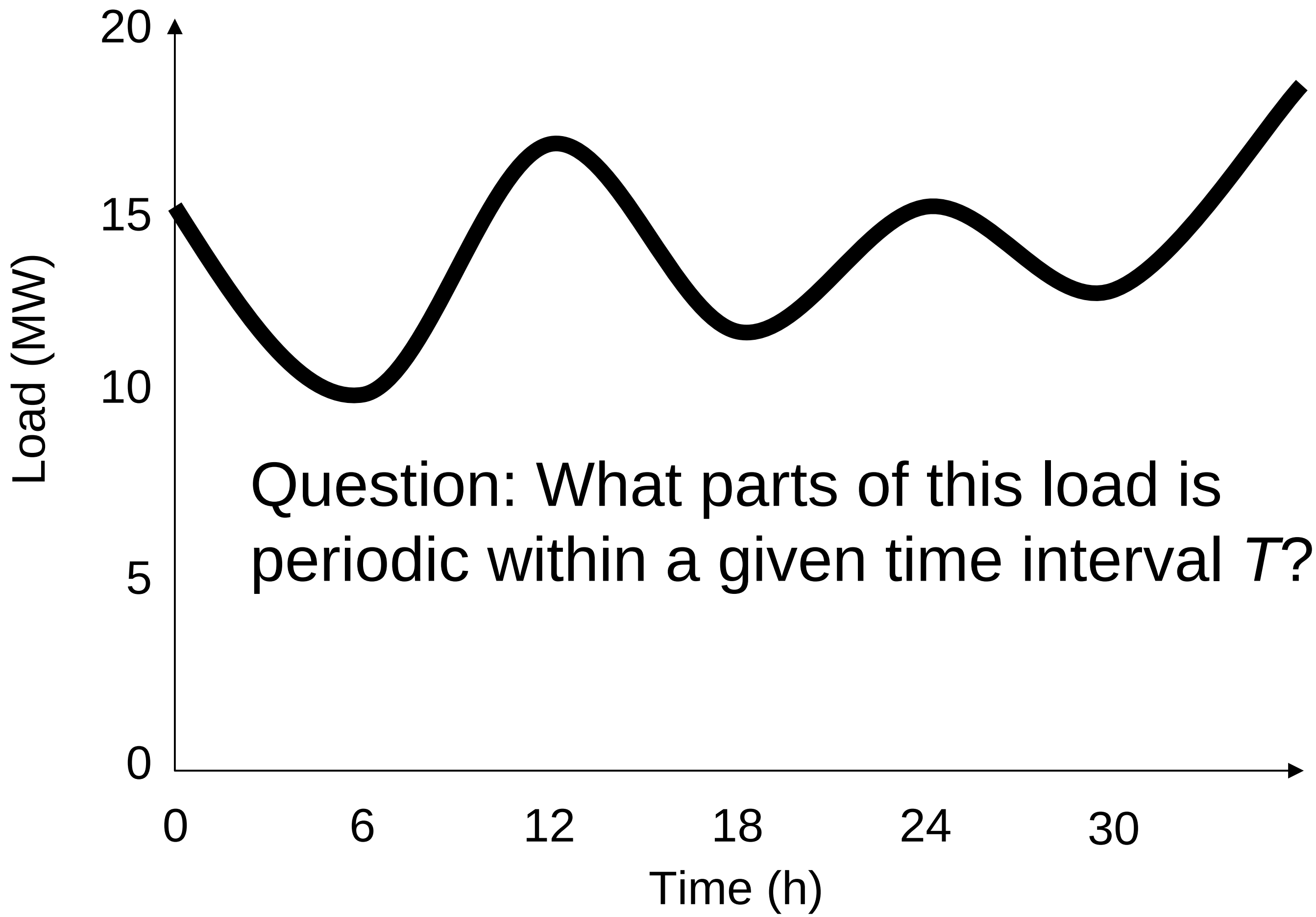


Drivers of diversity



- Different periods
  - Phases scatter as a result of cyclic with different periods
- Demand events
  - Demand “short circuits” normal cycle
  - Shortens diversification time
  - Increases mean load
- Diversity is entropy-like

Typical aggregate load shape

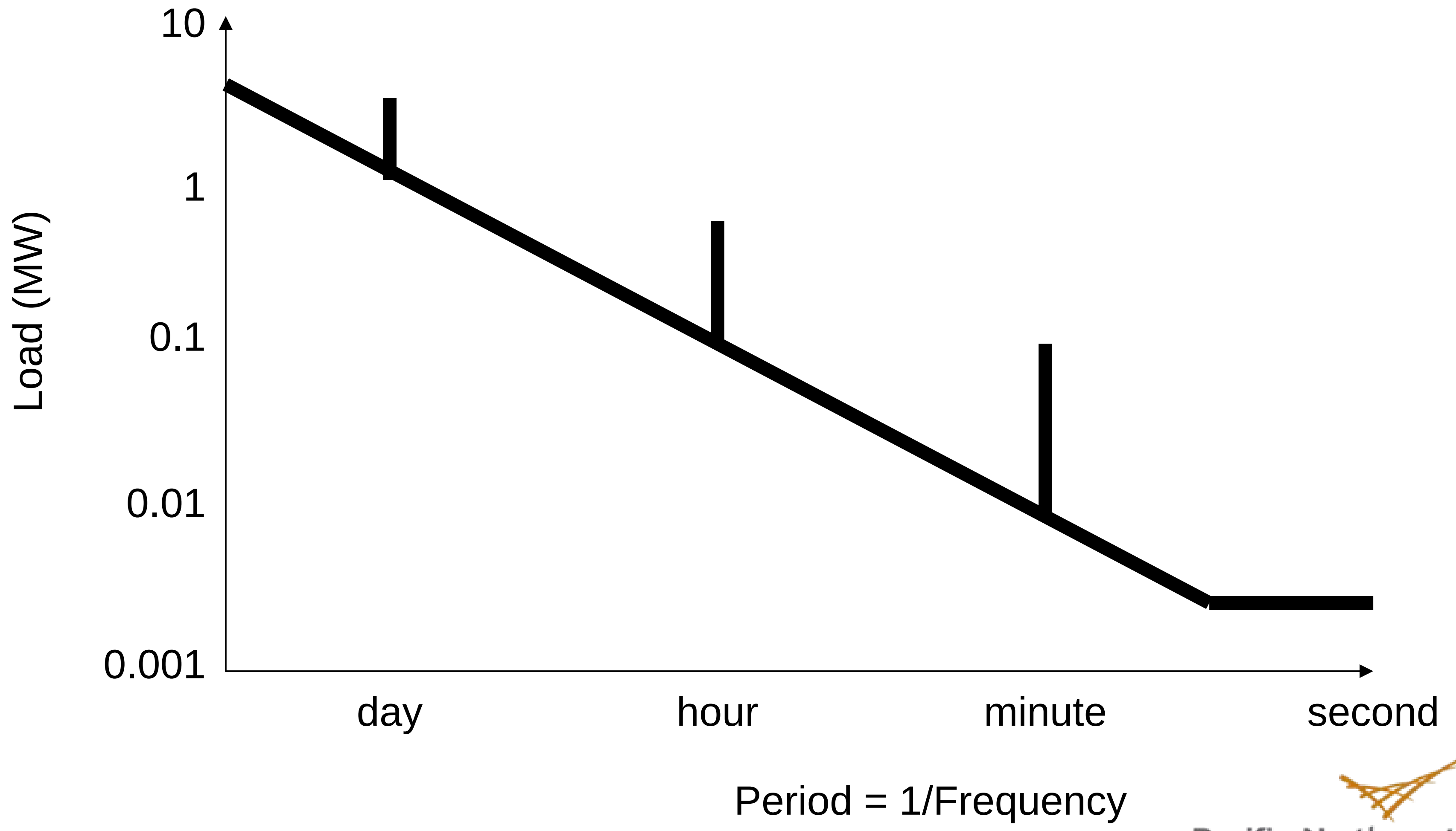


Question: What parts of this load is periodic within a given time interval *T*?

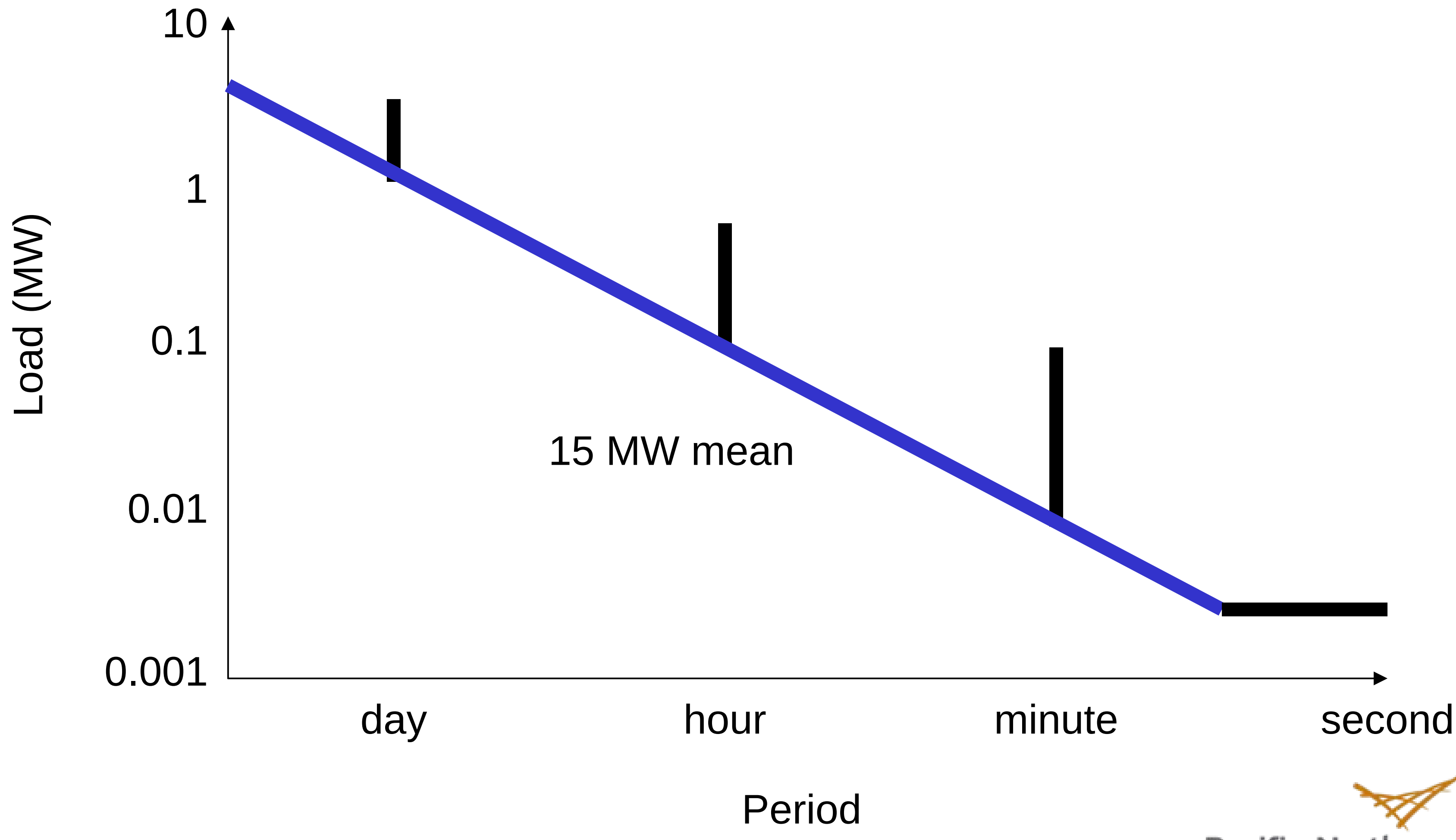
Simple Numerical Example

- 200 kW white noise over 15 MW mean
- Periodic loads introduced numerical
  - 1 minute 100kW
  - 1 hour 500kW
  - 1 day 2MW
  - 1 year 10MW
- Choose *T* to observe human/equipment cycles
  - < 1 day cycles ~ human/equipment
  - > 1 day cycles ~ natural

Load periodicity curve



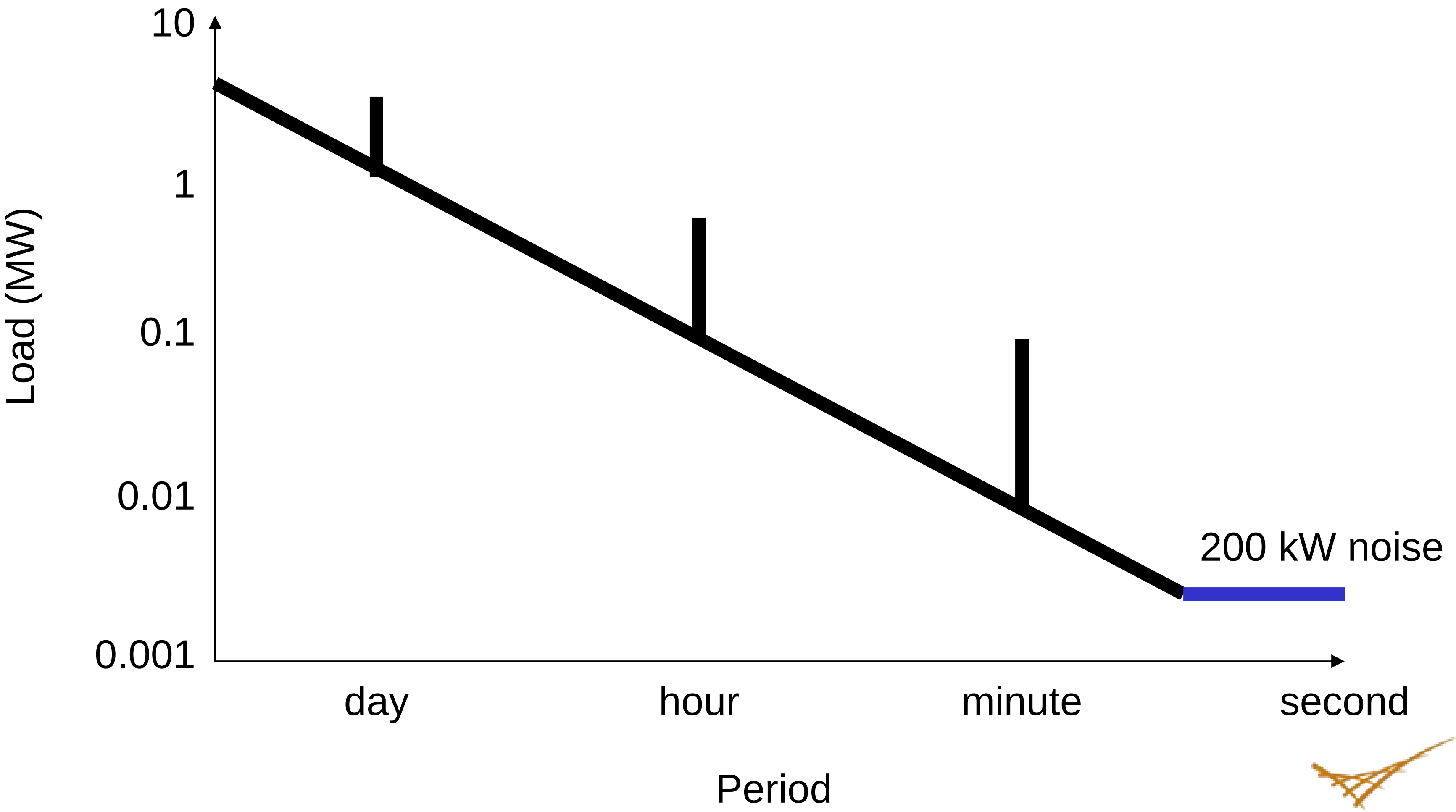
Mean load component



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

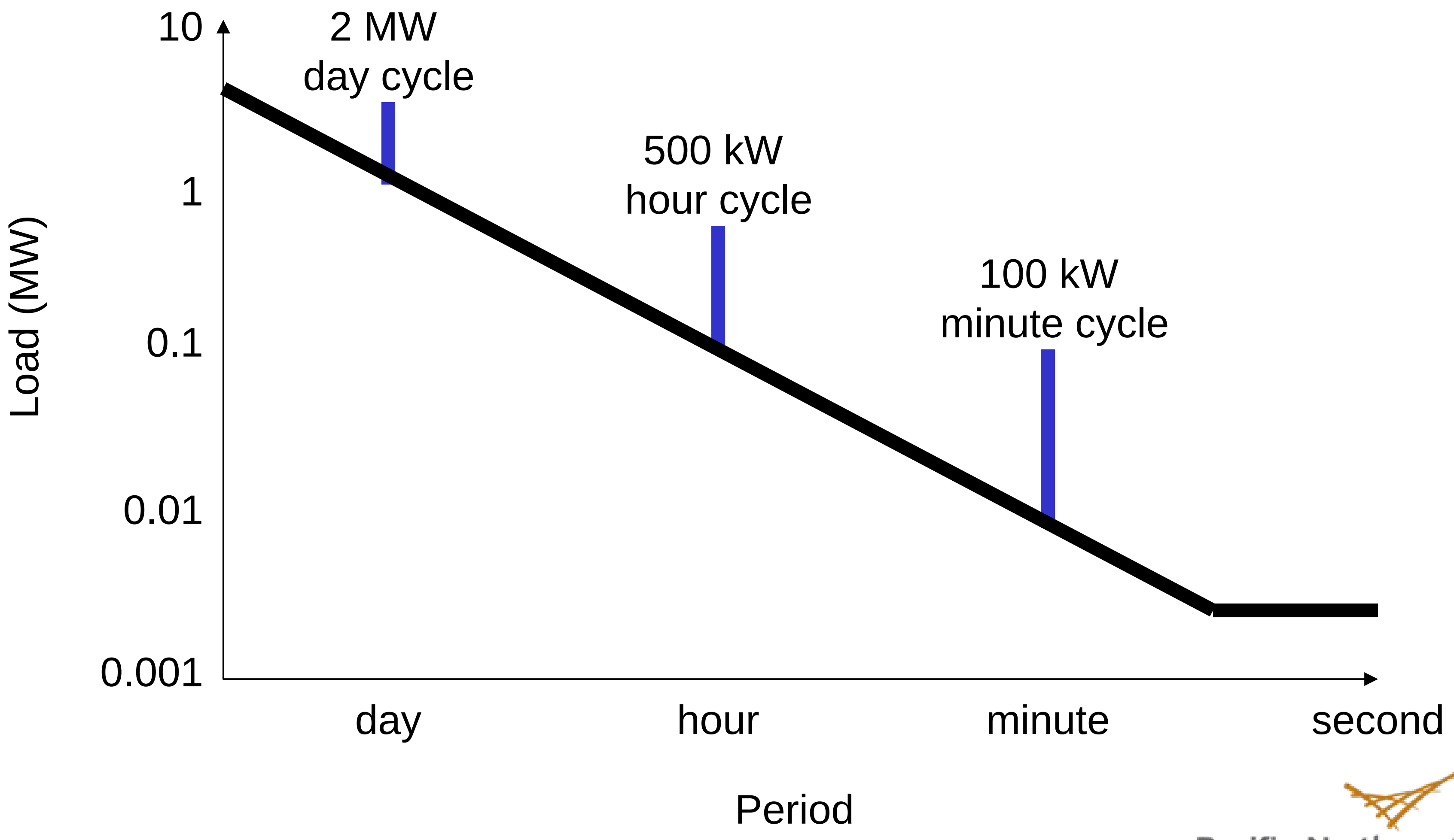
Noise component of load



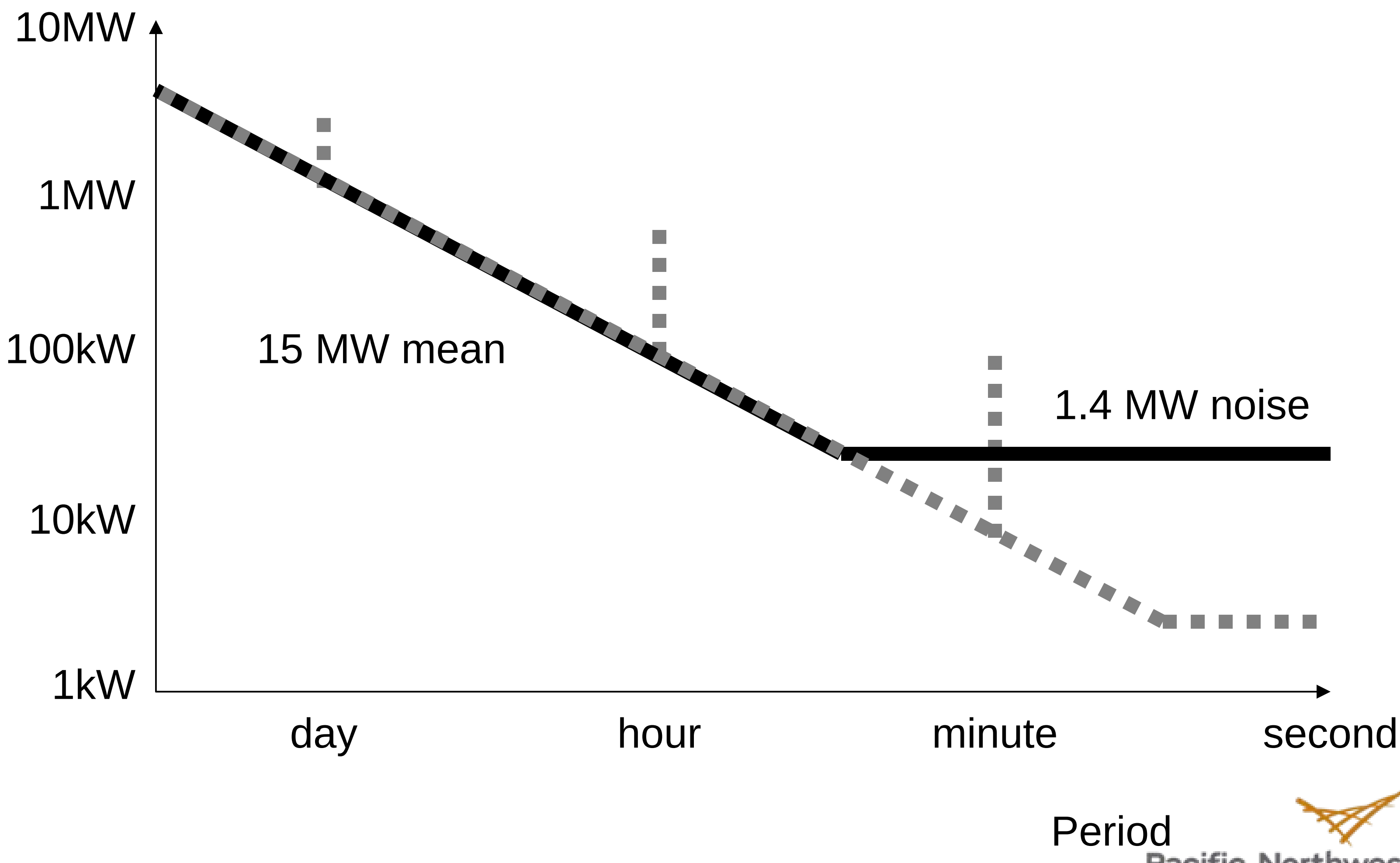
Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

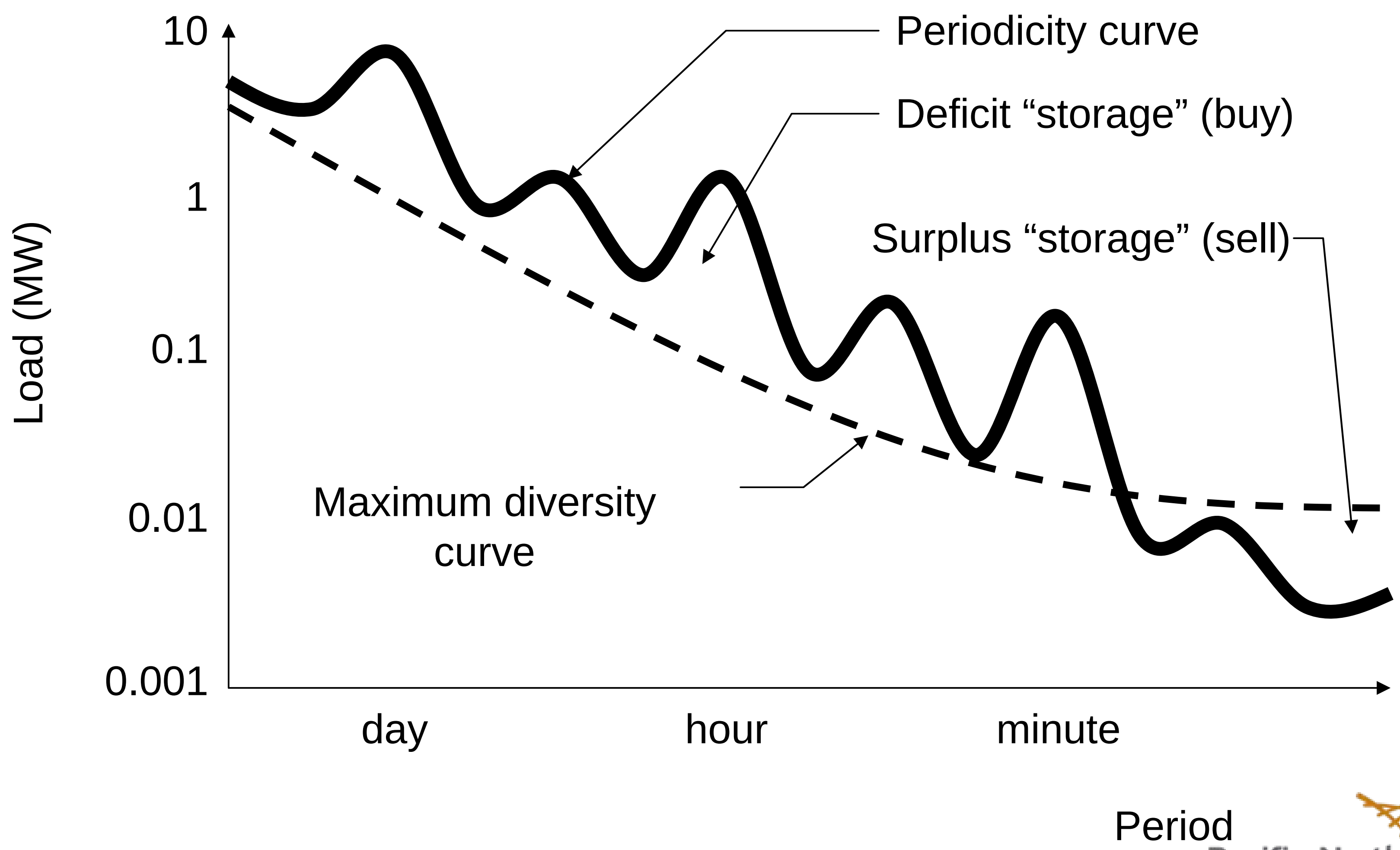
Cyclic components of load



Same load – maximum diversity



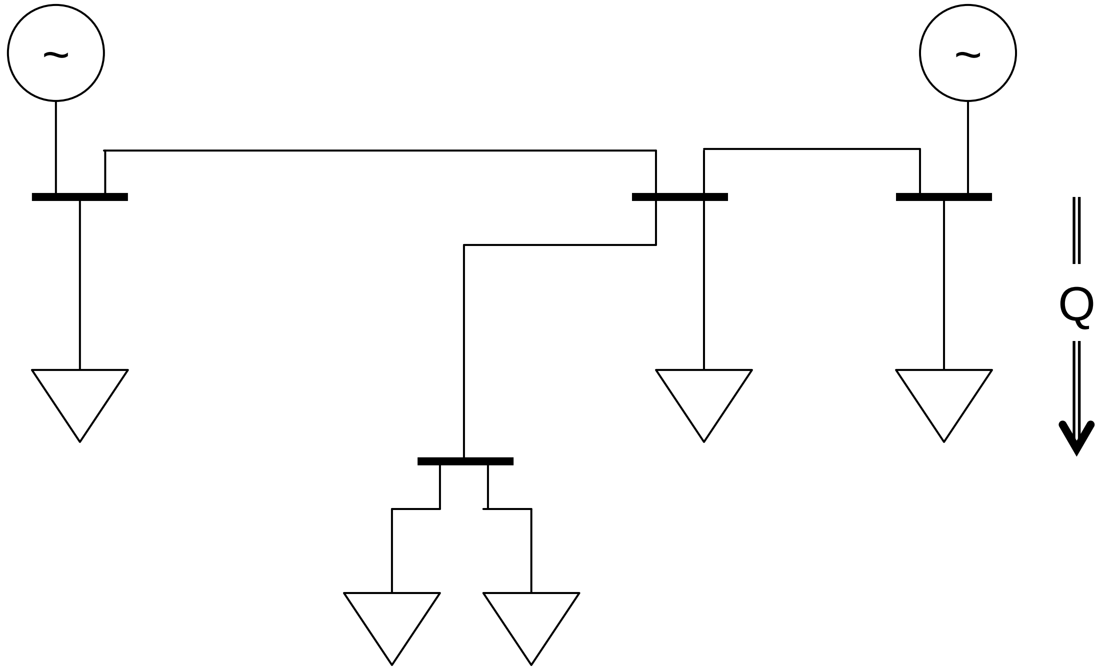
Virtual asset: demand response as storage



Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Power delivery: Vertically integrated utility



Central generation

Bulk transmission (>200kV)

Sub-transmission (50-200kV)

Industrial loads

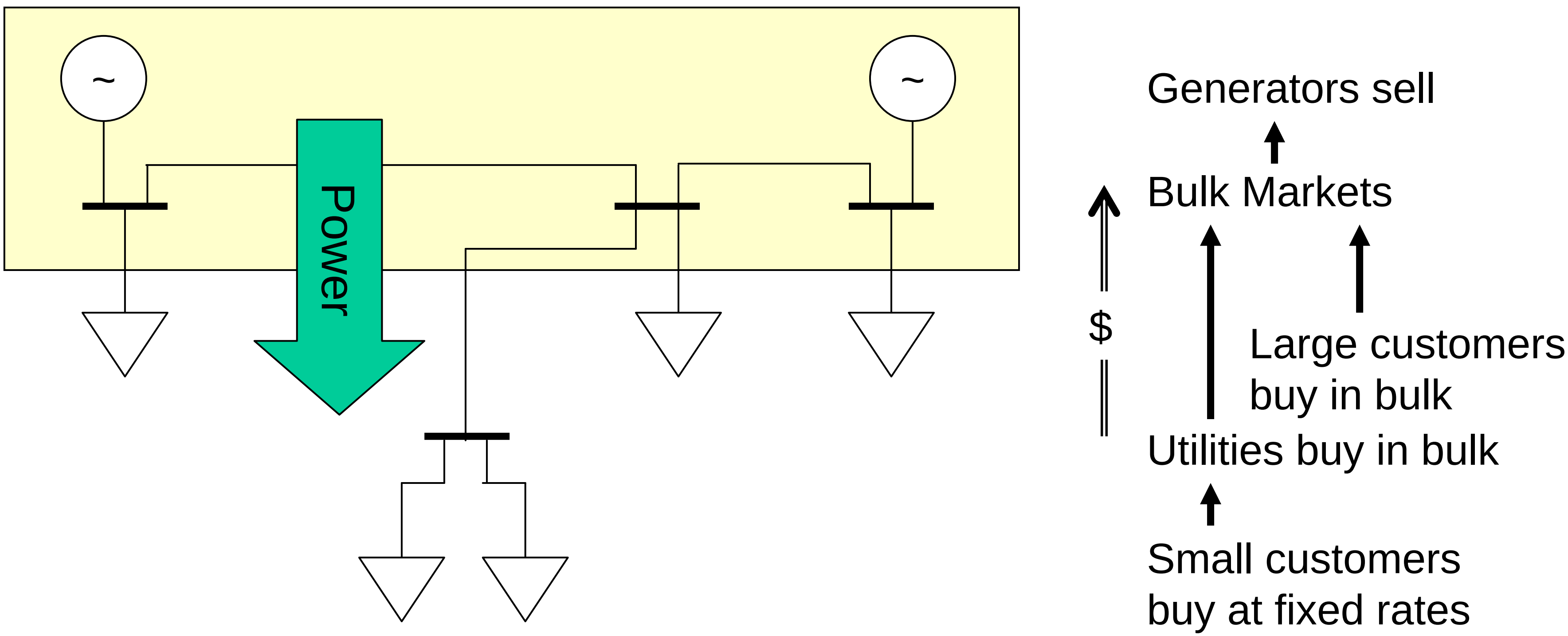
Distribution (<50kV)

Commercial & residential loads

Topology	**Capacity**	***Feeders***	***Gens***	***Model Nodes***	***225+kV Nodes***	***Total Nodes***	***Boundary Nodes***
Eastern Interconnect	450 GW	192,857	5,791	37,259	37,343	235,907	198,564
Western System	150 GW	64,285	2,264	11,667	11,764	78,216	66,452

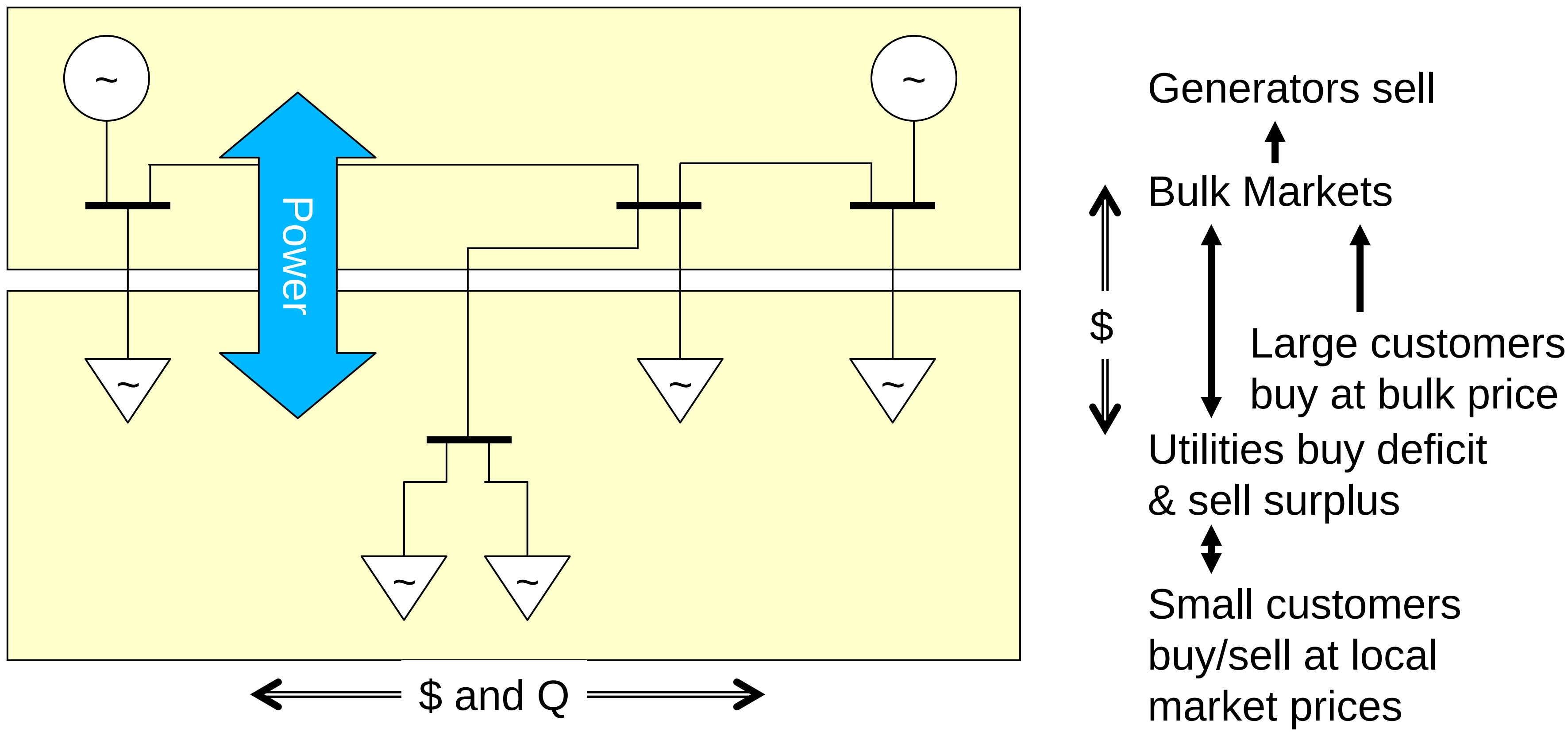
Source: **Chassin DP, and C Posse, "Evaluating North American electric grid reliability using the Barabasi-Albert network model,"** ***Physica A,*** **355(2-4):667-677, 2005**.

Today: Market-based operation



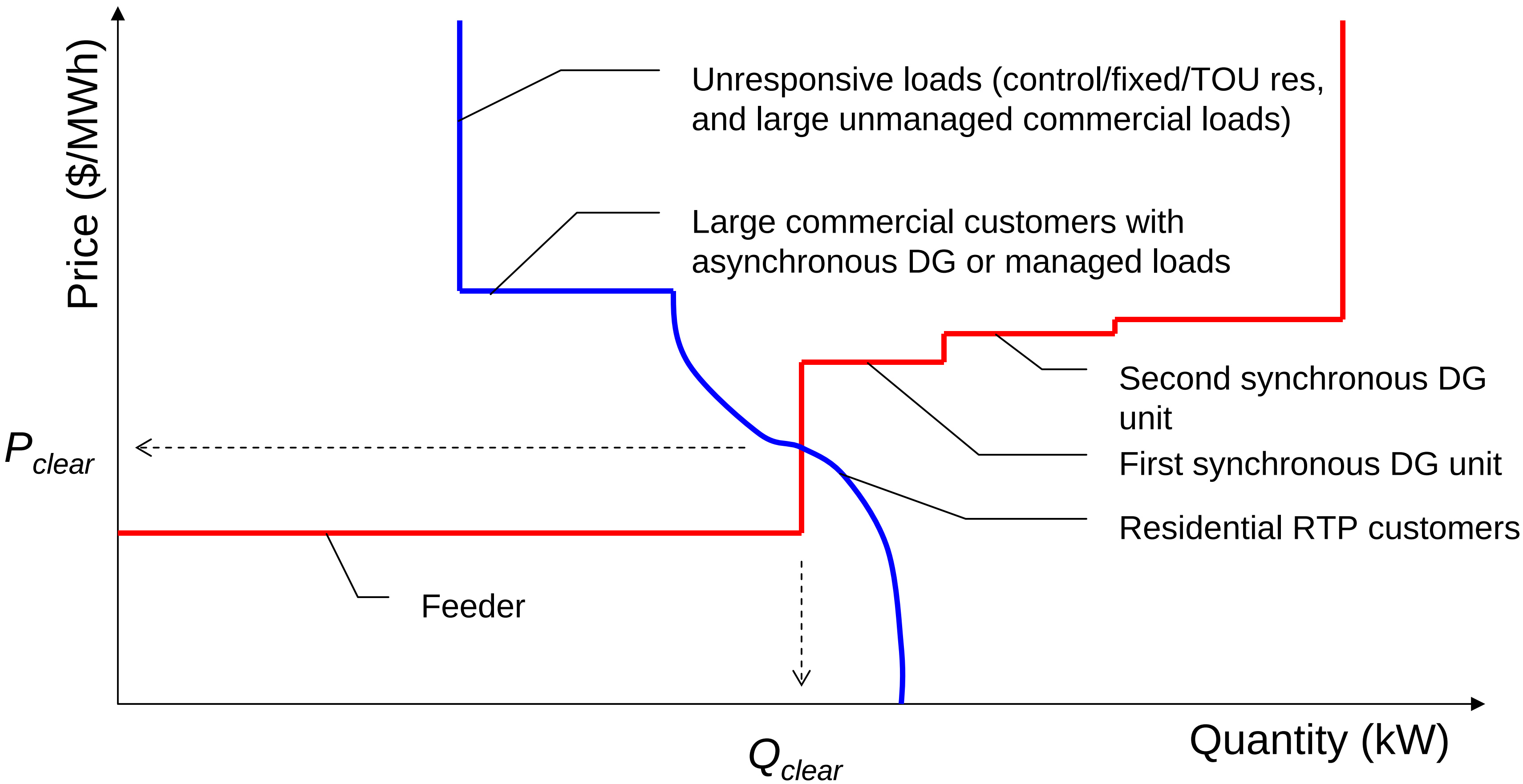
Fairly limited number of market participants: N < 1000

Tomorrow: Smart Grid power system

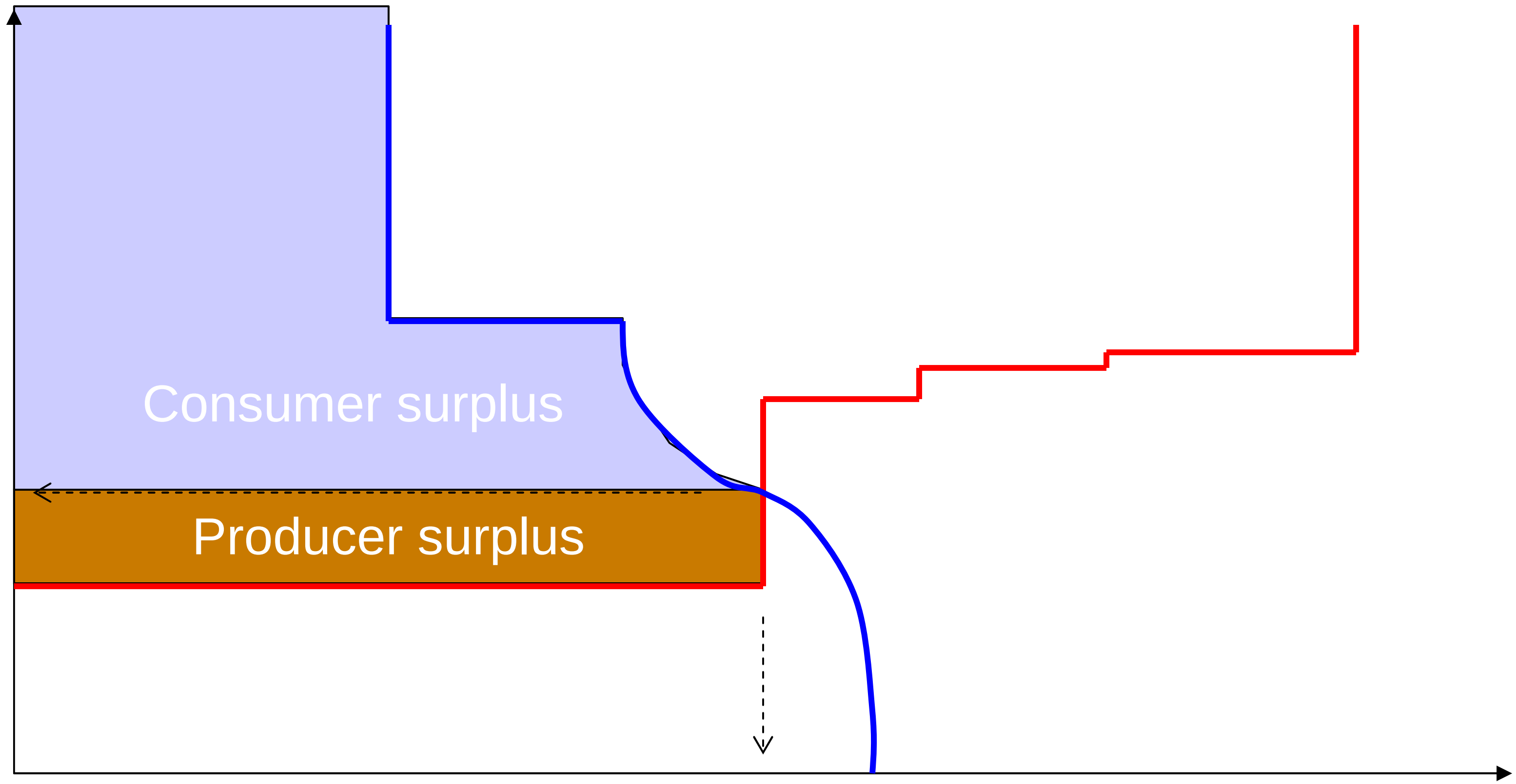


Much greater number of market participants: $N > 10^6$

Using price to control resources



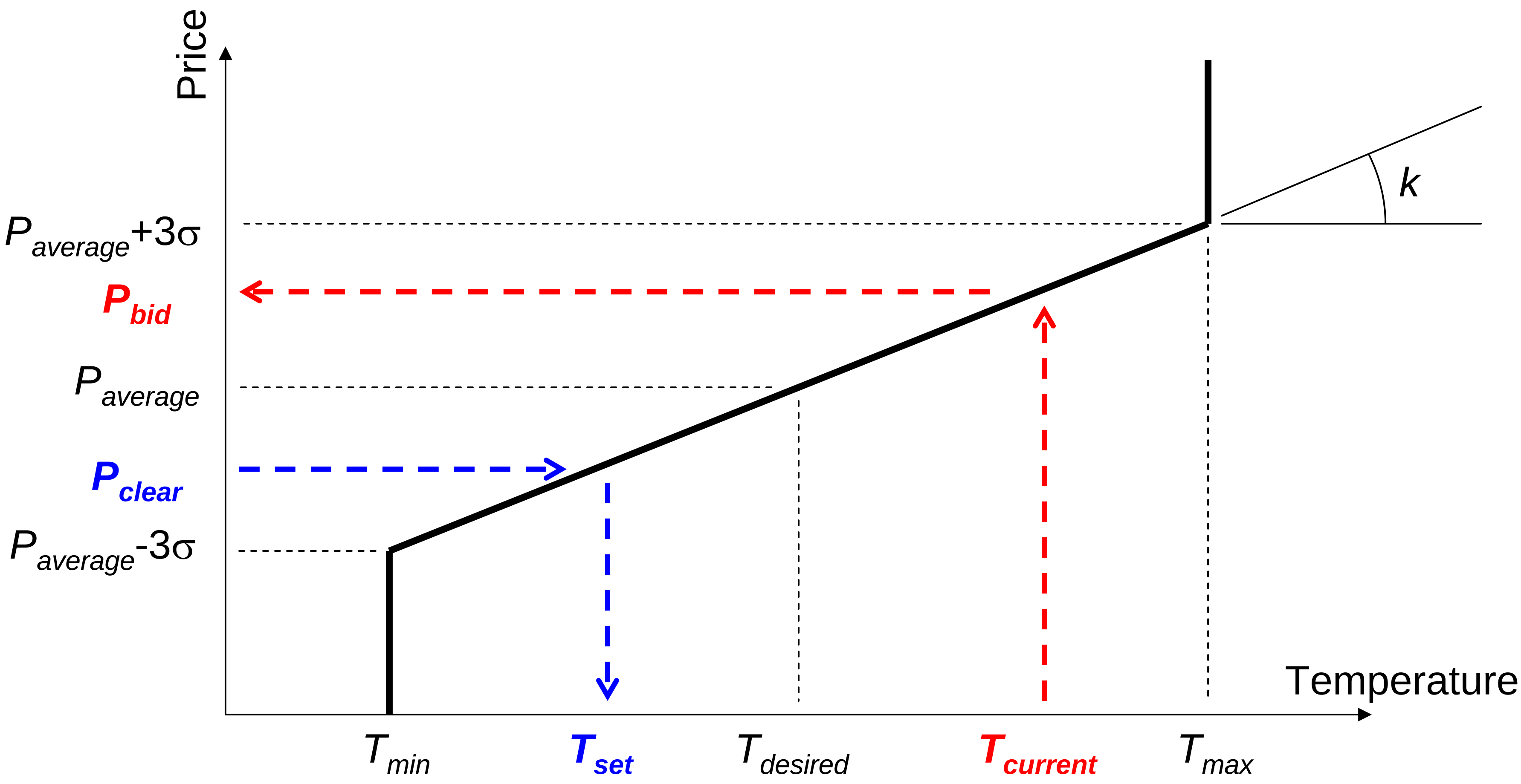
Consumer and producer surplus



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

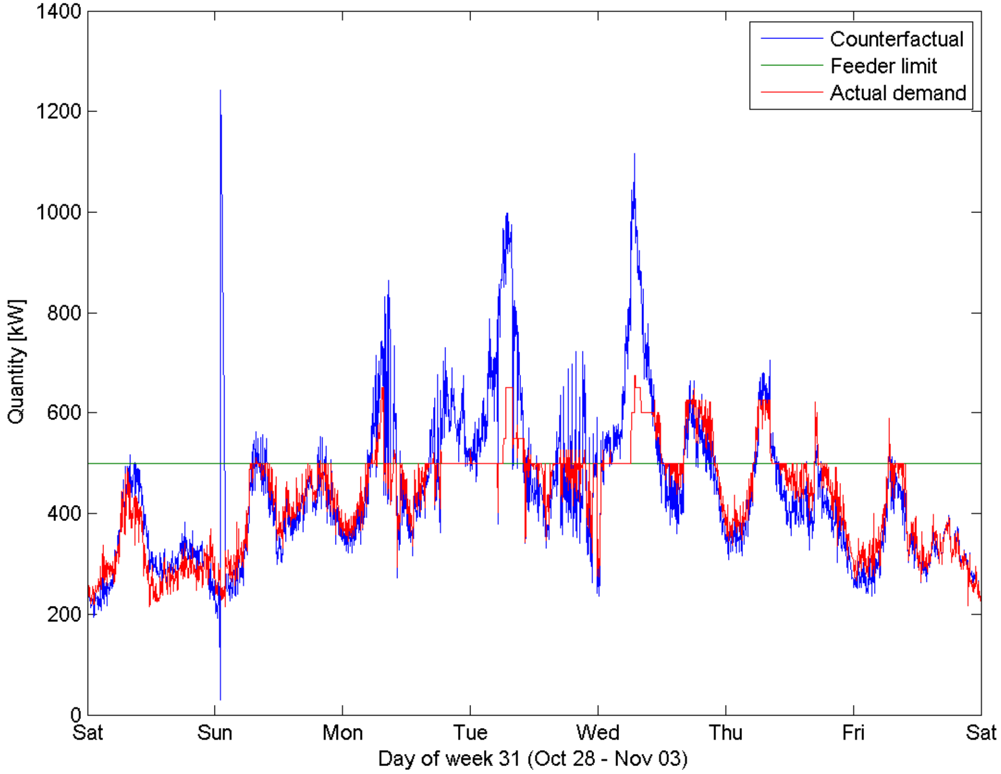
Real-time price thermostats



Small *k*: low comfort, high demand response

Large *k*: high comfort, low demand response

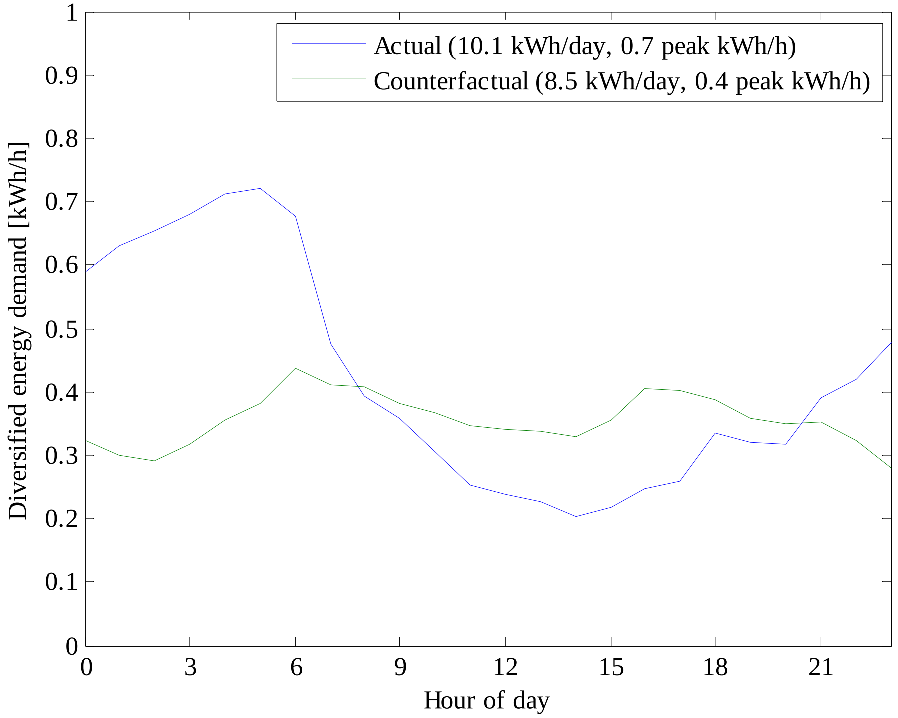
Feeder capacity impact
High load with good response

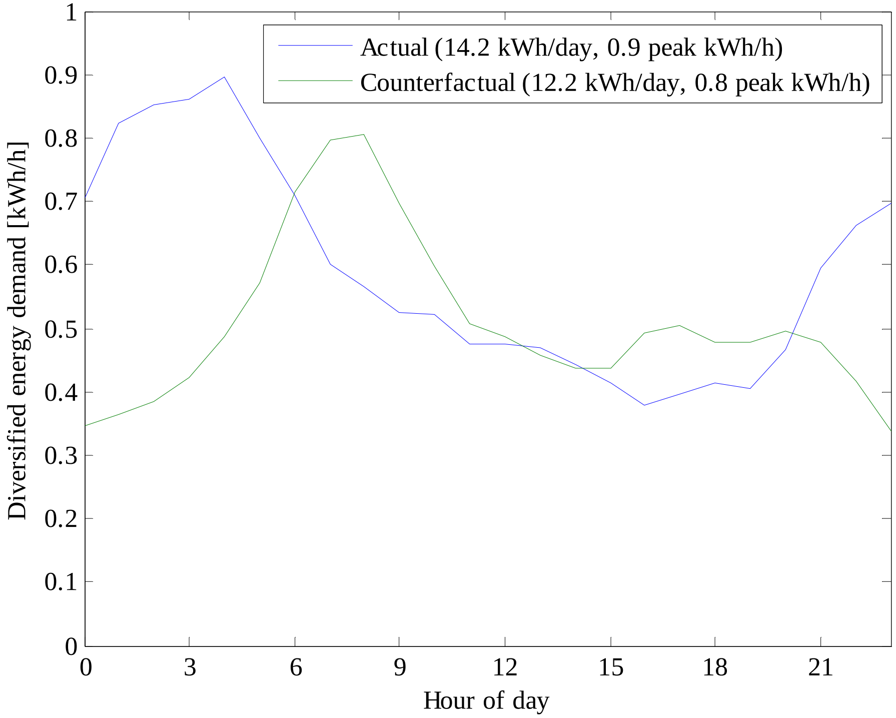


Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

RTP load shifting

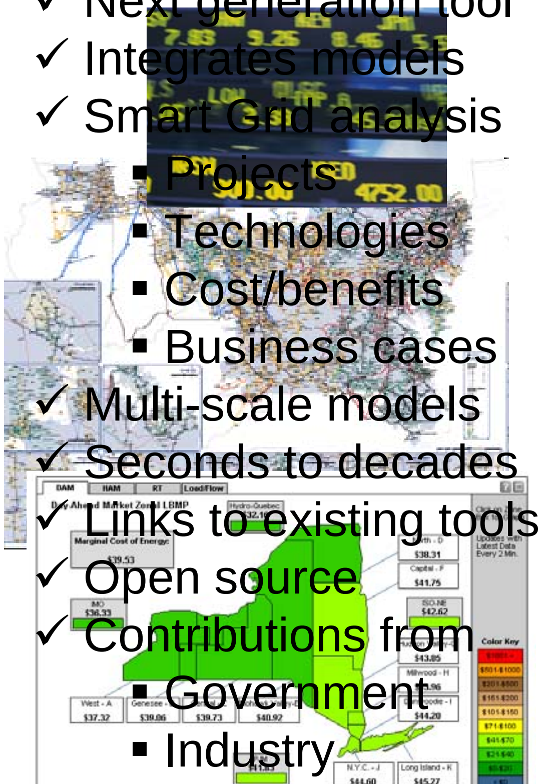




GridLAB-D: Simulating the Smart Grid

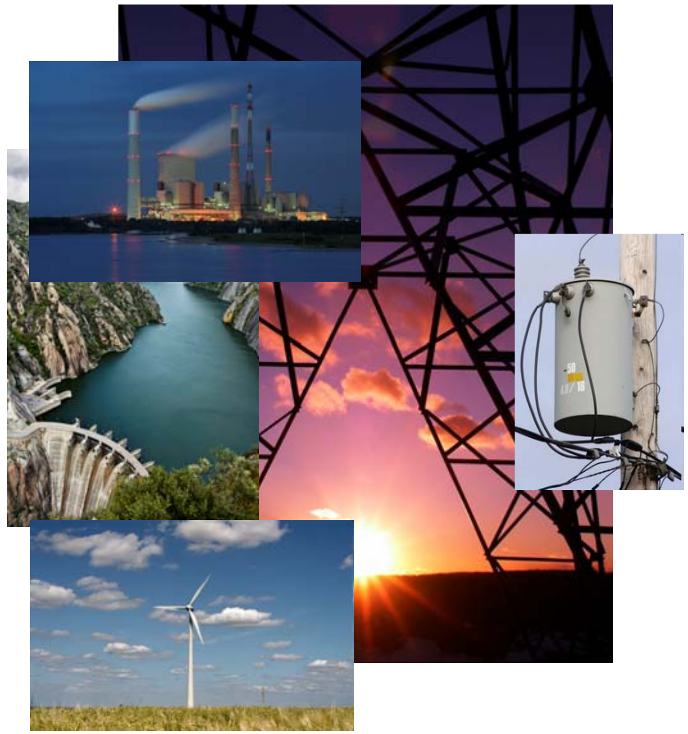
GridLAB-D model unifies keys elements of a Smart Grid

Market models



- ✓ Next generation tool
- ✓ Integrates models
- ✓ Smart Grid analysis
  - Projects
  - Technologies
  - Cost/benefits
  - Business cases
- ✓ Multi-scale models
- ✓ Seconds to decades
- ✓ Links to existing tools
- ✓ Open source
- ✓ Contributions from
  - Government
  - Industry
  - Academic
  - Vendors

Power system models



Load models

✓Vendors can add/extract modules for their own uses

✓Drives need for high performance computers

GridLAB-D Issues

- There are problems
  - Models are difficult to create (lack of good data, input detail)
  - Simulation can be very slow
  - Convergence is not always guaranteed
  - No first principles foundation for model order reduction
  - Few analytic insights
  - Lacks some generality
- Need for alternative modeling approaches
  - Ab initio model necessary
  - More general approach to modeling Smart Grid
  - Elucidate aggregate behavior (emergence)
  - Basis for monitoring and diagnosis
  - Foundation of better control design/theory

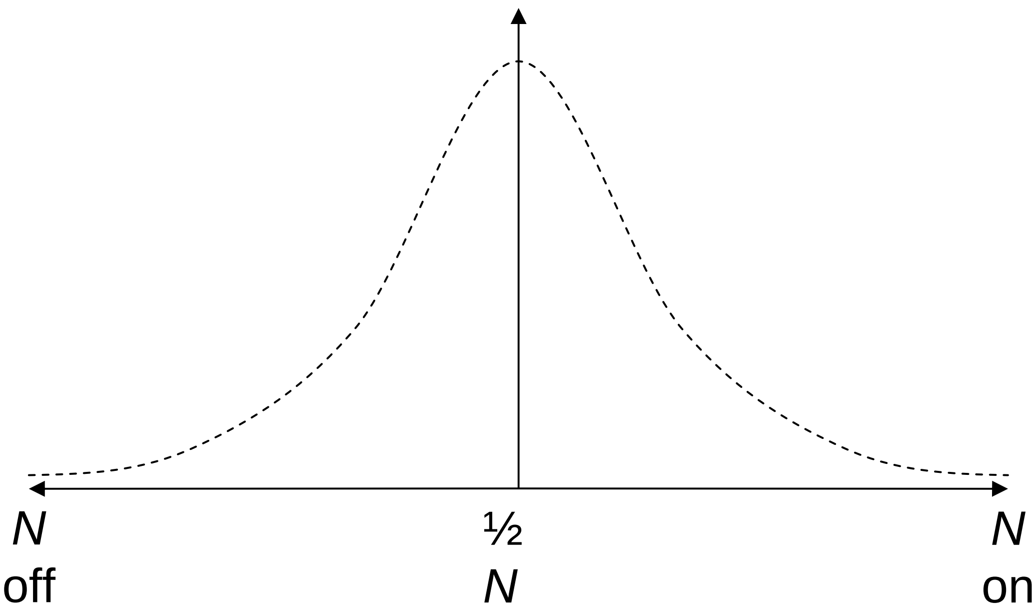
Thermodynamic analogy

- Some interesting observations
  - Many independent devices (> 10^8)
  - States are primarily driven by internal variables
  - States influenced by external "forces"
  - Few global parameters (price, frequency)
  - Few conserved quantities (money, surplus, income)
  - Identifiable constraints (supply, demand)
- Questions: Are there…
  - aggregate properties that describe the system?
  - these properties usable to manage the system?

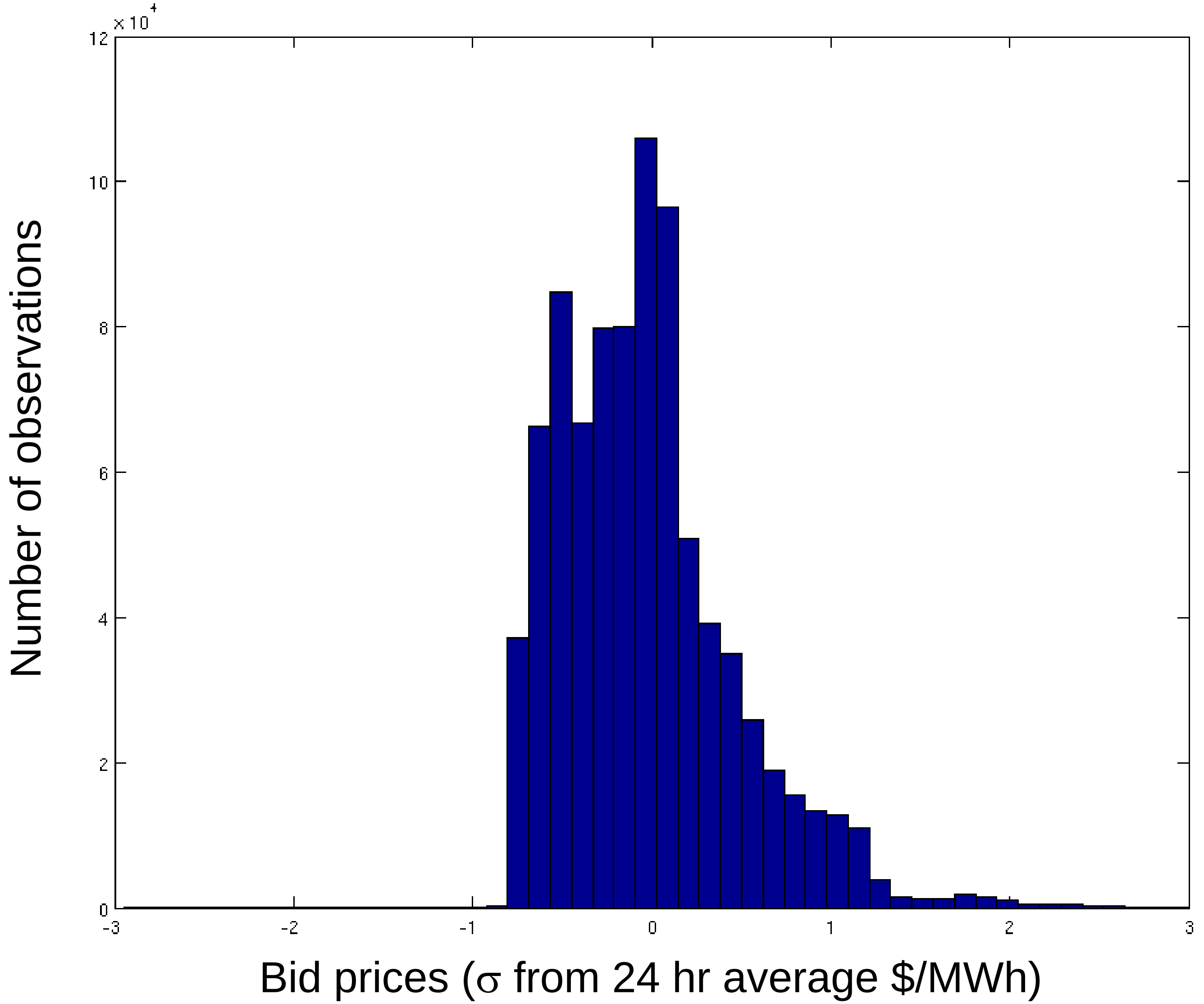
Ensembles

<u>Example: electric water heaters</u>

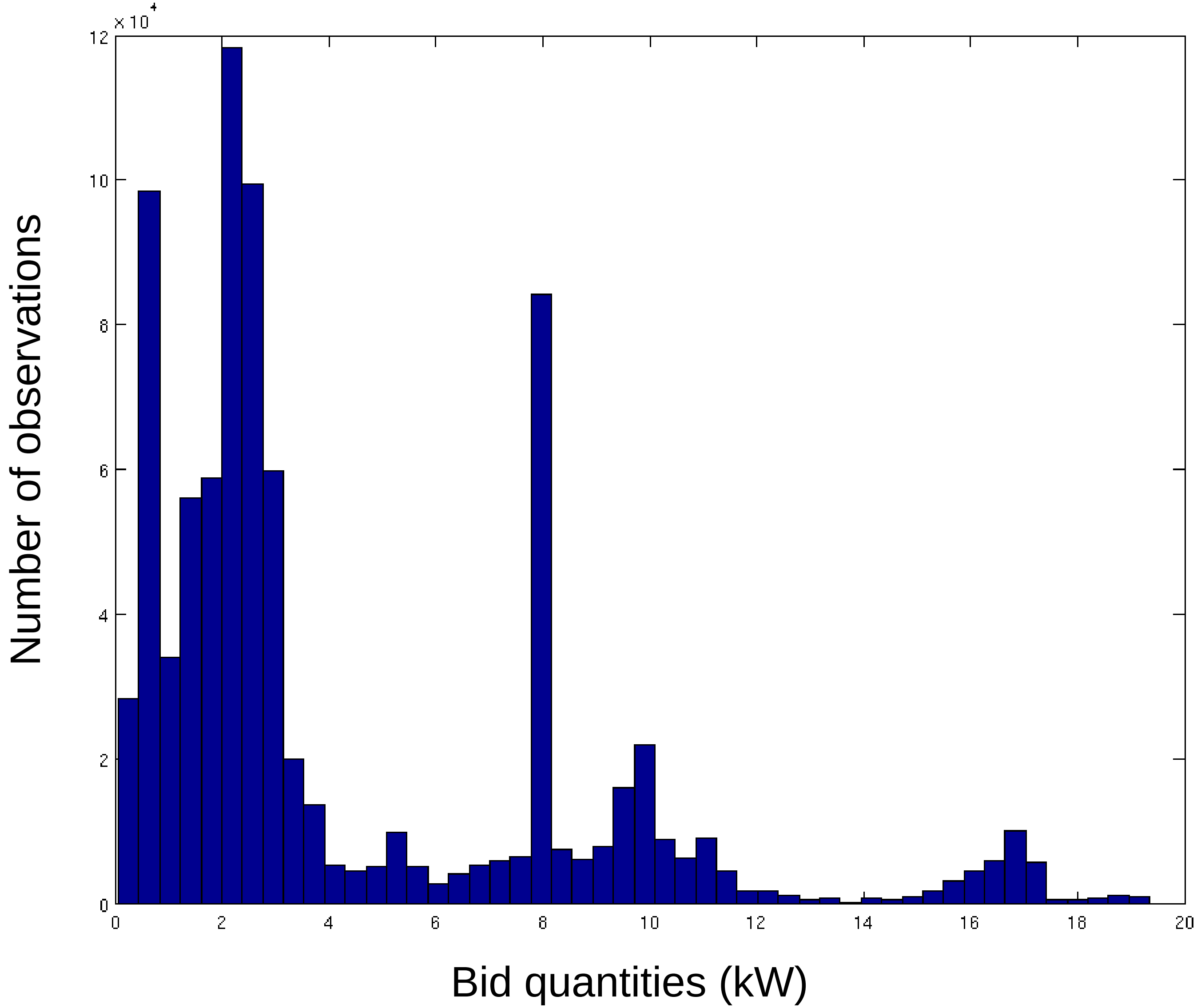
- 1 heater has 2 states: *on* or *off*
- *N* heaters have 2^N configurations
- Only *N*+1 distinct states
- Enumeration of states is binomial
- Utilities call this ***load diversity***



Olympic Peninsula Prices



Olympic Peninsula Quantities

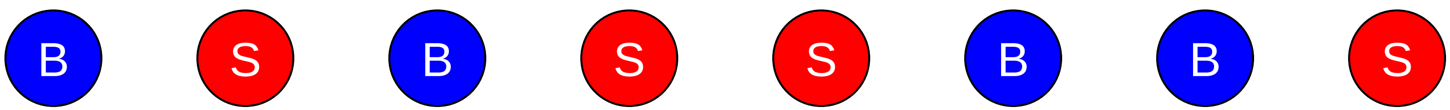


Conserved Quantities

- Conservation laws exist for some properties
  - Funds available for trading (e.g., gold, fiat, credit)
  - Number of devices
  - Limits and constraints
- Constant are for a given ensemble
  - But certainly can and do vary over time
  - Time-dynamics can be very complex

Entropy in a closed system

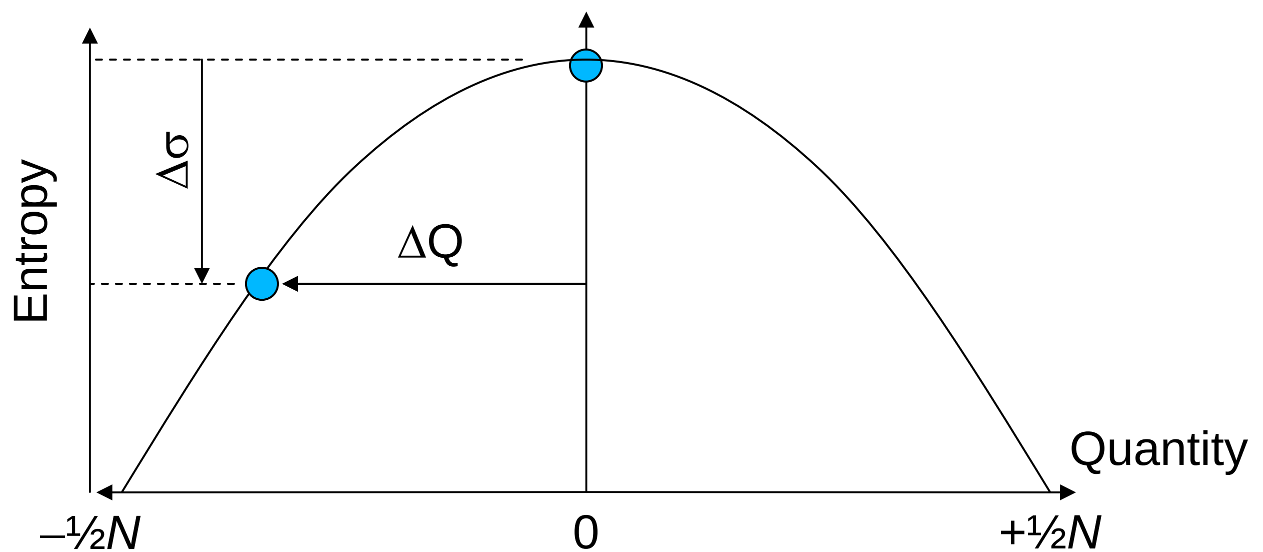
- Counts the number of ways of clearing market
- Must meet ensemble specifications (Q_{clear})
- Example: 8 ideal storage devices



  - $N = 8$
  - 256 possible configurations
  - 9 distinct states: $Q = \{-8, -6, -4, -2, 0, +2, +4, +6, +8\}$
  - $Q = 0$ (4S and 4B) is most probable (70/256)
  - $Q = \pm 8$ (8S or 8B) is least probable (1/256)
  - Entropy $\sigma(Q) = \log (N \text{ choose } \tfrac{1}{2}Q) \approx (N+\tfrac{1}{2})\log 2 - \tfrac{1}{2}\log \pi N - Q^2/2N$
- P_{clear} emerges in the absence of external price

Impact of bulk power prices (open system)

- Changes in P_{bulk} result in changes to Q_{clear}.
- $P_{bulk} > P_{clear} \rightarrow$ fewer local buyers and more local sellers
- $P_{bulk} < P_{clear} \rightarrow$ fewer local sellers and more local buyers
- $P_{bulk} = P_{clear} \rightarrow$ decoupling of bulk and local system

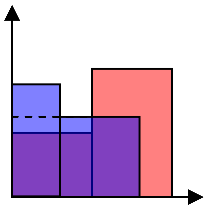


Total surplus

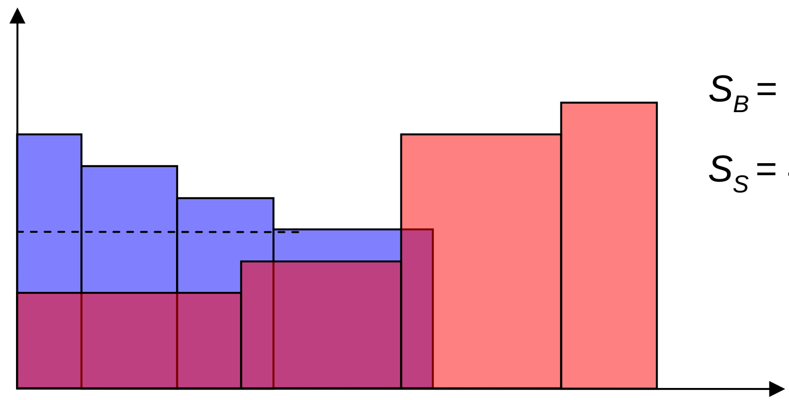
- Markets convert potential value of trading into surplus

$S_B = 6$

$S_S = 5$



$Q = 5$, $P = 6$



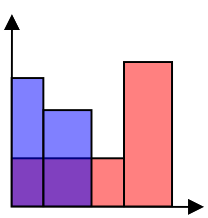
$S_B = 6+6+3 = 15$

$S_S = 4+6+5+4 = 19$

$Q = 12$, $P = 5$

$S_B = 10+9 = 19$

$S_S = 0$



$Q = 5$, $P = 3$

Total surplus change is $\Delta S = (34-30) = +4$

Markets minimize potential value and maximize total surplus.

Trading activity

- Activity τ is defined as the change in total surplus with respect to the change in entropy

$$\frac{1}{\tau} = \left(\frac{\partial \sigma}{\partial U} \right)_N$$

- Observations about entropy and activity:
  - Total surplus is maximized when entropy is maximum
  - Entropy tends to increase -- Second Law applies
  - Entropy is additive
  - Surplus increases as activity increases
  - Prices can be used to regulate activity (reduce entropy)
  - Fractional fluctuations from entropy max usually small

Migration potential

- Migration potential is the change in number of agents with respect to a change in entropy (as a function of activity)

$$\mu = -\tau \left(\frac{\partial \sigma}{\partial N} \right)_U$$

- Observations about migration potential
  - Transfer of control/ownership is a form of "migration"
  - More agents raises potential
  - Agents migrate from higher potential markets to lower potential markets
  - Price can regulate effect of potential: higher price differentials tend to increase potential

* Victor Sergeev coined the term "migration potential"

Partition function

- Need factor to find average properties over ensemble

$$\mathcal{Z}(\mu,\tau)=\sum_{N=0}^{\infty}\sum_{l}e^{\frac{N\mu-s_l(N)}{\tau}}$$

- The probability of finding the system in the state *1* is

$$P(N_1,s_1)=\frac{e^{[N_1\mu s_1(N_1)]/\tau}}{\mathcal{Z}}$$

- When number of agents is invariant we define

$$Z(N,\tau)=\sum_{l}e^{-s_l/\tau}$$

- The ensemble average total surplus S is

$$S=\langle s\rangle=\frac{\sum_l s_l e^{-s_l/\tau}}{Z}$$

Negative trading activity

- It is possible to have ∂σ/∂U, so that trading activity can be negative:
  - There must be a finite upper limit to the value of states
  - The market must be at internal equilibrium (relaxed)
  - The negative states must be isolated from the positive ones
- The trading activity scale is +0…+X…+∞,–∞…–X…–0
  - This can happen in markets with rules the prevent otherwise natural trades
  - When isolated states become accessible (e.g., cheating, changing the rules), the result can be abrupt/dislocating "relaxation" of the system.
- Reverses effect of migration potential (flow reverses)

Free surplus

- Agent constraints mean not all potential surplus can be obtained by agents
- Most system have surplus obtained by suitable controls
- This is called free surplus

$$F = S - \tau\sigma = -\tau log Z$$

- Suggests that a Carnot-like cycle is possible for markets
  - Buy in system 1 at constant low activity (raise σ)
  - Move to system 2 at constant high entropy (raise τ)
  - Sell in system 2 at constant high activity (lower σ)
  - Move to system 1 at constant low entropy (lower τ)
- Net revenue *W* is at most free surplus and limited by efficiencies

$$\frac{|W|}{Q_F P} = 1 - \frac{\tau_{low}}{\tau_{hi}} \qquad \frac{Q_R P}{W} = \frac{\tau_{low}}{\tau_{hi} - \tau_{low}}$$

Net revenue

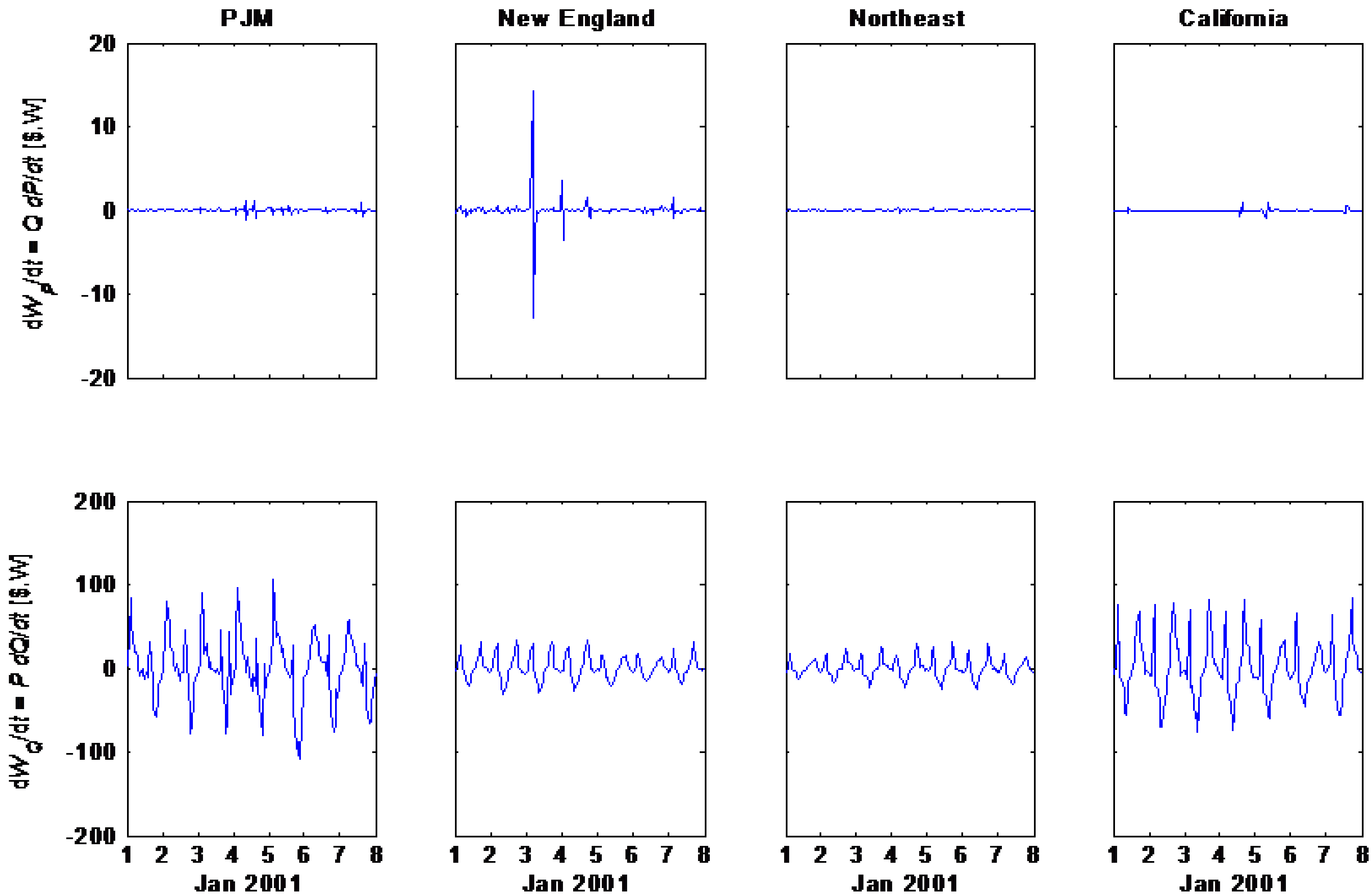
- Net revenue should never exceed free surplus
- Change in net revenue can be broken in two components

$$\frac{dW}{dt} = \frac{d}{dt}QP = \frac{dQ}{dt}P + Q\frac{dP}{dt}$$

- Unitary elasticity is same as *dW* = 0
- Differences in components can be indicators of changes in markets

  dW_P/dt : change in net revenue from a change in price

  dW_Q/dt : change in net revenue from a change in quantity


PJM
New England
Northeast
California
$dW_p/dt = Q\ dP/dt$ [$.W]
$dW_Q/dt = P\ dQ/dt$ [$.W]
Jan 2001

Open issues and questions

- Even the simplest agents aren't strictly $\pm q$ equaprobable states, so things are usually more complicated
- Most proposed Smart Grid projects don't have clear enough rules to make predictions easy
- Data collection is a serious unresolved issue
  - Most AMI networks don't have enough bandwidth
  - Projects are not viewed as a hypothesis/model test
  - Need first principles predictions to know what data to collect
- Most Smart Grid project aren't really considering many of the observations made
  - Differences between those that do and those that do may be discernable given a thorough analysis of the data
  - Need for a single comprehensive data clearinghouse

Conclusions

- Within limits of assumptions thermal physics methods can be used
  - What do we do about unmet assumptions?
- Short term: Should we build Smart Grid systems we can't model/don't understand generally?
- Long term: Models of most programs should be possible using such an approach
  - May end up being very arcane and difficult to use
  - Probably beyond the reach of most utility planners

Questions and comments

Contact

david.chassin@pnl.gov