Management of Electric Vehicle Charging to Mitigate Renewable Energy Intermittency and Distribution Network Congestion

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BOSTON UNIVERSITY

May 5-6, 2009
NREL and LANL

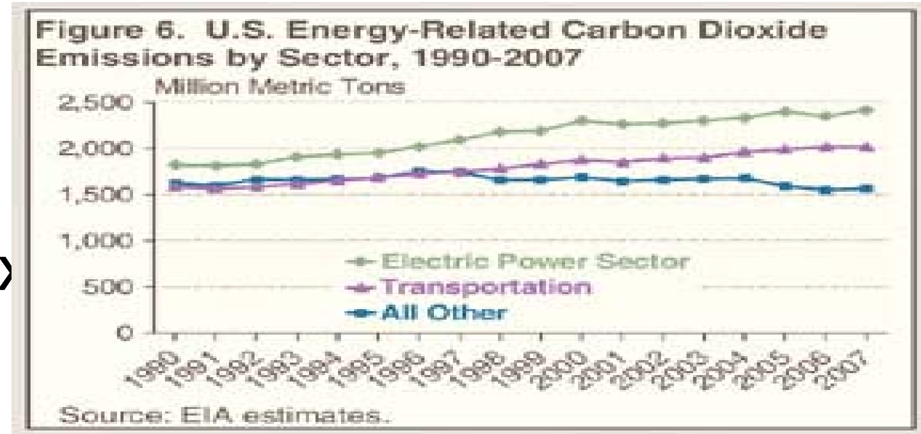
The Center for Information and Systems Engineering
CISE

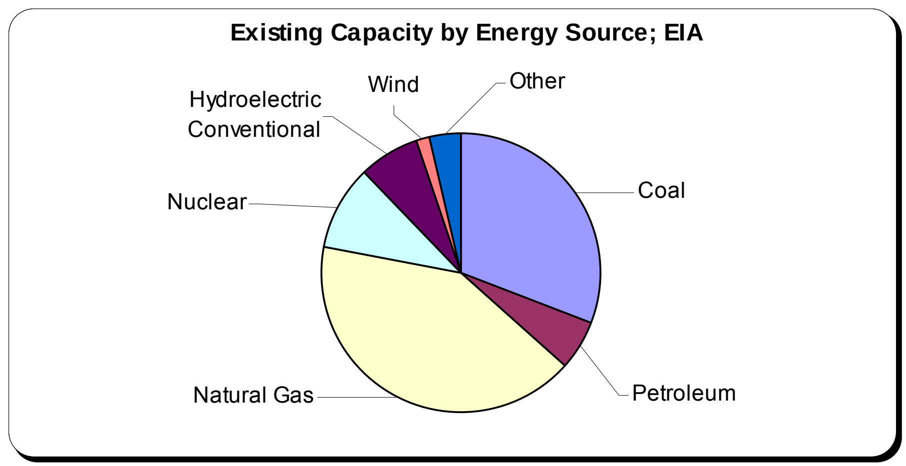
Outline

I. Sustainable Energy Future
II. Description of physical energy grid
III. Description of energy markets
IV. Introduce ESCo
   i. Simplifying Assumptions
   ii. Incorporation to energy market
V. Decision Support Model
VI. Computational Results

Sustainable Energy Future

- Best Strategy to Conserve Fossil Fuels is to stop using them for heating (heat pumps 3-4x more efficient)
- Electrification of transportation sector a must
- New load must come from Clean generation not fossil fuel powered generation!





Multi-Disciplinary Approach Required

- Power Engineering
- Finance, Risk Management, Contract Design
- Regulatory Economics
- Information Technology
- Cyber Physical Interface
- Decision Support, OR, Stochastic Control
- Social Science and Human Behavior
- Organizational Behavior
- Climate/Environment Science

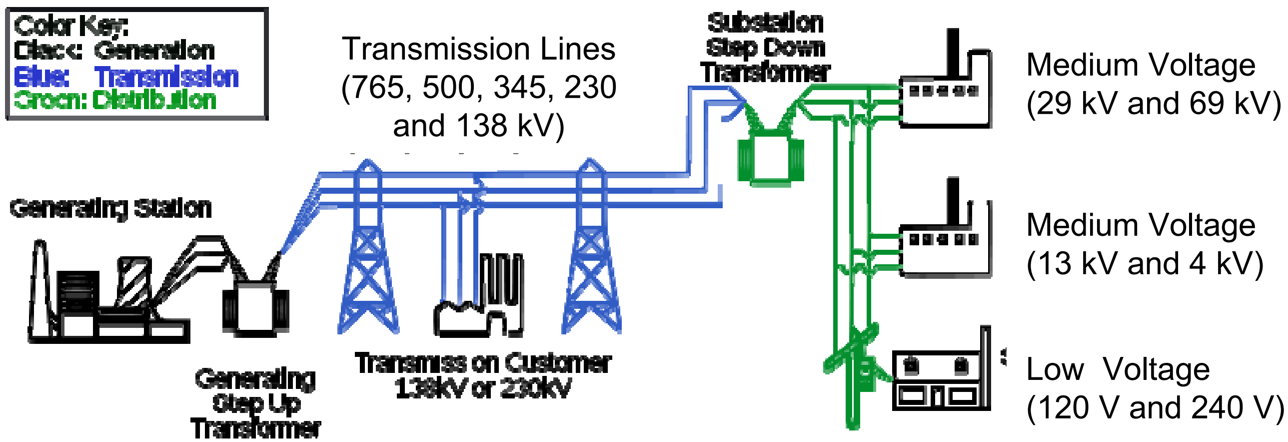
The Million Dollar Question: Resilient/Sustainable Infrastructure

- Is potential infrastructure Congestion a likely Show stopper (e.g. wind, PV, HEV)?
- Embedded in this question is how do we make renewable energy and EV economically feasible?

A Few Energy Definitions

- Generation technologies include - hydro, nuclear, coal, oil, gas, wind, thermo solar, photovoltaic, fuel cells, biomass, geothermal, etc.

A Few Energy Definitions cont…



Source: FERC

- Transmission and Distribution (T&D)
  - Transmission – high voltage lines (765, 500, 345, 230, 138 kV), substations
  - Medium voltage (<50kV)
  - Low Voltage (220/110V) Transformer and Feeder Lines service residential and commercial customers,

Electricity Generation, T&D Goals

- Assure system integrity and security through contingency planning that assures robustness to uncertainties that may threaten system stability (possibly cause a blackout!)
- This is done by securing sufficient reserve capacity resources to avoid congestion:
  - Transmission capacity (Schedule Gen and Loads =>LMP)
  - generation capacity reserves
- Achieved in various ways: (Central planning, Long term contracts, Energy markets (Commodities futures, inter- and intra-day, real time-5 min)

Generation Capacity Reserves

- Primary Reserves (Frequency Control); respond to real-time distributed monitoring of frequency
- Secondary Reserves (Regulation Service); Commands sent in 5-8 sec intervals, full reserve deployment response required within 60-90 seconds
- Tertiary Reserves (Spinning or Operating Reserves); scheduling commands sent in 5 minute intervals, full reserve deployment response required within 15 minutes
- Slower Tertiary Reserves; required responce in 0.5 to 2+ hours

Congestion

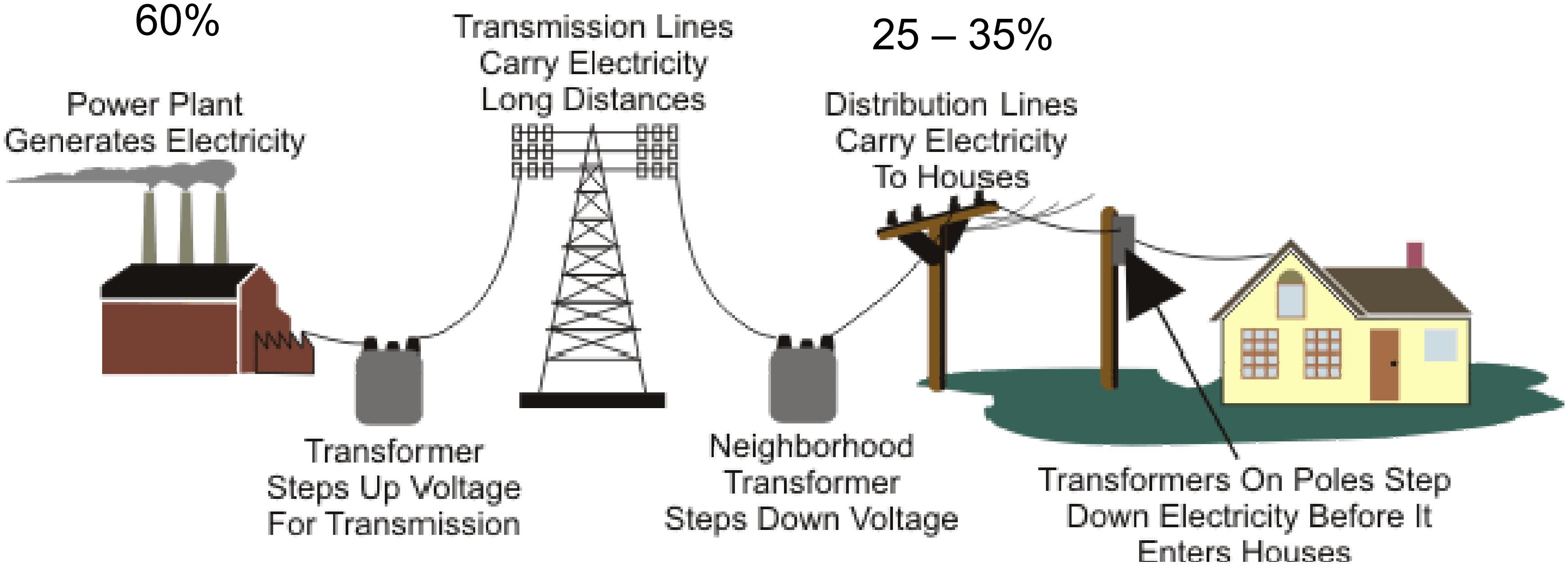
- Energy (MWh) needed to meet demand
- Transmission Equipment capacity needed for N-1 contingency planning
- Capacity Reserves (MW)
- Distribution network equipment (transformers) utilization constraints.

The Cost of Congestion

60%

5 - 10%

25 – 35%

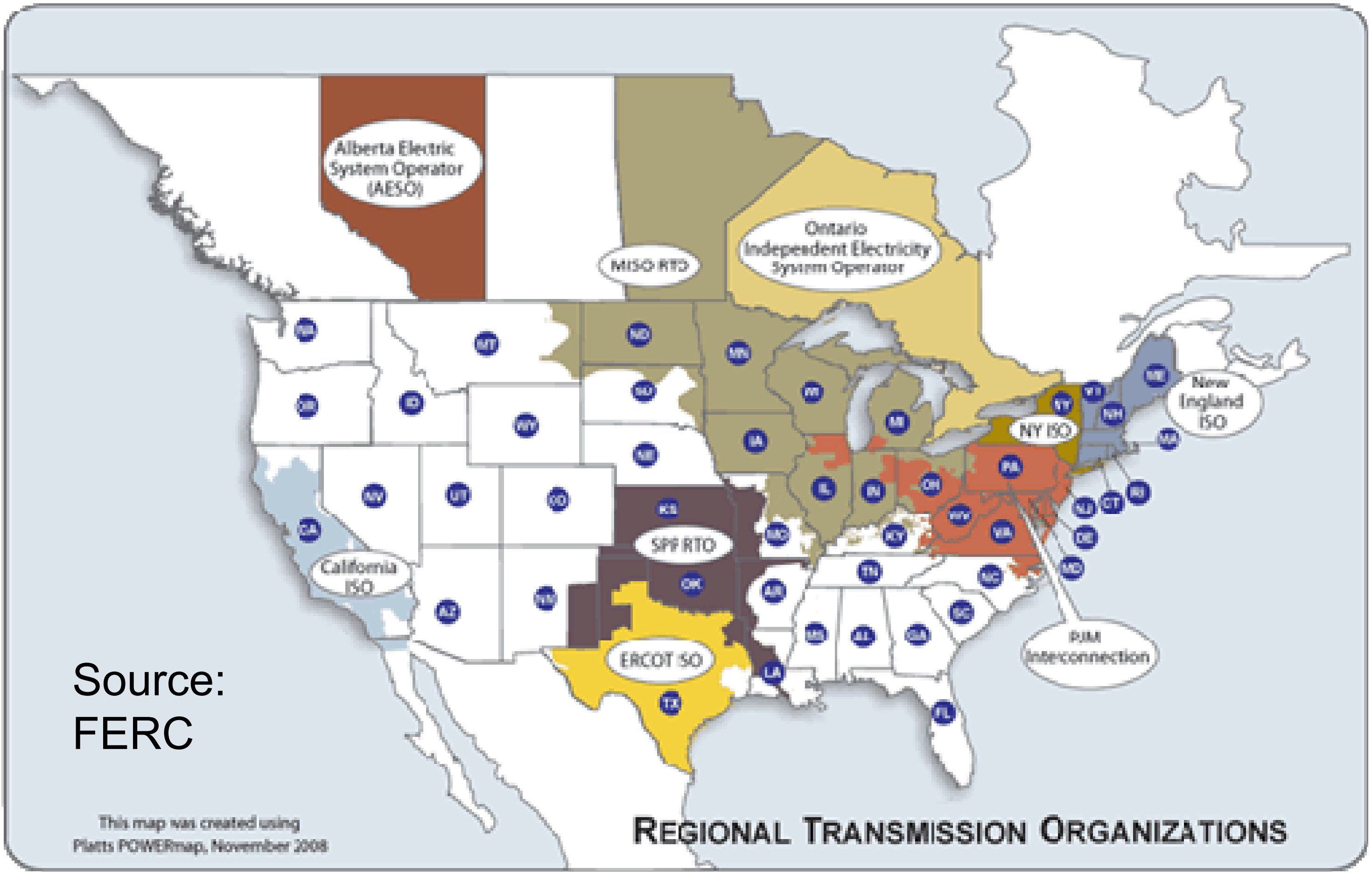


Source: EIA

De-regulation of the Power Sector

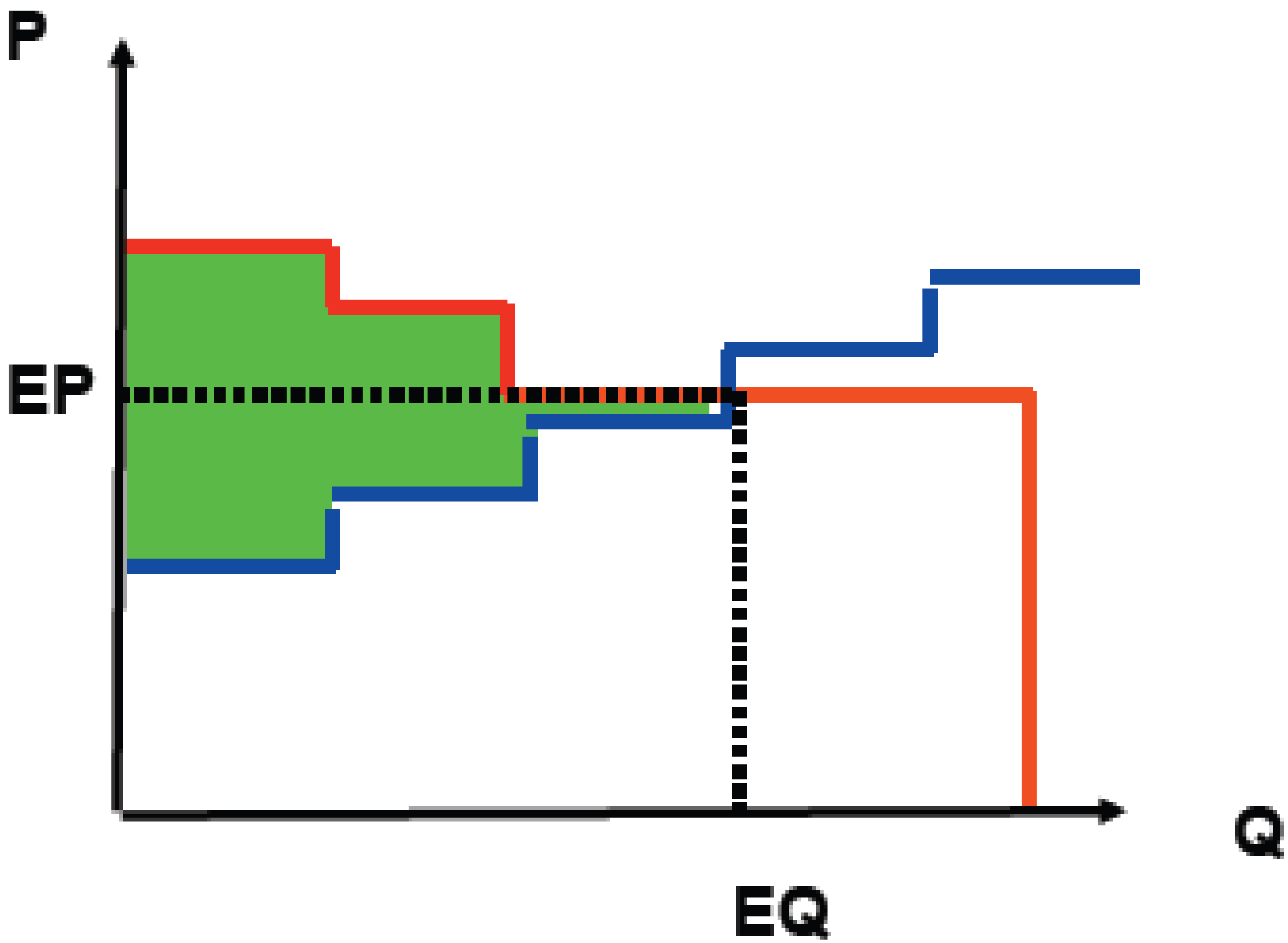
- Power sector initially developed with a vertically integrated structure that required heavy regulation
- In order to have electricity prices reflect the marginal cost of electricity there was a movement for de-regulation of energy markets in the 1990s
- The result was the development of regional ISOs

Independent System Operators (ISOs)

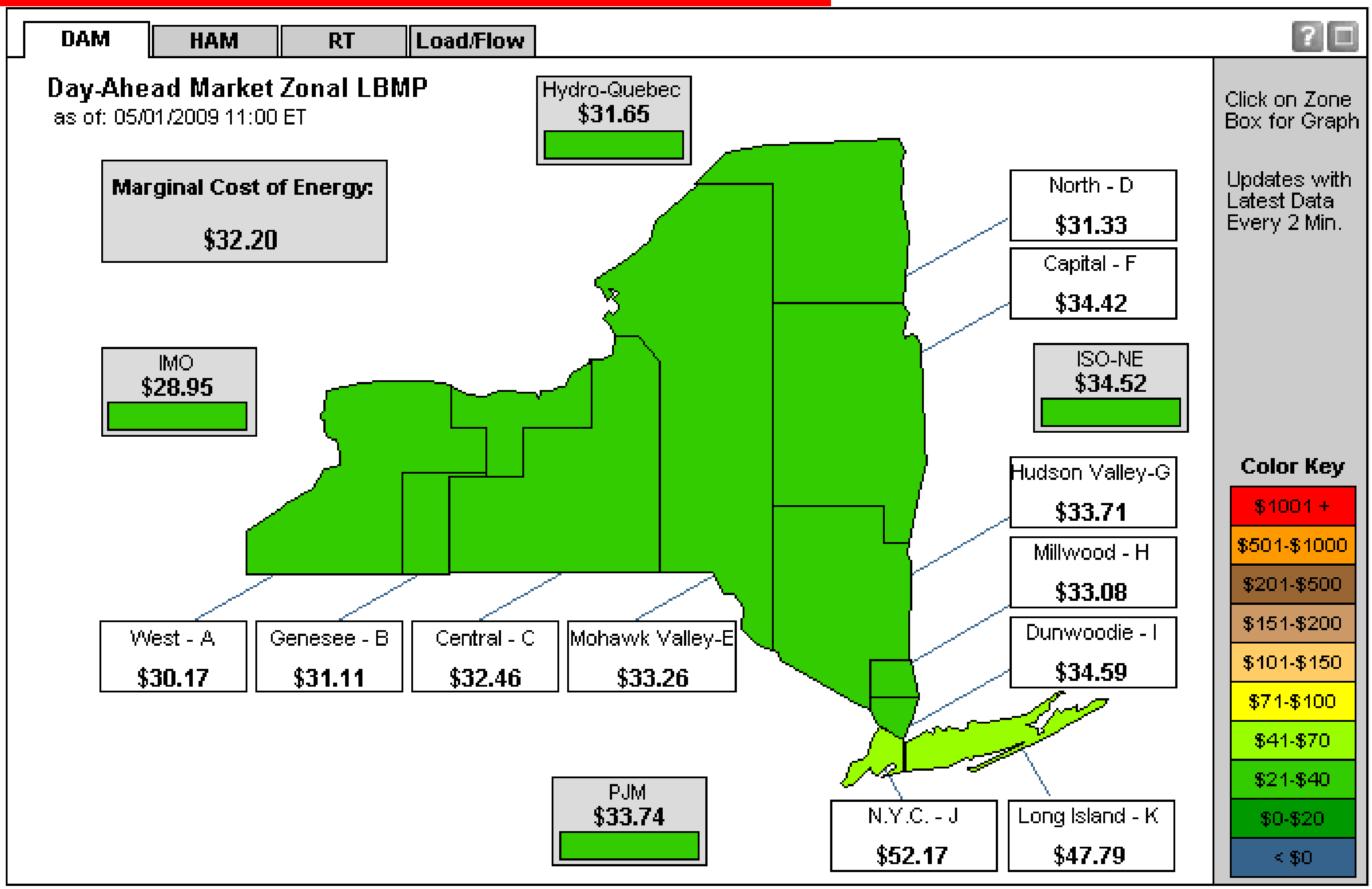


Source:
FERC

Market Clearing Criteria



Zonal and Nodal Pricing



Market Example

- Give an example of market clearing criteria for energy and for reserve capacity. Explain obligations/promises, services offered and payments received for energy and for stand by capacity

Nodal Pricing

- Islands of Different LMPs are created when Transmission constraints become active. Cost varies by Location

Back to the Million Dollar Question…

- Recall – types of congestion
  - Generation of Energy
  - Capacity Reserves (Primary, secondary, tert.)
  - Distribution (max utilization, losses)
  - Transmission (LMP)
- Cyber-Physical investment trade offs: Expand the existing infrastructure…or use info and intelligence to exploit/create synergies

Issues with Wind Generation

- Due to its intermittency, wind generation requires additional reserve capacity (~5% to 10% of installed wind capacity)
- RS is currently on the order of 1-2% of load
- Potentially prohibitive cost implications – at current cost of $20-30 per MW per hour

Issues with Mass Adoption of Hybrid Electric Vehicles (EVs)

- Cost of hybrid vehicles is approaching competitiveness with oil powered vehicles
- BUT Congestion issues loom: Is distribution network capacity sufficient? Utilization today ~50-60%. However, considering a feeder servicing 50 homes each with one or more EVs plugging-in simultaneously and requiring 2-4 KW each does not guarantee excess capacity ON THE AVERAGE can suffice!

Synergy of Renewable Wind Generation and EV Battery Charging

- We claim that EV battery charging can be managed so as to *both* increase the supply of regulation service thus controlling its cost *and* mitigate distribution network congestion!!!

Role of Energy Service Company (ESCo) or Coordination Service Provider

- Contracts with EV owners to manage charge EV batteries plugging in at several feeders
- Access to local congestion constraints, namely the maximal additional load that may be applied along a specific feeder without stressing the transformer and other distribution hardware tolerances
- Smart interface – measures real-time energy needs and EV owner input (e.g., departure time)
- Access to wind farm forecasts and wholesale market aggregate features that determine clearing prices in related (co-optimized or co-cleared) Energy AND Reserve markets

Decision Support Methodology

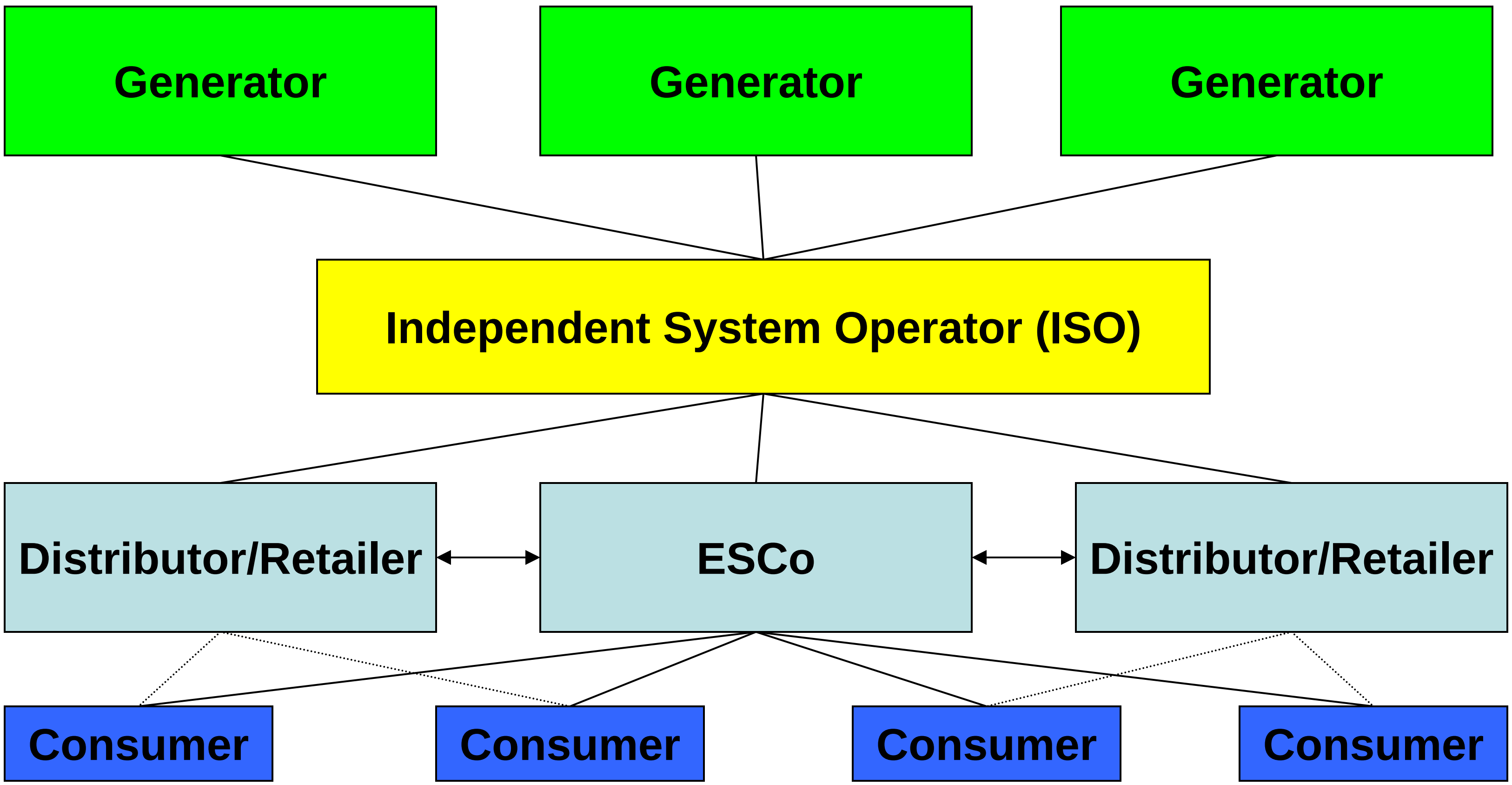
- ESCo manages EV charging
- Participates in wholesale power market both for energy and reserve capacity transactions
- Reg. Service (RS) can be provided by controlling the time of switching on and off battery chargers under the ESCO's control

- Costs/Benefits include:
  i. Energy Clearing Price in day-ahead market
  ii. Real-time Energy Clearing Price (5-min. time scale)
  iii. Real-time RS clearing price revenues when RS offer accepted
  iv. Distribution network charge discounts
  v. Potential penalties for not fully charging batteries by terminal times

Impacts of intermittent charging on electric vehicle batteries

- Vehicle to Grid power flow requiring discharging of Batteries to offer RS is uneconomical with today's technology as it impacts battery life (~7000 charge Discharge cycles degrade capacity by no more than 80%. At a rate of two per day => 10 year battery life.
- Impact of frequent on/off switching: Battery Life? Harmonics to distribution network?

ESCo in the Energy Market Framework



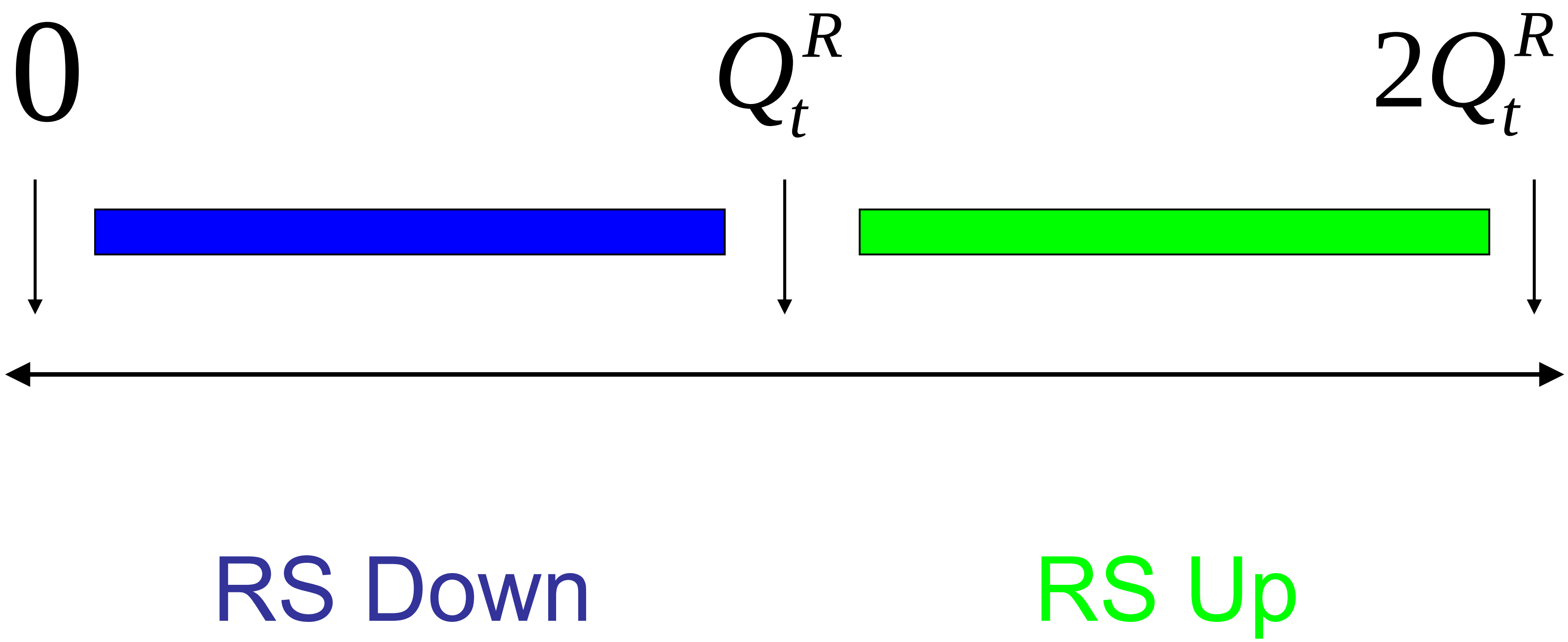
Day-Ahead Market

- Closes to bids and offers at 11am of the previous day – results (LMP and hourly generation consumption schedule) posted by 12 noon of previous day
- ISO maximizes Consumer + Producer Surplus solving a mixed integer LP mathematical program to (co)-optimize energy and capacity reserve bids and offers subject to energy balance and reserve constraints as well as many inter-temporal (ramp) and integer (technical minimum) constraints

Real-Time Market

- 5 minute interval economic Dispatch
- ISO re-dispatches generation and loads to return Capacity Reserves to nominal operating levels, i.e. to restore Capacity Reserve constraints while maintaining Area Control Error to 0. New clearing prices evaluated for Energy and Capacity Reserves.
- Together with distributed AFC and 5 sec. central control, 5 min dispatch results in Energy provided through RS to be white noise, i.e. have a 0 average over a ~ ½ hour period.
- Optimizes over a Rolling 1-2 hour horizon which determines the next 5 minutes and forecasts 15 minute intervals over the next 60-90 minutes

Regulation Service Provider Obligation: (Quantity only offered in Real time?)



Regulation Service Clearing Price

- Opportunity Cost for given energy and RS price offers relative to clearing prices (why?)

$$\left| P_t^E - u_t^{RE} \right|$$

- Condition for Accepting RS offer

$$\left| P_t^E - u_t^{RE} \right| + u_t^{RC} \leq P_t^R$$

Decision Variables – Time Scales

- Day-ahead market quantities and prices
- Real-time market (hour-to-5-minute)

– Firm energy bid

$$Q_t^E, u_t^E$$

– Regulation service capacity offered in real time (prices in day ahead?)

$$Q_t^R, u_t^{RE}, u_t^{RC}$$

- Operational level: reasonable to pursue target of equal charged level across batteries at same feeder with same declared departure time?

Simplifying Assumptions

- Group time periods (t) with similar characteristics (e.g., feeder conditions)
- ESCo receives forecasts for time period t at time $t^* \leq t$:
  - Feeder capacity
  - Joint Probability Distribution of Energy and RS clearing prices depending on
    - Forecasts of wind generation (affects RS requirements and Energy cl. Pr)
    - System outage state during period t
  - EVs connecting with declared departure time
- No cars un-plug from a feeder location before their declared departure time

Model Formulation

- Hour-to-5-min. time scale
- Feeder sub-problem
- Stochastic Dynamic Program
- Finite Horizon

Random Variables, Density Functions, and Exogenous Forecasts

$t, \Delta t$: Decision period t and its duration

$\widehat{W}_t^{t*}, \widehat{Y}_t^{t*}$: Wind output and system outage state

$\widehat{C}_t^{\max,t*}$: Feeder-specific unused capacity

$\widehat{\Delta n}_t^{\tau}(t*), \widehat{\Delta x}_t^{\tau}(t*)$: Expected to plug-in

P_t^E, P_t^R : Realized real-time market prices for energy and RS, respectively

$f_{t*}\left(P_t^E, P_t^R \middle| \widehat{W}_t^{t*}, \widehat{Y}_t^{t*}\right)$: pdf of clearing prices conditional upon wind and outage forecasts

State and Decision Variables

n_t^{τ}, x_t^{τ} : Number and capacity of uncharged EVs

$\hat{\theta}_t^{t*} = [\widehat{W}_t^{t*}, \hat{Y}_t^{t*}, \hat{C}_t^{\max,t*}]$: State augmentation with forecasts

$Q_t^E(\tau), Q_t^R(\tau)$: Energy rate bid and Regulation Capacity offer

$u_t^{RE}(\tau), u_t^{RC}(\tau)$: RS price bids

Probability a RS Offer is Accepted

$$\Pi_t^{\tau}(t^*) \triangleq \Pr\left(\left|P_t^E - u_t^{RE}(\tau)\right| + u_t^{RC}(\tau) \le P_t^R\right)$$

Prob. Unit function $1_{\left|P_t^E - u_t^{RE}(\tau)\right| + u_t^{RC}(\tau) \le P_t^R} = 1$

which depends on

$$f_{t^*}\left(P_t^E, P_t^R \middle| \widehat{W}_t^{t^*}, \hat{Y}_t^{t^*}\right)$$

Cost Rates

c : Penalty per KWh of uncharge energy

λ_N : Estimated marginal cost of charging x_N^{N+1}

Period and Terminal Costs

$$cx_t^t + \sum_{\tau} \mathbf{E}_{t*}\left[P_t^E Q_t^E(\tau) + \left(P_t^E - P_t^R\right) Q_t^R(\tau) 1_{\left|P_t^E - u_t^{RE}(\tau)\right| + u_t^{RC}(\tau) \le P_t^R} \right] \Delta t$$

$$+\, cx_N^N + \lambda_N x_N^{N+1}$$

System Dynamics

$$n_{t+1}^{\tau} = n_t^{\tau} + \widehat{\Delta} n_t^{\tau}\left(t*\right)$$

$$x_{t+1}^{\tau} = x_t^{\tau} + \widehat{\Delta} x_t^{\tau}\left(t*\right) - \left(Q_t^E\left(\tau\right) + 1_{\left|P_t^E - u_t^{RE}(\tau)\right| + u_t^{RC}(\tau) \leq P_t^R}\left\{Q_t^E\left(\tau\right)\right\}\right)$$

$$\hat{\theta}_{t+1}^{(t+1)*} = \left[\widehat{W}_{t+1}^{(t+1)*}, \widehat{Y}_{t+1}^{(t+1)*}, \widehat{C}_{t+1}^{\max,(t+1)*}\right]$$

Feeder Capacity and RS Delivery Capability Constraints

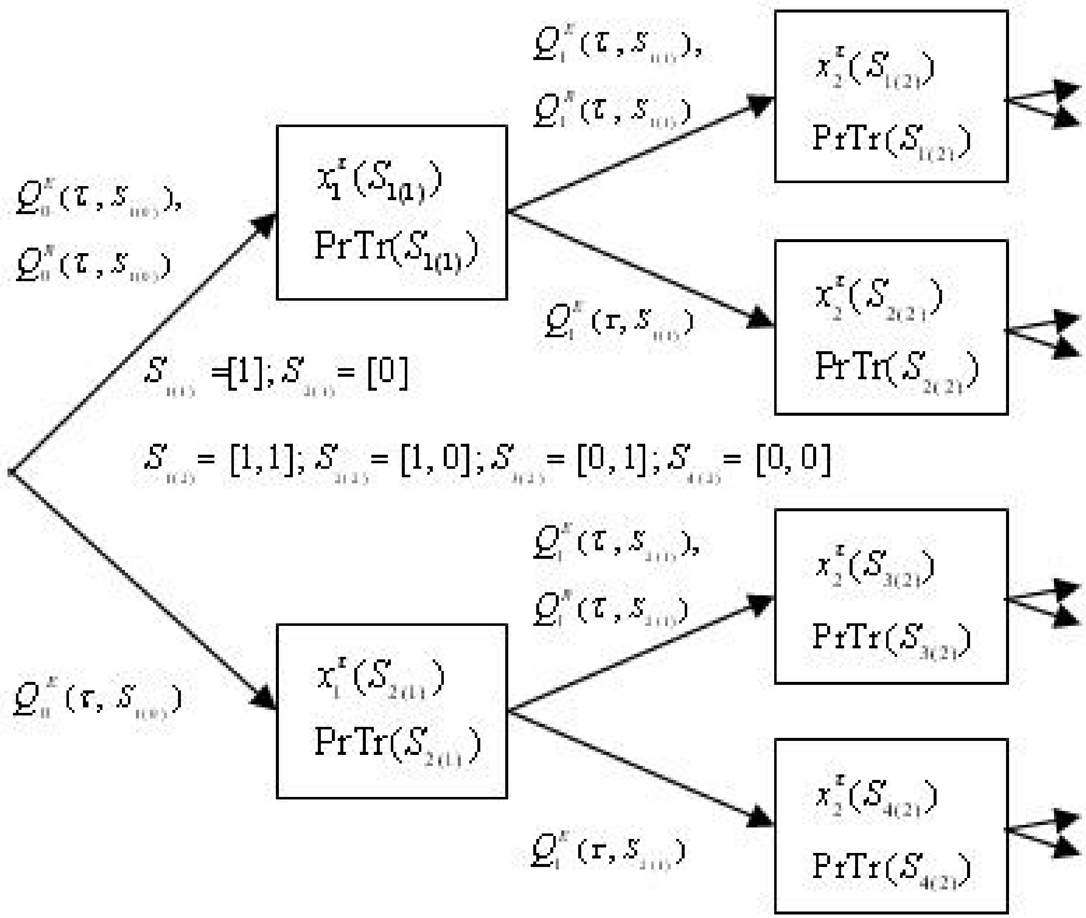
$$\sum_{\tau}\left(Q_t^E(\tau)+2Q_t^R(\tau)\right)\le \widehat{C}_t^{\max,t*}, \quad \forall t \qquad 0\le t\le N-1$$

$$Q_t^E(\tau)+2Q_t^R(\tau)\le rn_t^{\tau}, \qquad \forall t,\tau \quad 0\le t\le N-1, t\le\tau\le N+1$$

Solution Approach Adopted

- Deterministic (Optimal Open Loop Feedback Control) Approximation based on inclusion of robust/worse case contingencies
- Resulting finite period look ahead formulation of a binary Expansion Tree (accepted/rejected RS offer)
- Comments on Finite look ahead formulation:
  - (i) Large number of decision variables limits application to 16-18 periods (65K-262K branches)
  - (ii) May be employed as a “cost to go” function approximation

Forward Trajectories



Ongoing Research and Application Effort

- Multiple feeders coupled sub problems under day-ahead market hedging (Lagrangian relaxation?)
- Extension period model improvement: explicitly run an extension period model.
- Challenges: (i) Large state and control space, (ii) non-linearity when price offers included in decision variables. (recall probability RS offer is accepted depends on pdf)
- Use feature based state aggregation for value or policy function approximation
- Reasonable Policy Evaluation through Monte Carlo Simulation.

Promising Research Directions?

- Variable time resolution/aggregation model
- Coupling of Day-ahead hedging Master Problem with Real-Time market feeder Sub-problems
- Robust optimization analysis on forecast and random variable probability distributions
- Use stochastic DP algorithm with look ahead model acting as estimate of “cost to go” function
- Monte Carlo based evaluation of policies: Explore fluid approximation and hybrid (continuous-discrete) formulations

Computational Experience

- Simplify further the look-ahead dynamic program to use linear programming solution algorithm
- Select offer prices to maximize probability that RS is accepted. This reduces the number of decision variables to rate offers for each departure time

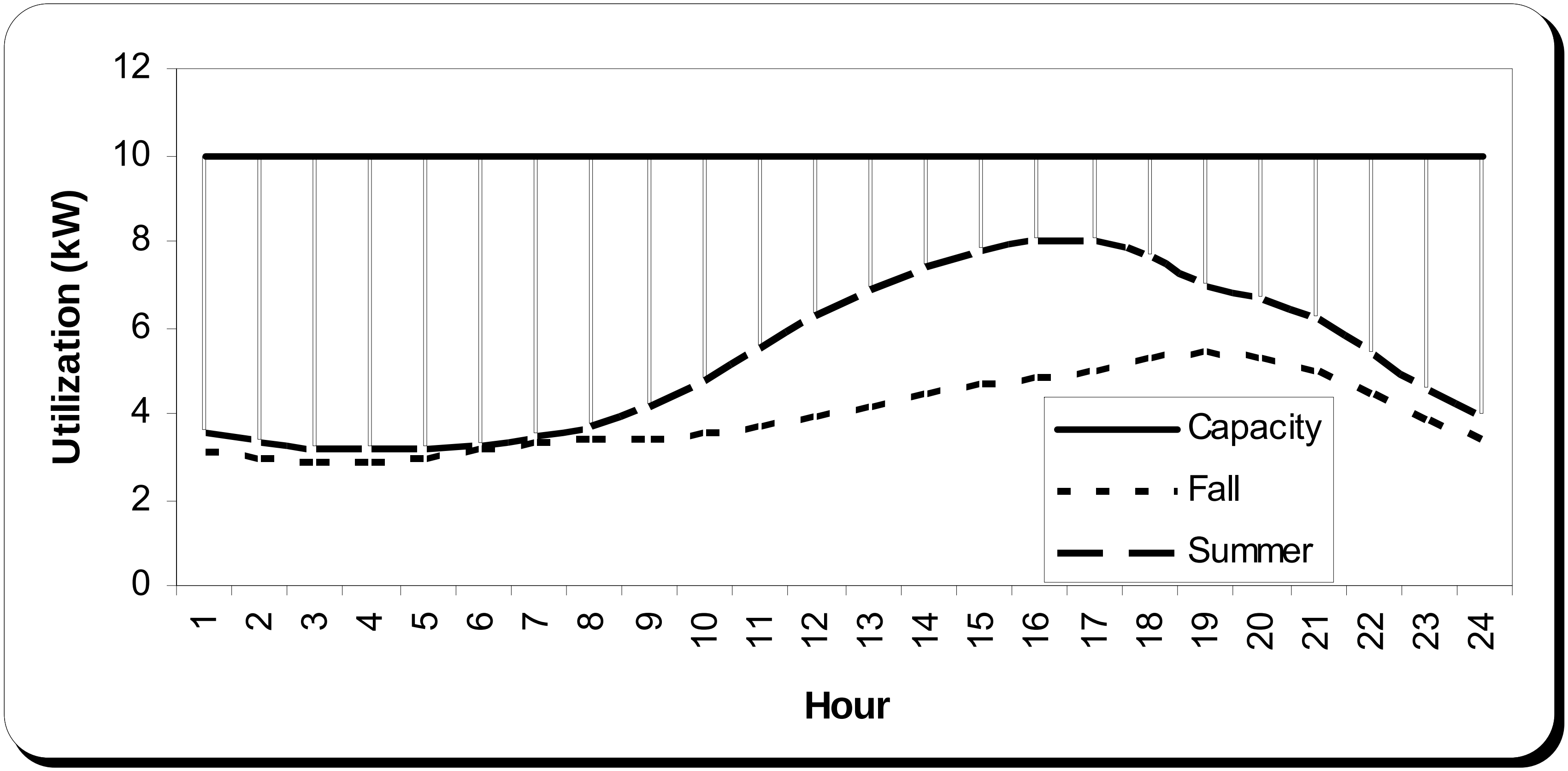
$$u_t^{RE}\left(\tau, S_{k(t)}^{\tau}\right), u_t^{RC}\left(\tau, S_{k(t)}^{\tau}\right)$$

$$Q_t^{E}\left(\tau, S_{k(t)}^{\tau}\right), Q_t^{R}\left(\tau, S_{k(t)}^{\tau}\right)$$

Computational Results

- Four period look-ahead model with extension period
- ERCOT data – wind farm generation is already substantial and will likely achieve fastest growth in the U.S.
- Reasonable assumptions were made on distribution capacity and residential EV battery charge demand patterns

Fall and Summer Load Profiles



Vehicles Plugging-in

Values	τ=1	τ=2	τ=3	τ=4	τ=4+
x_0^{τ}	4	212	48	24	12
n_0^{τ}	1	20	5	2	1
$\Delta x_0^{\tau}(0)$	n/a	220	0	20	0
$\Delta x_1^{\tau}(0)$	n/a	n/a	4	8	12
$\Delta x_2^{\tau}(0)$	n/a	n/a	n/a	8	20
$\Delta x_3^{\tau}(0)$	n/a	n/a	n/a	n/a	300
$\Delta n_0^{\tau}(0)$	n/a	20	0	2	0
$\Delta n_1^{\tau}(0)$	n/a	n/a	1	1	1
$\Delta n_2^{\tau}(0)$	n/a	n/a	n/a	1	3
$\Delta n_3^{\tau}(0)$	n/a	n/a	n/a	n/a	29

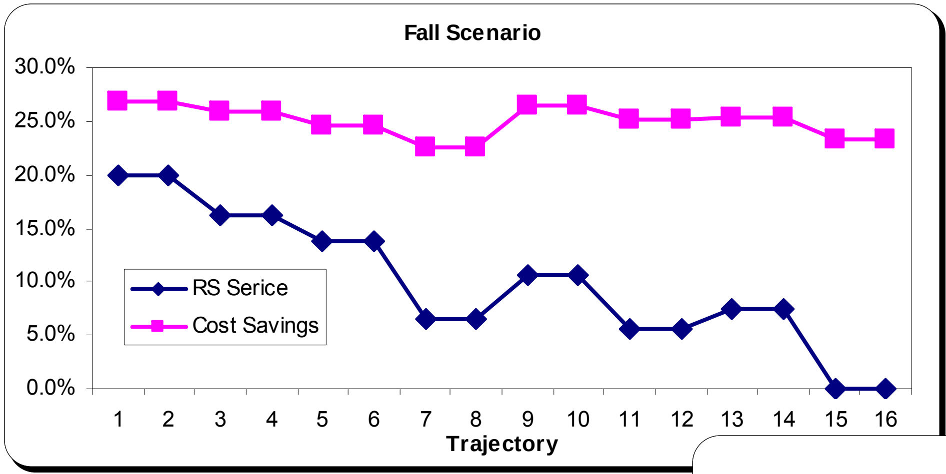
Expected Energy and Regulation Service Market Clearing Prices

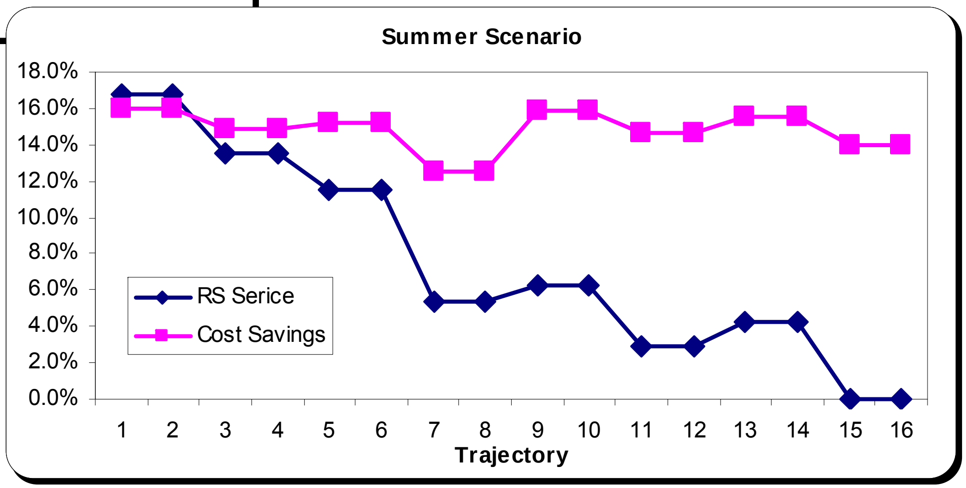
t	Fall			Summer		
	$\mathbf{E}_{\omega}\left[P_t^E\right]$	$\mathbf{E}_{\omega}\left[P_t^R\right]$	$\Pi_t(0)$	$\mathbf{E}_{\omega}\left[P_t^E\right]$	$\mathbf{E}_{\omega}\left[P_t^R\right]$	$\Pi_t(0)$
0	0.048	0.020	0.90	0.102	0.033	0.88
1	0.022	0.015	0.80	0.061	0.014	0.80
2	0.040	0.017	0.85	0.075	0.019	0.83
3	0.068	0.019	0.89	0.157	0.045	0.90

Computational Results

- Fall
  - $0.0249 per KWh
  - RS accounted 17.2% of daily load
  - 26.2% cost savings
- Summer
  - $0.0760 per KWh
  - RS accounted 13.9% of daily load
  - 15.6% cost savings

Computational Results cont…





NEISO Data

- Current situation
  - Peak load ~ 30,000 MW
  - No (or negligible) wind capacity
  - 150 MW of reserve capacity (0.5% of peak, 1% of average)
- For a load increase of 20-30% from EV adoption:
  - Assuming EV load will be matched by wind farm generation, an additional RS ~5 % of installed wind capacity will be required, i.e. an additional 600MW. Note that given a 30% load factor of wind generators compared to 50-60% for conventional generators, wind farm capacity will represent ~35% of total, namely ~12K MW.
  - Our results indicate it is reasonable to expect approximately 10% to 15% of EV load to provide RS, i.e., 400-600MW.
  - CONCLUSION: The additional demand and supply of RS mach quite closely.

Conclusion

- Results support that smart management of the charging of electric vehicles can
  - Help with renewable generation intermittency
  - Result in cost savings
  - Be accomplished within congestion constraints
- Synergies can be created and managed to remove barriers to widespread market penetration of EVs and Renewable generation.