Renewable Energy Integration: Technological and Market Design Challenges

A PSERC Future Grid Initiative Progress Report

Shmuel Oren, Duncan Callaway,
Anthony Papavasiliou, Johanna Mathieu
(UC Berkeley)
Timothy Mount, Robert Thomas, Max Zhang
(Cornell University)
Alejandro Dominguez-Garcia, George Gross
(University of Illinois at Urbana/Champaign)

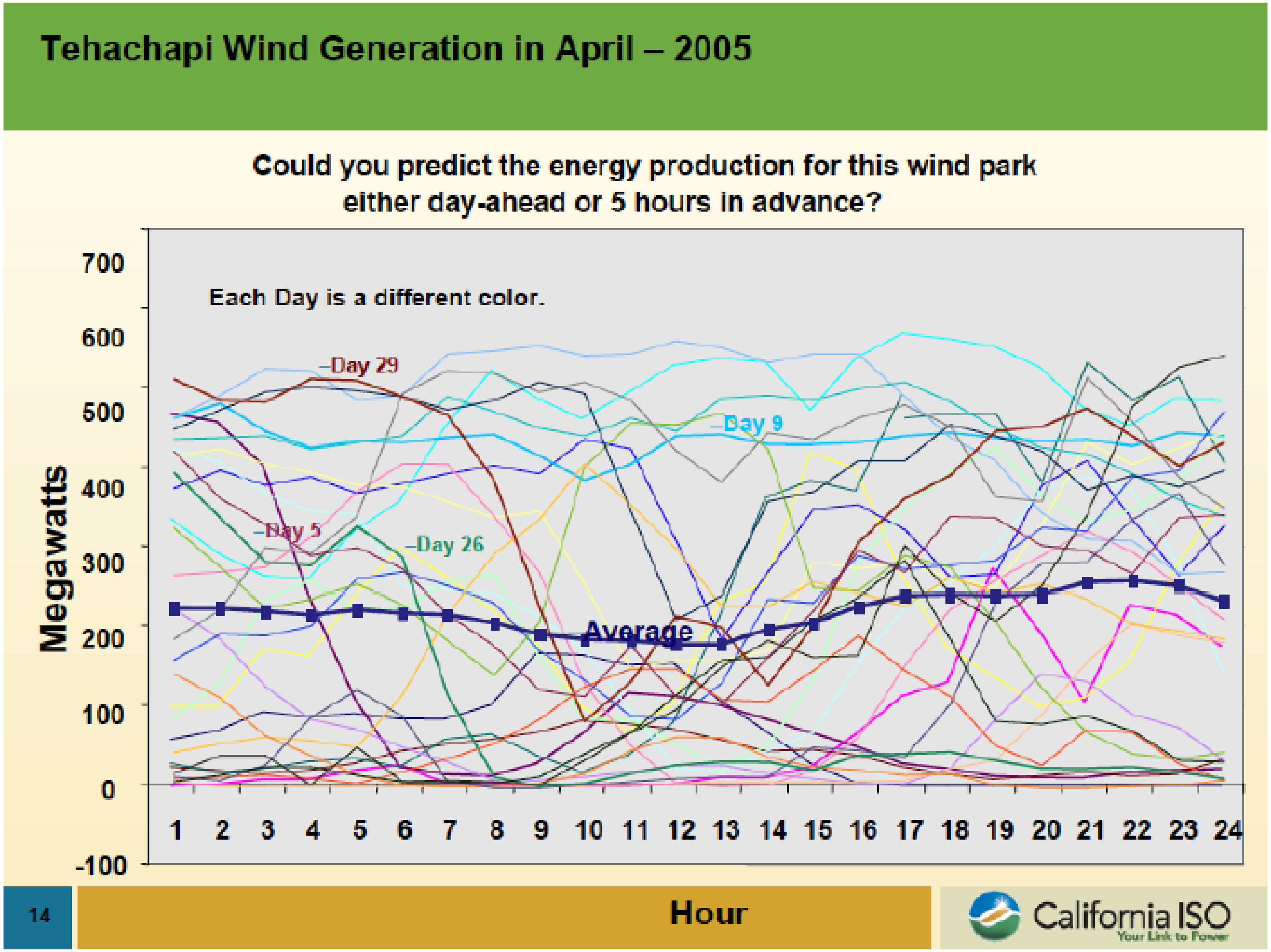
PSERC Future Grid Webinar
February 19, 2013

PSERC Future Grid Initiative

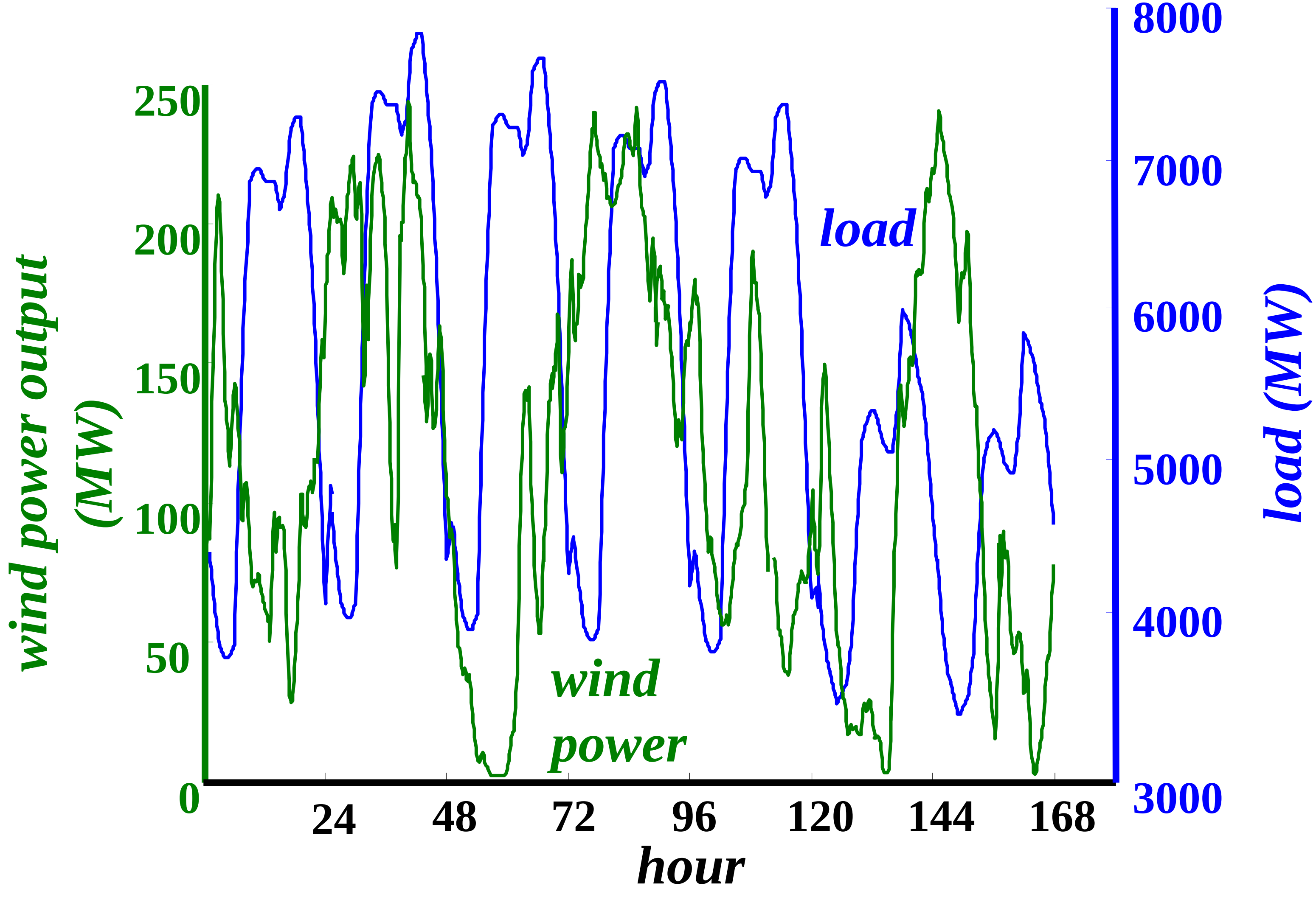
- DOE-funded project entitled "The Future Grid to Enable Sustainable Energy Systems"(see http://www.pserc.org/research/FutureGrid.aspx)
- Focus of this webinar: Accomplishments in the thrust area "Renewable Energy Integration: Technological and Market Design Challenges"
- Objectives of this thrust area: Explore technological solutions, market design, resource dispatch tools and new planning frameworks for dealing with the uncertainty and variability of intermittent renewable generation resources. Task objectives include:
  - Develop distributed control paradigms and business models for mobilizing demand response to mitigate the uncertainty and variability introduced by massive integration of renewable energy resources
  - Develop market mechanisms that will incentivize load response and flexibility and correctly price uncertainty (or uncertainty reduction) on the demand and supply side.
  - Develop dispatch and planning tools that can explicitly account for uncertainty, variability and flexibility (e.g. storage) in resource optimization and reserves procurement.
  - Develop simulation tools that can account for increased uncertainty in verifying system and market performance

Context and Motivation

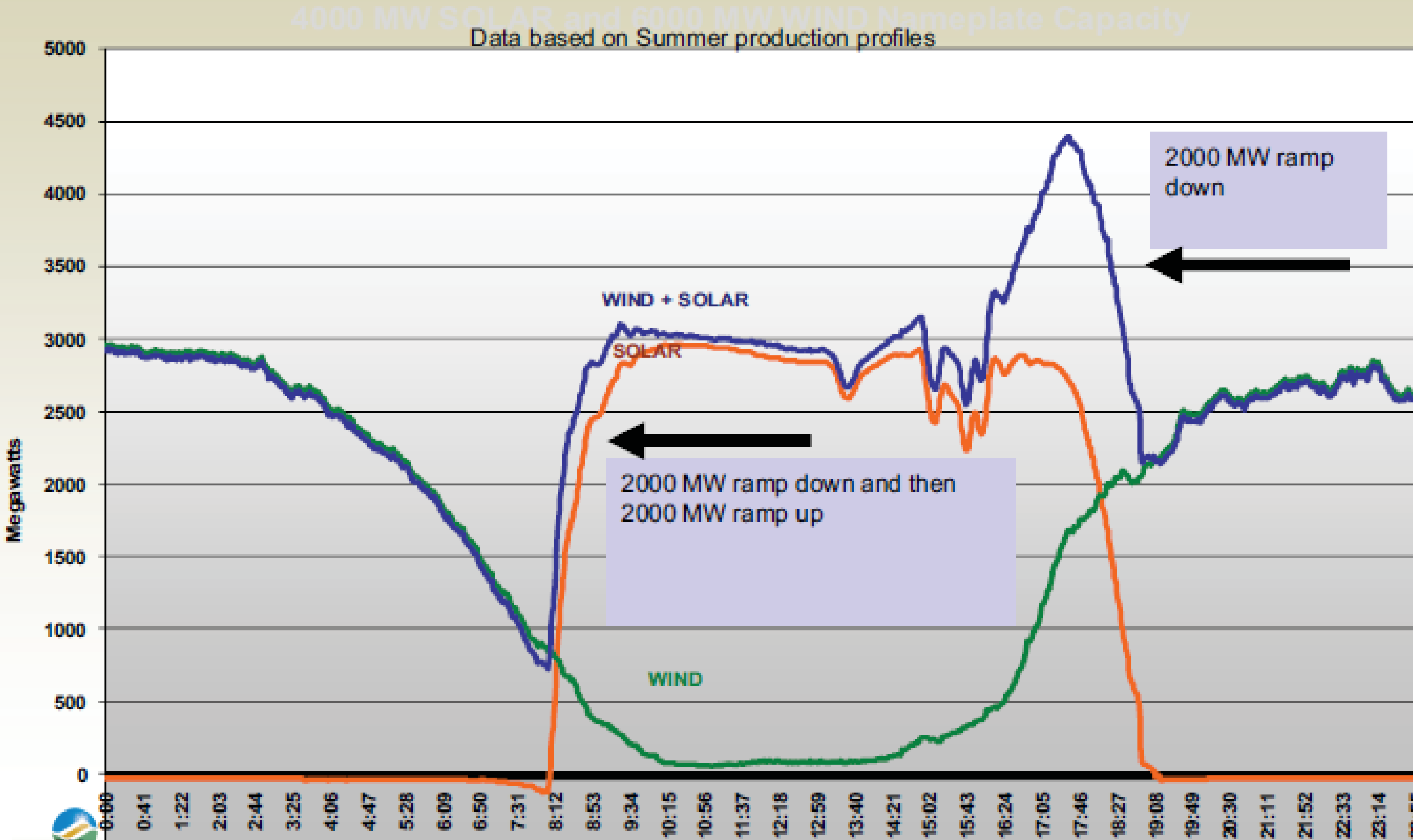
Uncertainty



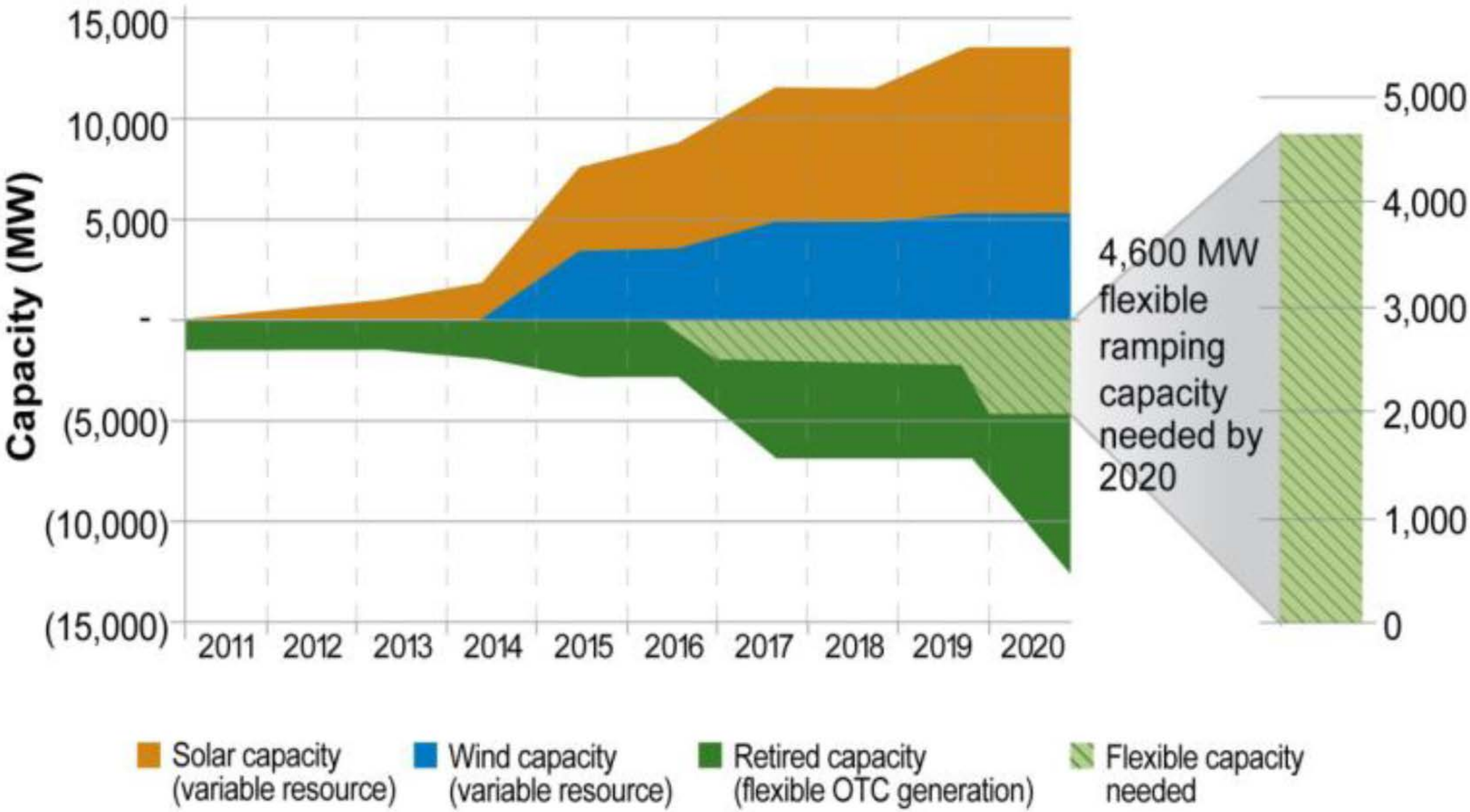
Negative Correlation with Load



Example of ramping challenges at ~20% RPS



Conventional Solution



Source: CAISO

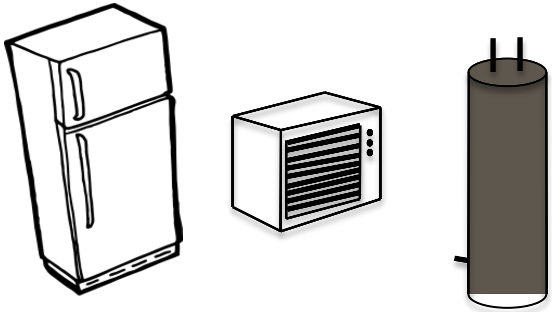
I Need a Brain

Source: GE

Making the Grid Smarter

- Accounting explicitly for uncertainty in operation and planning
  - Stochastic unit commitment (with endogenous reserves determination) to support renewable penetration and demand response
  - Probabilistic planning and simulation models (accounting for renewables, storage and demand response

- Mobilizing demand response (DR) and a paradigm shift to “load following available supply” provides an economically viable and sustainable path to a renewable low carbon future.
  - Price responsive load
  - Energy efficiency
  - Deferrable loads:
    - EV/PHEV
    - HVAC
    - Water heaters
    - Electric space heaters
    - Refrigeration
    - Agricultural pumping



Thermostatically Controlled Loads (TCLs)

Today's Presentations on Future Grid Tasks

Direct and Telemetric Coupling of Renewable Energy Resources with Flexible Loads	Shmuel Oren with Anthony Papavasiliou UC Berkeley
Mitigating Renewables Intermittency Through Non-Disruptive Load Control	Duncan Callaway with Johanna Mathieu and Mark Dyson UC Berkeley
Planning and Market Design for Using Dispatchable Loads to Meet Renewable Portfolio Standards and Emissions Reduction Targets	Max Zhang, Tim Mount and Bob Thomas Cornell University
Probabilistic Simulation Methodology for Evaluating the Impact of Renewables Intermittency on Operation and Planning	George Gross and Alejandro Dominguez-Garcia with Yannick Degeilh University of Illinois at Urbana-Champaign

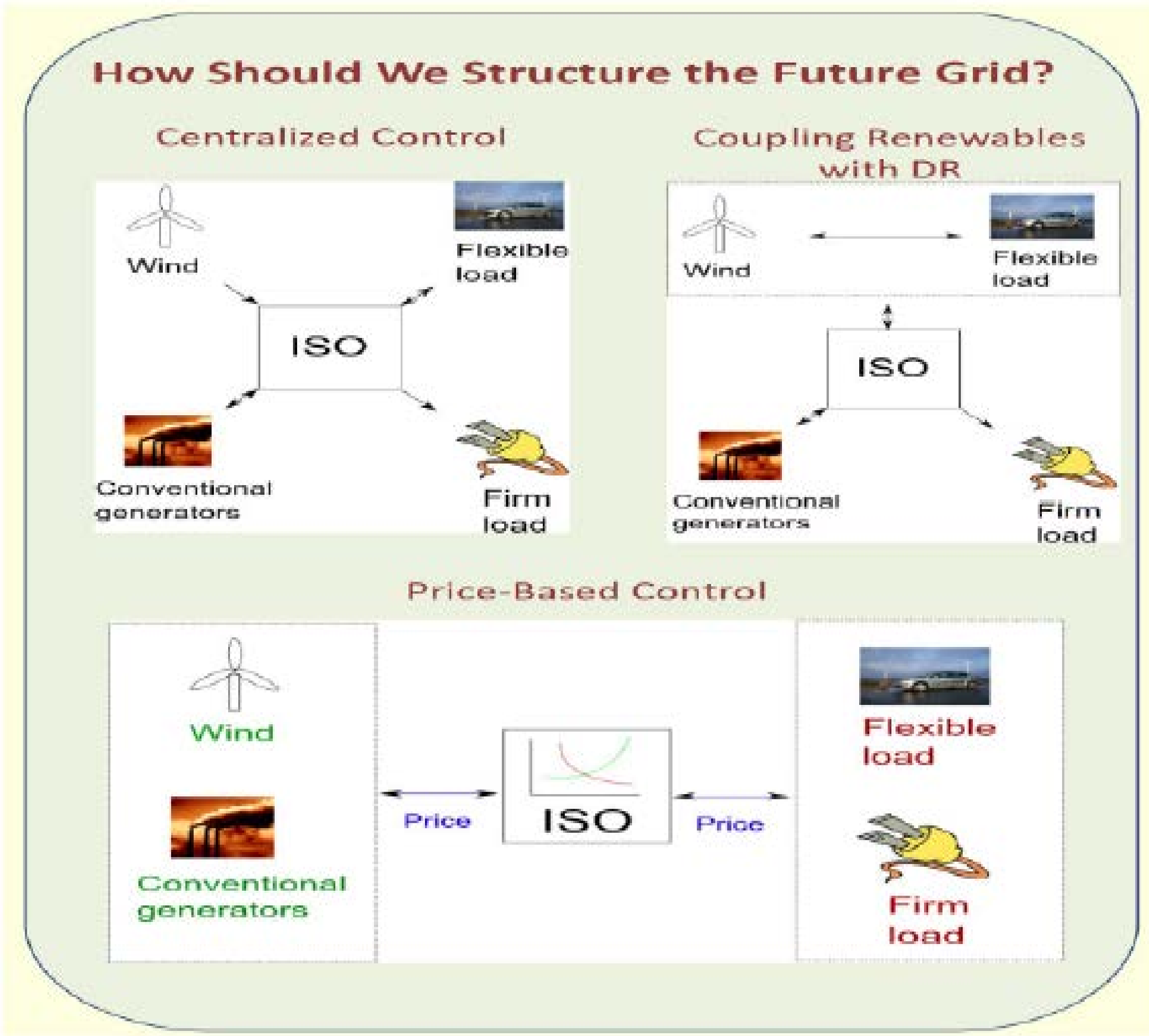
Task 1: Direct and Telemetric Coupling of Renewable Energy Resources with Flexible Loads

Shmuel Oren
Anthony Papavasiliou

UC Berkeley

PSERC

Alternative Demand Response Paradigms



Alternative Demand Response Paradigms

1. Centralized co-optimization of dispatchable supply resources and flexible loads by system operator
2. Price response:
   - Renewable producers bid in centralized real-time market
   - Consumers can communicate with system through instantaneous response to price
3. Coupling aggregated load with renewables:
   - Flexible loads communicate basic needs to renewable suppliers
   - Flexible loads follow dynamic supply signal from renewable resources, system operator faces reduced variability

Evaluation Methodology

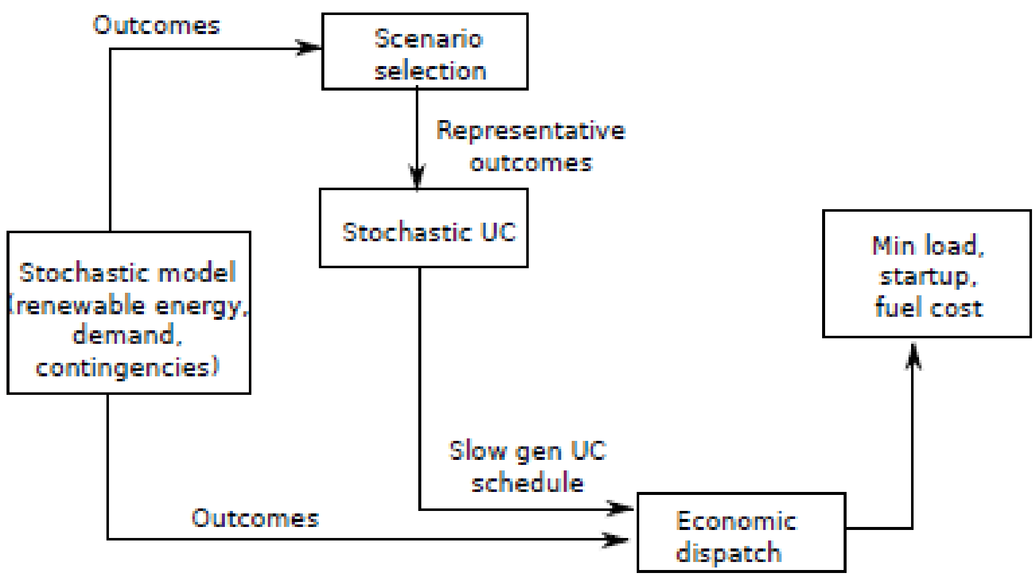
- Comparison of alternative approaches to flexible loads mobilization requires explicit consideration of uncertainty for consistent determination of locational reserves.
- Stochastic unit commitment optimization accounts for uncertainty by considering a limited sample of probabilistic wind and contingency scenarios, committing slow reserves early with fast reserves and demand response adjusted after uncertainties are revealed.
- Economic and reliability outcomes are calculated using Monte Carlo simulation with large number of probabilistic scenarios and contingencies

Results and Benefits

- Developed a stochastic optimization method for efficient reserves deployment in an environment with high renewables penetration
- Developed a consistent method for assessing alternative demand response integration strategies (direct coupling vs. market)
- Advanced the state of the art for stochastic unit commitment at practical scale employing High Performance Computing (HPC)
- Study of how computational time for stochastic unit commitment scales with number of processors and solution accuracy

Model Structure

- Application: stochastic unit commitment for large-scale renewable energy integration
- Two-stage model representing DA market (first stage) followed by RT market (second stage)



Unit Commitment

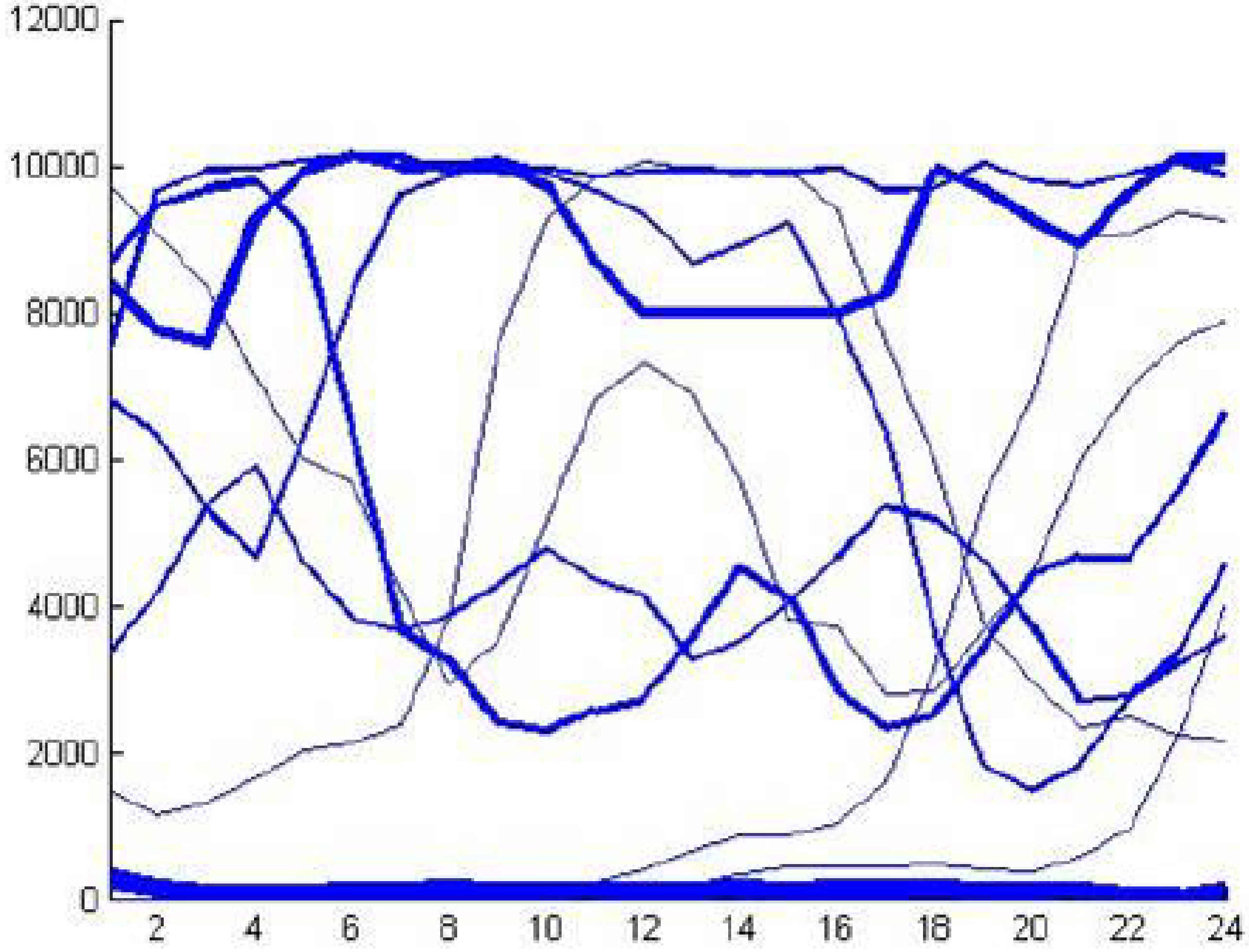
- Objective: $\min \sum_{g,t}(K_g u_{gt} + S_g v_{gt} + C_g p_{gt})$
- Load balance: $\sum_{g \in G} p_{gt} = D_t, \forall t$
- Min / max capacity limits: $P_g^- u_{gt} \leq p_{gt} \leq P_g^+ u_{gt}, \forall g, t$
- Ramping limits: $-R_g^- \leq p_{gst} - p_{gs,t-1} \leq R_g^+, \forall g, t$
- Min up times: $\sum_{q=t-UT_g+1}^{t} v_{gq} \leq u_{gt}, \forall g, t \geq UT_g$
- Min down times: $\sum_{q=t+1}^{t+DT_g} v_{gq} \leq 1 - u_{gt}, \forall g, t \leq N - DT_g$
- State transition: $v_{gt} \geq u_{gt} - u_{g,t-1}, \forall g, t$
- Integrality: $v_{gt}, u_{gt} \in \{0, 1\}, \forall g, t$
- Transmission line thermal constraints
- Kirchhoff voltage/current laws

Two Stage Stochastic Unit Commitment

1. In the first stage we commit slow generators: $u_{gst} = w_{gt}, v_{gst} = z_{gt}, g \in G_s, s \in S, t \in T$ (corresponds to day-ahead market)
2. Uncertainty is revealed: net demand D_{nst}, line availability B_{ls}, generator availability P_{gs}^{+}, P_{gs}^{-}
3. Fast generator commitment and production schedules are second stage decisions: $u_{gst}, g \in G_f$ and $p_{gst}, g \in G_f \cup G_s$ (corresponds to real-time market)
4. Objective:

$$\min \sum_{g \in G} \sum_{s \in S} \sum_{t \in T} \pi_s (K_g u_{gst} + S_g v_{gst} + C_g p_{gst})$$

Scenario Sample Selection

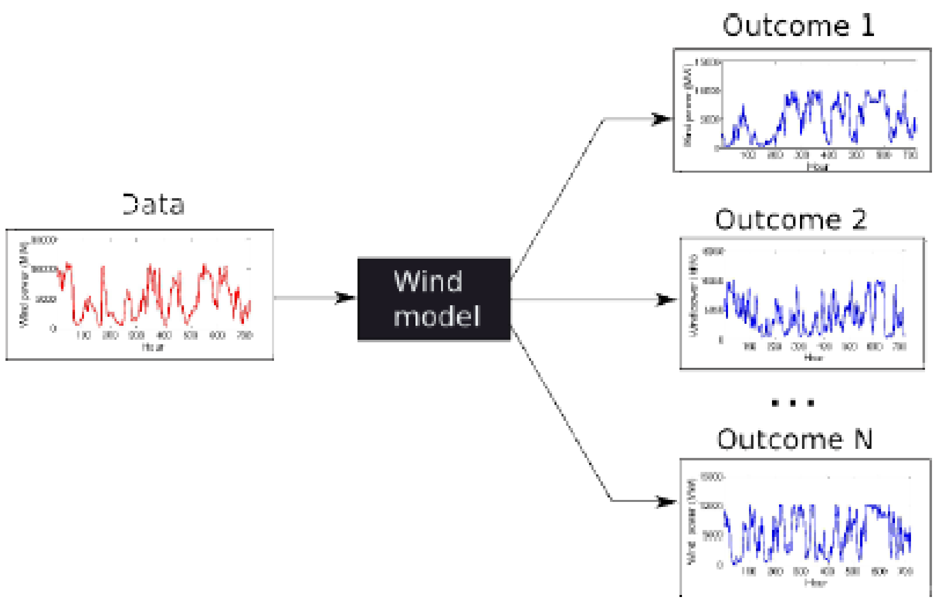


New Scenario Selection Method

- Past work: (Gröwe-Kuska et al., 2002), (Dupacova et al., 2003), (Heitsch and Römisch, 2003), (Morales et al., 2009)
- Scenario selection algorithm inspired by importance sampling
  1. Generate a sample set $\Omega_S \subset \Omega$, where $M = |\Omega_S|$ is adequately large. Calculate the cost $C_D(\omega)$ of each sample $\omega \in \Omega_S$ against the best deterministic unit commitment policy and the average cost $\bar{C} = \sum_{i=1}^{M} \frac{C_D(\omega_i)}{M}$.
  2. Choose N scenarios from Ω_S, where the probability of picking a scenario ω is $C_D(\omega)/(M\bar{C})$.
  3. Set $\pi_s = C_D(\omega)^{-1}$ for all $\omega^s \in \hat{\Omega}$.

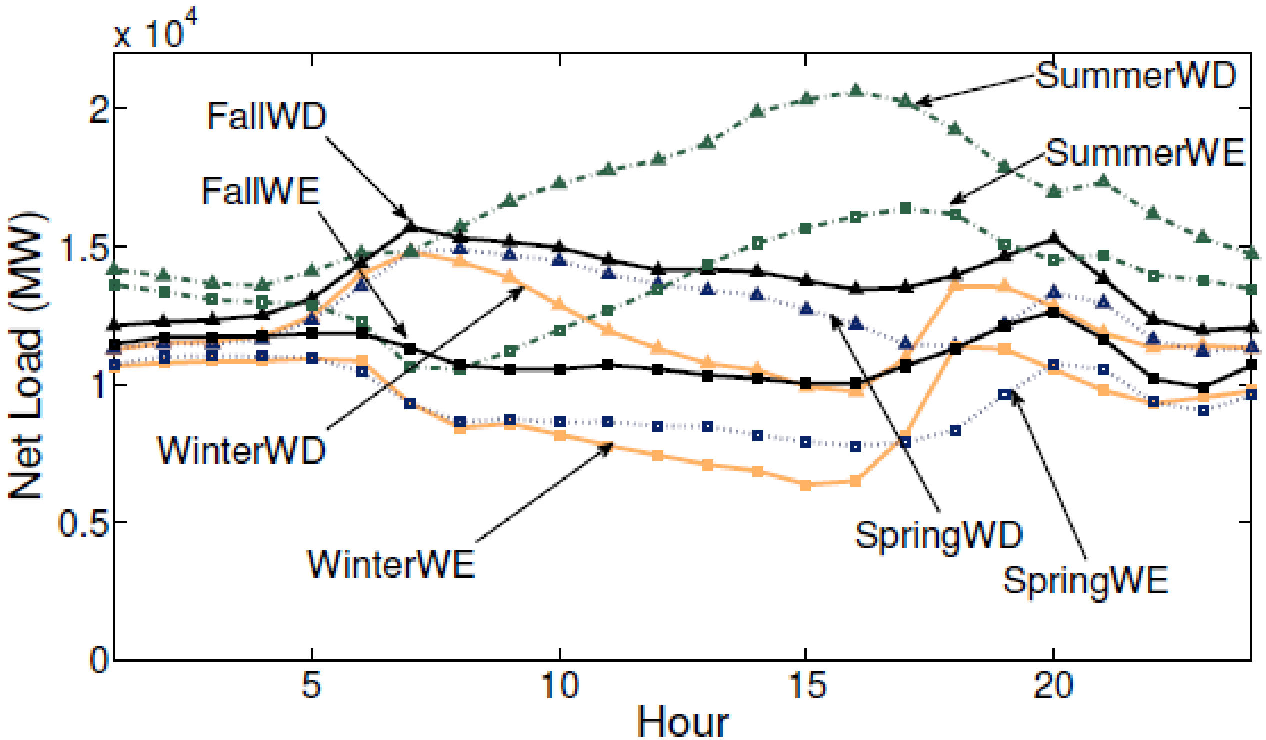
Wind Modeling and Data Sources

- 2 wind integration cases: moderate (7.1% energy integration, 2012), deep (14% energy integration, 2020)
- California ISO interconnection queue lists locations of planned wind power installations
- NREL Western Wind and Solar Interconnection Study archives wind speed - wind power for Western US

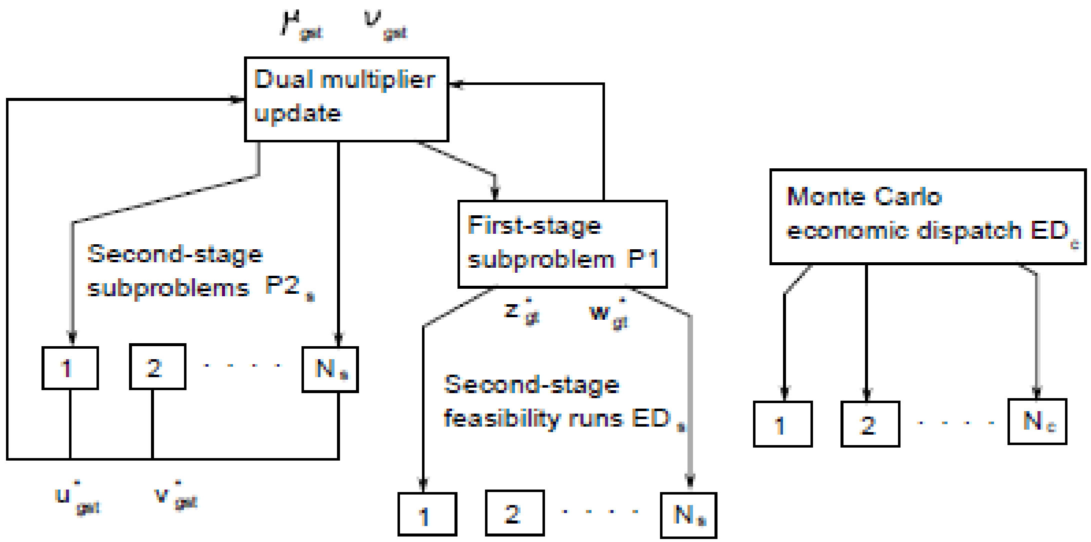


Load Variation Represented by Day Types

- 8 day types considered, one for each season, one for weekdays/weekends
- Day types weighted according to frequency of occurrence

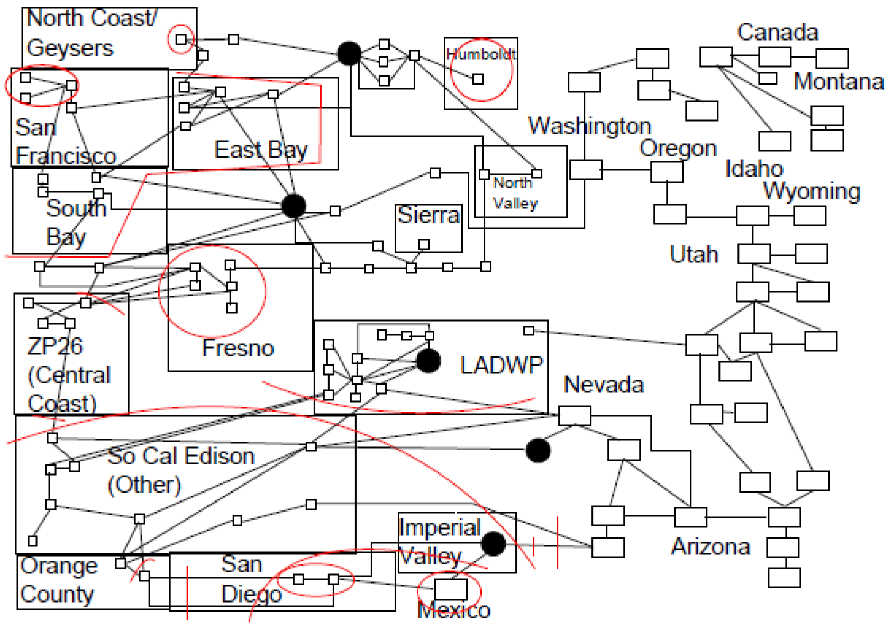


Parallelization and HPC Application



- Lawrence Livermore National Laboratory Hera cluster: 13,824 cores on 864 nodes, 2.3 Ghz, 32 GB/node
- MPI calling on CPLEX Java callable library

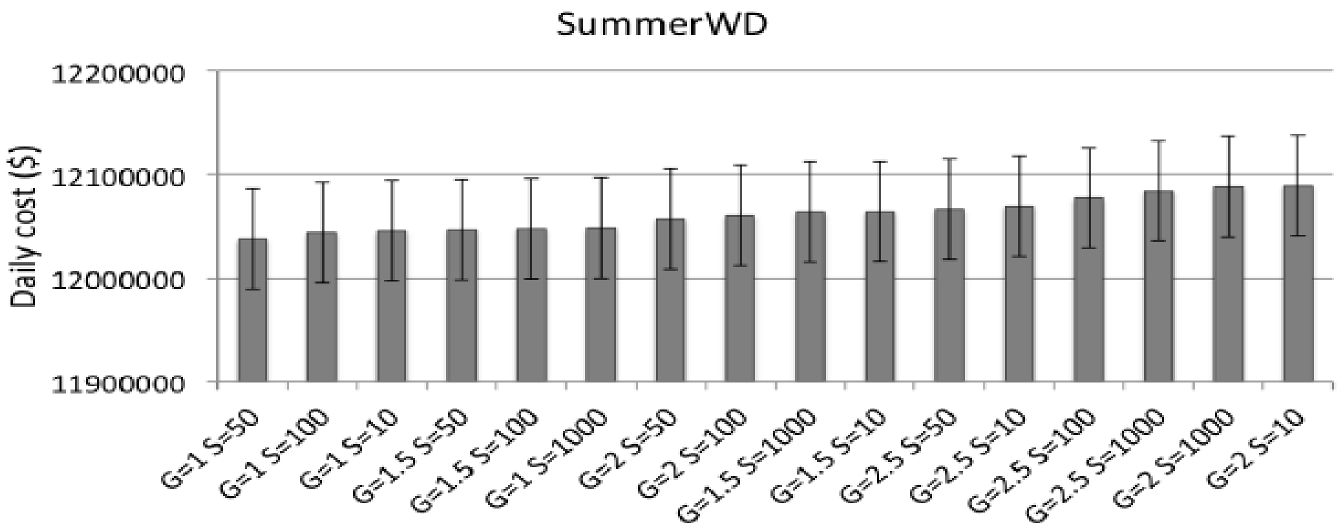
California Case Study

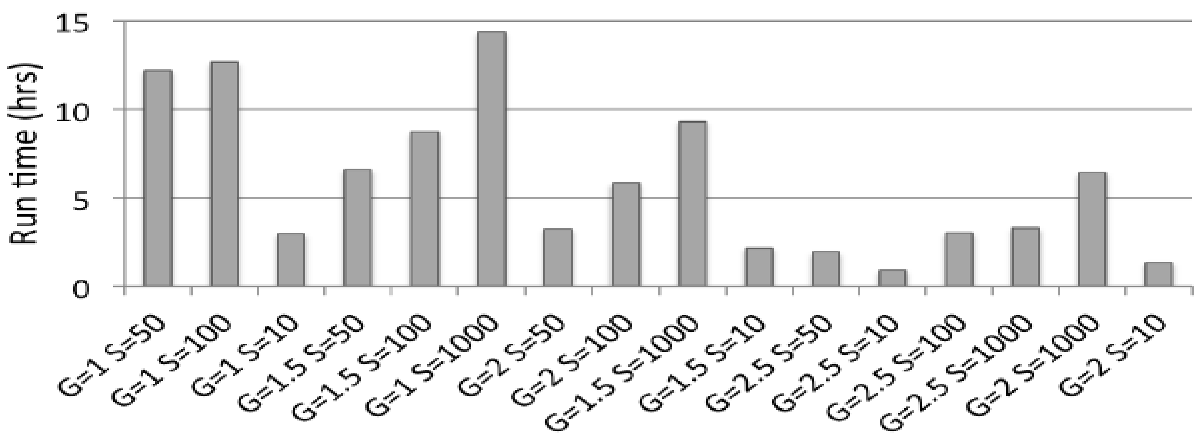


- 225 buses
- 375 transmission lines
- 124 units (82 fast, 42 slow)
- 53665 MW power plant capacity
- 42 scenarios
- Four studies
  - With transmission constraints, contingencies:
    - No wind
    - Moderate (7.1% energy integration, 2012)
    - Deep (14% energy integration, 2020)
  - Deep (14% energy integration) without transmission constraints, contingencies

- Stochastic Optimization captures nearly 50% of gains under perfect forecasting of load and wind outcomes
- Direct coupling marginally more expensive than a centralized market but reduces load shedding due to better representation of load flexibility
- Transmission constraints can play a significant role in determining cost and resource adequacy

Computational Efficiency Study





References

- Papavasiliou Anthony, Shmuel Oren and Richard O'Neill, "Reserve Requirements for Wind Power Integration: A Scenario-Based Stochastic Programming Framework", *IEEE Transactions on Power System,* Vol 26, No4 (2011), pp. 2197-2206
- Papavasiliou A. and S. S. Oren, "Integrating Renewable Energy Contracts and Wholesale Dynamic Pricing to Serve Aggregate Flexible Loads" Invited Panel Paper, Proceeding of the IEEE PES GM, Detroit, Michigan, July 24-28, 2011.
- Papavasiliou A. and S. S. Oren "Integration of Contracted Renewable Energy and Spot Market Supply to Serve Flexible Loads", Proceedings of the 18th World Congress of the International Federation of Automatic Control, August 28 – September 2, 2011, Milano, Italy.
- Papavasiliou A.and S. S. Oren, "Stochastic Modeling of Multi-area Wind Power Production ", Proceedings of PMAPS 2012, Istanbul Turkey, June 10-14, 2012.
- Oren S. S., Invited Panel Paper " Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid ", Proceeding of the IEEE PES GM, San Diego CA, July 22-26, 2012.
- Papavasiliou A., S. S. Oren, " A Stochastic Unit Commitment Model for Integrating Renewable Supply and Demand Response" Invited Panel Paper, Proceeding of the IEEE PES GM, San Diego, CA, July 24-28, 2012.
- Papavasiliou A., S. S. Oren, "Large-Scale Integration of Deferrable Demand and Renewable Energy Sources in Power Systems", Accepted for publication in a special issue of the IEEE PES Transaction.
- Papavasiliou A., S. S. Oren, "Multi-Area Stochastic Unit Commitment for High Wind Penetration in a Transmission Constrained Network", Accepted for publication in Journal of Operations Research.
- Papavasiliou Anthony, Shmuel Oren, Barry Rountree "Applying High Performance Computing to Multi-Area Stochastic Unit Commitment for Renewable Energy Integration", Submitted to Mathematical Programming (February 2013)

Mitigating Renewables Intermittency Through Nondisruptive Load Control

Duncan Callaway
Johanna Mathieu
Mark Dyson

University of California, Berkeley

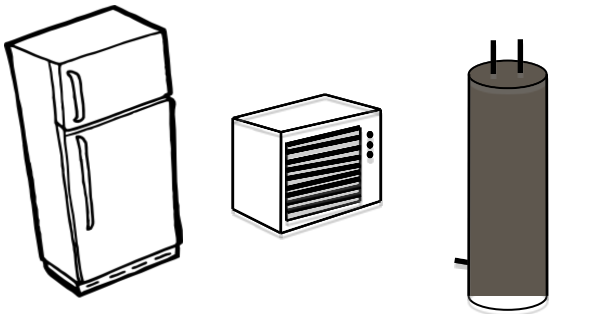
Notes: Callaway is the Task leader, dcal@berkeley.edu. Mathieu is currently a postdoctoral scholar in the Power Systems Laboratory at ETH Zurich. Dyson was not funded by the project, but contributed to the resource assessment.

Context

- Renewables integration requires power system flexibility (e.g., managing frequency response and energy imbalances)
- Centralized control of load resources could be a low cost solution: the grid connected resources exist already
- But the costs could be pushed upward by:
  - Communications & metering infrastructure requirements (system operators need high quality telemetry data in certain applications)
  - Customer payments (if end-use function has to be seriously compromised)

Research Goals

- New methods to model and control aggregations of thermostatically-controlled loads (TCLs) that
  - Reduce communications and power measurement requirements
  - Minimize temperature deviations
- Evaluate how different real time communications abilities affect
  - Ability to accurately estimate local temperature and ON/OFF state of loads
  - Controllability of load resources
- Analyze TCL resource potential, costs, and revenue potential associated with TCL control

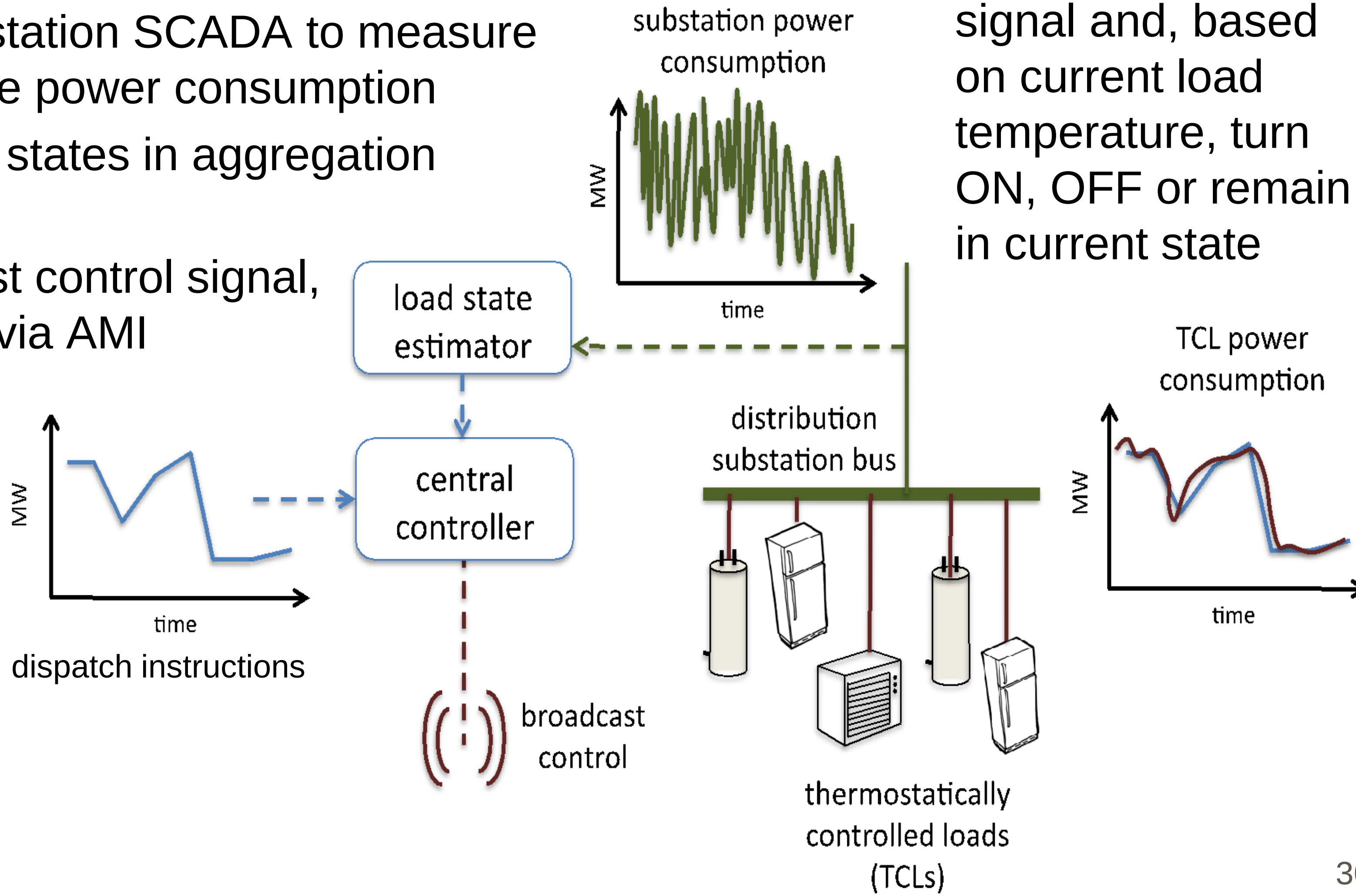


TCLs

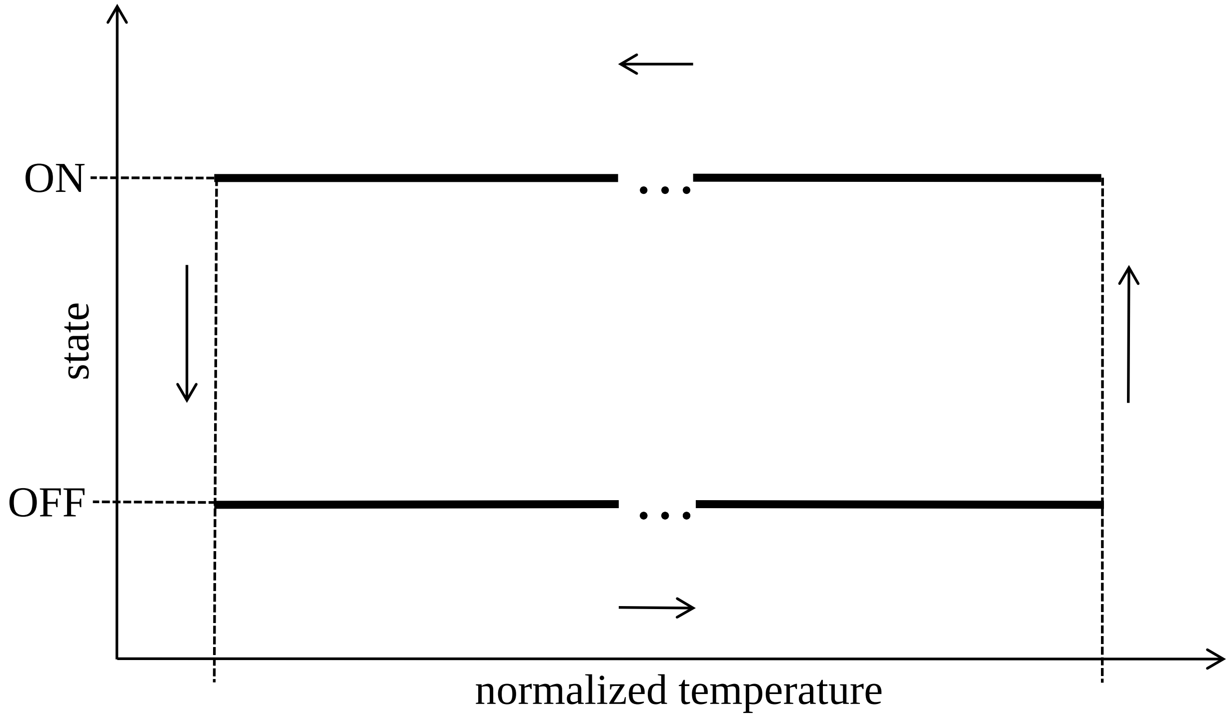
Basic Residential TCL Control Architecture

- All control occurs within existing TCL temperature deadband
- Use substation SCADA to measure aggregate power consumption
- Estimate states in aggregation model
- Broadcast control signal, possibly via AMI

- Loads receive broadcasted control signal and, based on current load temperature, turn ON, OFF or remain in current state

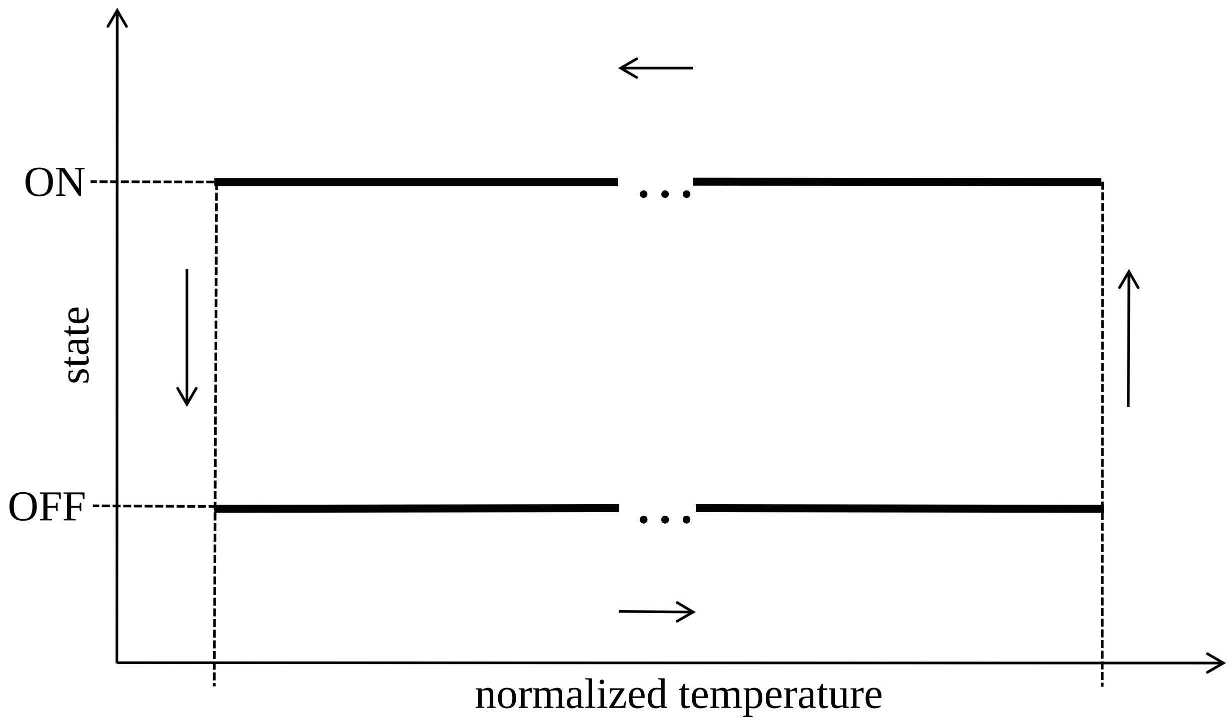


Aggregated TCL Model
‘State bin transition model’



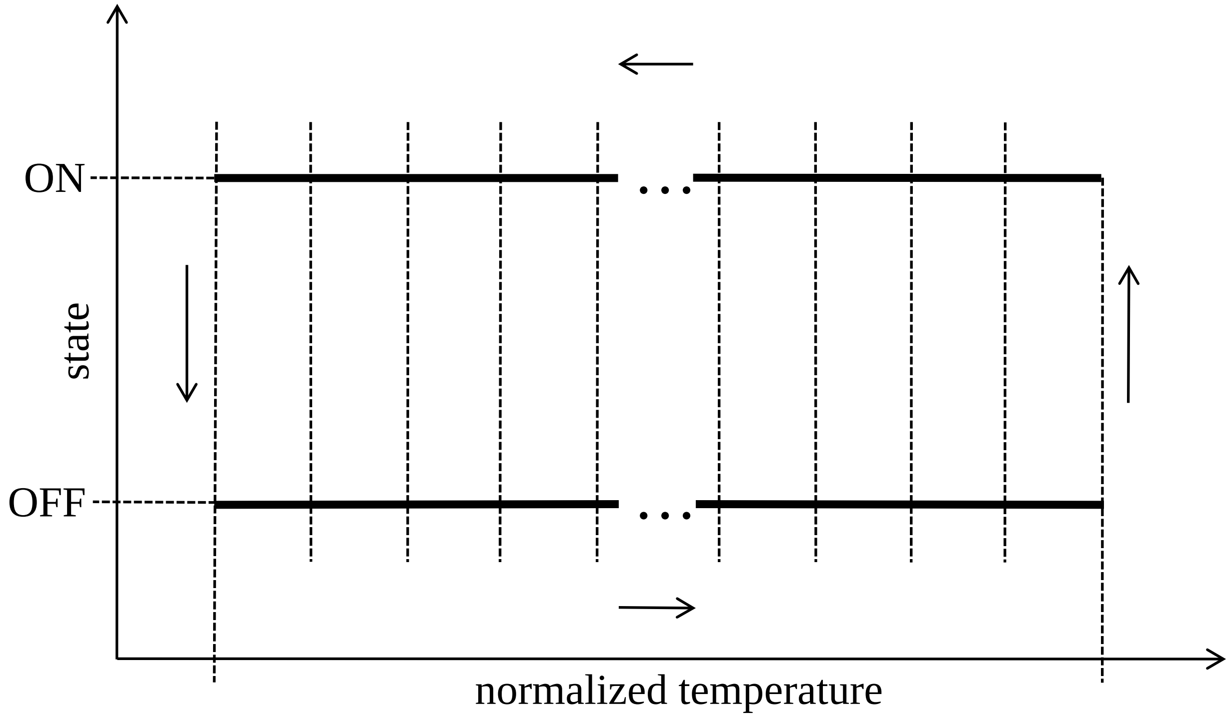
[Similar to that proposed by Lu and Chassin 2004; Lu et al. 2005; Bashash and Fathy 2011; Kundu et al. 2011]

Aggregated TCL Model
'State bin transition model'



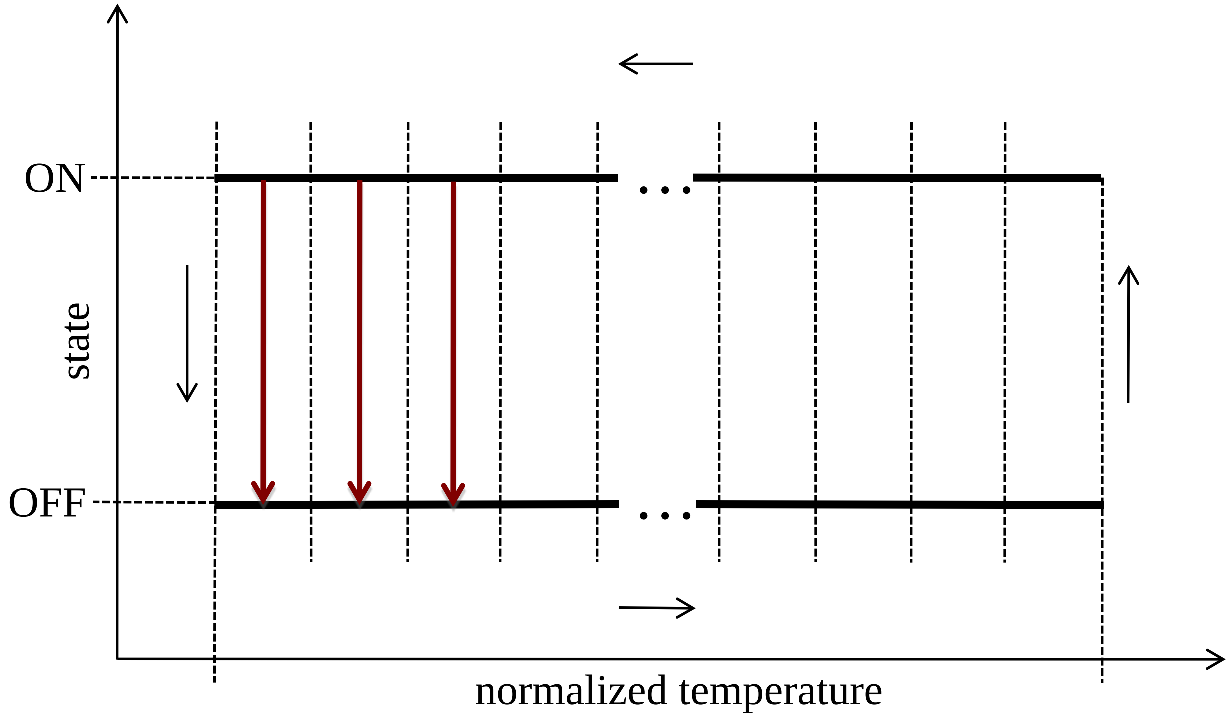
Consider thousands of TCLs traveling around a normalized temperature dead-band.

Aggregated TCL Model
‘State bin transition model’



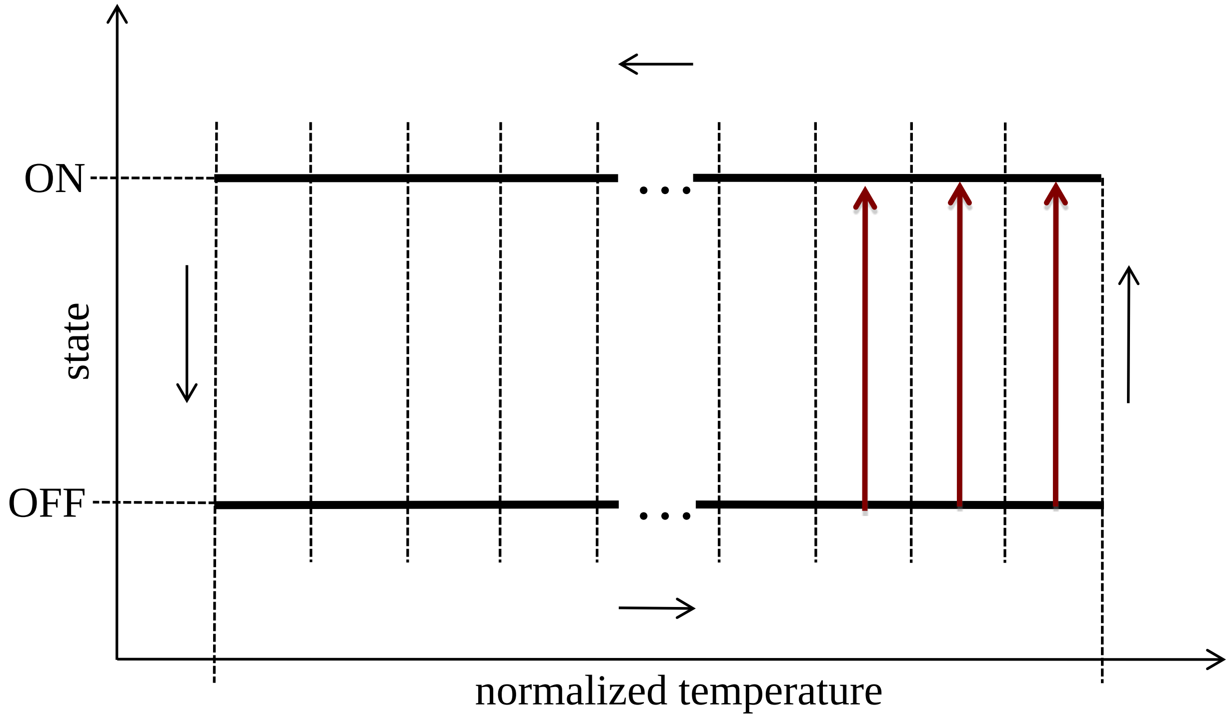
Divide it into discrete temperature intervals.

Aggregated TCL Model
'State bin transition model'



Forcing the system: decreasing aggregate power.

Aggregated TCL Model
‘State bin transition model’



Forcing the system: increasing aggregate power.

Question: How important is real time metering?

- Reference case: Meter power and temperature at all controlled loads, error following dispatch signal = **0.6% RMS** (smaller is better)
- Case 1: Meter the ON/OFF state at all loads, measure aggregate power at the distribution substation.
  Result: error = **0.76% RMS**
- Case 2: Meter only aggregate power at distribution substation. Result: error = **5% RMS**
  - Note, this error compares favorably to conventional generators

Answer: Not important; state estimation works

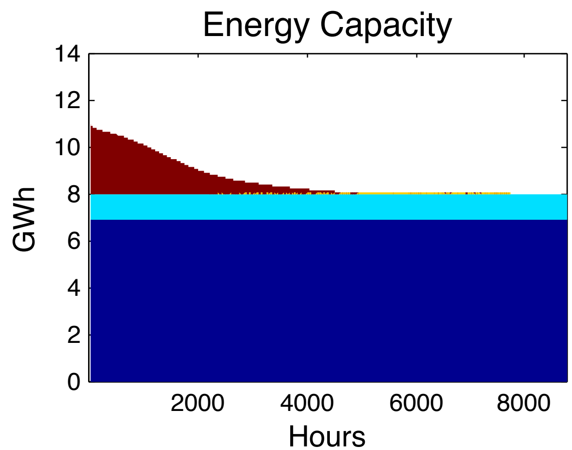
All results assume:

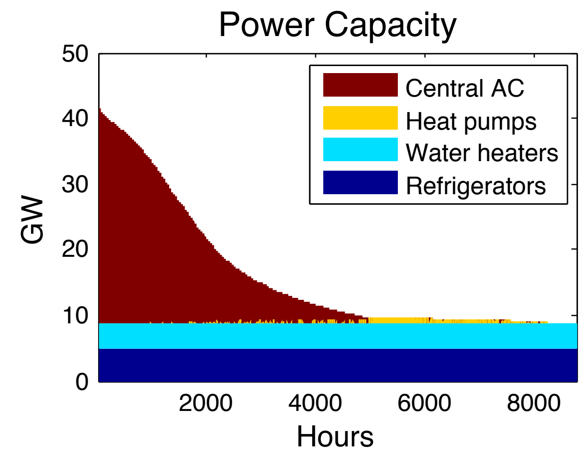
- 17 MVA substation load
- 15% of load (1,000 TCLs) is controlled
- Aggregate power measurements include *all* loads on substation
- Total substation load can be forecasted with 5% average error on a one minute horizon

How LARGE is the Resource Potential?

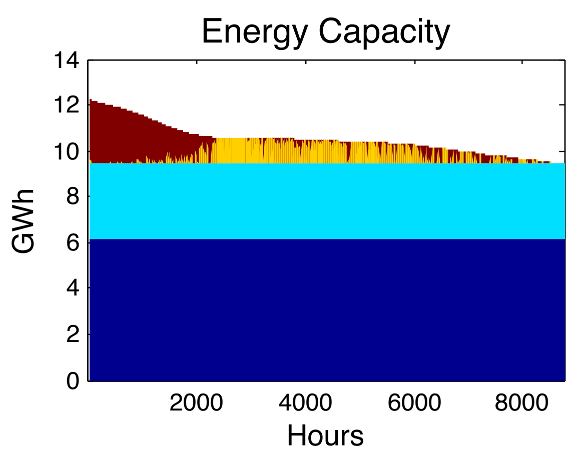
Estimates for most of California (5 largest utilities) based on Renewable Energy Certificates and California Energy Commission data.

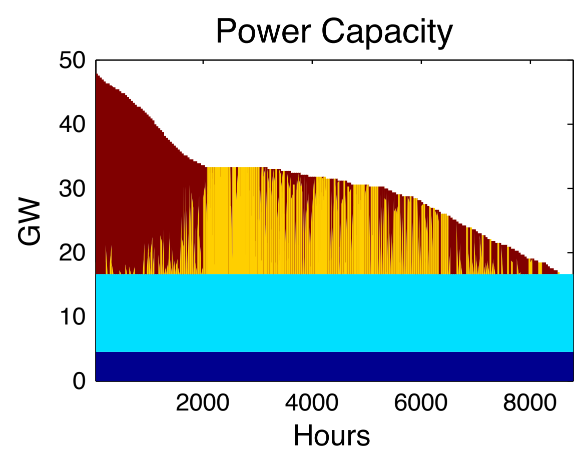
2012 Resource Duration Curve





2020 Resource Duration Curve, assuming increased efficiency and 30% of water/space heaters converted to electric





Potential Revenues for Regulation and Load Following (per TCL per year)

	Regulation	Load Following
Air conditioners*	$9-79	$2-9
Heat pumps*	$100-170	$9-14
Combined AC/HP*	$160-220	$16-18
Water heaters	$61	$35
Refrigerators	$25	$14

*Results depend on the climate zone

Note: cost requires a separate analysis!

Uses and Potential Benefits of Results

- Reduced cost to deploy centralized control of loads on distribution circuits
  - AMI could broadcast control signals
  - Substation SCADA may be all that is required for real time measurement
- Roadmap for which loads are best for fast demand response
  - Electrification of heating has big benefits
- Results lay groundwork for demonstration
  - Currently in discussion with several load aggregators to run a pilot

References

- Mathieu, J.L.; M.E. Dyson, and D.S. Callaway. *Using Residential Electric Loads for Fast Demand Response: The Potential Resource, the Costs, and Policy Recommendations*. To appear in the Proceedings of the 2012 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August 12-17, 2012.
- Mathieu, J.L.; S. Koch, and D.S. Callaway. *State Estimation and Control of Electric Loads to Manage Real-Time Energy Imbalance*. IEEE Transactions on Power Systems (in press), 2012.
- Mathieu, J.L.; and D.S. Callaway. *State Estimation and Control of Heterogeneous Thermostatically Controlled Loads for Load Following*. Proceedings of the 45th Hawaii International Conference on System Sciences (HICSS45), Wailea, Hawaii, January 4-7, 2012.

Using Deferrable Demand to Meet Renewable Portfolio Standards and Emission Reduction Targets

Cornell Research Team:

K. Max Zhang

Timothy D. Mount

Robert J. Thomas

PSERC

Summary

Premises:

1) Need improved methods for evaluating the operations and planning of a future grid with:
   a. High penetrations of renewable sources
   b. Storage and deferrable demand*
2) Establishing public support for the future grid will require that customers see tangible benefits (e.g., lower bills)

* Decouples the purchase of electricity from the delivery of an energy service.

Contributions:

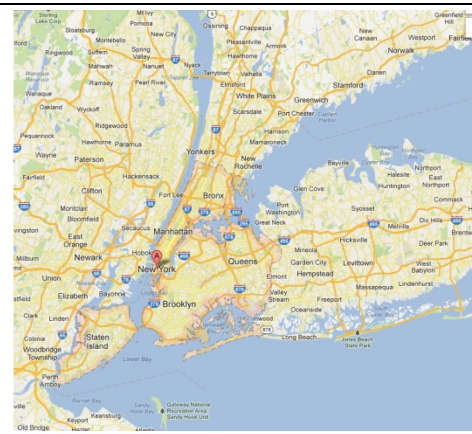
1) Developed an *integrated multi-scale physical and economic* framework for modeling deferrable demand
2) Evaluated the effects of *stochastic renewable sources* and *deferrable demand* on total system costs and emissions from generating units (to be completed)

Accomplishments

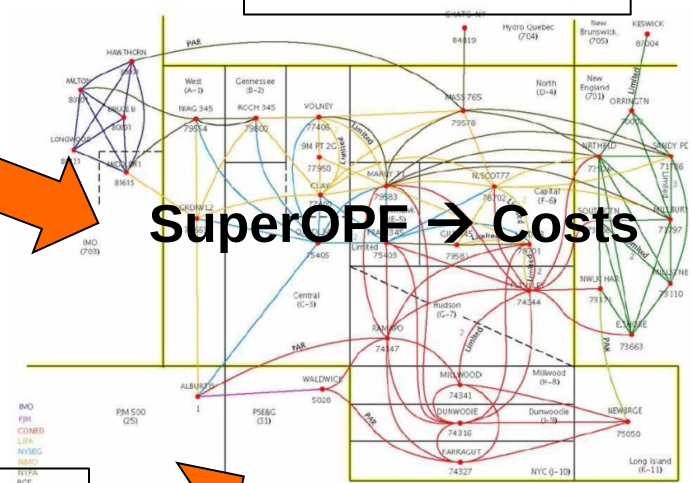
1) Developed a model *for aggregating customers with electric vehicles* to determine the maximum hourly charge limited by the capacity of chargers and commuting patterns
2) Developed a model for *aggregating buildings with thermal storage capabilities for cooling* limited by the capacities of compressors and the energy stored
3) Used #1 and #2, in addition to *stochastic wind generation*, as inputs into the SuperOPF, a stochastic form of multi-period Security Constrained Optimal Power Flow (SCOPF)
4) Augmented the SuperOPF by adding *emission/damage coefficients* to the operating costs of generating units
5) Used #1- 4 to simulate the *system effects and costs* of using deferrable demand to mitigate the variability of generation from wind sources and reduce emissions (to be completed)

Context of the Research:
An Integrated Multi-Scale Framework

PEV charger capacities → Commuting Patterns → Nodal Capabilities

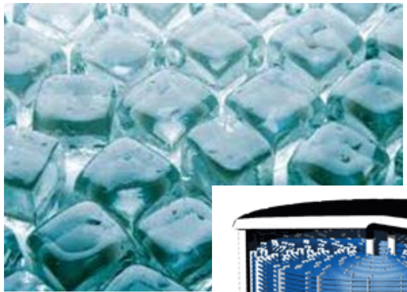


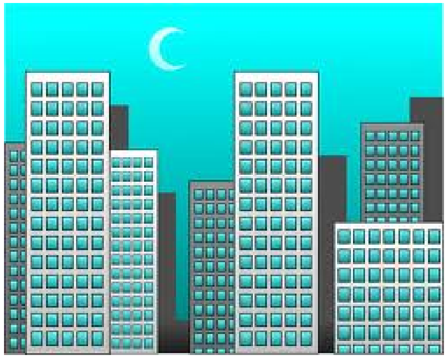
North East Test Network

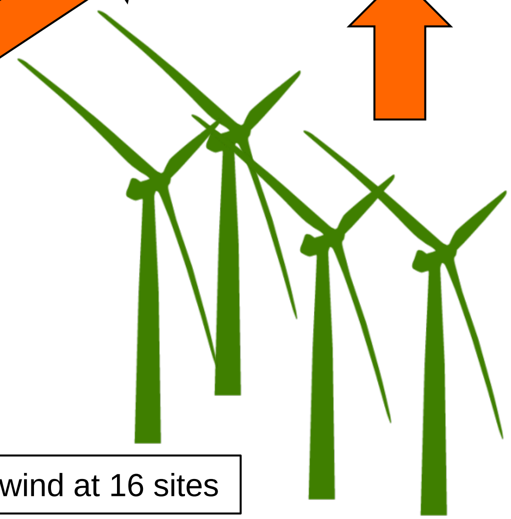


SuperOPF → Costs

Ice storage systems → Buildings → Nodal Capabilities



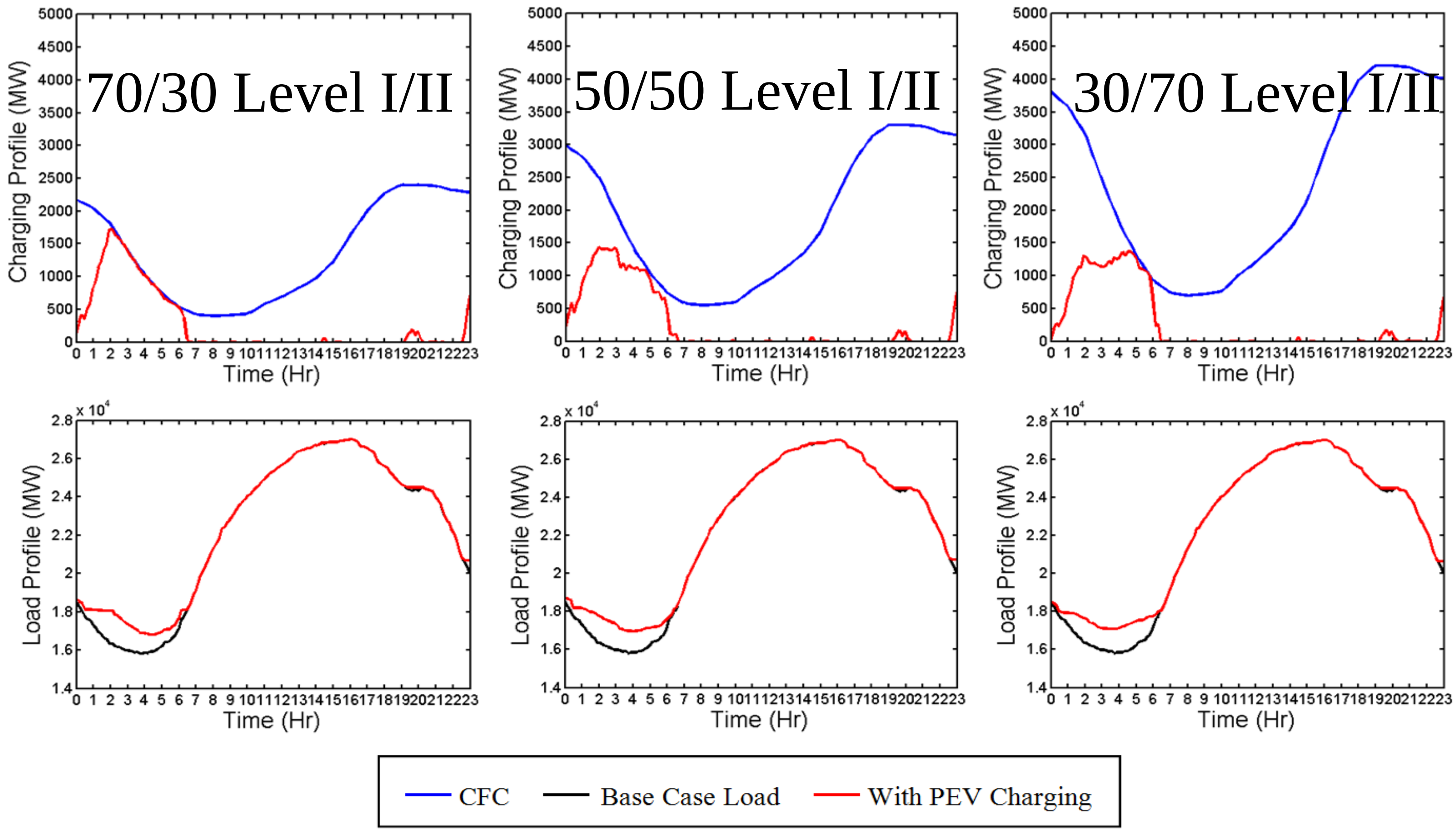




Stochastic wind at 16 sites

Results I:

System Load with "Intelligent" Charging of PEVs under Different Penetrations of Low and High PEV Charging Rates

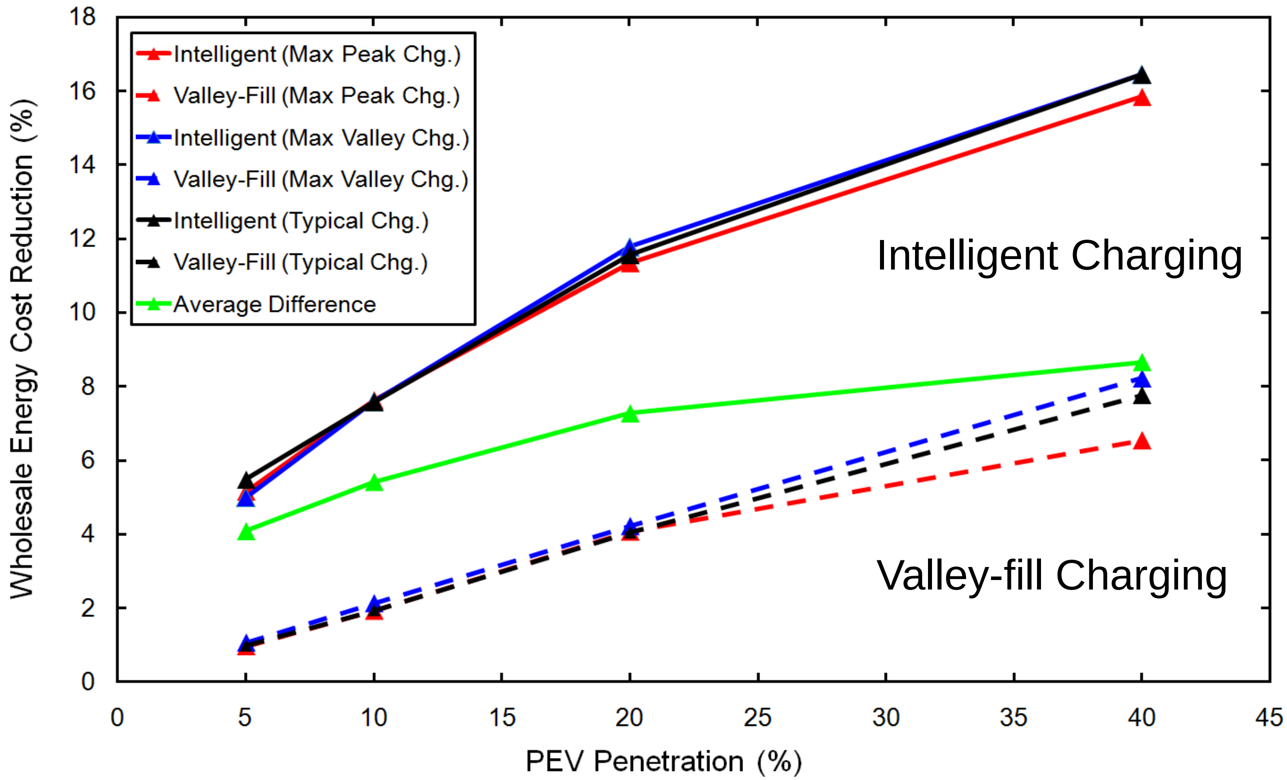


- A 20% penetration of commuters are assumed to use PEVs in the NPCC region.
- 80% of the PEV load is assigned to valley hours to take advantage of the low prices.
- The remaining 20% is assigned to shoulder and peak hours to reduce ramping costs
- The Charging Flexibility Constraint (CFC) may restrict PEV charging during the morning commuting hours

Valentine, Temple and Zhang (2011) J. Power Sources

Results II:

Percent Reduction in Wholesale Energy Costs Using "Intelligent" Charging and Valley-Fill Charging vs. Charging-at-Will

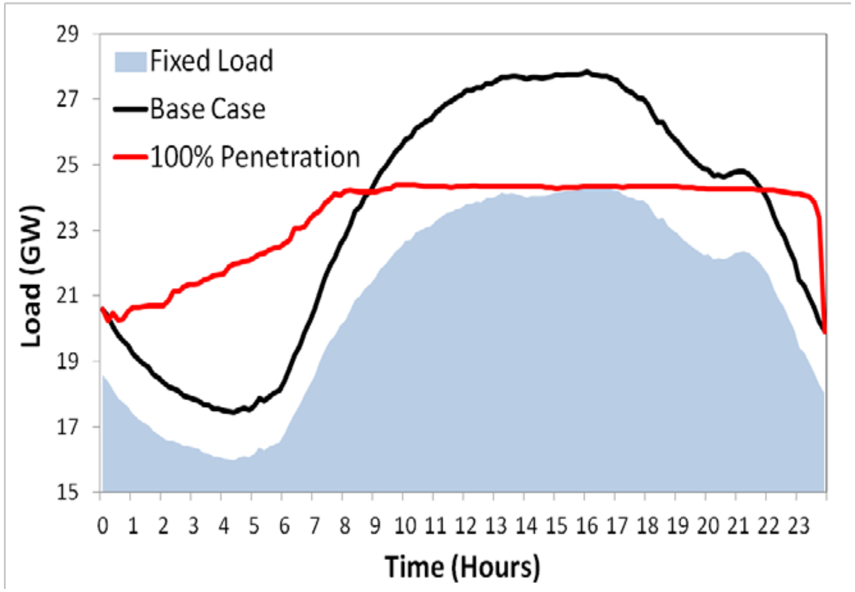


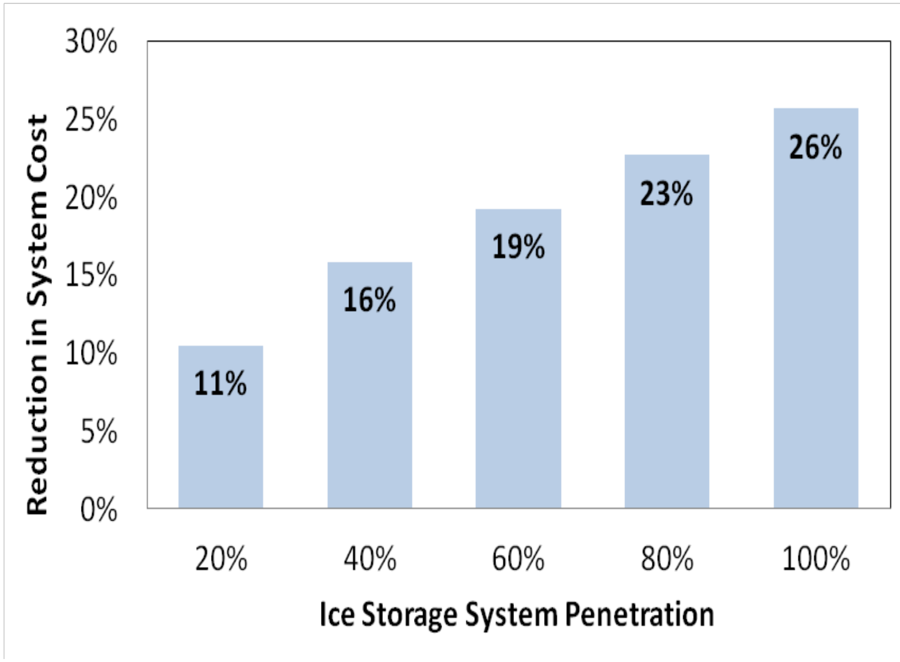
- Charging-at-Will (i.e., commuters charge their PEVs as soon as they arrive at home) is the baseline.
- Intelligent charging results in significant reductions in the costs compared to charging-at-will and valley-fill charging.
- Percentage reductions in the costs with intelligent charging are higher with higher penetrations of PEVs because more PEVs provide a greater capability for modifying wholesale prices and the system cost of ramping.

Valentine, Temple and Zhang (2011) J. Power Sources

Results III:

System Load and System Cost Reductions with Price-Responsive Ice Storage Systems





- The system benefits of aggregating Ice Storage Systems in large commercial and industrial buildings in New York State were evaluated for the NYCA.
- Heuristic methods were used to reduce system costs in a two-settlement wholesale market that accounts for both the steady-state costs and ramping costs of generating units.
- The optimal management of thermal storage significantly reduces both the peak load and total system costs, and also flattens out the daily load profile of conventional generating units.

Palacio et al. In preparation

Results IV:
Structure of the SuperOPF

OBJECTIVE FUNCTION FOR DAILY OPERATIONS:

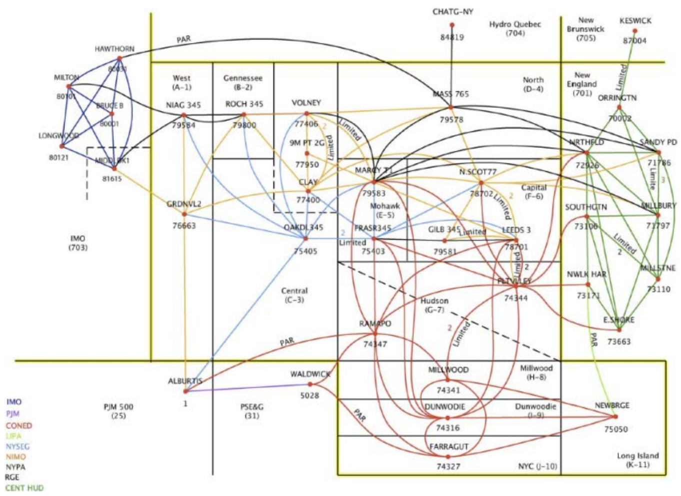
Minimize the expected cost of meeting load, including the costs of load-not-served, reserves and ramping, for a set of credible system states over 24 hours subject to:

1) Network constraints,
2) Stochastic wind inputs,
3) Contingencies.

DETERMINE THE OPTIMUM NODAL VALUES FOR:

1) Hourly dispatch profiles for generating units,
2) Amount of wind dispatched/spilled,
3) Amount of Load-Not-Served,
4) Up and down reserve capacity,
5) Amount of ramping,
6) Nodal energy prices,
7) Charging/discharging of deferrable demand,
8) Charging/discharging of collocated storage,

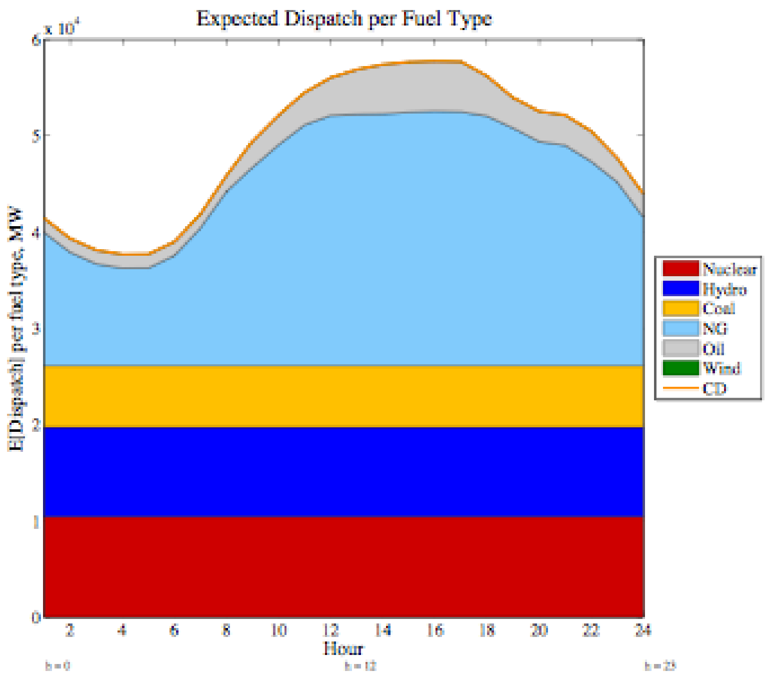
APPLIED TO:
North East Test Network (NET Net)
Hot Summer Day



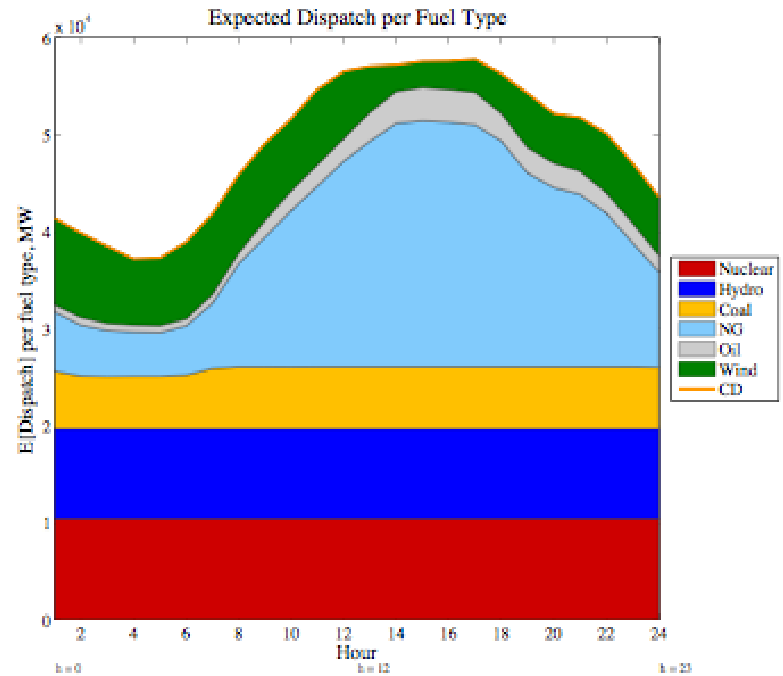
Results V:

Optimum Daily E[Pattern of Generation] for the NET Net with and without Wind Capacity Installed

Case 1: Base



Case 2: Base + 29GW Wind



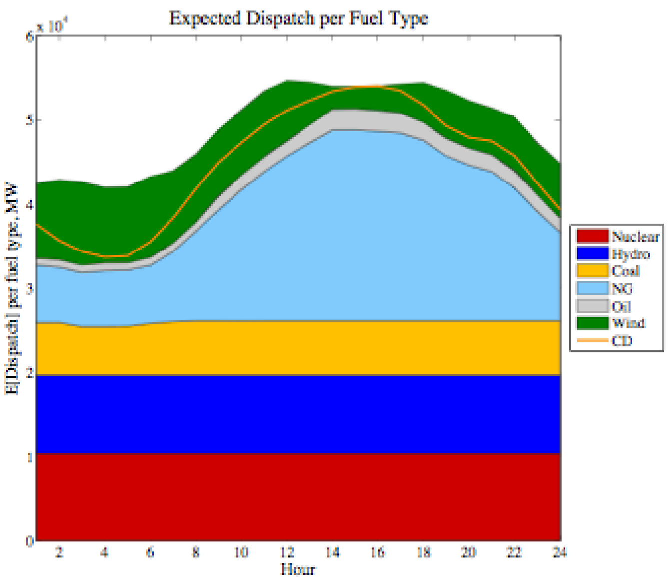
Case 1: Ramping for the daily load profile is provided by oil and natural gas capacity.

Case 2: Wind displaces mainly oil and natural gas capacity, but this conventional capacity provides the additional ramping services needed to mitigate the uncertainty of wind generation. Some wind is spilled.

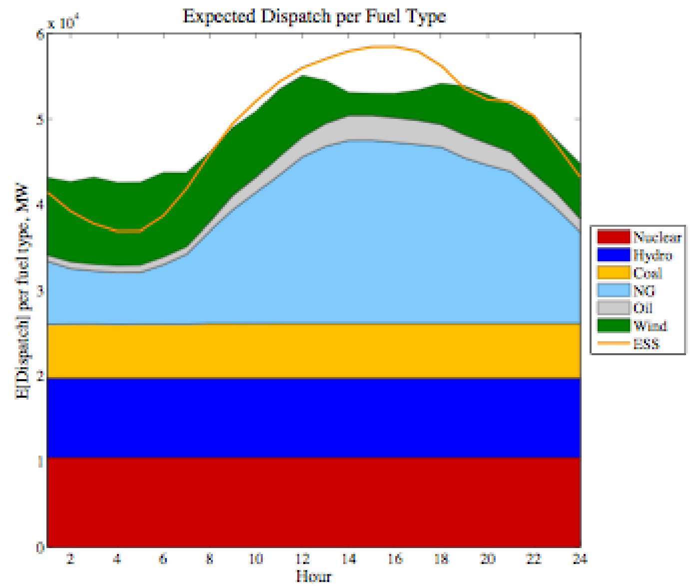
Results VI:

Optimum Daily E[Pattern of Generation] for the NET Net with Deferrable Demand or Collocated Storage

Case 3: Base + 29GW Wind
+ 33GWh Deferrable Demand



Case 4: Base + 29GW Wind
+ 33GWh Collocated Storage



Cases 3 & 4 v Case 2: More wind generation is dispatched and the daily dispatch profile of conventional generating units is flatter.
Case 3 v Case 4: More wind generation is dispatched in Case 4 BUT the peak system load is lower in Case 3 → less congestion on the grid and less utility-owned capacity needed to maintain System Adequacy → lower capital costs → lower bills for customers.

Environmental Analysis
(to be completed)

- Initially, fixed coefficients were used to link generator outputs and emission rates in the SuperOPF, but the emission coefficients for carbon are now being modified to depend on the generator types and operating conditions.
- Time-dependent and location-dependent damage coefficients are being developed to make it feasible to determine how dispatch patterns could be modified to reduce the severity of air pollution (e.g., ozone episodes).
- Using storage and/or deferrable demand may be effective ways to mitigate ozone episodes and increase social benefits by discharging more energy during critical periods when the damage coefficients of the precursor emissions are high (primarily NO_x).

Potential Benefits

1) Provide a comprehensive analytical framework for evaluating how deferrable demand (electric vehicles and buildings with thermal storage) can affect the operations and costs of an electric delivery system
2) Demonstrate how deferrable demand can:
   - Flatten the daily dispatch pattern of conventional generators,
   - Mitigate the variability of wind generation,
   - Reduce ramping costs and maintain reliability,
   - Lower costs to customers,
   - Improve environmental quality (to be completed).
3) The software is open source, and when it is sufficiently robust, it will be added to the programs available with MATPOWER <http://www.pserc.cornell.edu/matpower/>.

Publications

1. Lamadrid, Alberto; Wooyoung Jeon, and Tim Mount. The Effect of Stochastic Wind Generation on Ramping Costs and the System Benefits of Storage. *Proceedings of the 46th IEEE HICSS Conference*, Maui, HI, January 2013.

2. Jia, Liyan; Lang Tong and Tim Mount. Pricing and Competition for Large Scale Charging of Electric Vehicles. *Proceedings of the 46th IEEE HICSS Conference*, Maui, HI, January 2013.

3. Mount, Tim, Judy Cardell, Lindsay Anderson and Ray Zimmerman, Coupling Wind Generation with Controllable Load and Storage: A Time-Series Application of the SuperOPF, Final Project Report for Project M-22*, PSERC Publication 12-29*, Nov. 2012.

4. Valentine, K.; W. Temple, and K. M. Zhang. Electric Vehicle Charging and Wind Power Integration: Coupled or Decoupled Electricity Market Resources? *Proceedings of the 2012 IEEE PES General Meeting*, San Diego, CA, July, 2012.

5. Lamadrid, Alberto. Alternate Mechanisms for Integrating Renewable Sources of Energy into Electricity Markets. *Proceedings of the 2012 IEEE PES General Meeting*, 22 - 26 July 2012, San Diego, CA, July 22-26, 2012.

6. Lamadrid, Alberto; and Tim Mount. Ancillary Services in Systems with High penetrations of Renewable Energy Sources, the Case of Ramping. *Energy Economics*, 34:1959–1971, 2012.

7. Mount, Tim; and Alberto Lamadrid. Using Deferrable Demand to Increase Revenue Streams for Wind Generators. *Proceedings of the 25th Annual CRRI Western Conference*, Monterey CA, June 27-29, 2012.

8. Mount, Tim; Alberto Lamadrid, Wooyoung Jeon, and Hao Lu. Is Deferrable Demand an Effective Alternative to Upgrading Transmission Capacity? *Proceedings of the 31st Annual CRRI Eastern Conference*, Shawnee, PA, May 16-18, 2012.

9. Palacio, S.; K.; Valentine; M. Wong, K. M. Zhang. System-level price responsive ice storage systems. *World Renewable Energy Forum*, Denver, Colorado, May 2012.

10. Valentine, K.; W. Temple, and K. M. Zhang. Intelligent electric vehicle charging: Rethinking the valley fill. *Journal of Power Sources*, 196 (24): 10717-10726, 2011.

11. Mount, Timothy D.; Alberto J. Lamadrid, Surin Maneevitjit, Robert Thomas, and Ray Zimmerman. The Hidden System Costs of Wind Generation in a Deregulated Electricity Market. *Journal of Energy Economics*, 33 (1), 173-198, 2011.

12. Mount, Timothy D.; Alberto J. Lamadrid, Wooyoung Jeon, and K. M. Zhang. The Potential Benefits for Electricity Customers from Controllable Loads. *Proceedings of the 24th Annual CRRI Western Conference*, Monterey, CA, June 2011.

Task 4: Stochastic Simulation of Power Systems with Integrated Variable Energy Resources

George Gross
Alejandro Dominguez-Garcia
Yannick Degeilh

University of Illinois at Urbana-Champaign

THE NEED FOR A NEW SIMULATION APPROACH

- Conventional probabilistic simulation cannot capture the time-varying nature and the inter-temporal effects that characterize storage and renewable resources, nor the impacts of transmission constraints on market outcomes
- Moreover, the detailed representation of such features is analytically intractable

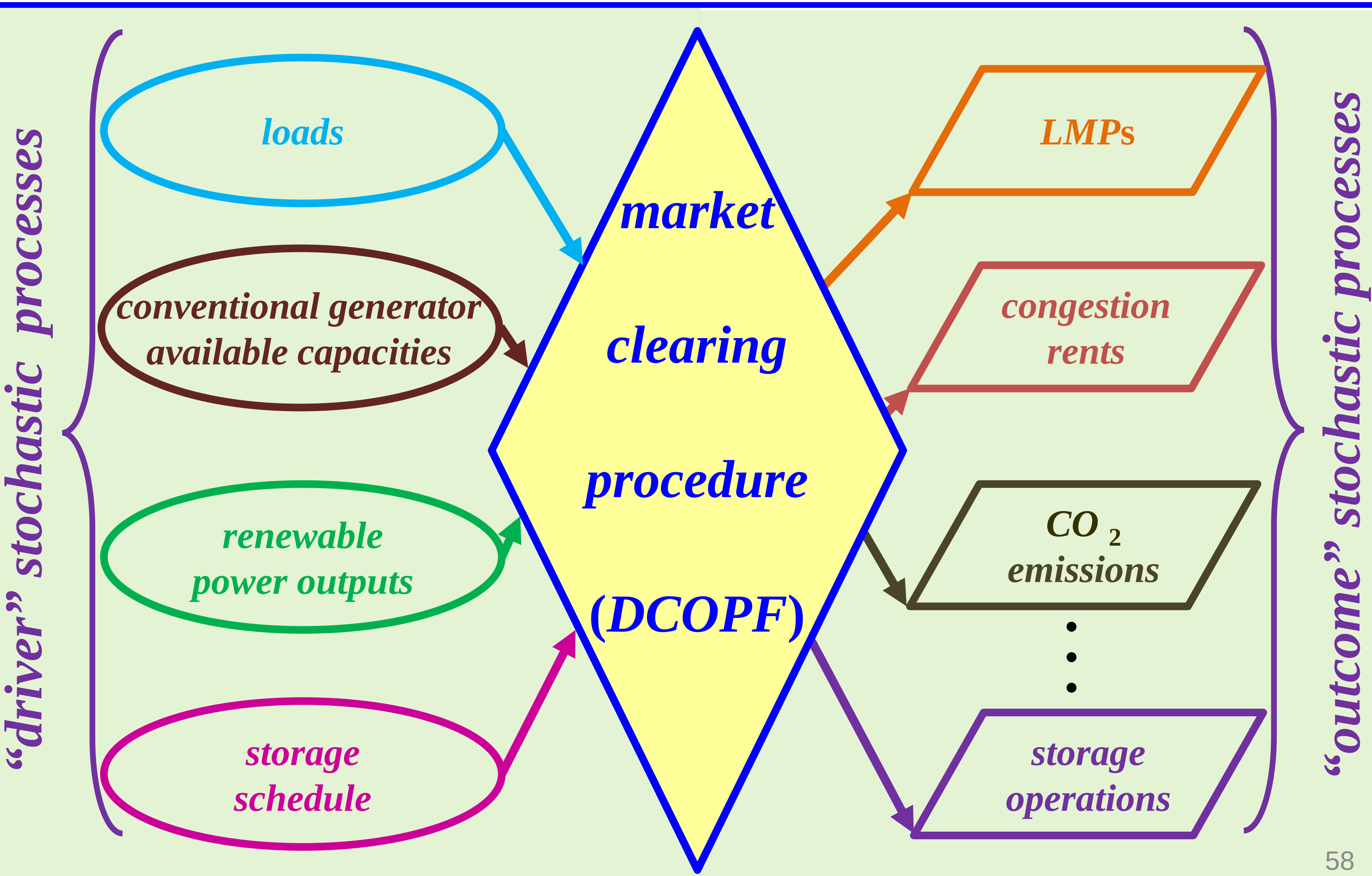
THE NEED FOR A NEW SIMULATION APPROACH

- We developed a new, comprehensive simulation approach using stochastic process representation in a Monte Carlo framework
- Our simulation approach is able to represent the uncertainty in and time–varying nature of the loads, renewable resource outputs and conventional unit available capacities, as well as the time-dependent transmission impacts

THRUST OF THE SIMULATION APPROACH

- **We developed a comprehensive, computationally efficient *Monte Carlo simulation* approach to emulate the behavior of the power system with integrated storage and renewable energy resources**
- **We model the system load and the resources by *discrete-time stochastic processes***
- **We use a *storage scheduler* to exploit arbitrage opportunities in the storage unit operations**
- **We emulate the *transmission-constrained hourly day-ahead markets (DAMs)* to determine the power system operations in a competitive environment**

SIMULATION APPROACH: CONCEPTUAL STRUCTURE



THRUST OF THE APPROACH

- We collect sample paths of the market outcome stochastic processes to evaluate the expected system variable effects
- Metrics we evaluate include:
  - nodal electricity prices (*LMP*s)
  - generation by resource and revenues
  - congestion rents
  - CO_2 emissions
  - *LOLP* and *EUE* system reliability indices

KEY CONTRIBUTIONS

- Development of an effective simulation approach able to address power industry challenges
- Salient features include:
  - quantification of the power system expected variable effects – economics, reliability and environmental impacts – in each sub-period
  - computationally tractable for practical systems

KEY CONTRIBUTIONS

- detailed stochastic models of the time–varying resources and loads allow the representation of spatial and temporal correlations
- storage scheduler for optimized storage operation to exploit arbitrage opportunities
- representation of the transmission–constrained market outcomes
- flexibility in the representation of the market environment/policies in effect

APPLICATION AREAS

- **Resource planning studies**
  - **year of commissioning of a wind farm or storage plant**
  - **siting of a storage unit**
  - **transmission utilization under deepening *ADRR* implementation**
- **Production costing issues**
  - **impacts of various penetration levels of wind and/or storage resources**
  - **impacts of increases in fossil fuel prices**

APPLICATION AREAS

- **Transmission utilization issues**
  - **impacts of renewable storage integration on transmission utilization**
  - **identification of frequently-congested transmission lines for use in the construction of portfolios of financial transmission rights**

APPLICATION AREAS

- **Environmental assessments**
  - **identification of appropriate generation resource mix composition to reduce CO_2 emissions by x % by a specified point in time**
  - **wind and storage resource synergies in terms of CO_2 emission impacts**

APPLICATION AREAS

- Reliability analysis
  - assessment of the effective load carrying capability of renewable resource additions requirements
  - evaluation of the reserves in a power system with deepening levels of renewable penetration

APPLICATION AREAS

- **Investment analysis**
  - **assessment of the expected returns of wind resources investments**
  - **risk assessment of investing in deeper penetration of renewable resources**

APPLICATION AREAS

- **Policy formulation and analysis**
  - **incorporation of a 'cap and trade' carbon market for the US**
  - **assessment of the impacts of a policy aimed at providing financial incentives for the retrofitting of old generation units**

APPLICATION AREAS

- **Broad range of questions**
  - **sensitivity studies on storage sizing**
  - **selection of remuneration schemes for *DRR*s**
  - **scenario analysis of the impacts of future technology developments**
  - **various *what if* questions**

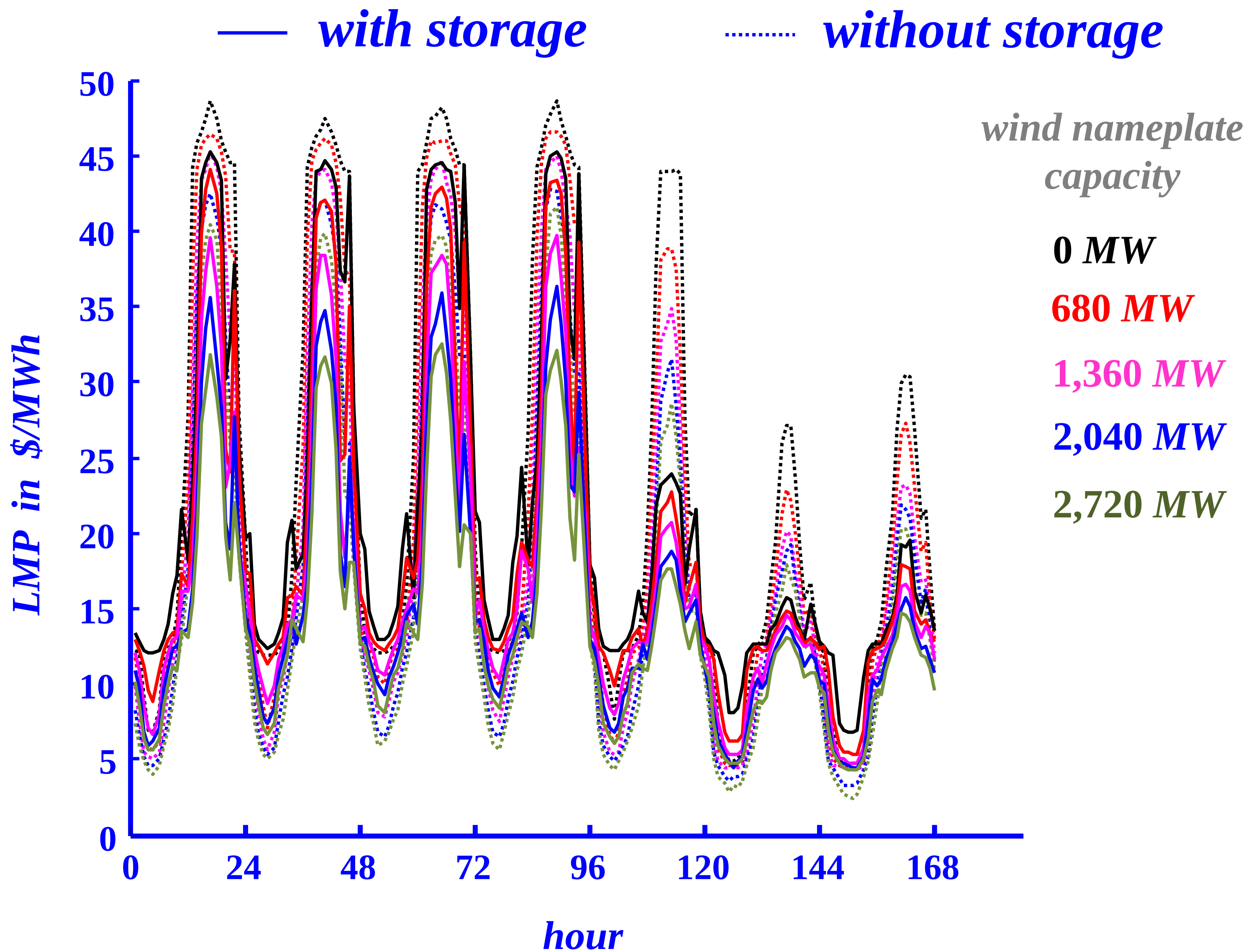
CASE STUDY : DEEPENING WIND PENETRATION

- The objective of this study is to perform a wind penetration sensitivity analysis and to quantify the enhanced ability to harness wind resources with the addition of a storage energy resource
- We evaluate the key metrics for variable effect assessment, including wholesale purchase payments, reliability indices and CO_2 emissions

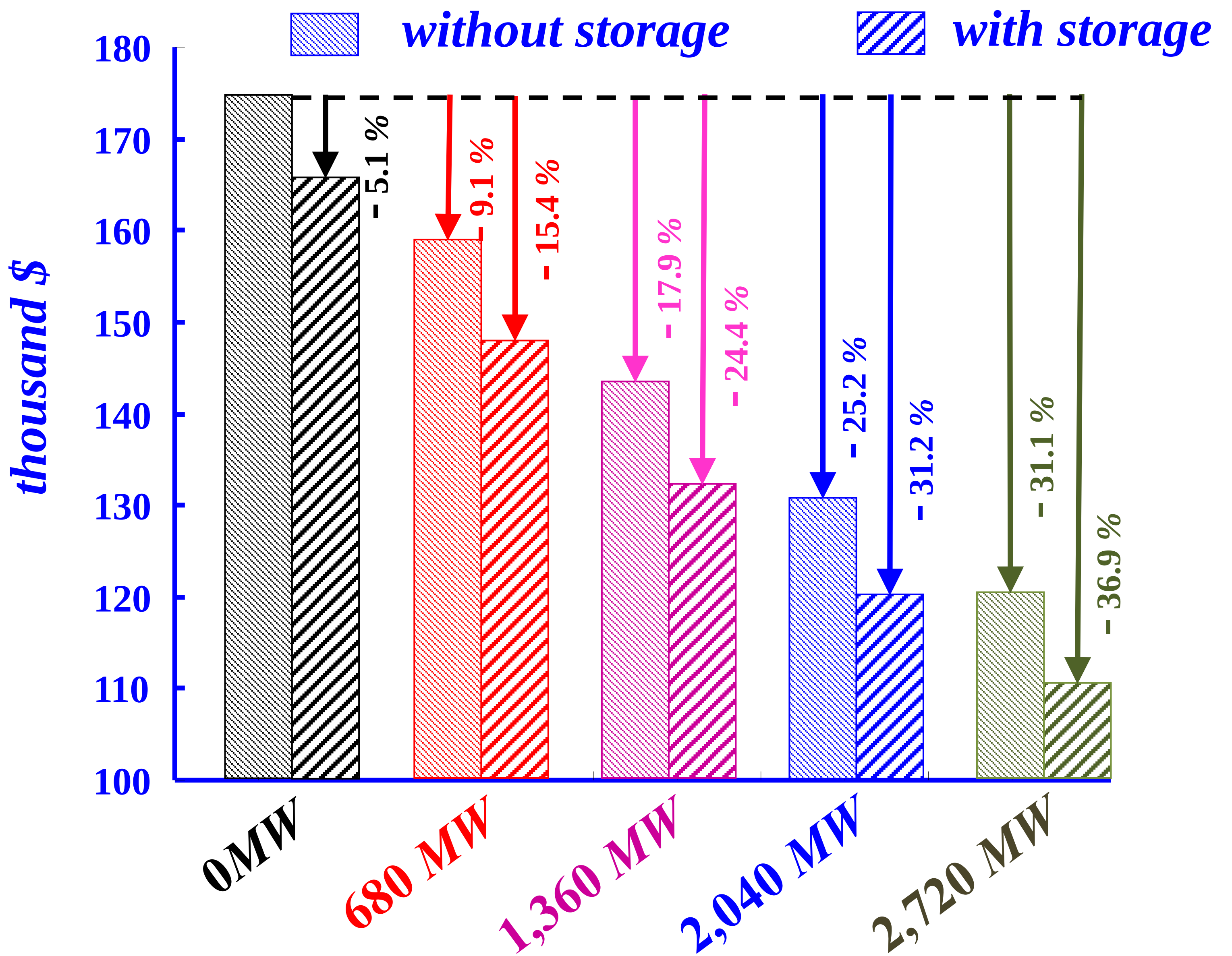
THE STUDY TEST SYSTEM: A MODIFIED IEEE 118-BUS SYSTEM

- **Annual peak load: 8,090.3 *MW***
- **Conventional generation resource mix: 9,714 *MW***
- **4 wind farms located in the Midwest with total nameplate capacity in multiples of 680 *MW***
- **A storage unit with 400 *MW* capacity, 5,000 *MWh* storage capability and 89 *%* round-trip efficiency**
- **Unit commitment uses a 15 *% reserves margin* provided by conventional units *and the storage resources***
- **Wind power is assumed to be offered at *0 $/MWh***

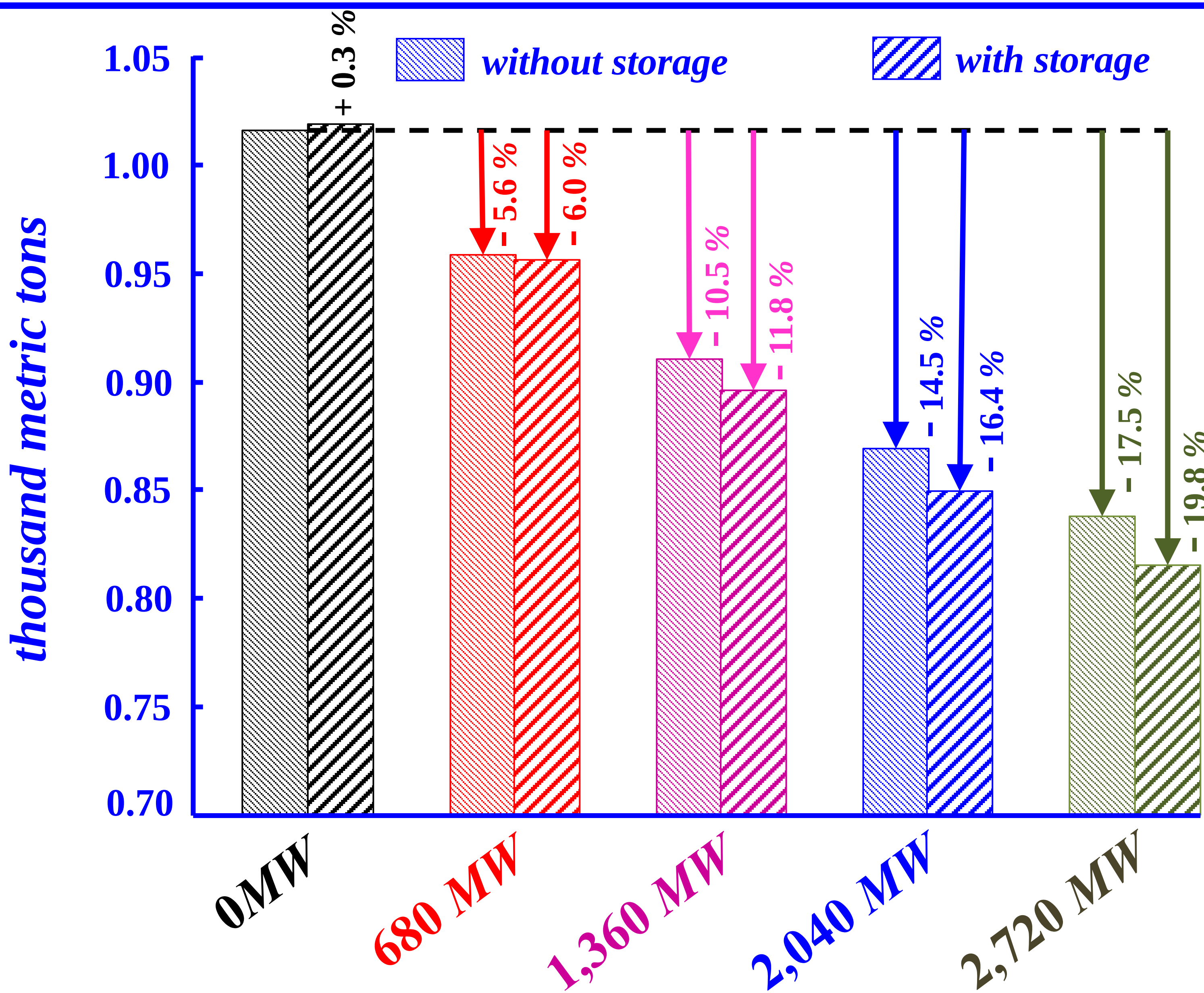
NODE 80 AVERAGE HOURLY *LMP*s



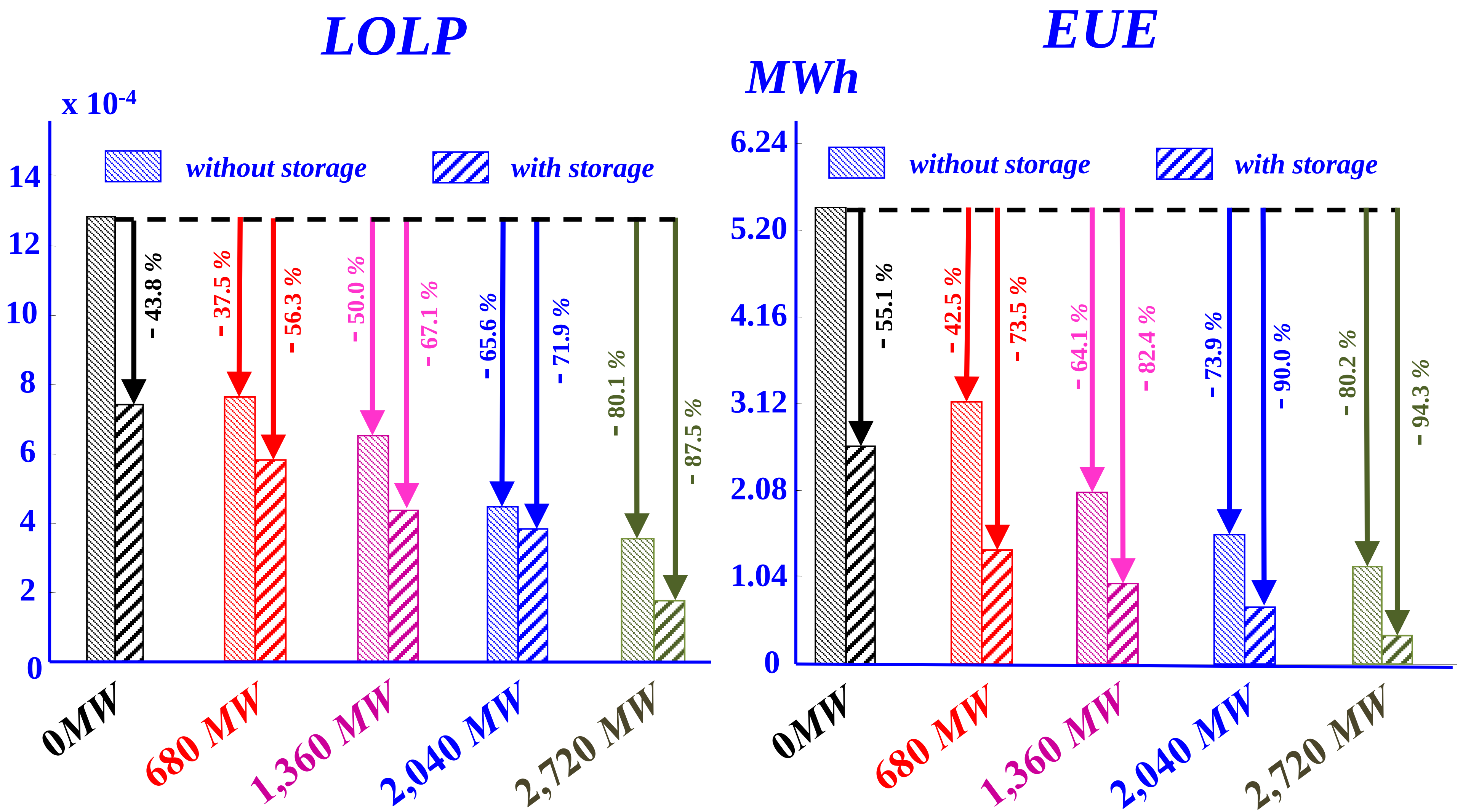
EXPECTED WHOLESALE PURCHASE PAYMENTS



EXPECTED CO_2 EMISSIONS



ANNUAL RELIABILITY INDICES



CONCLUDING REMARKS

- Storage and wind resources consistently pair well together: they reduce wholesale purchase dollars and improve system reliability; storage seems to attenuate the “diminishing returns” trend seen with deeper wind power penetration
- Additional studies are needed to evaluate the impacts of multiple storage units on the power system variable effects and the impacts of storage siting and sizing

REFERENCES

- **Y. Degeilh and G. Gross, "Stochastic Simulation of Power Systems with Integrated Intermittent Energy Resources," under preparation for submission to the *IEEE Transactions on Power Systems*, 2013.**
- **Y. Degeilh and G. Gross, "Simulation of Energy Storage Plants in Power Systems with Integrated Intermittent Energy Resources," under preparation for submission to the *IEEE Transactions on Power Systems*, 2013.**
- **Y. Degeilh, "Stochastic Simulation of Power Systems with Variable Energy Resources," thesis to be submitted to the Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL to fulfill the Ph. D. degree requirements, 2013.**

Contact Information

Shmuel Oren (oren@ieor.berkeley.edu)

Duncan Callaway (dcal@berkeley.edu)

George Gross (gross@illinois.edu)

Tim Mount (tdm2@cornell.edu)