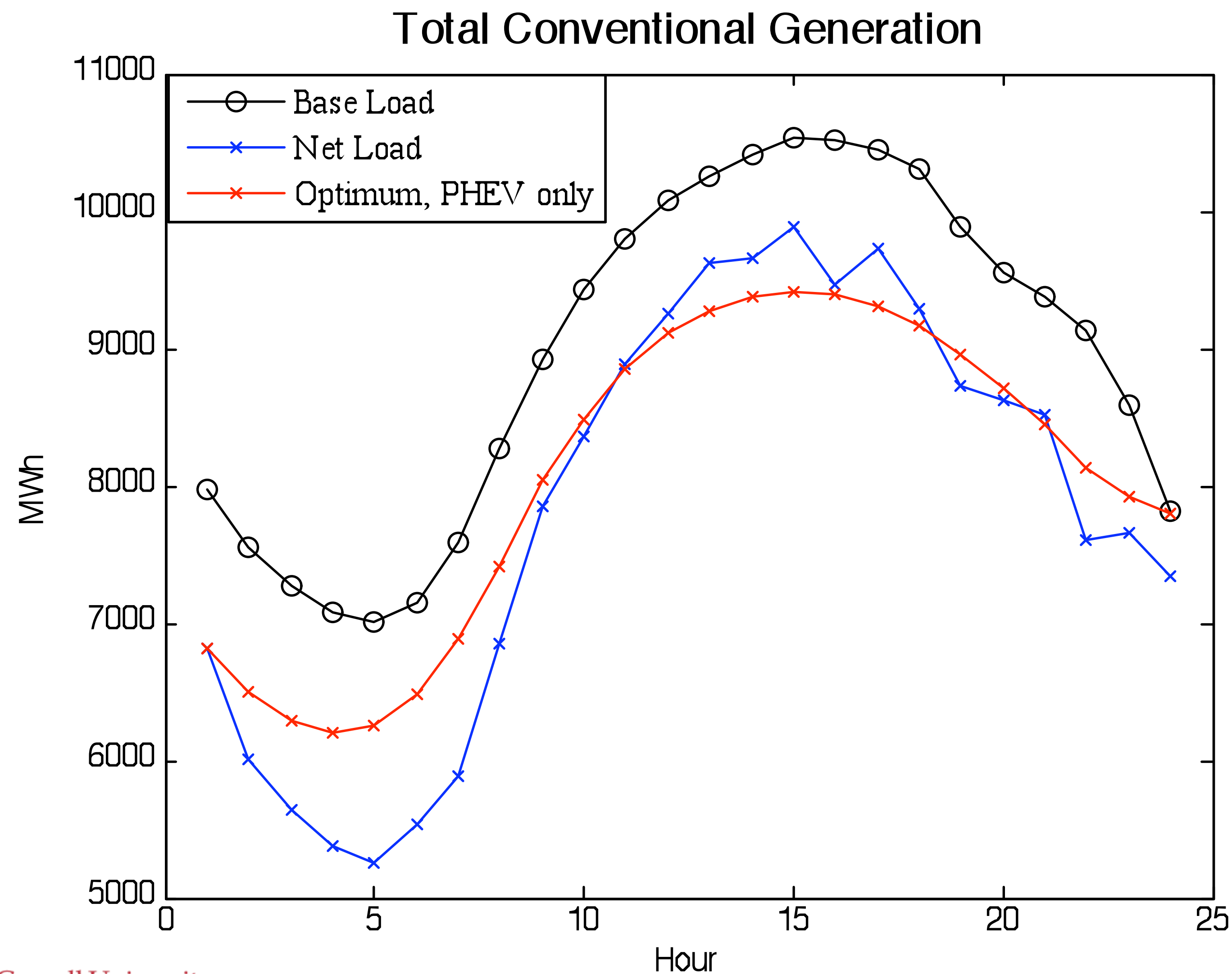
Utopia Electric: Developing a Smart Grid that Customers can Afford

Tim Mount, Wooyoung Jeon and Jung Youn Mo
Cornell University

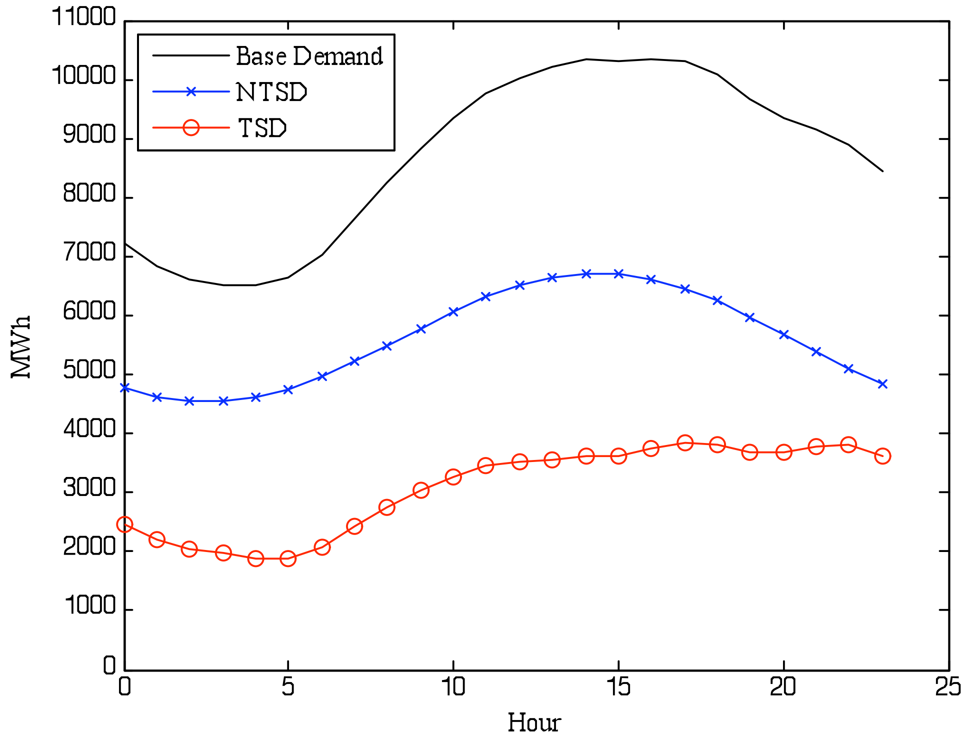
The Problems

- The Transition to a Low-Carbon Economy
  – Electrify the delivery of almost all energy services (e.g. transportation and heating)
  – Rely more on variable generation from renewable sources (e.g. wind and solar)
  – Maintain current standards of reliability
- The Economic Effects on Electricity Markets
  – Lower wholesale prices for energy because renewable sources displace fossil fuels
  – Higher amounts of “missing money” for conventional generation and transmission capacity
- The Economic Effects of a Smart Grid
  – Customers must see some direct economic benefit
  – Need to find substantial cost reductions in operating the conventional generation and transmission system

The System Effects from a High Penetration of PHEVs are Relatively Small



Demand for a hot summer day in New York City (July 16, 2010)



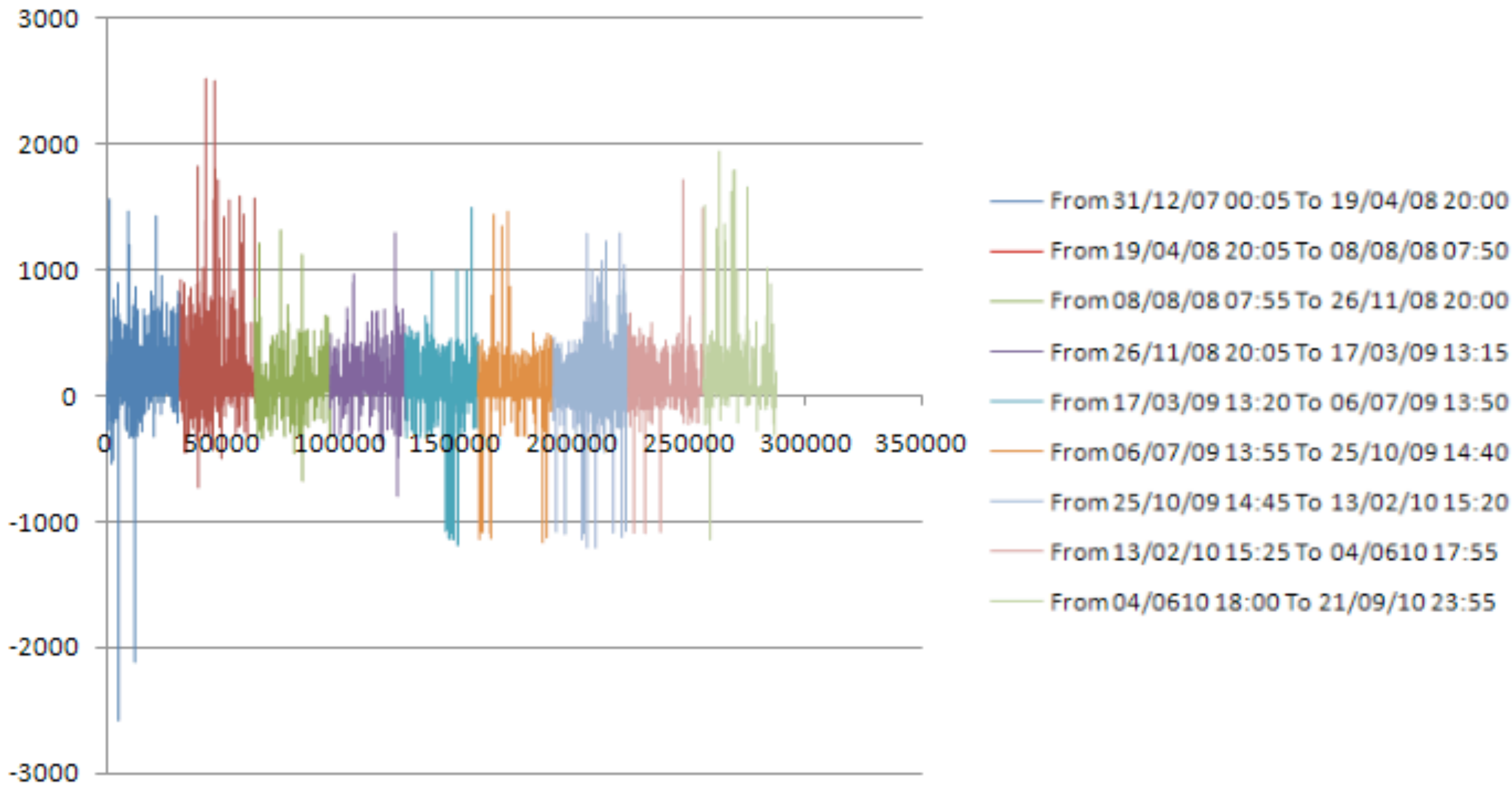
- Cumulative Demand for electric energy over 24 hrs: 208 Gwh
- Cumulative Temperature-Sensitive Demand over 24 hrs: 74 Gwh
- TSD is 35% of the cumulative demand (and 35% of the peak system demand)
- Consistent with EIA data (30% of the total electricity demand is used for cooling during the summer)

Distinguishing Temperature-Sensitive Demand (TSD) from Non-Temperature-Sensitive Demand (NTSD)

TSD is a potentially large source of controllable demand

Frequent Low Prices Caused by Wind

Five Minute Prices in New York City



Economically attractive to buy electric energy when the price is negative

Model Specifications

Specifications for the Analysis

- 10 GWh of customer storage is added to the system
  - 5 GWh from electric vehicles (PHEV Volt)
  - 5 GWh from thermal storage (Ice batteries)
- A System Operator controls all storage to minimize the total system costs, including ramping
- Customers pay for both Energy and Ramping using prices determined by the System Operator
- All customers are assumed to have identical patterns of demand for electrical energy services
  - Thermal storage disconnects the timing of the purchases of electricity from the delivery of cooling services
  - Electric vehicles increase electricity demand but have smart chargers, V2G capabilities and reduce gasoline purchases

Storage Specification

	THERMAL	PHEV
Capacity (GWh)	5	5
individual storage size (KWh)	20	10
# of Customer with Storage	250,000	500,000
Penetration Rate	6.4%*	44.2%**
Charging Efficiency	90%	90%
Discharging Efficiency	90%	90%
Charging Speed (KWh/hr)	2	3.31
Discharging Speed (KWh/hr)	5	3.31

- * Of the total Temperature Sensitive Demand
- ** Of the number of commuters into New York City
  - Drivers commute during 7~9AM & 4~6PM
  - Average driving distance is 27.2 miles
  - All vehicles are PHEV Volts

Simplified Optimization Criterion

Minimize the daily cost of energy and ramping

$$\underset{Th_t, Ph_t}{Min} \sum_{t=1}^{24} EP_t \cdot (L_t - W_t + C_{Th} \cdot Th_t + DP \cdot C_{Ph} \cdot Ph_t)$$

$$+ RP_t \cdot \left| \Delta (L_t - W_t + C_{Th} \cdot Th_t + DP \cdot C_{Ph} \cdot Ph_t) \right| - P_{FEIS} \cdot FEIS$$

s.t.

$$SCL_{Th} \le \sum_{t=0}^{T'} Th_t \le SCU_{Th}, \qquad 0 \le T' \le T$$

$$SCL_{Ph} \le \sum_{t=0}^{T'} Ph_t \le SCU_{Ph}, \qquad 0 \le T' \le T$$

$$HCL_{Th} \le Th_t \le HCU_{Th}$$

$$HCL_{Ph} \le Ph_t \le HCU_{Ph}$$

$$EP_t = a + b \cdot (L_t - W_t + C_{Th} \cdot Th_t + DP \cdot C_{Ph} \cdot Ph_t)$$

$$RP_t = c \cdot EP_t \cdot \left| \Delta (L_t - W_t + C_{Th} \cdot Th_t + DP \cdot C_{Ph} \cdot Ph_t) \right|$$

Glossary for the Optimization

EP_t : Energy Price at t

RP_t : Ramping Price at t

L_t : Base Load at t

W_t : Wind Load at t

Th_t : Load stored or discharged by THERMAL Storage at t

Ph_t : Load stored or discharged by PHEV Storage at t

C_{Th} : Charging Efficiency of THERMAL Storage

C_{Ph} : Charging Efficiency of PHEV Storage

DP : Driving Profile

SCL:Storage Capacity Lower bound

SCU:Storage Capacity Upper bound

HCL:Hourly Charging Lower bound

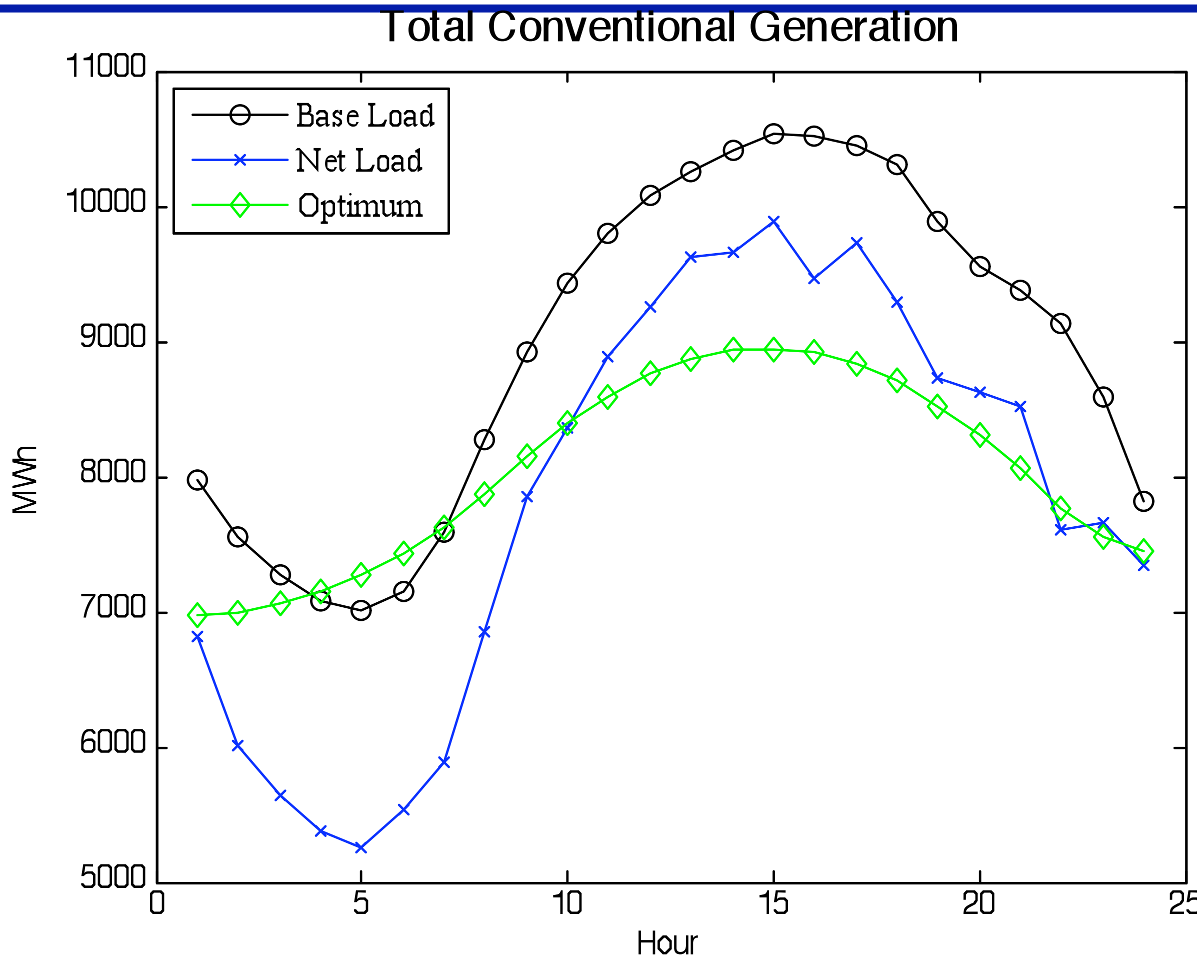
HCU:Hourly Charging Upper bound

a, b:estimated from market data

c:Scaling parameter for Ramping Price, $\frac{1}{100}$

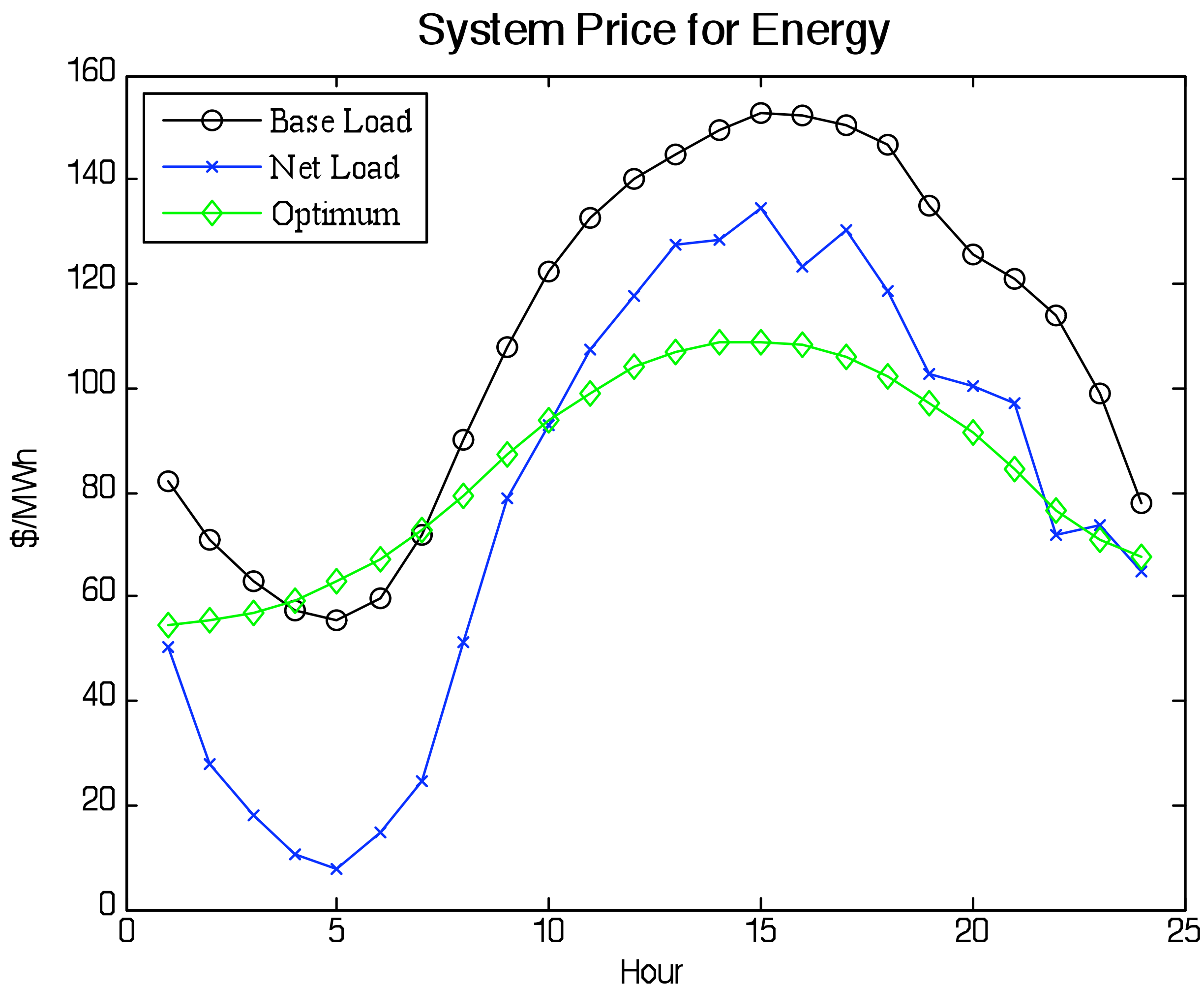
System Level Results

Total Conventional Generation

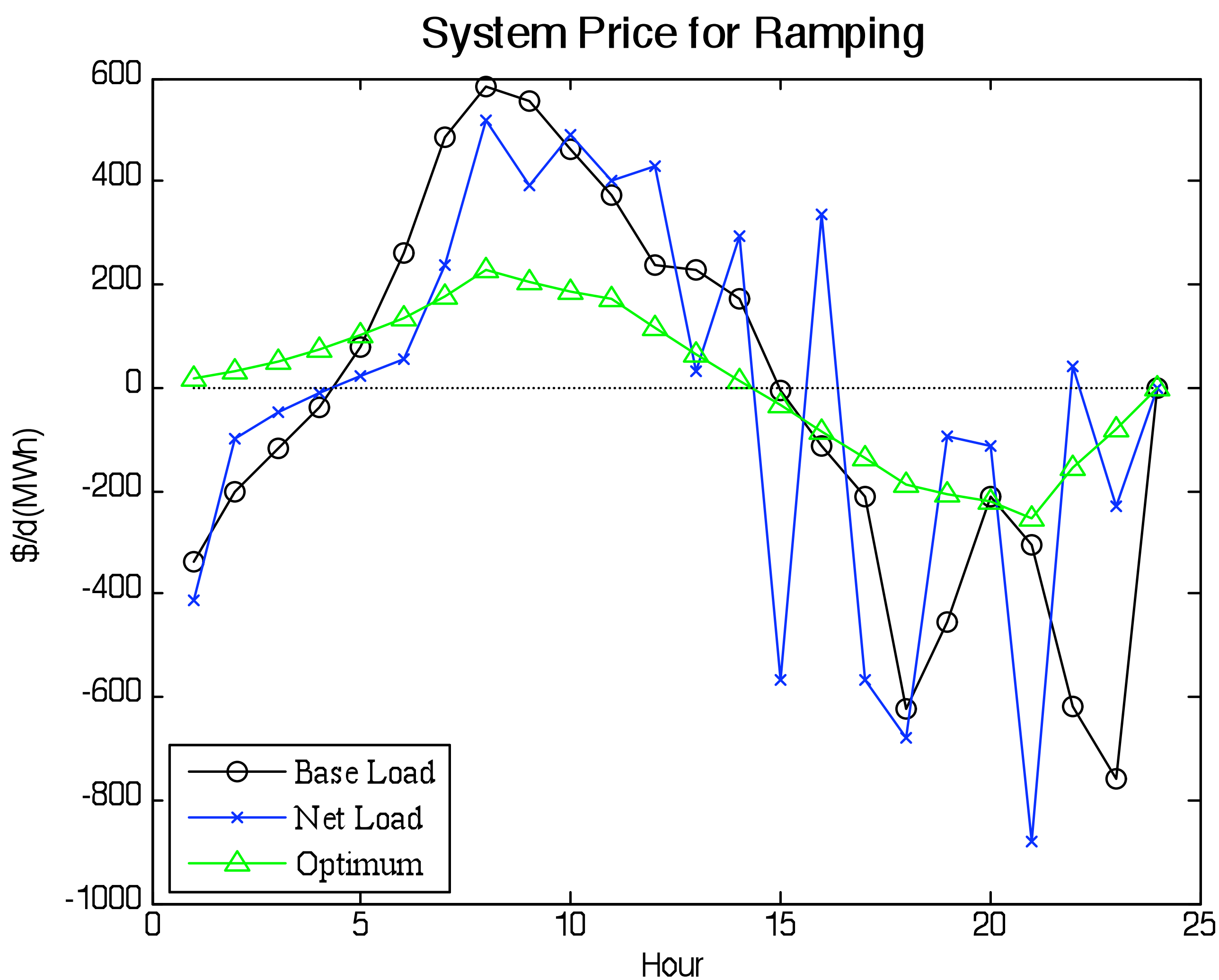


- Net Load is defined as Base Load – Wind
- Wind data are from NREL and wind capacity is assumed to be 2GW
- Wind generation accounts for 12% of total daily demand

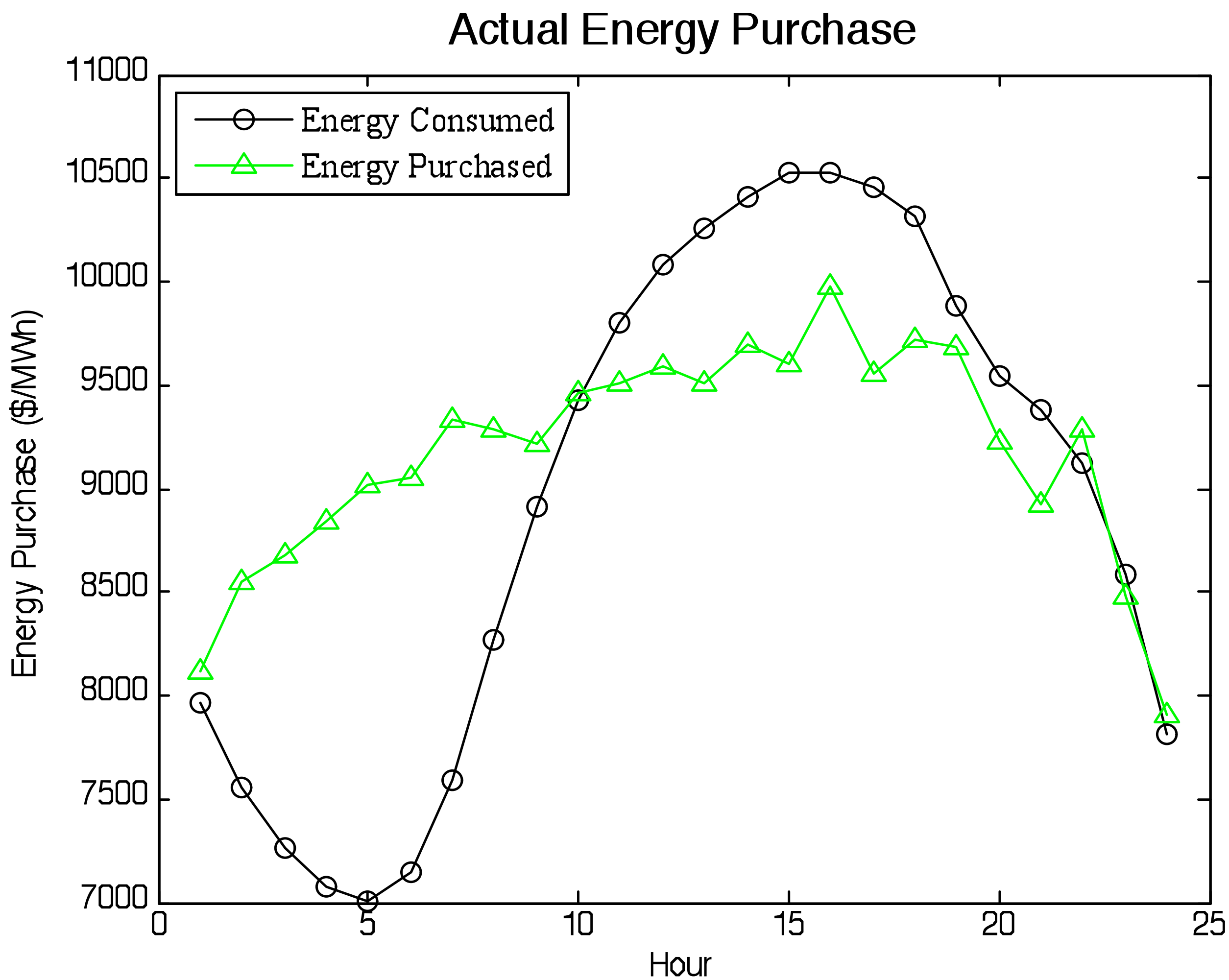
System Price for Energy



System Price for Ramping



Optimum Energy Purchased and Energy Consumed



Total System Costs and Total Payments by All Customers

	Base Load	Net Load	Optimum Load	Payment at Optimum
Energy Cost ($1000)	24,477	16,236	16,547	18,734
Ramping Cost($1000)	3,204	3,855	469	296
Total Operating Cost($1000)	27,681	20,091	17,016	19,030
FEIS(MWh)*	0	0	123	-
Value of FEIS($1000)*	0	0	25	25
Total Cost of Serving Load($1000)	27,681	20,091	16,991	19,006
Max System Load(MW)	10,529	9,879	8,838	-
Capacity Cost($1000)**	18,530	17,386	15,554	16,698
TOTAL SYSTEM COST($1000)	**46,211**	**37,477**	**32,546**	**35,704**
Total Saving in Gasoline($1000)***	0	0	2,720	2,720
TOTAL COST TO CUSTOMERS	**46,211**	**37,477**	**29,826**	**32,984**
% Cost Reduction from Base Load	**-**	**18.9%**	**35.5%**	**28.6%**

* Final Energy In Storage(FEIS), Valued at $120/MWh (Average Peak Price).

** Annual Capital Cost for Peaker $88k/MW/year allocated to 100 peak hours. Specify 2 peak hours for this hot day.

***Each vehicle drives 27.2 Miles at 20 Miles/Gal at $4/Gal.

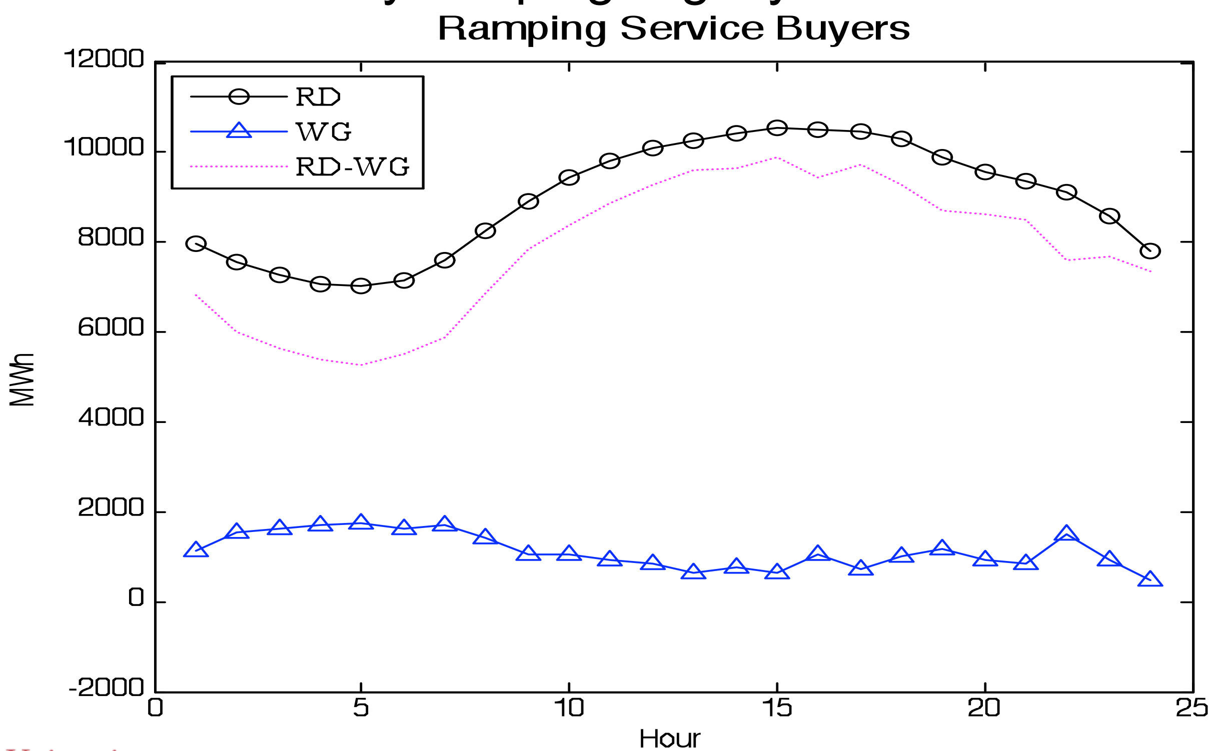
Ramping Service Buyers
(Cause Ramping)

1) Regular Demand (RD)

   Creates the initial daily pattern of ramping.

2) Wind Generation (WG)

   Increases daily ramping slightly and adds variability



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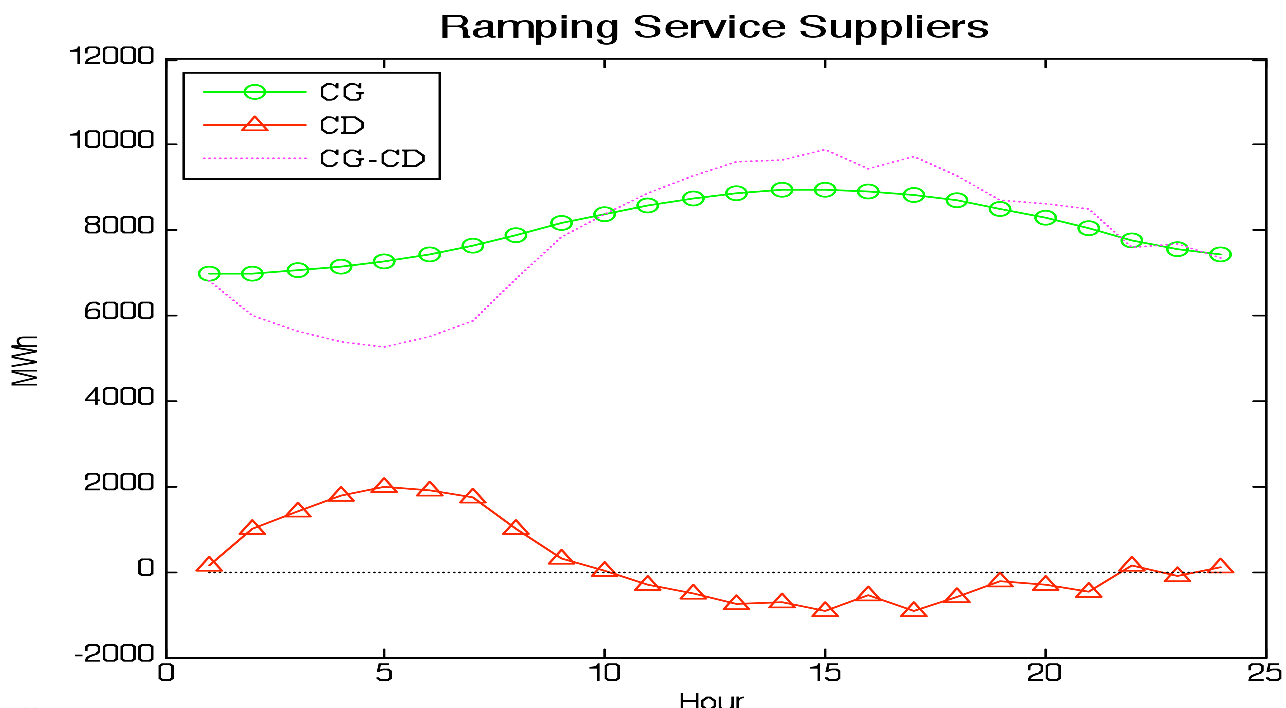
Ramping Service Suppliers (Mitigate Ramping)

3) Conventional Generation (CG)

Offsets some of the ramping caused by 1) RD – 2) WG

4) Controllable Demand (CD)

Provides most of the ramping service



Composition of Payments

	Ramping Payment ($1000)	Energy Payment ($1000)	Total Payment ($1000)	Total Energy (MWh)	Average Payment ($/MWh)
1) RD	2,120	18,599	20,719	214,911	96
2) WG	1,735	-2,186	-451	27,070	-17
3) CG	-858	-17,001	-17,859	197,814	-90
4) CD	-2,997	588	-2,408	14,941	-161
Buyers	(1)+(2) = 3,855	(1)+(4) = 19,187			
Suppliers	(3)+(4) =-3,855	(2)+(3) =-19,187			

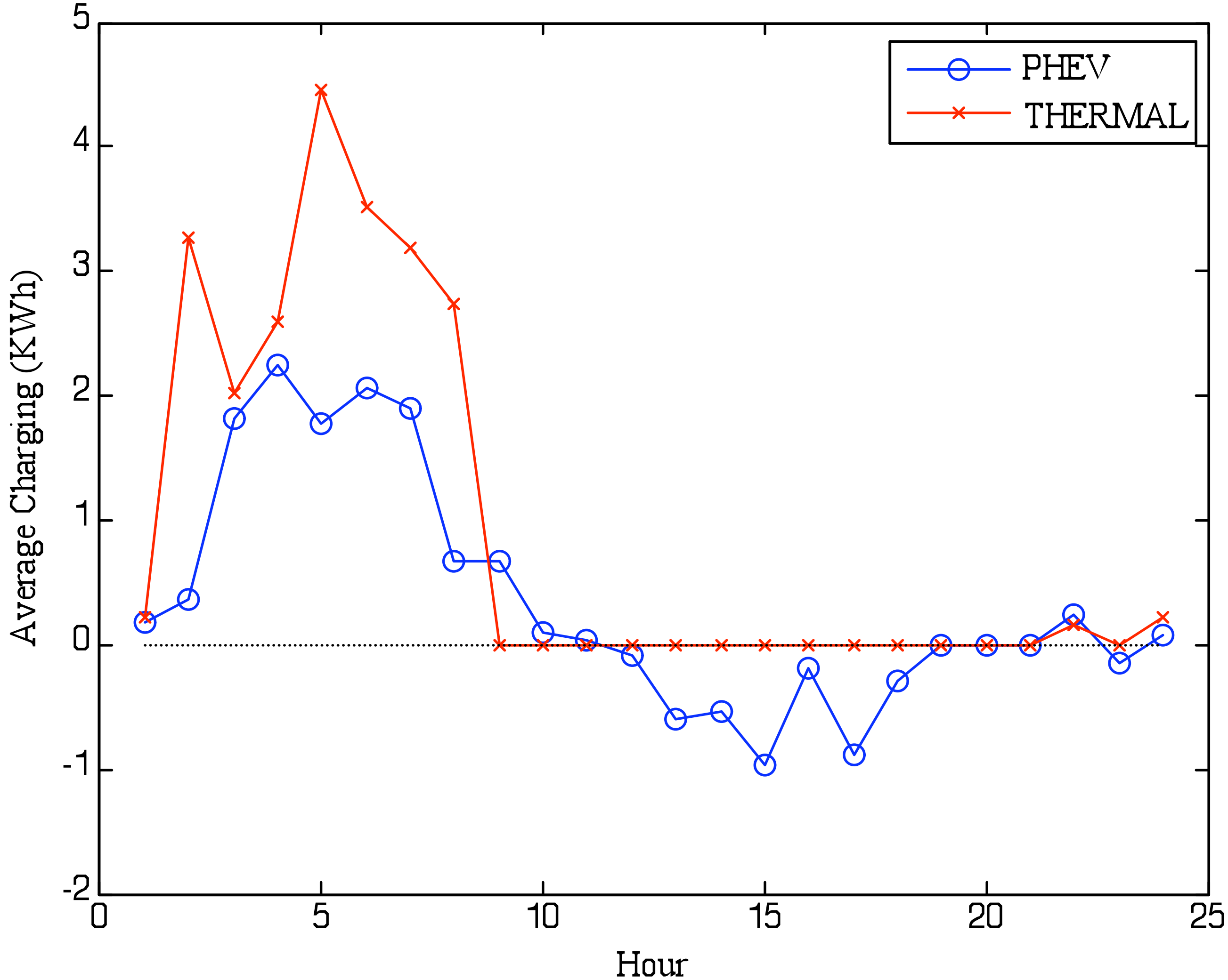
- Positive (Negative) payments indicate Paying (Being Paid) for a service.
- RD, Regular Demand and CD, Controllable Demand
- WG, Wind Generation and CG, Conventional Generation
- The SYSTEM COST of ramping is caused by ramping CG
- WG accounts for 12% of Energy Supply and 45% of Ramping Demand
- CD accounts for 3% of Energy Demand and 78% of Ramping Supply

Results for Different Types of Customer

Consider Four Types of Customer

- Assume that there are one million customers with identical initial daily patterns of demand
  - Type 1 → No storage capabilities
  - Type 2 → Add THERMAL storage
  - Type 3 → Buy a PHEV Volt
  - Type 4 → Both THERMAL and PHEV
- All customers pay for:
  - ENERGY using real-time prices (PHEV can be paid)
  - CAPACITY at the peak system load
  - RAMPING using real-time prices (can be paid for reducing the system ramp)

Hourly Purchases per Customer for PHEV and THERMAL



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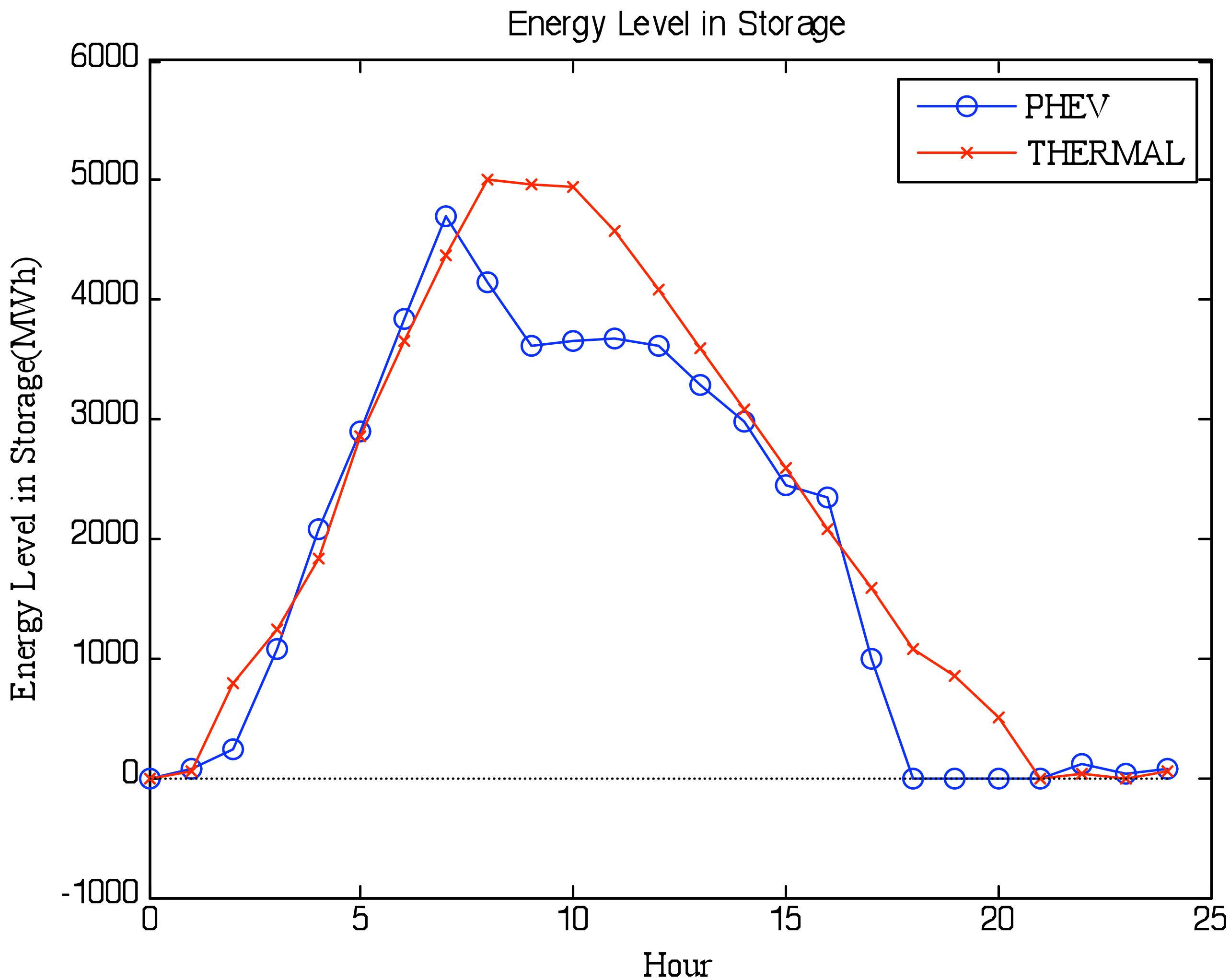
Hourly Levels of Optimum Stored Energy in PHEV and THERMAL



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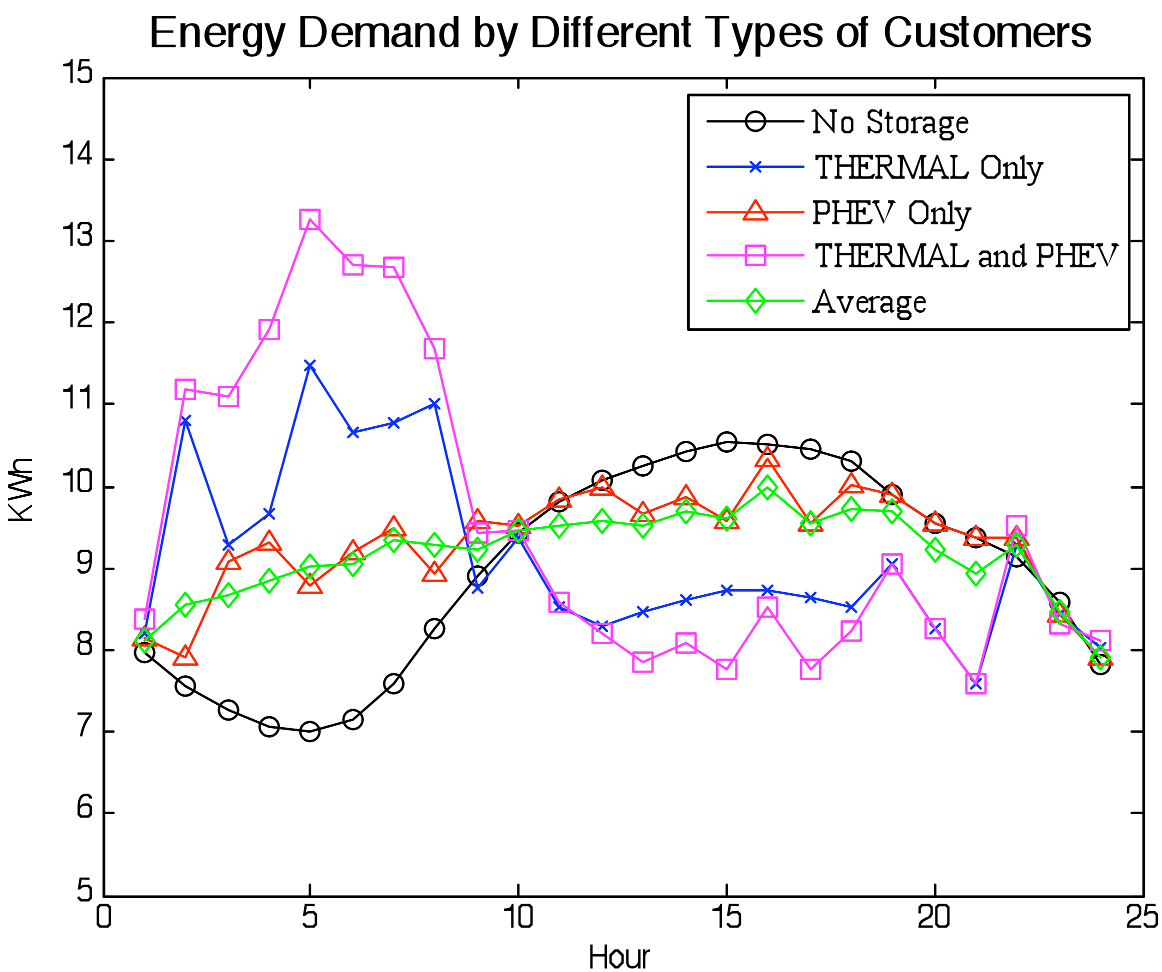
Energy Purchased by Different Types of Customer



THERMAL customers do the heavy lifting

Total Payments Per Customer

	Base Load	Net Load	No Storage	THERMAL only	PHEV only	THERMAL & PHEV	Average
Energy Payment ($)	24.48	18.03	18.60	18.27	19.03	18.71	18.73
Ramping Payment ($)	3.20	2.12	0.89	-0.37	0.33	-0.92	0.30
Total Payment ($)	27.68	20.15	19.49	17.90	19.37	17.78	19.03
Value of FEIS ($)	0	0	0	0.04	0.01	0.05	0.01
Total Payment of Serving Load ($)	27.68	20.15	19.49	17.86	19.36	17.73	19.02
KW at System Peak (KW)	10.53	10.53	10.53	8.73	9.35	7.55	9.49
Capacity Payment ($)	18.53	18.53	18.53	15.36	16.45	13.28	16.70
Total SYSTEM Payment ($)	**46.21**	**38.68**	**38.02**	**33.22**	**35.81**	**31.02**	**35.71**
Saving in Gasoline ($)	0	0	0	0	5.44	5.44	2.72
AVERAGE PAYMENT ($)	**46.21**	**38.68**	**38.02**	**33.22**	**30.37**	**25.58**	**32.99**
% Reduction from Base Load		**16.3%**	**17.7%**	**28.1%**	**34.3%**	**44.7%**	**28.6%**

Optimum ENERGY payments are similar for all types of customer.
Optimum CAPACITY and RAMPING payments are lower with storage.
Customers with both THERMAL and PHEV are the big winners.

Conclusions

CONCLUSIONS

- High penetrations of wind generation lower the wholesale price of energy BUT increase ramping (variability) costs for the conventional generators
- Storage/controllable demand shifts demand from peak to off-peak periods AND mitigates the variability of generation from renewable sources
- Customers (aggregated) who own some controllable demand can get substantial economic benefits by:
  - Purchasing more energy at low off-peak prices
  - Reducing their demand (capacity) during peak load periods
  - Selling ramping services to mitigate wind variability
- All market participants should pay for the services they use and get paid for the services they provide

Issues for Future Research
(Issues for FERC are RED)

- The economic benefits of controllable demand for the grid are not adequately represented by the rates charged to customers
  - Net payments by customers to the grid must be lower
  - Correct measurement and payments needed for each customer's peak demand
  - Customers should pay/get paid for using/supplying ramping services
- The inherent variability of generation from renewable sources and the difficulty of forecasting these sources accurately are incompatible with the current structure of day-ahead markets and unit commitment
  - Need a rolling horizon for optimizing real-time dispatch that uses updated forecasts of potential renewable generation and system conditions
  - Customers or aggregators should get updated (non-binding) projections of future prices at least 24hrs ahead to manage storage efficiently (e.g. like Australia)
- The structures/capabilities of existing distribution networks are major weak links in the electric delivery system for a future smart grid
  - Need scheduling algorithms for coordinating multiple stochastic sinks of controllable demand to improve grid efficiency and for accommodating multiple sources of variable generation from renewable sources of energy