Carnegie Mellon Electricity Industry Center

Overview of Research in the Carnegie Mellon Electricity Industry Center

Jay Apt
Tepper School of Business
and Department of Engineering & Public Policy

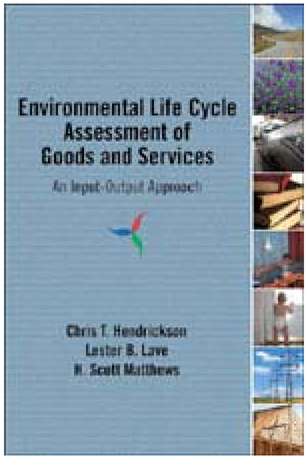
Overview of CEIC

- We are in our 7th year
- 20 CMU faculty plus 5 associates elsewhere
- 16 current Ph.D. students
- 15 Ph.D. dissertations completed
  - Former Ph.D. students now at U. of British Columbia, U. of Calgary, Duke, U. of Minnesota, Penn State, U. of Vermont, E3, EPA, LECG, RFF, WorleyParsons

- One of 27 Sloan Centers of Excellence
- Created jointly with EPRI
- Founded in August 2001 after competitive proposals.
- We define ‘Electricity Industry’ broadly to include the companies that supply the equipment, all the organizations that build and operate the nation’s electric power system, agencies that shape and regulate the system as well as customers who use the power.
- Close cooperation with all stakeholders: Industry, regulators, government agencies, consumers, labor, national laboratories.
- Strategic focus on middle and long-term issues

Some research grows from tools developed here

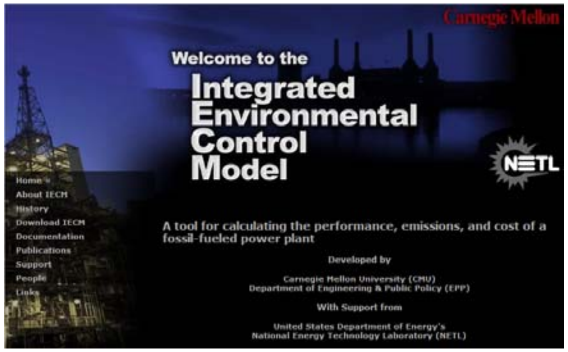
- EIO-LCA
- IECM
- Risk Analysis
- Risk Communication
- Expert Elicitation



Environmental Life Cycle
Assessment of
Goods and Services

An Input-Output Approach

Chris T. Hendrickson
Lester B. Lave
H. Scott Matthews



Carnegie Mellon

Welcome to the
Integrated
Environmental
Control
Model

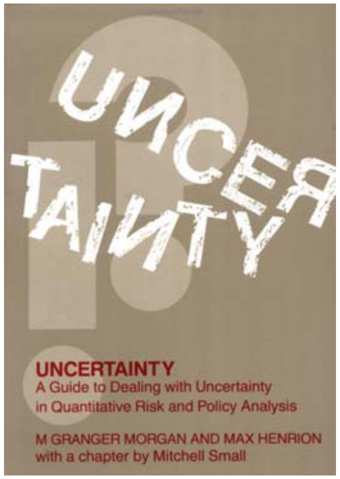
A tool for calculating the performance, emissions, and cost of a fossil-fueled power plant

Developed by

Carnegie Mellon University (CMU)
Department of Engineering & Public Policy (EPP)

With Support from

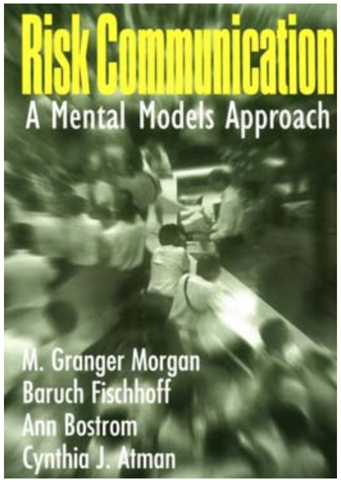
United States Department of Energy's
National Energy Technology Laboratory (NETL)



UNCERTAINTY

UNCERTAINTY
A Guide to Dealing with Uncertainty
in Quantitative Risk and Policy Analysis

M GRANGER MORGAN AND MAX HENRION
with a chapter by Mitchell Small



Risk Communication
A Mental Models Approach

M. Granger Morgan
Baruch Fischhoff
Ann Bostrom
Cynthia J. Atman

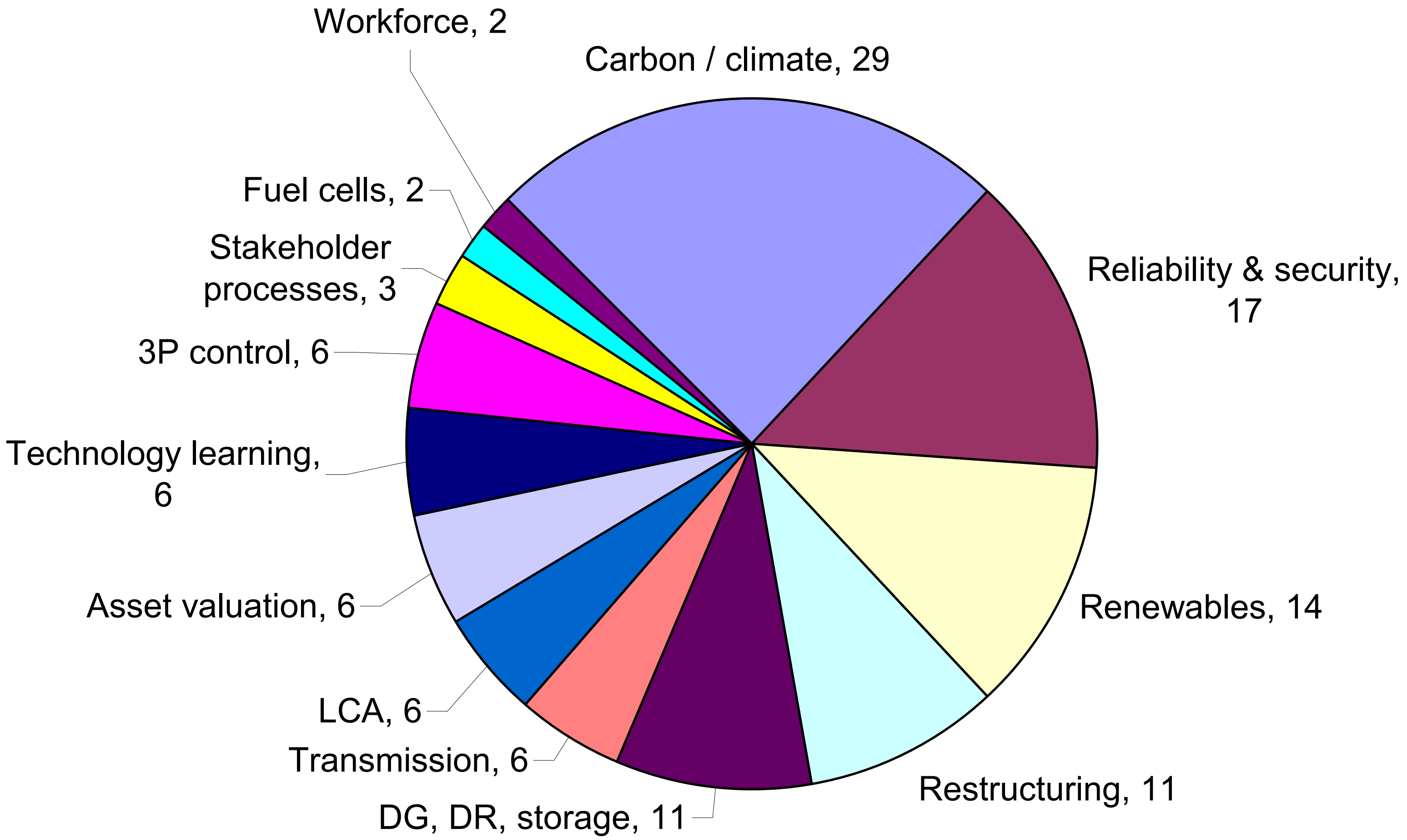
Research builds on our faculty’s expertise

- Public perceptions of CO_2 sequestration
- Sequestration regulatory environment
- Renewables (wind, solar, biomass)
- Air pollution, and human health
- DG, DER, micro-grids
- Agents, and control of cascading grid failures
- ASPEN-based plant modeling
- Energy efficiency

Strategic pieces

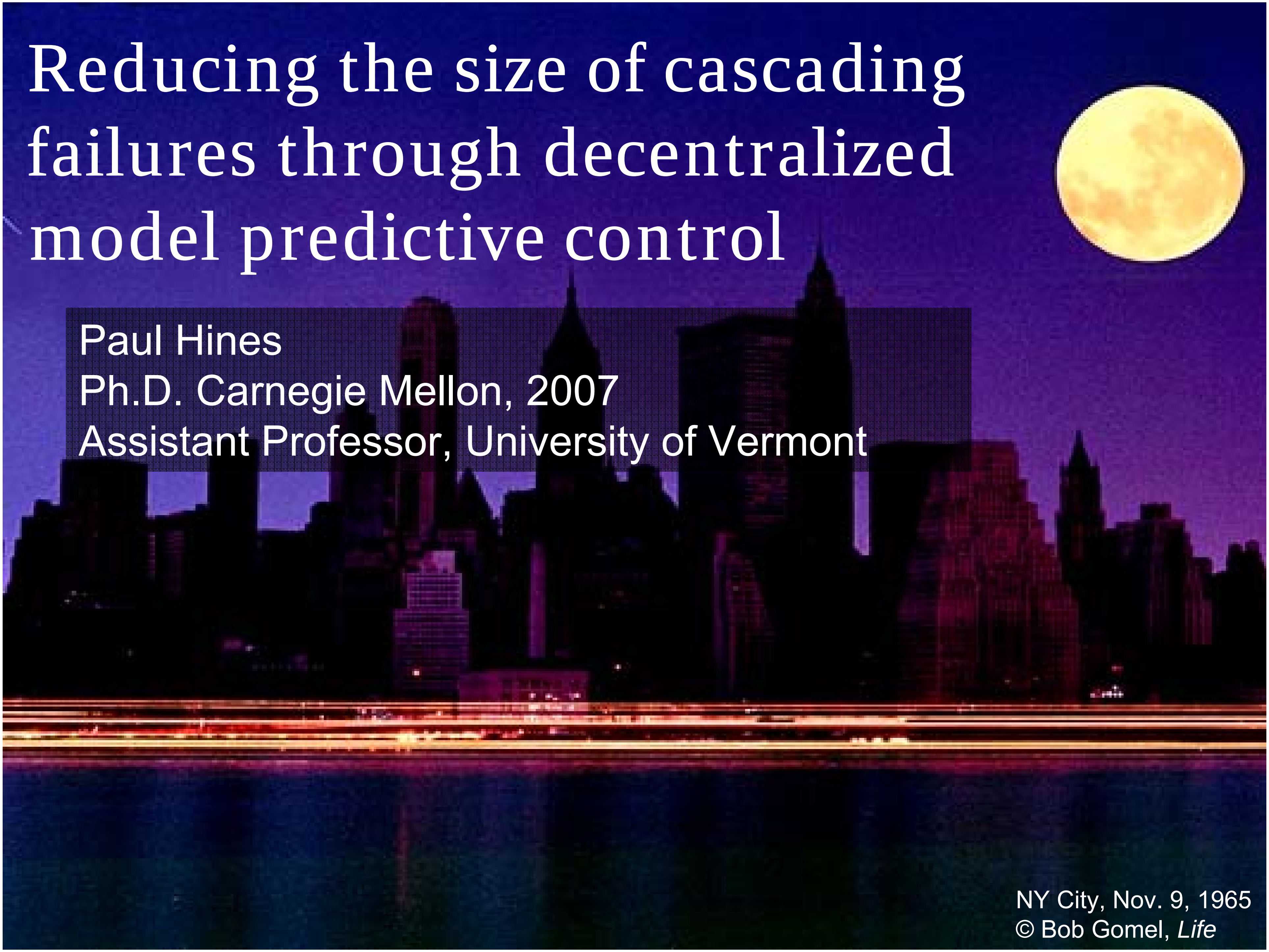
- Carbon dioxide control
- Reliability and security
- Renewables and their implications for reliability and 4P emissions
- Markets
- DG, DER, efficiency, storage
- Technology learning

Rough breakdown of journal articles



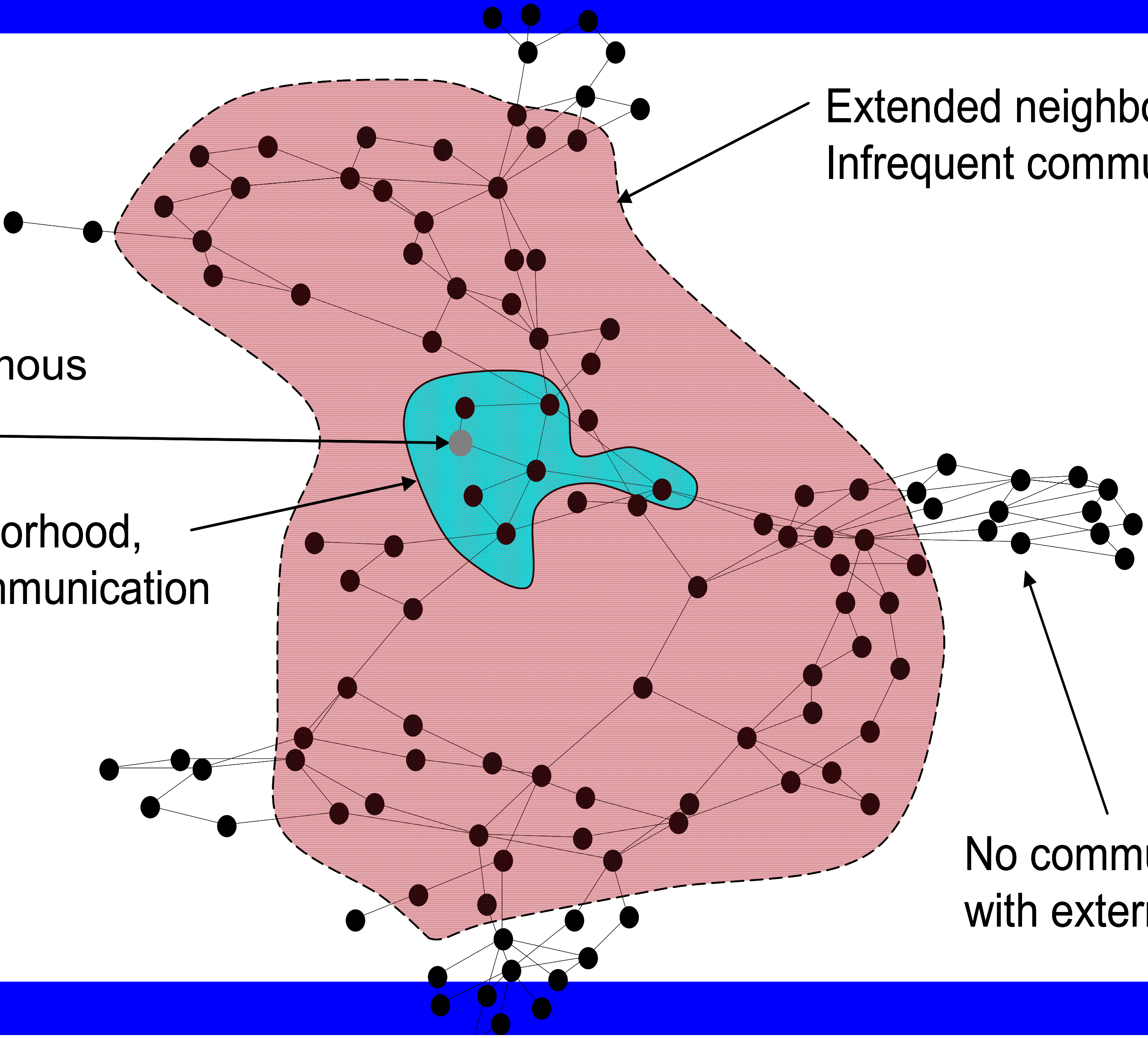
Reducing the size of cascading failures through decentralized model predictive control

Paul Hines
Ph.D. Carnegie Mellon, 2007
Assistant Professor, University of Vermont



NY City, Nov. 9, 1965
© Bob Gomel, *Life*

Agent neighborhoods



Extended neighborhood,
Infrequent communication

Autonomous

Agent

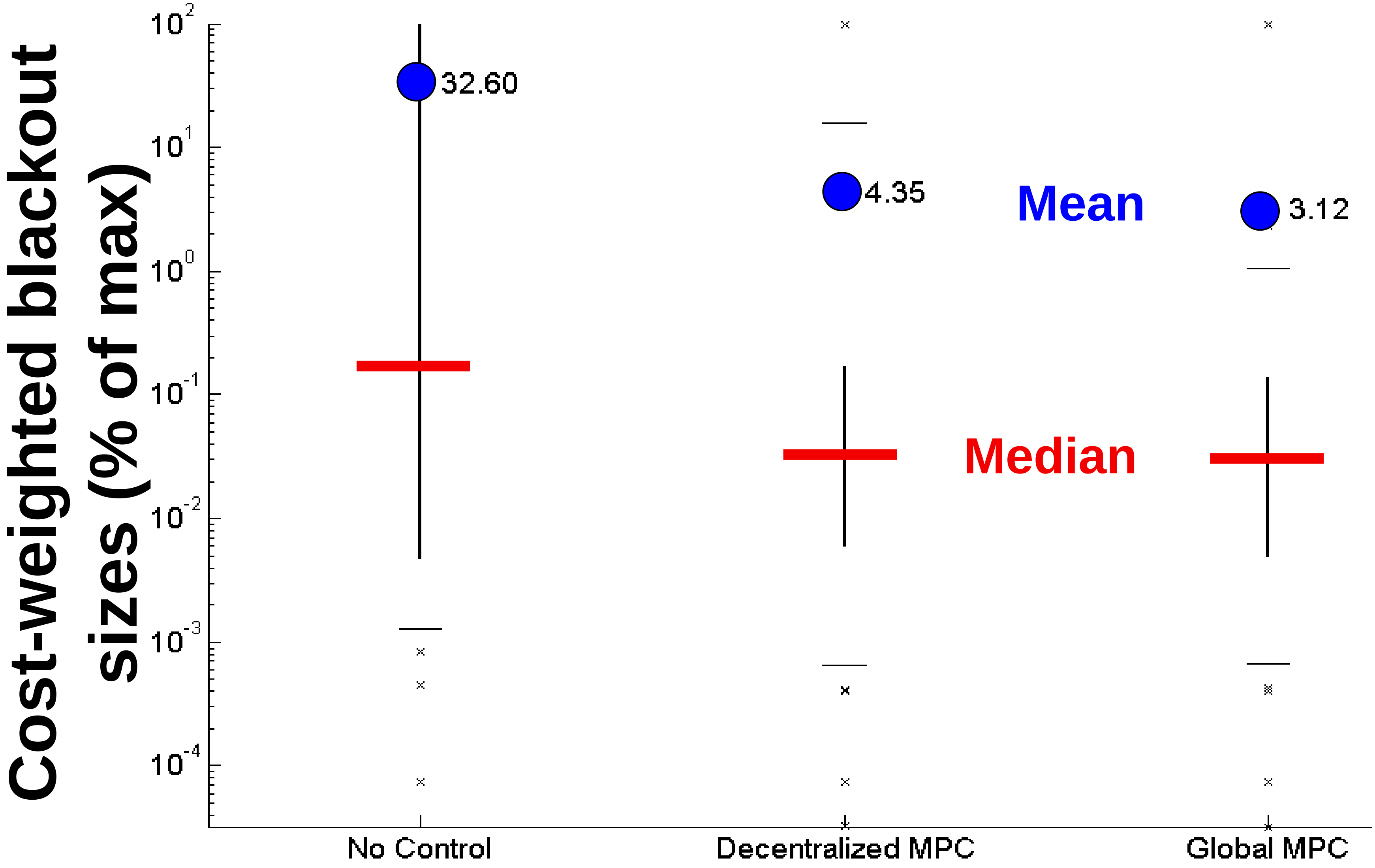
Local neighborhood,
frequent communication

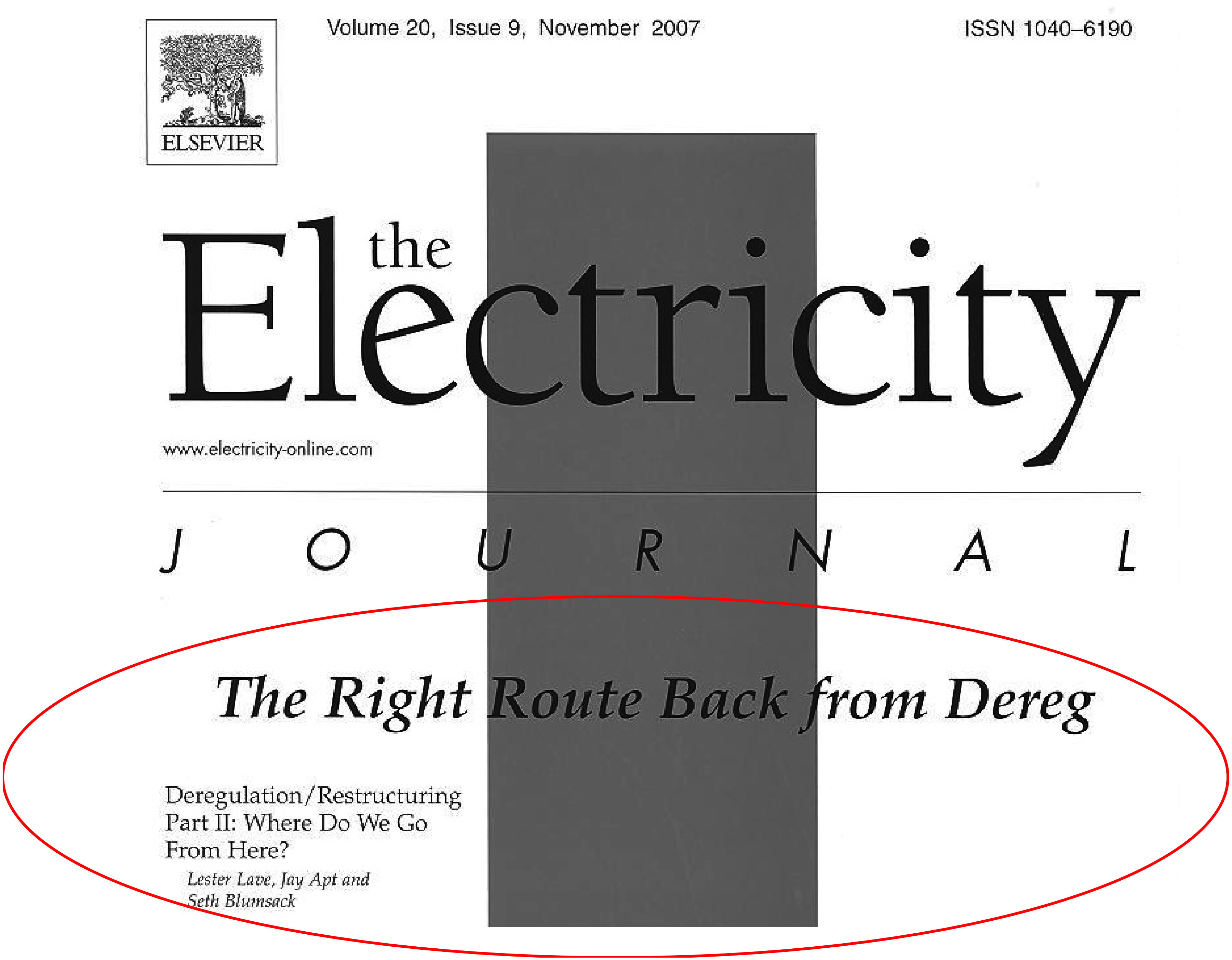
No communication
with external nodes

Experiment: **Can we reduce blackout sizes with DMPC agents?**

- Create 100 extreme cascading failures from the IEEE 300 bus (node) test case

Distribution of blackout sizes





Volume 20, Issue 9, November 2007

ISSN 1040–6190

ELSEVIER

the Electricity JOURNAL

www.electricity-online.com

The Right Route Back from Dereg

Deregulation/Restructuring
Part II: Where Do We Go
From Here?

Lester Lave, Jay Apt and
Seth Blumsack

Electricity Prices and Costs Under Regulation and Restructuring

Prof. Seth Blumsack, The Pennsylvania State University
Prof. Lester B. Lave, Carnegie Mellon University
Prof. Jay Apt, Carnegie Mellon University

We studied the markup between cost and price

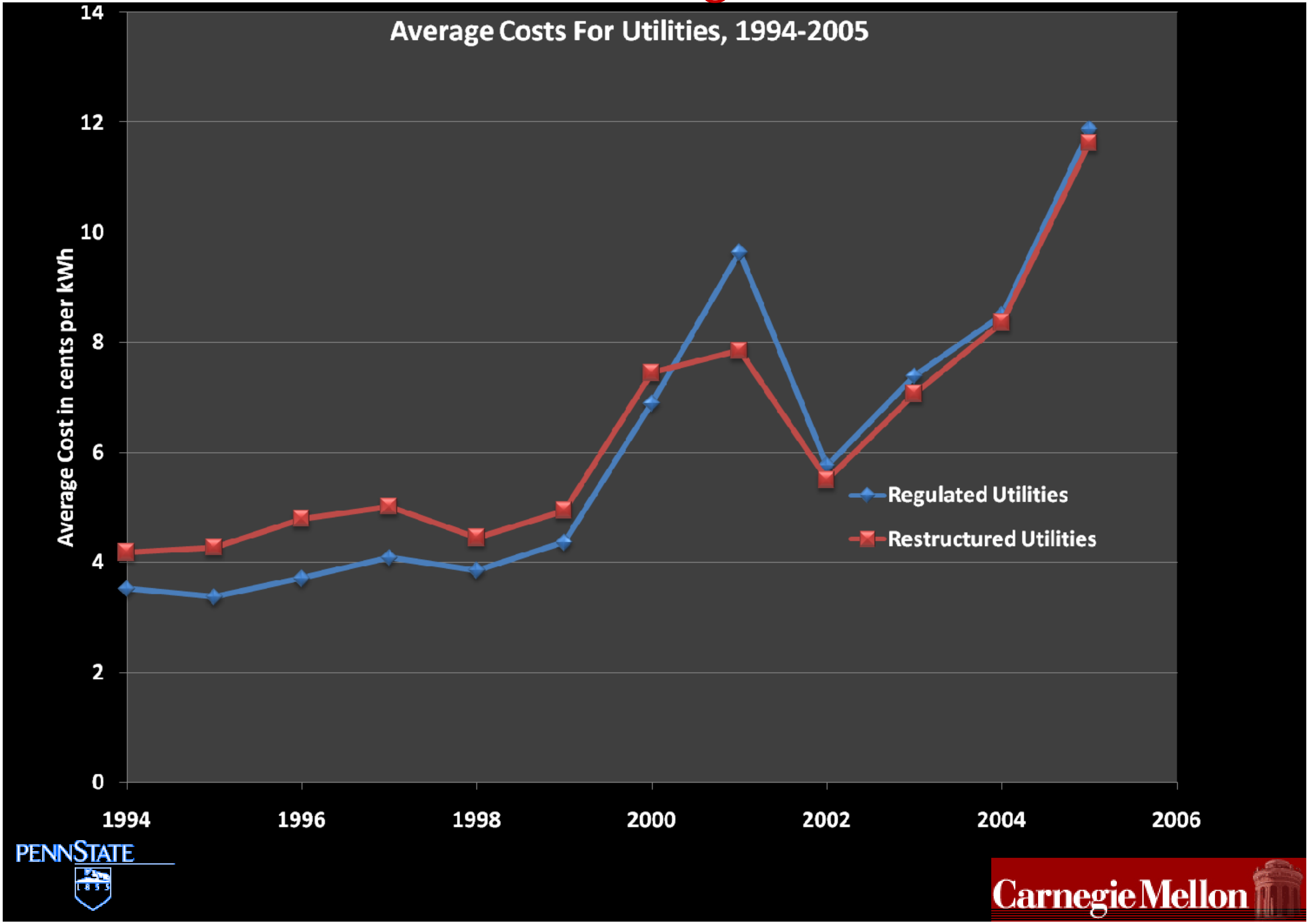
- Prices: Annual data from 1994 through 2005
  - 71 utilities
  - 37 states
  - Half the utilities participated in restructuring
    - Wholesale competition (joining an RTO/ISO)
    - Retail competition
    - Divesting generation assets
  - Rate data for each utility from detailed data collected every 6 months by EEI and published in “Average Rates and Typical Bills”
  - Cents per kWh for each customer class, including fuel cost adjustment (as permitted by the regulators), less stranded cost recovery allowance (Competitive Transition Charge) = net rate

We studied the markup between cost and price

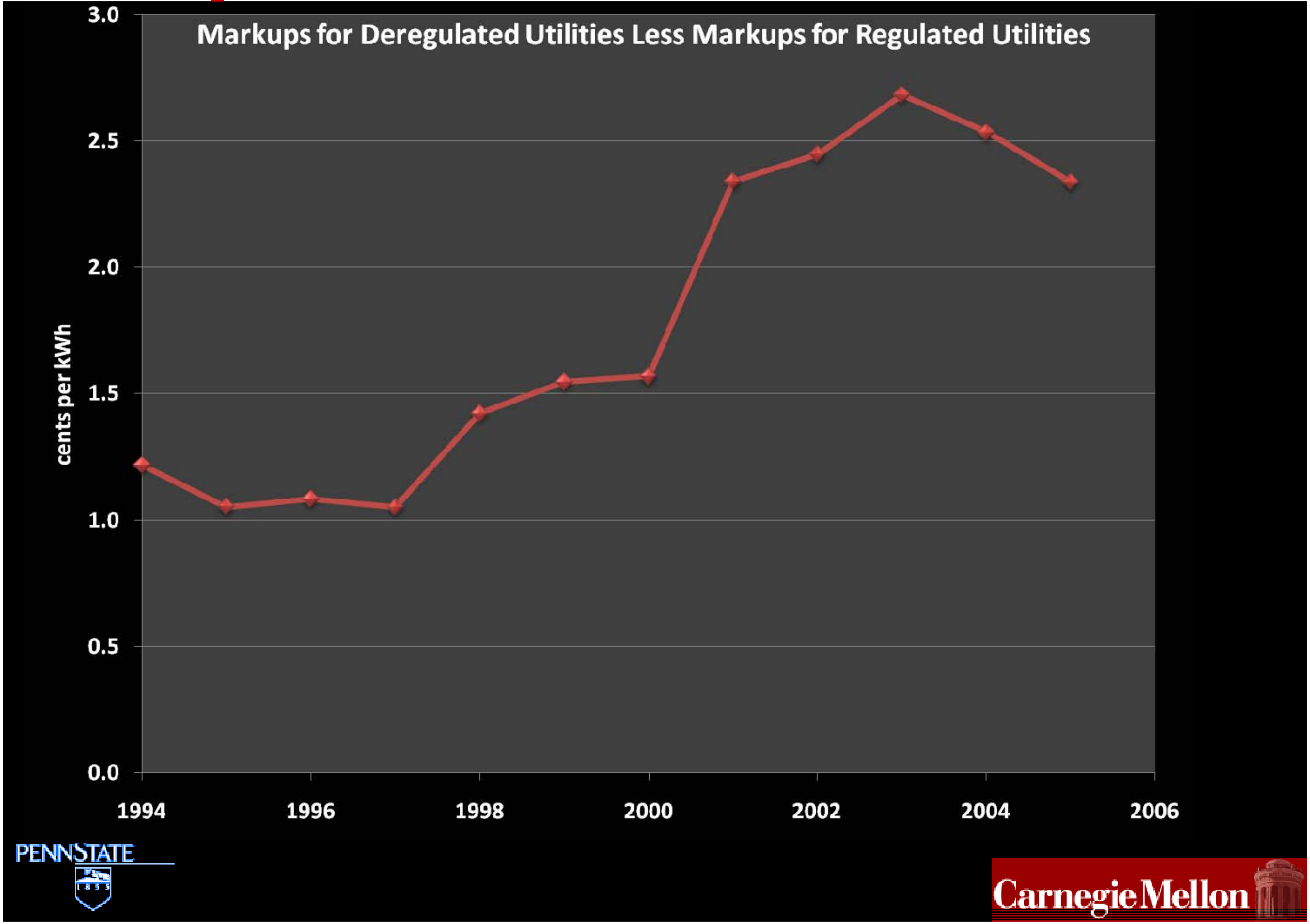
- Costs: Annual data from 1994 through 2005 as filed on FERC Form 1
  - Generation cost
  - Transmission & distribution costs
  - Cost of power purchases
  - Sales
- The effect of higher fuel prices are reflected in both the generation cost and the cost of power purchases, for each utility (rather than just a regional average fuel price that may not be what the utility actually pays)

- Retail prices and utility costs have been adjusted for inflation using the consumer and producer price indices
- Markup = Net Rate – Average Cost

Costs have risen for both regulated & restructured



Markups have increased more for restructured utilities



Results

Rather than examining customer prices, we looked at the markup between the utilities’ cost and the price each charged. We used econometric regressions to investigate if restructuring explains what factors increased the markup.

1. Simply joining an RTO has had little effect on the markup.

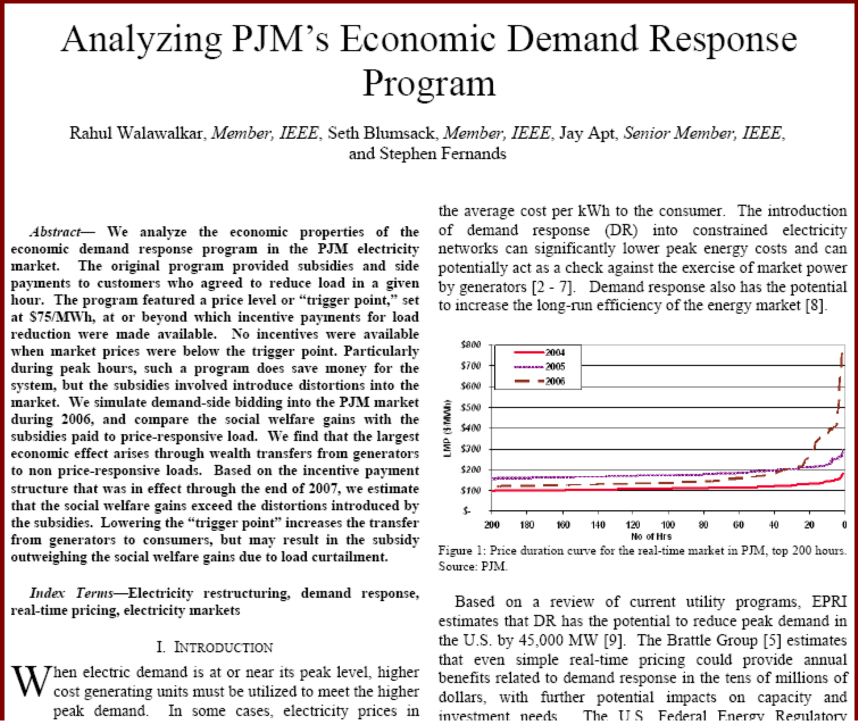
2. Utility divestiture of generation has increased the markup by 1 cent per kWh.

3. Retail competition has increased the markup by 2½ cents per kWh.

The results indicate that most of the gains from restructuring have, thus far, gone to producers rather than consumers.

Analyzing PJM's Economic Demand Response Program

Rahul Walawalkar, Seth Blumsack, Jay Apt, Stephen Fernands



Analyzing PJM's Economic Demand Response Program

Rahul Walawalkar, *Member, IEEE*, Seth Blumsack, *Member, IEEE*, Jay Apt, *Senior Member, IEEE*,
and Stephen Fernands

Abstract— We analyze the economic properties of the economic demand response program in the PJM electricity market. The original program provided subsidies and side payments to customers who agreed to reduce load in a given hour. The program featured a price level or "trigger point," set at $75/MWh, at or beyond which incentive payments for load reduction were made available. No incentives were available when market prices were below the trigger point. Particularly during peak hours, such a program does save money for the system, but the subsidies involved introduce distortions into the market. We simulate demand-side bidding into the PJM market during 2006, and compare the social welfare gains with the subsidies paid to price-responsive load. We find that the largest economic effect arises through wealth transfers from generators to non price-responsive loads. Based on the incentive payment structure that was in effect through the end of 2007, we estimate that the social welfare gains exceed the distortions introduced by the subsidies. Lowering the "trigger point" increases the transfer from generators to consumers, but may result in the subsidy outweighing the social welfare gains due to load curtailment.

Index Terms—Electricity restructuring, demand response, real-time pricing, electricity markets

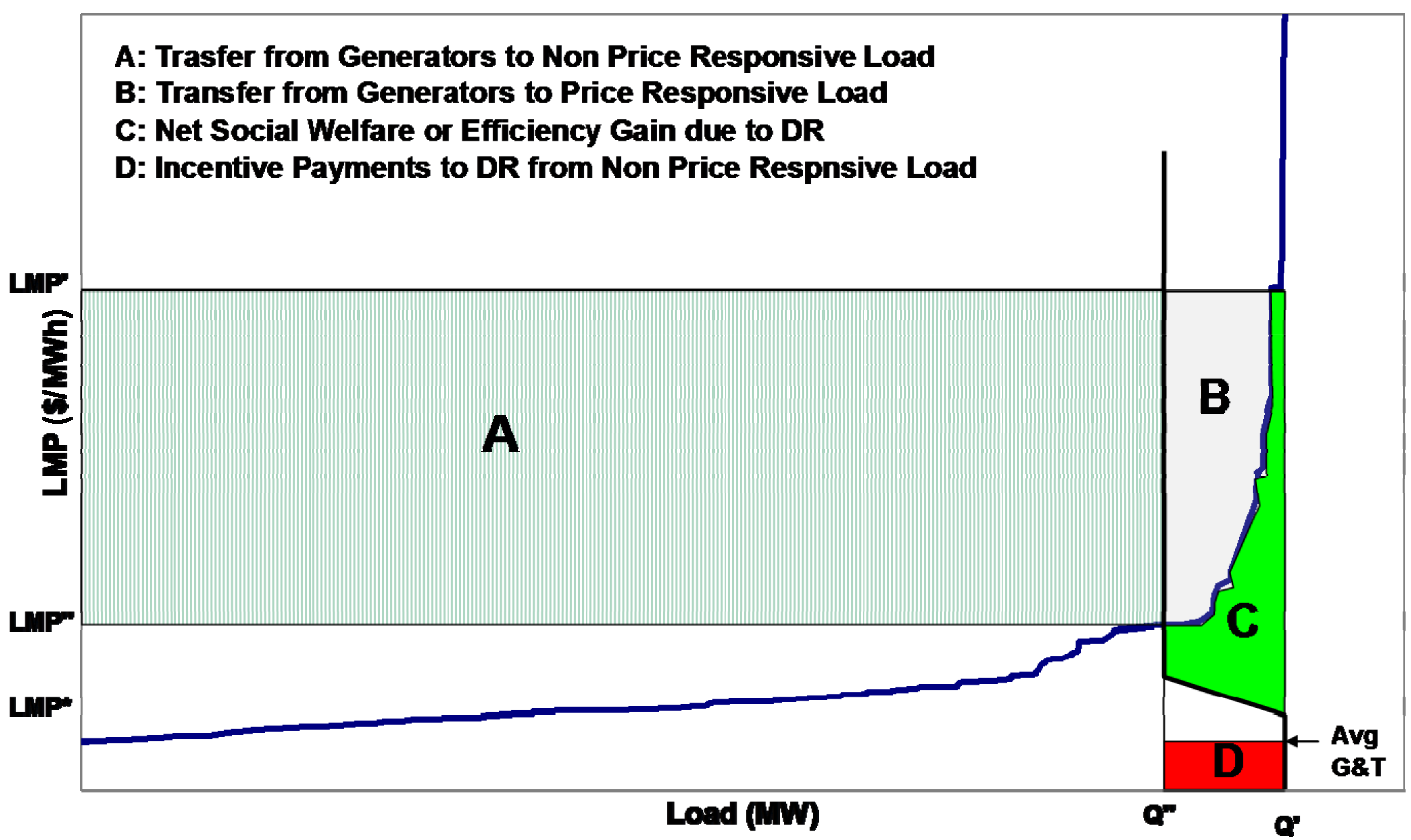
I. INTRODUCTION

When electric demand is at or near its peak level, higher cost generating units must be utilized to meet the higher peak demand. In some cases, electricity prices in the average cost per kWh to the consumer. The introduction of demand response (DR) into constrained electricity networks can significantly lower peak energy costs and can potentially act as a check against the exercise of market power by generators [2 - 7]. Demand response also has the potential to increase the long-run efficiency of the energy market [8].

Figure 1: Price duration curve for the real-time market in PJM, top 200 hours. Source: PJM.

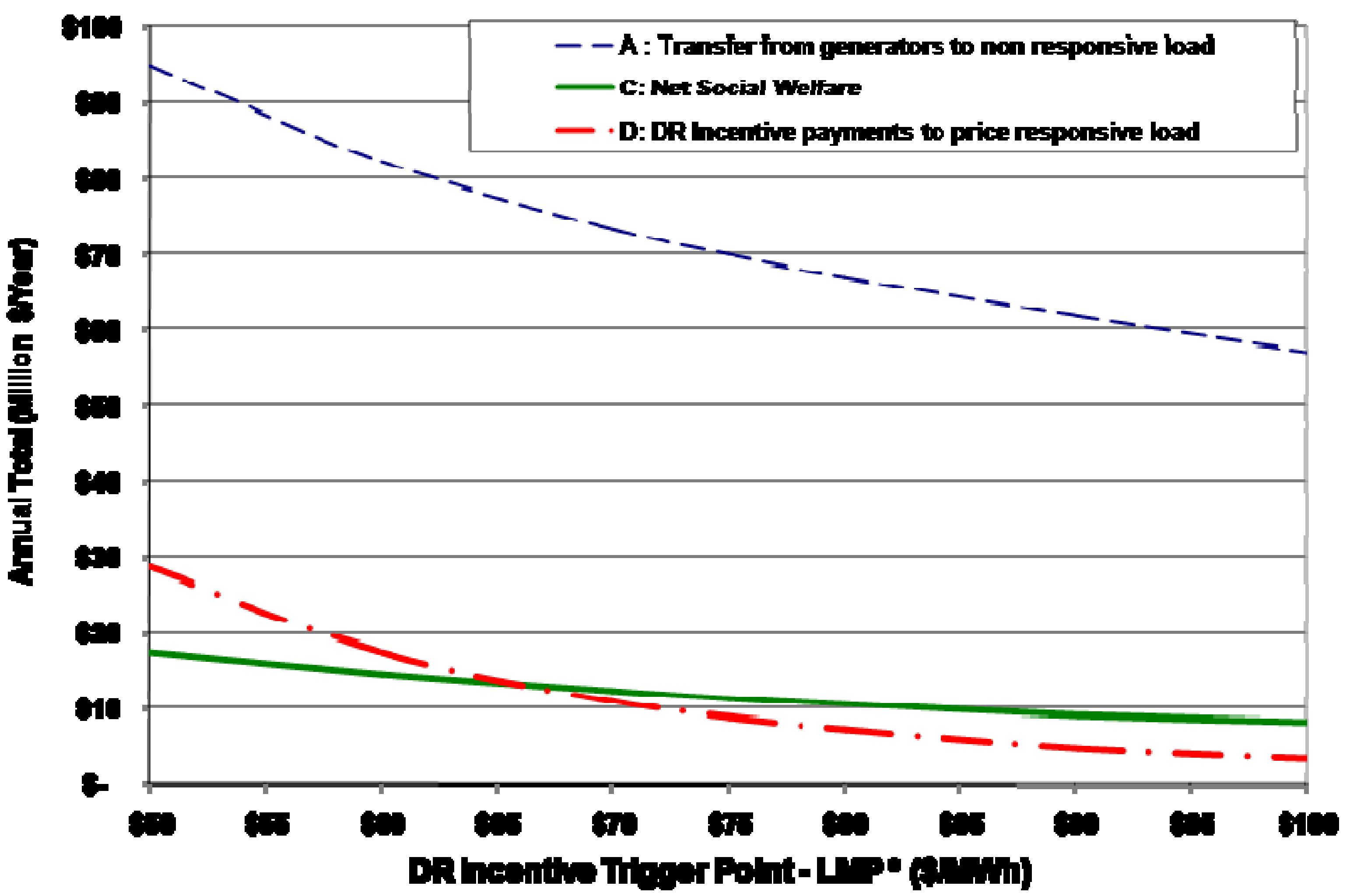
Based on a review of current utility programs, EPRI estimates that DR has the potential to reduce peak demand in the U.S. by 45,000 MW [9]. The Brattle Group [5] estimates that even simple real-time pricing could provide annual benefits related to demand response in the tens of millions of dollars, with further potential impacts on capacity and investment needs. The U.S. Federal Energy Regulatory

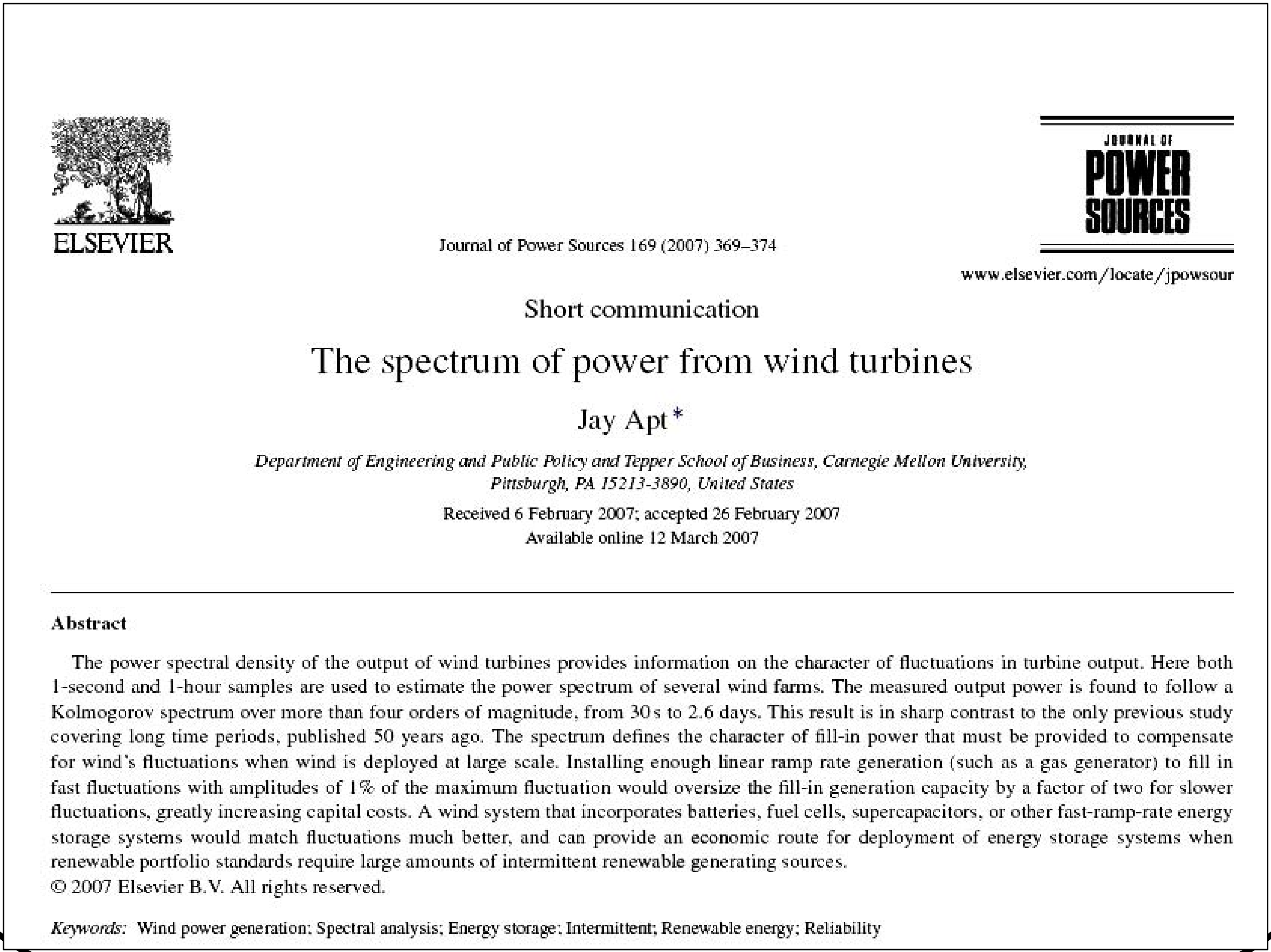
Net Social Welfare Analysis



A: Trasfer from Generators to Non Price Responsive Load
B: Transfer from Generators to Price Responsive Load
C: Net Social Welfare or Efficiency Gain due to DR
D: Incentive Payments to DR from Non Price Respnsive Load

NSW calculations in 2006 for a DR curve with slope of 0.15





ELSEVIER

Journal of Power Sources 169 (2007) 369–374

JOURNAL OF
POWER
SOURCES

www.elsevier.com/locate/jpowsour

Short communication

The spectrum of power from wind turbines

Jay Apt*

Department of Engineering and Public Policy and Tepper School of Business, Carnegie Mellon University,
Pittsburgh, PA 15213-3890, United States

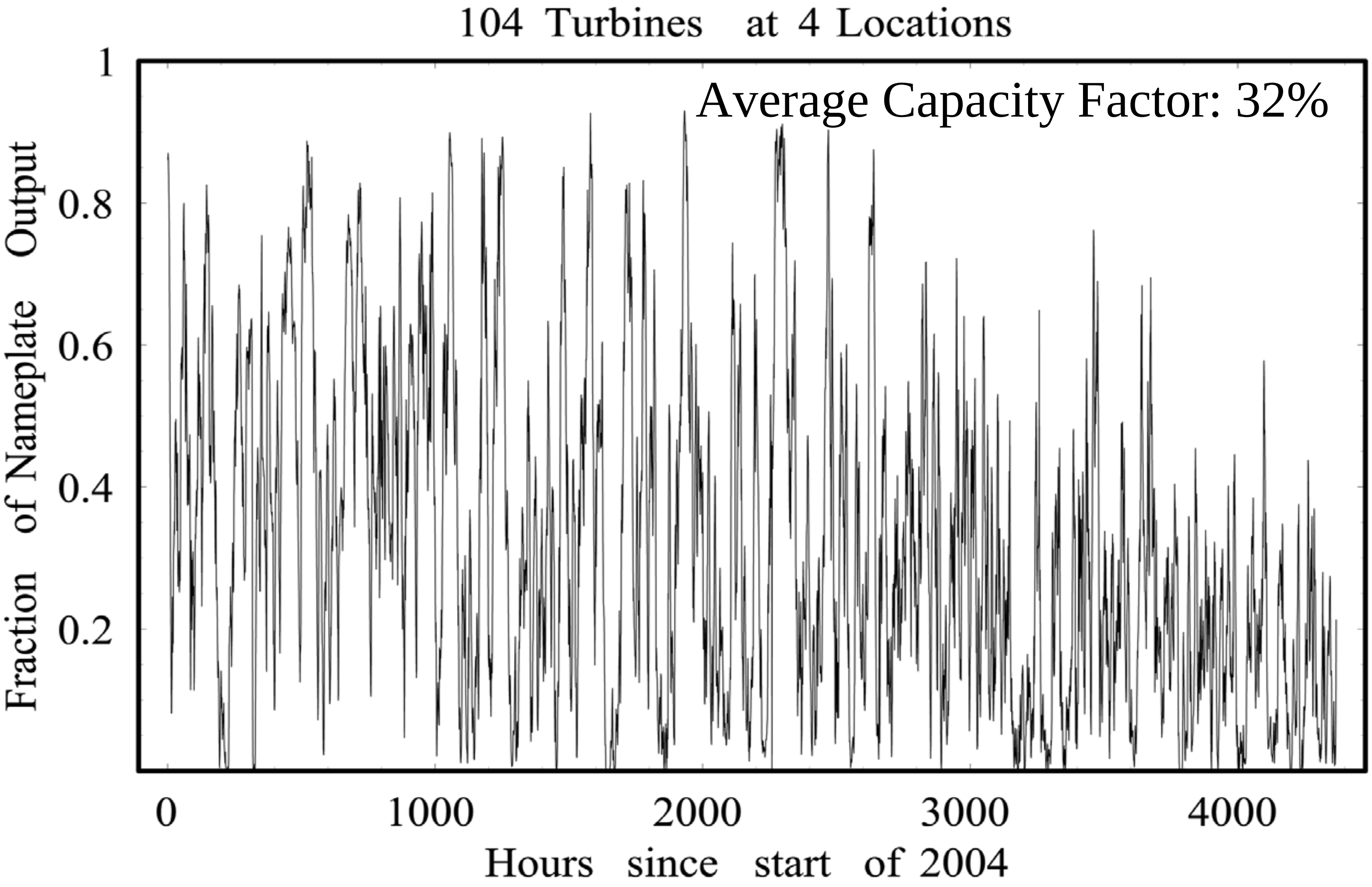
Received 6 February 2007; accepted 26 February 2007
Available online 12 March 2007

Abstract

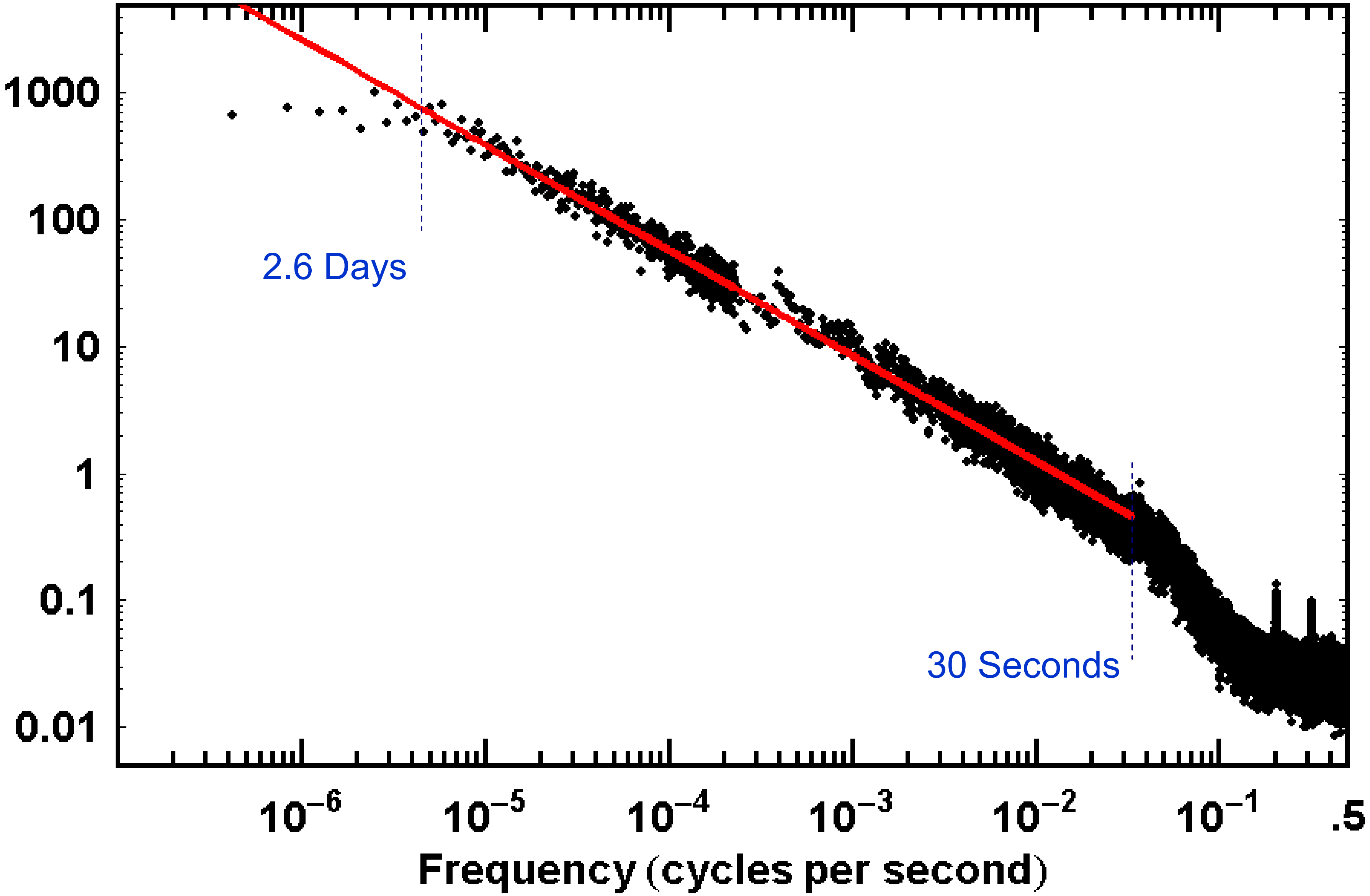
The power spectral density of the output of wind turbines provides information on the character of fluctuations in turbine output. Here both 1-second and 1-hour samples are used to estimate the power spectrum of several wind farms. The measured output power is found to follow a Kolmogorov spectrum over more than four orders of magnitude, from 30 s to 2.6 days. This result is in sharp contrast to the only previous study covering long time periods, published 50 years ago. The spectrum defines the character of fill-in power that must be provided to compensate for wind's fluctuations when wind is deployed at large scale. Installing enough linear ramp rate generation (such as a gas generator) to fill in fast fluctuations with amplitudes of 1% of the maximum fluctuation would oversize the fill-in generation capacity by a factor of two for slower fluctuations, greatly increasing capital costs. A wind system that incorporates batteries, fuel cells, supercapacitors, or other fast-ramp-rate energy storage systems would match fluctuations much better, and can provide an economic route for deployment of energy storage systems when renewable portfolio standards require large amounts of intermittent renewable generating sources.

Keywords: Wind power generation; Spectral analysis; Energy storage; Intermittent; Renewable energy; Reliability

6 Months of Wind



Power Spectral Density of Wind



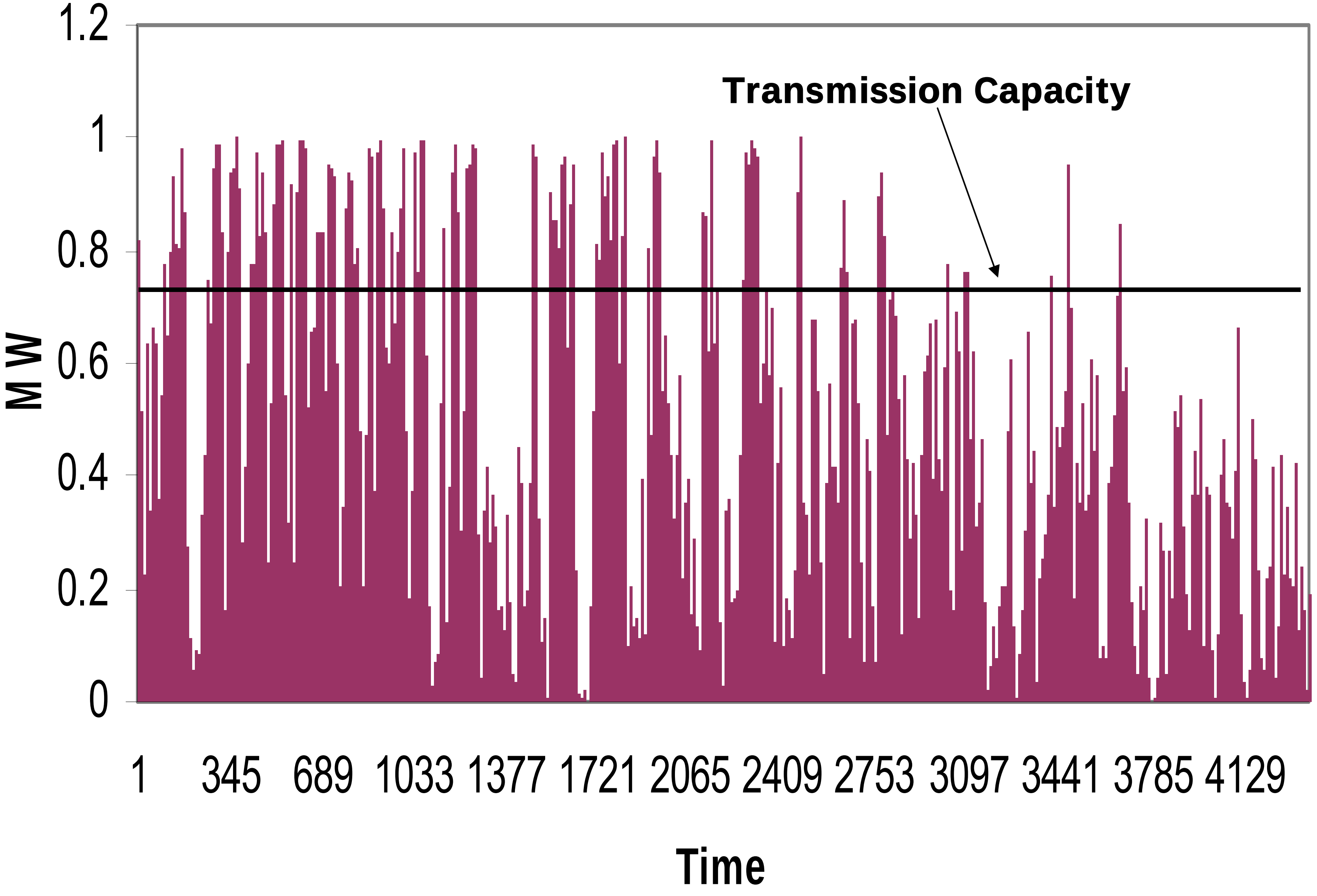
Summary - wind

- Even 104 summed 1.5 MW wind turbines have fast and large power fluctuations.
- The PSD of wind follows a Kolmogorov ($f^{-5/3}$) spectrum over 4 orders of magnitude.
- Wind’s PSD matches that of load 2½ min – 1 hr.
- A portfolio of slow, fast, and very fast sources is the most economic way to match wind.
- At large scale, wind is likely to have weather and climate effects.

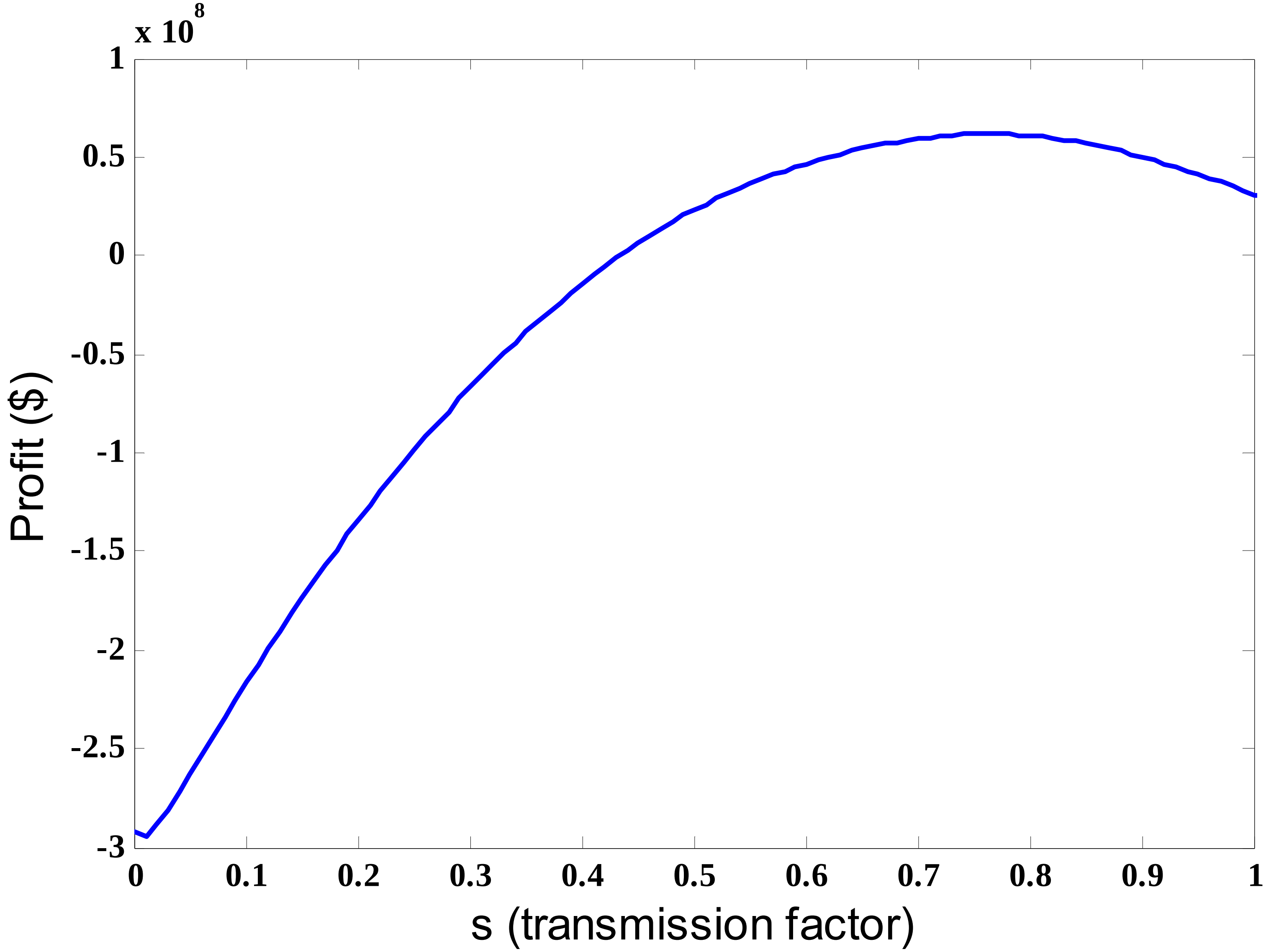
Optimal Size for a Wind Transmission Line

Sompop Pattanariyankool
Lester Lave
Tepper School of Business

Wind power distribution



Profit and transmission capacity



PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2007; **15**:

Application

The Character of Power Output from Utility-Scale Photovoltaic Systems

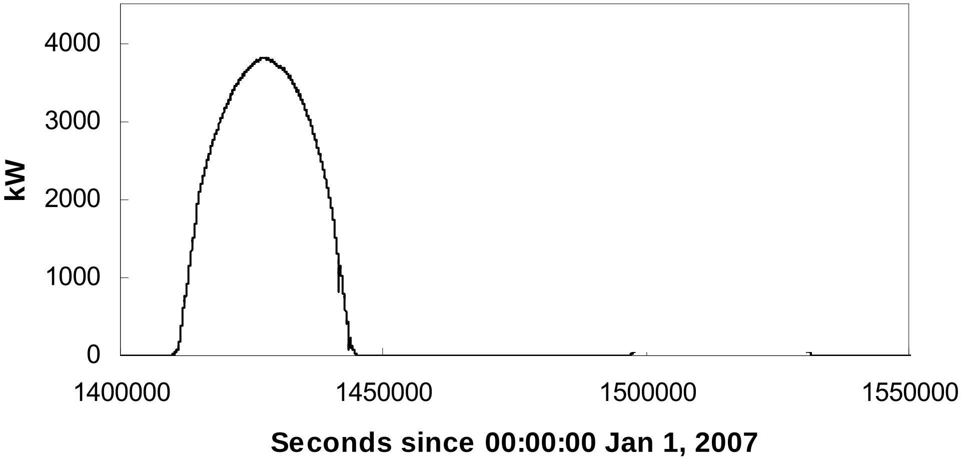
Aimee E. Curtright[1] and Jay Apt[1,2*,†]
[1] *Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, USA*
[2] *Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213, USA*

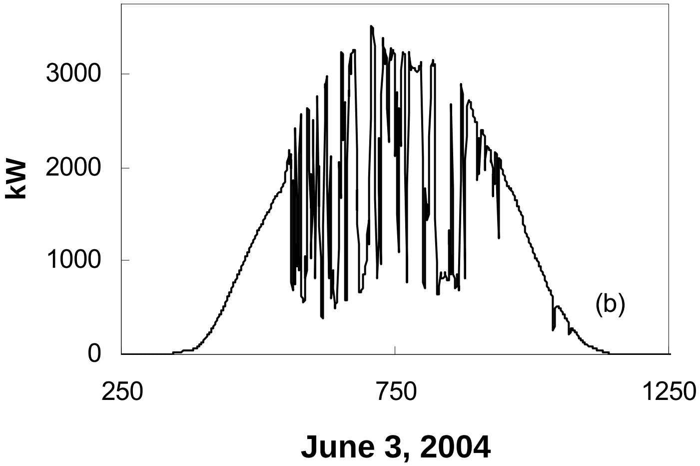
Power produced by utility-scale solar photovoltaic (PV) systems has fluctuations on both short and long time scales. Power spectral density (PSD) analysis provides information on the character of these power fluctuations. Examination of the correlation and step size of the power output between several PV sites within a multi-site system allows assessment of geographic diversification for addressing intermittency. Both techniques provide insight into the characteristics of required firm power and/or demand response required to accommodate large-scale PV deployment. Copyright © 2007 John Wiley & Sons, Ltd.

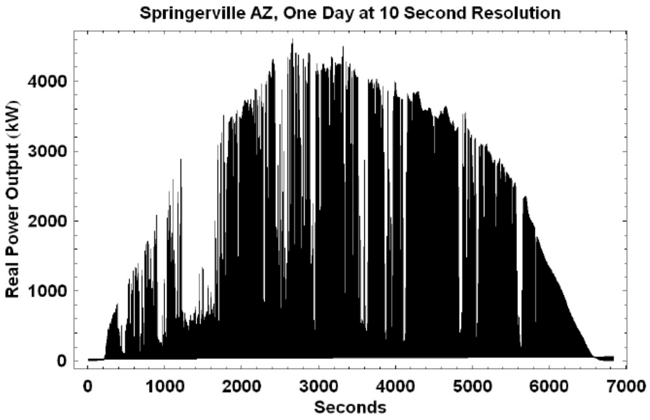
KEY WORDS: grid-connected PV systems; intermittency; spectral analysis

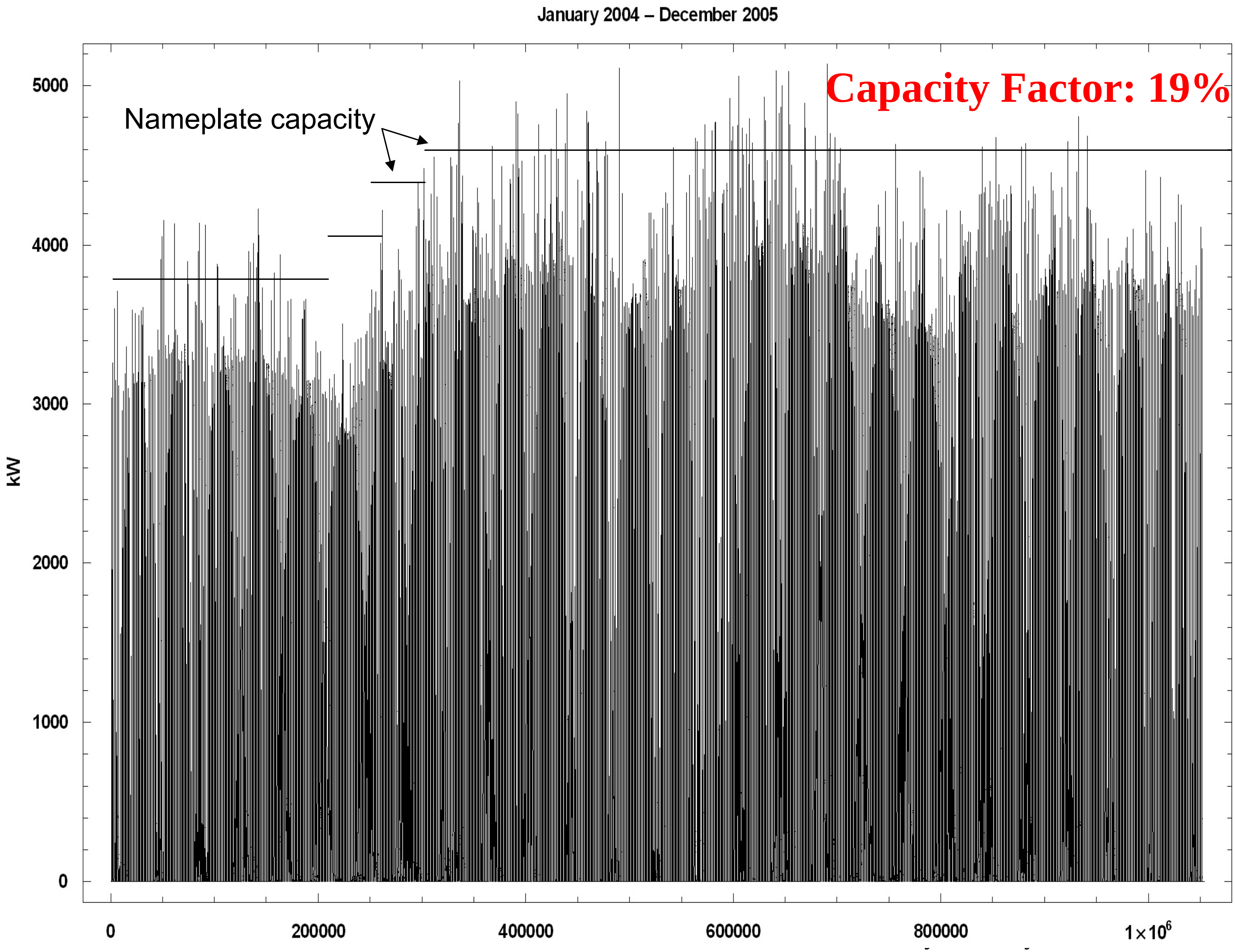
Received 14 June 2007

4.6 MW TEP Solar Array (Arizona)

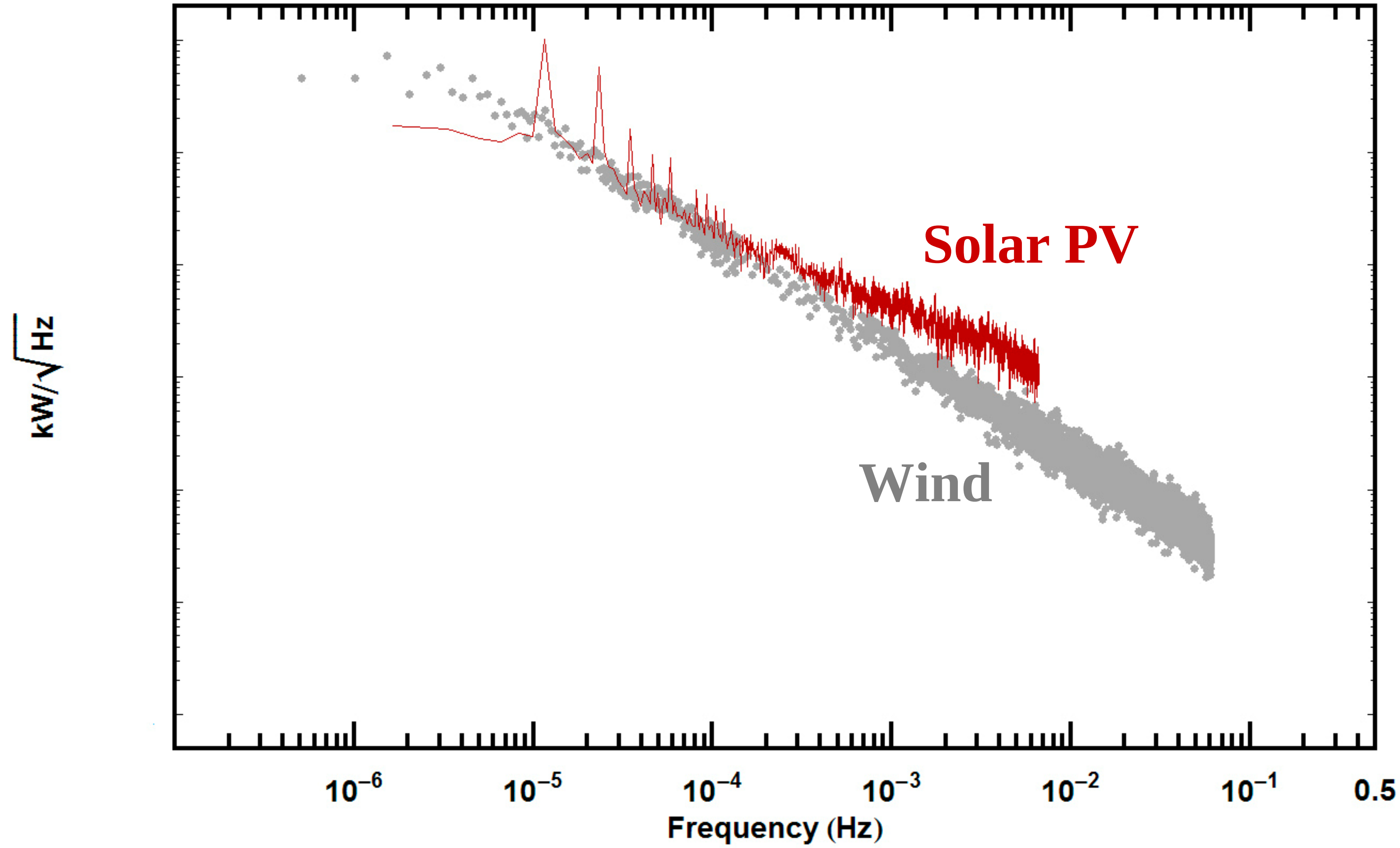






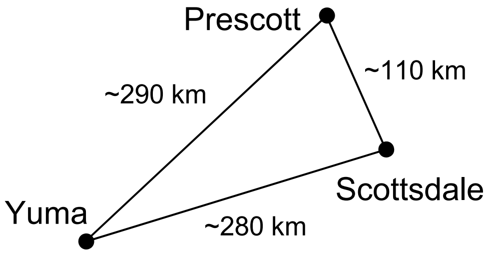

January 2004 – December 2005
Capacity Factor: 19%
Nameplate capacity
kW
5000
4000
3000
2000
1000
0
0
200000
400000
600000
800000
1×10^6

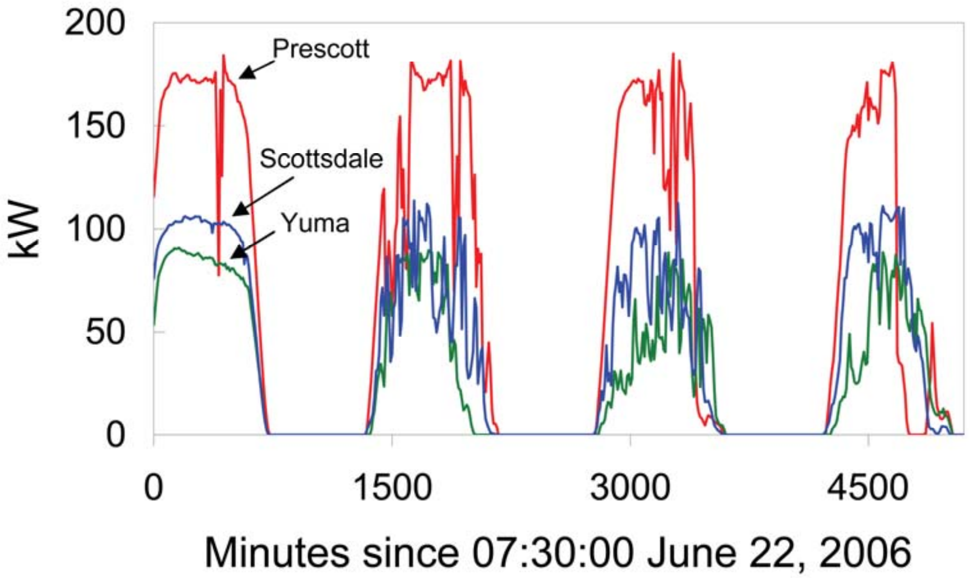
Comparison of wind and solar PV



Source: CEIC Working Paper CEIC-08-04, available at www.cmu.edu/electricity

3 Tracking Arrays (Arizona)





Summary – solar PV

- Solar PV in Arizona has fast and large power fluctuations.
- The capacity factor in NE Arizona over 2 years was 19%.
- The PSD of solar PV is significantly flatter than that of wind, implying more required firm power.
- There is no frequency region in which PV's fluctuations match the PSD of load.
- 300 km separation provides very little smoothing.

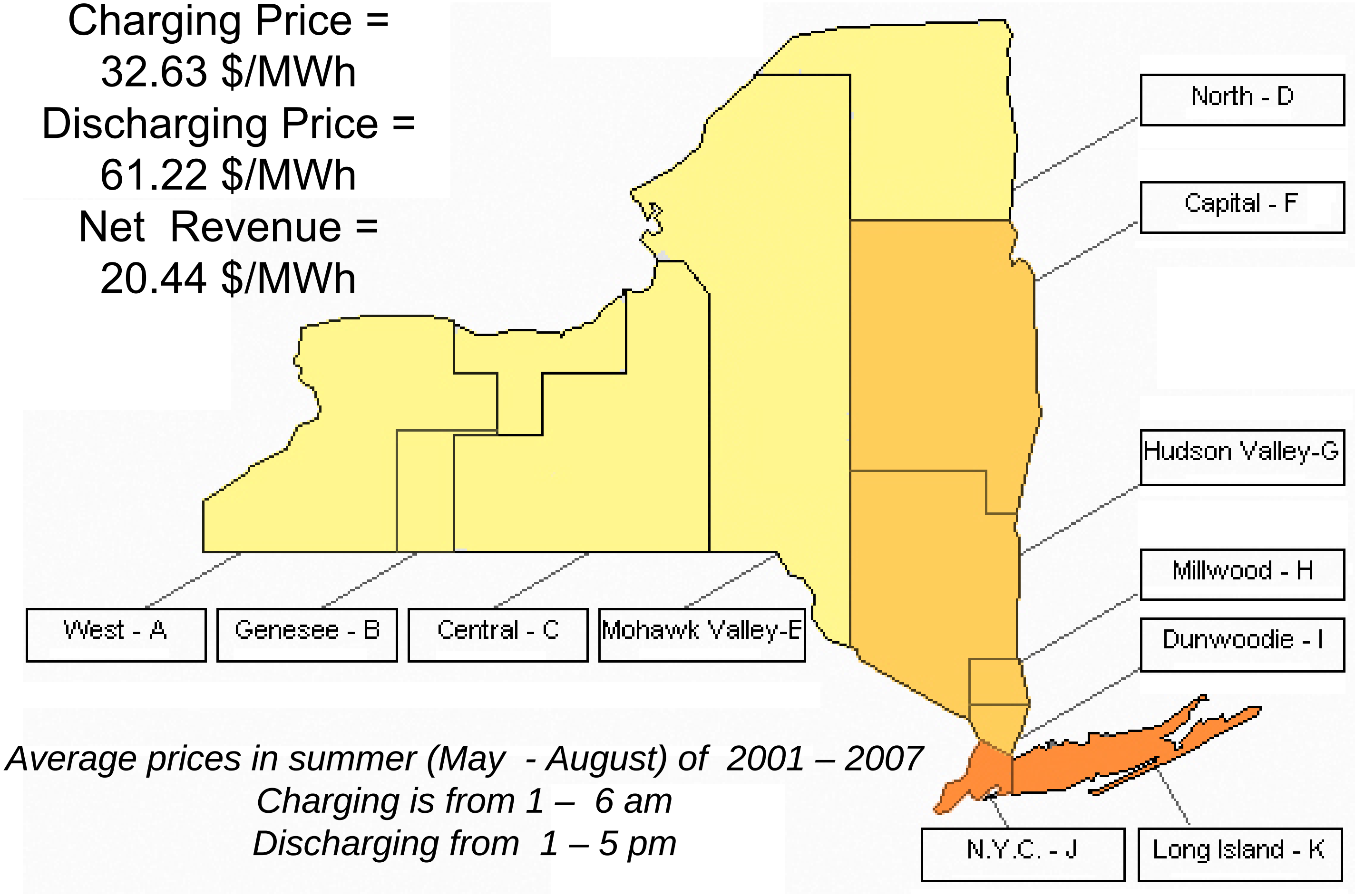
The Air Quality and Human Health Effects of Electric Energy Storage in New York State

Elisabeth A. Gilmore, Rahul Walawalkar
Peter Adams, Jay Apt, and Lester Lave
Carnegie Mellon Electricity Industry Center (CEIC)

EES Revenue opportunities

4 Hr Energy Arbitrage in $/MWh

NY West
Charging Price =
32.63 $/MWh
Discharging Price =
61.22 $/MWh
Net Revenue =
20.44 $/MWh

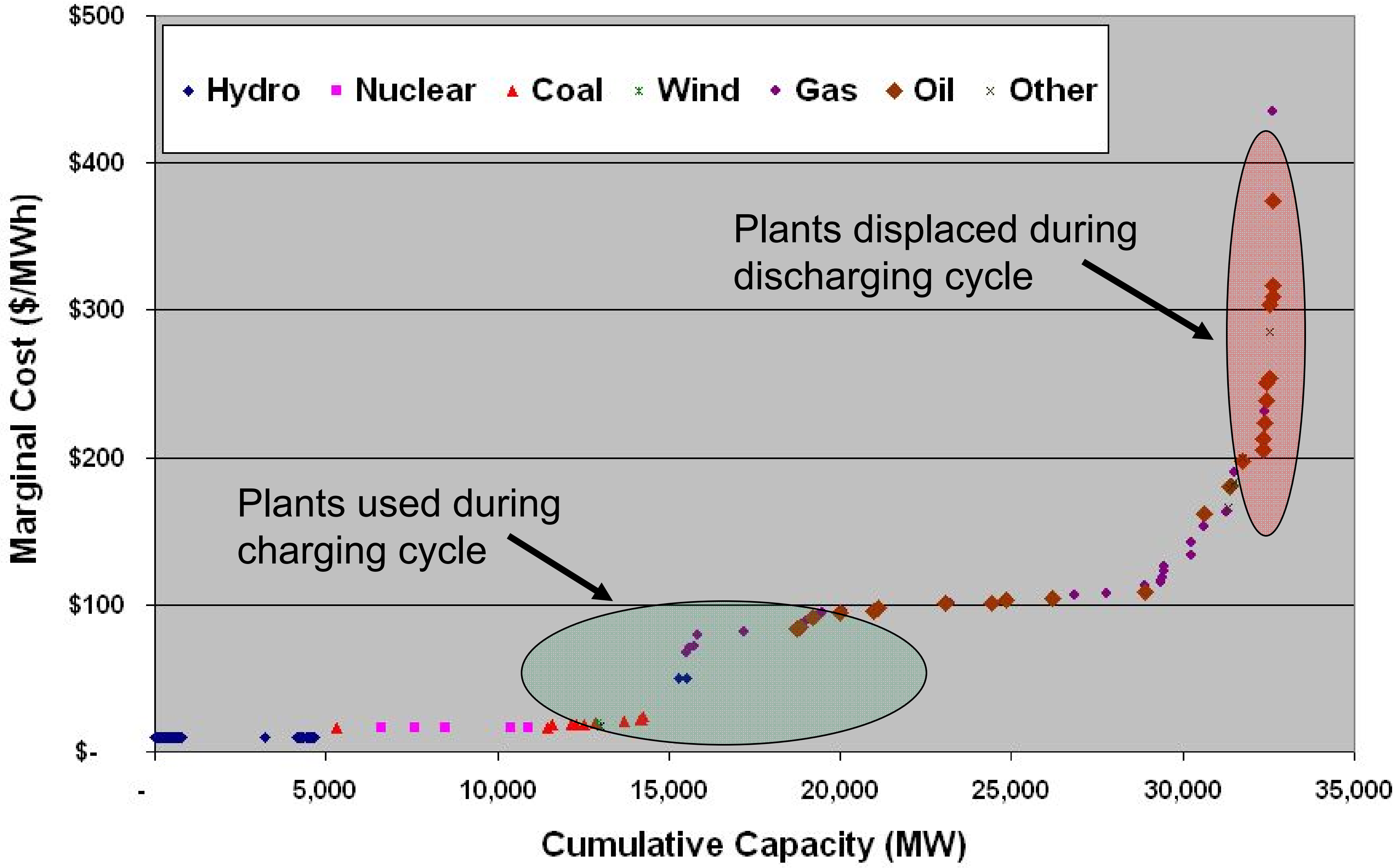


NY East
Charging Price =
33.96 $/MWh
Discharging Price =
63.17 $/MWh
Net Revenue =
20.44 $/MWh

NYC
Charging Price =
41.07 $/MWh
Discharging Price =
88.08 $/MWh
Net Revenue =
36.75 $/MWh

Average prices in summer (May - August) of 2001 – 2007
Charging is from 1 – 6 am
Discharging from 1 – 5 pm

Charging and Displaced Plants

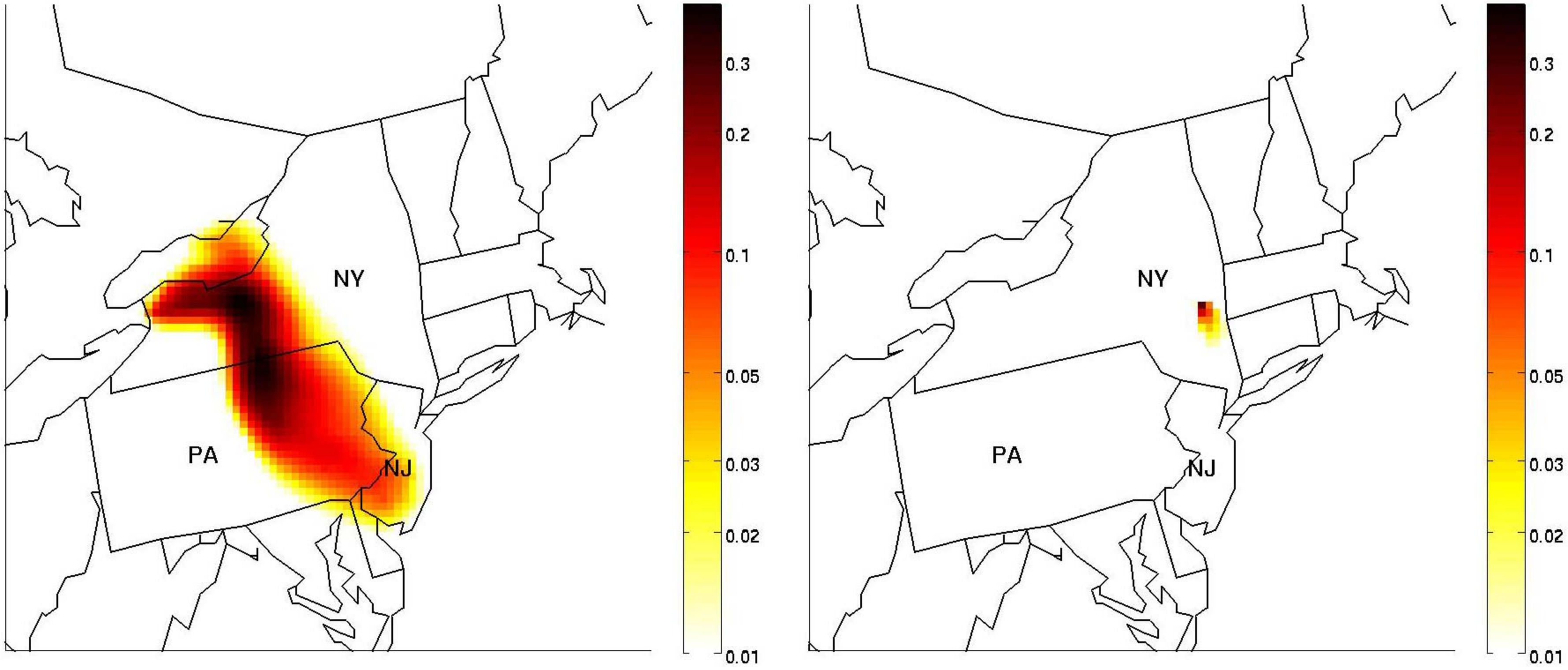


Plants displaced during discharging cycle

Plants used during charging cycle

Upstate $PM_{2.5}$ Concentrations

Difference in mean daily $PM_{2.5}$ ($\mu g/m^3$) [July 21,2001]

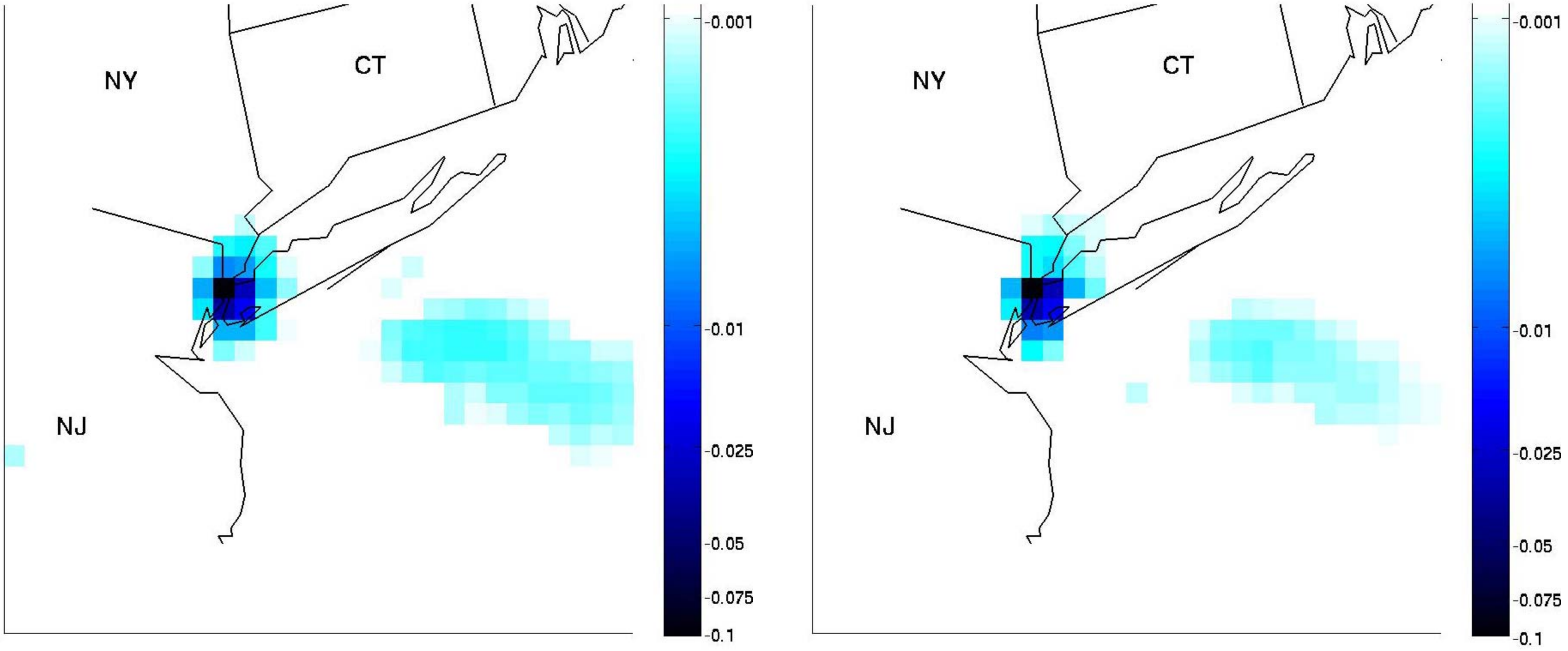


Coal Plant Charging

Natural Gas Charging

$PM_{2.5}$ Concentrations in NYC

Difference in mean daily $PM_{2.5}$ ($\mu g/m^3$) [July 21,2001]



Distillate Fuel Oil Displaced

Natural Gas Displaced

$$\text{Net Social Cost} = \sum_{1}^{i} x_i \cdot SC_i + \sum_{1}^{j} y_j \cdot SC_j$$

x_i = fraction of time plant charging upstate

SC_i = social cost of charging with plant i

y_j = fraction of time plant is displaced in NYC

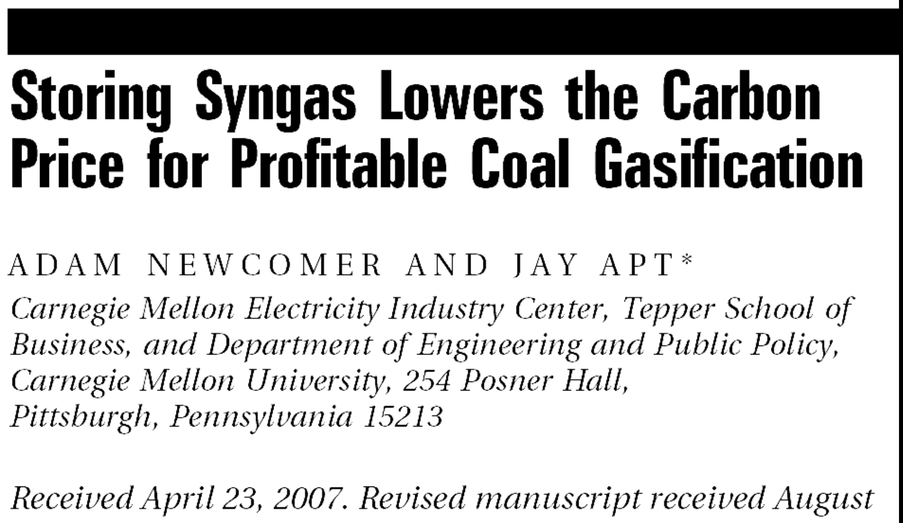
SC_j = social cost of displacing plant j

	Upstate	NYC	Net Costs
Case I (All Natural Gas)	+3.80	-26.6	-22.9
Case II (Natural Gas/Residual Fuel Oil)	+30.4	-26.6	+3.70

Policy Implications

- The short-term benefits and costs of EES are a function of the characteristics of the system
- Benefits from EES in NYC are large due to high population density
- System net benefits depends on the mix of charging units (e.g. natural gas/residual fuel oil)
- NYISO needs to examine the marginal plants to evaluate the environmental benefits and costs of EES

Environmental Science & Technology



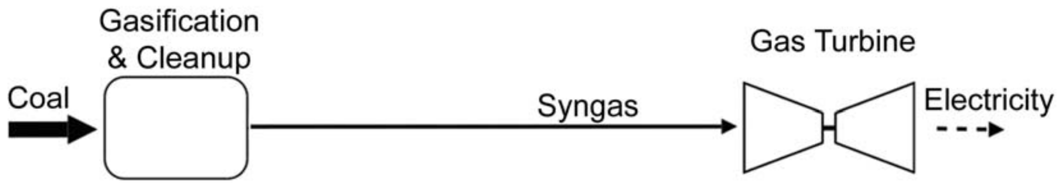
Storing Syngas Lowers the Carbon Price for Profitable Coal Gasification

ADAM NEWCOMER AND JAY APT*

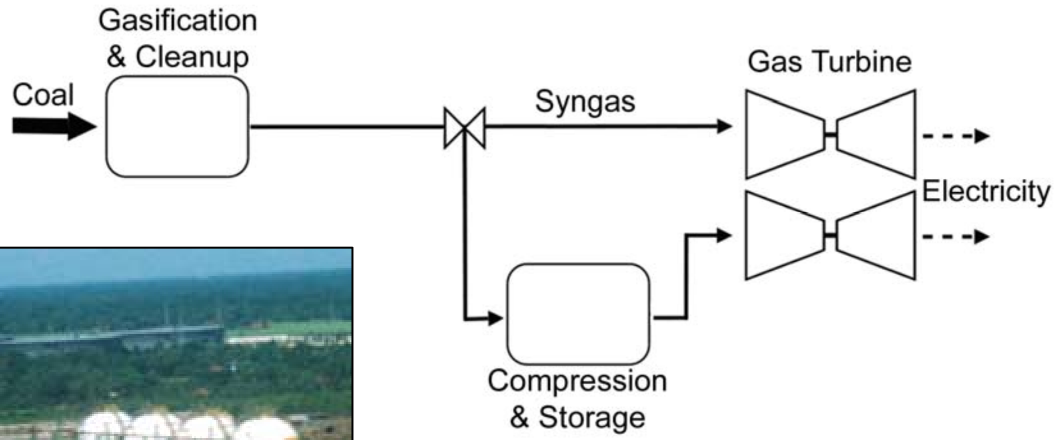
Carnegie Mellon Electricity Industry Center, Tepper School of Business, and Department of Engineering and Public Policy, Carnegie Mellon University, 254 Posner Hall, Pittsburgh, Pennsylvania 15213

Received April 23, 2007. Revised manuscript received August 27, 2007. Accepted September 12, 2007.

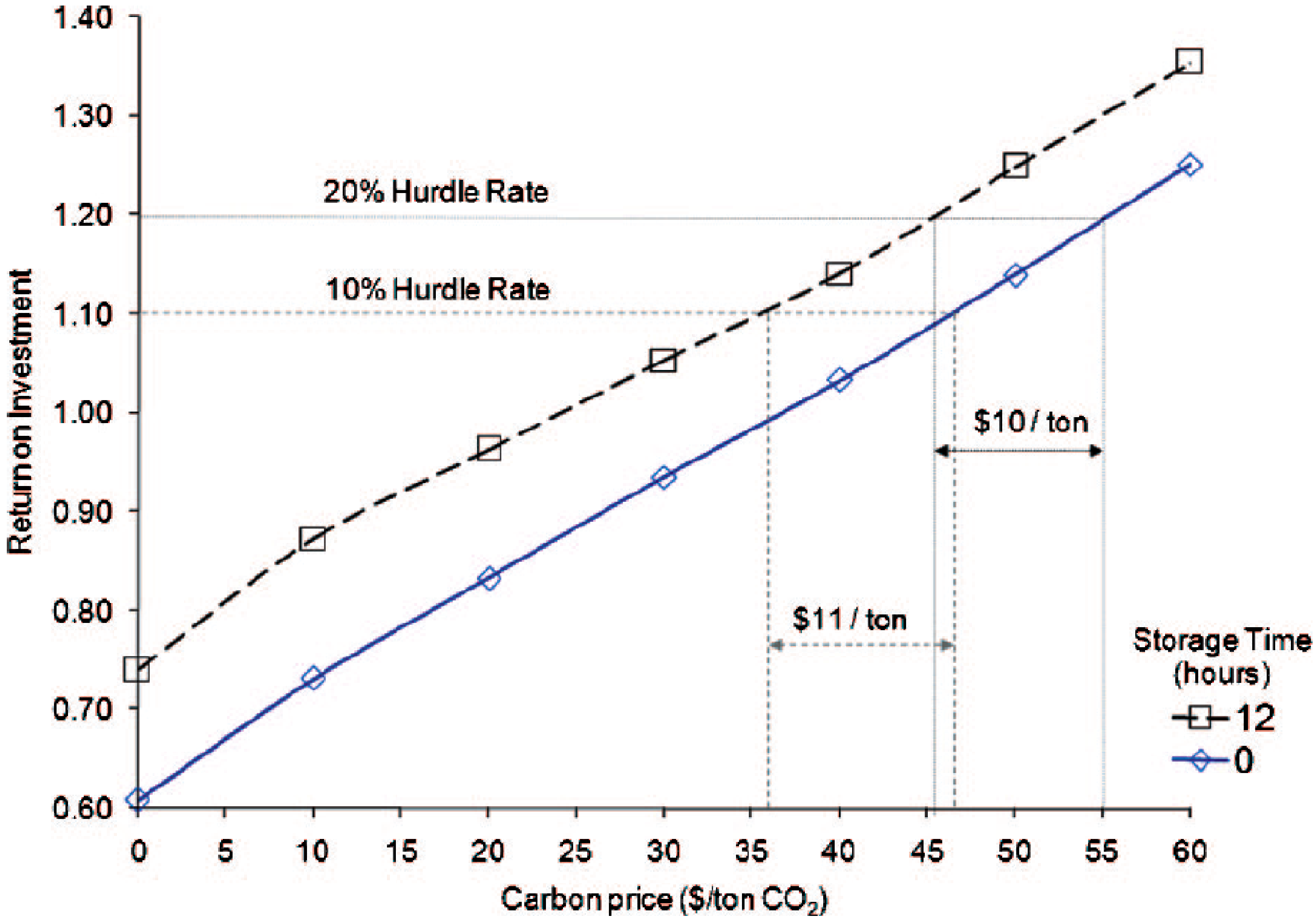
Technical and Economic Analysis of Syngas Storage in the Context of Flexible IGCC Operations



Current gasification operations: End use (turbine) tightly coupled with gasifier



Syngas storage lowers the carbon price at which IGCC is profitable



Carnegie Mellon Electricity Industry Center

Short run effects of a price on carbon dioxide emissions from US electric generators

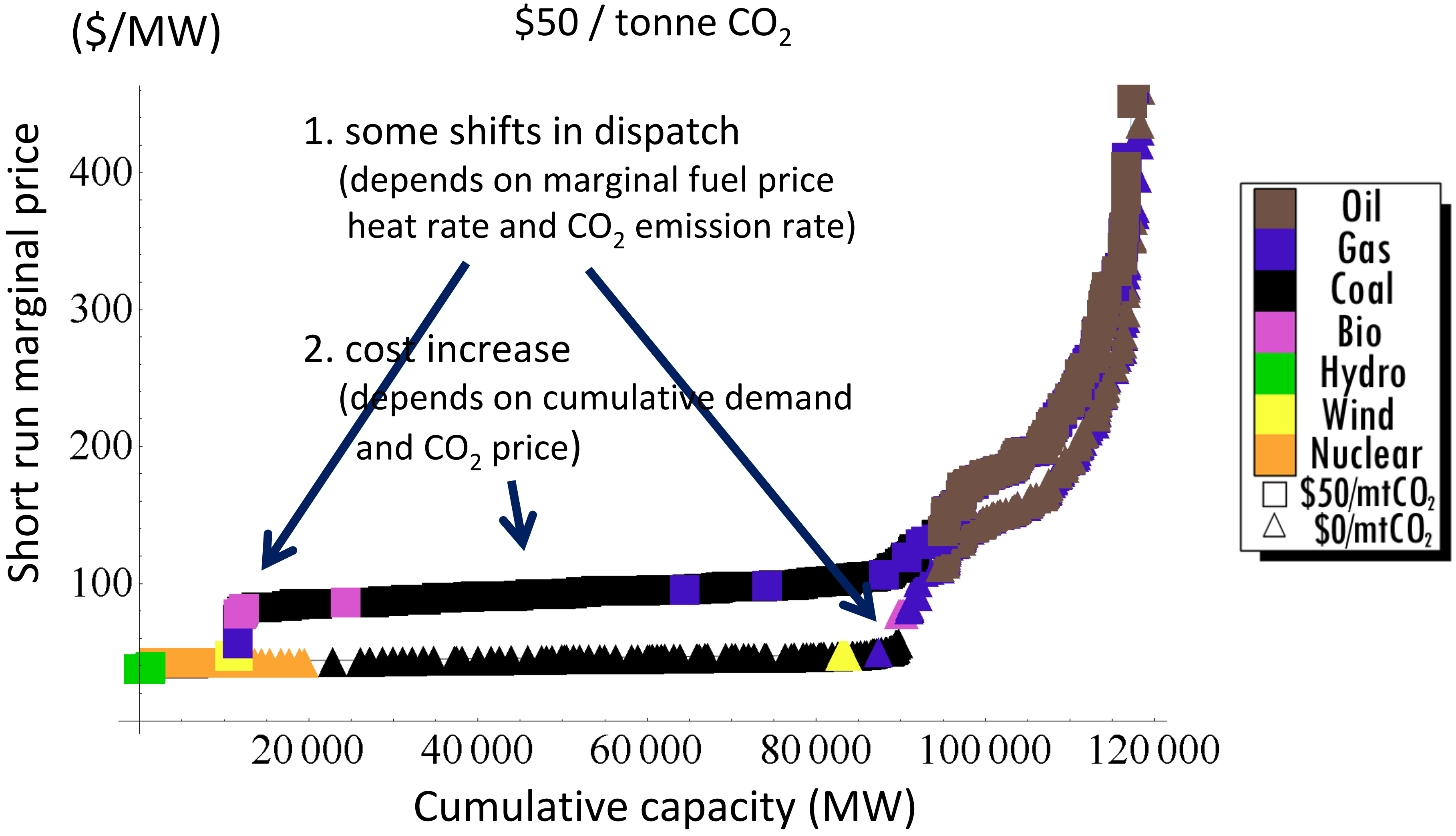
Adam Newcomer, Seth Blumsack[†], Jay Apt,
M. Granger Morgan and Lester Lave

Carnegie Mellon University

[†] now at Penn State University

Midwest ISO

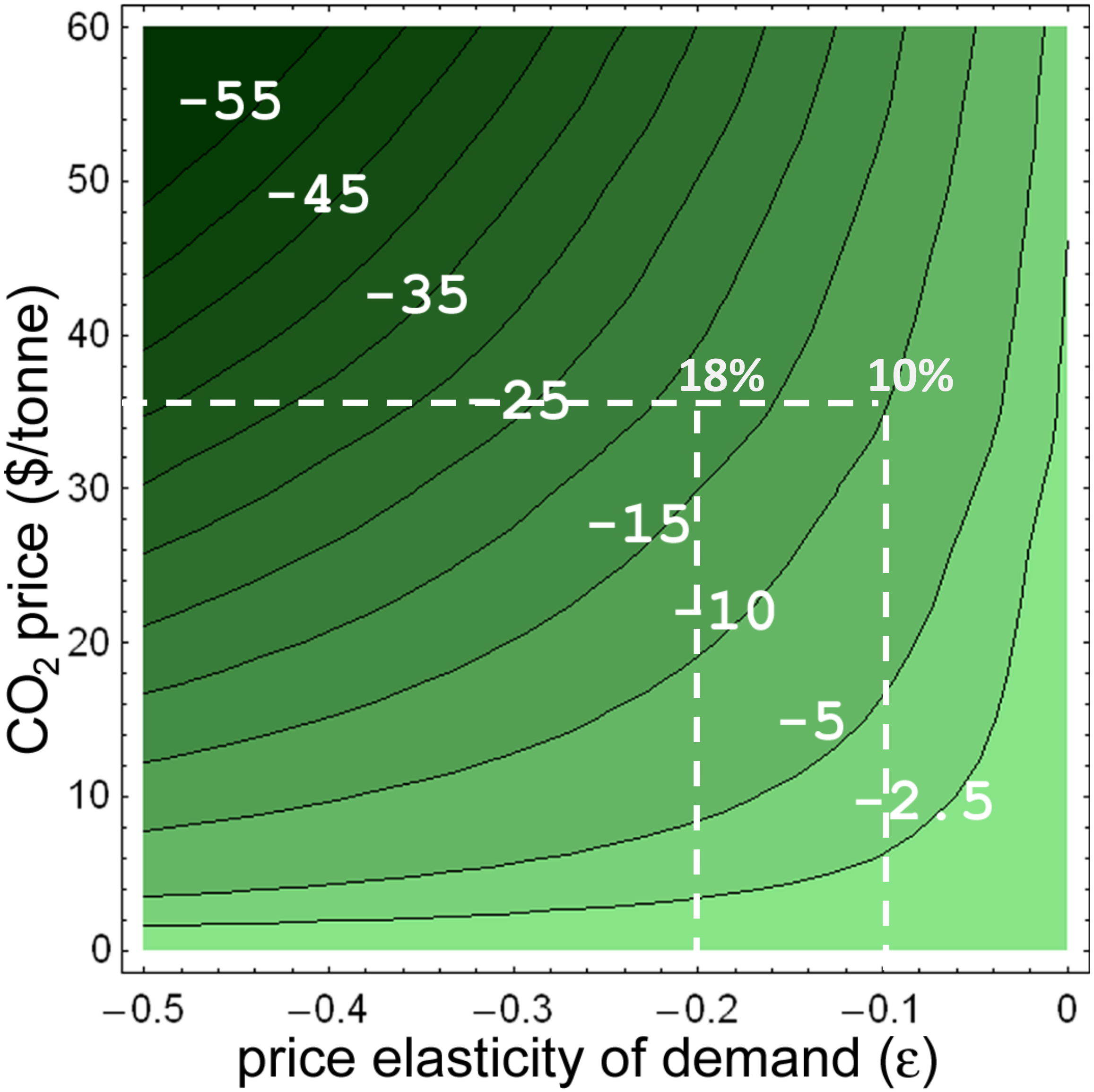
$50 / tonne CO_2



1. some shifts in dispatch
(depends on marginal fuel price
heat rate and CO_2 emission rate)

2. cost increase
(depends on cumulative demand
and CO_2 price)

Midwest ISO percent CO_2 emissions reductions



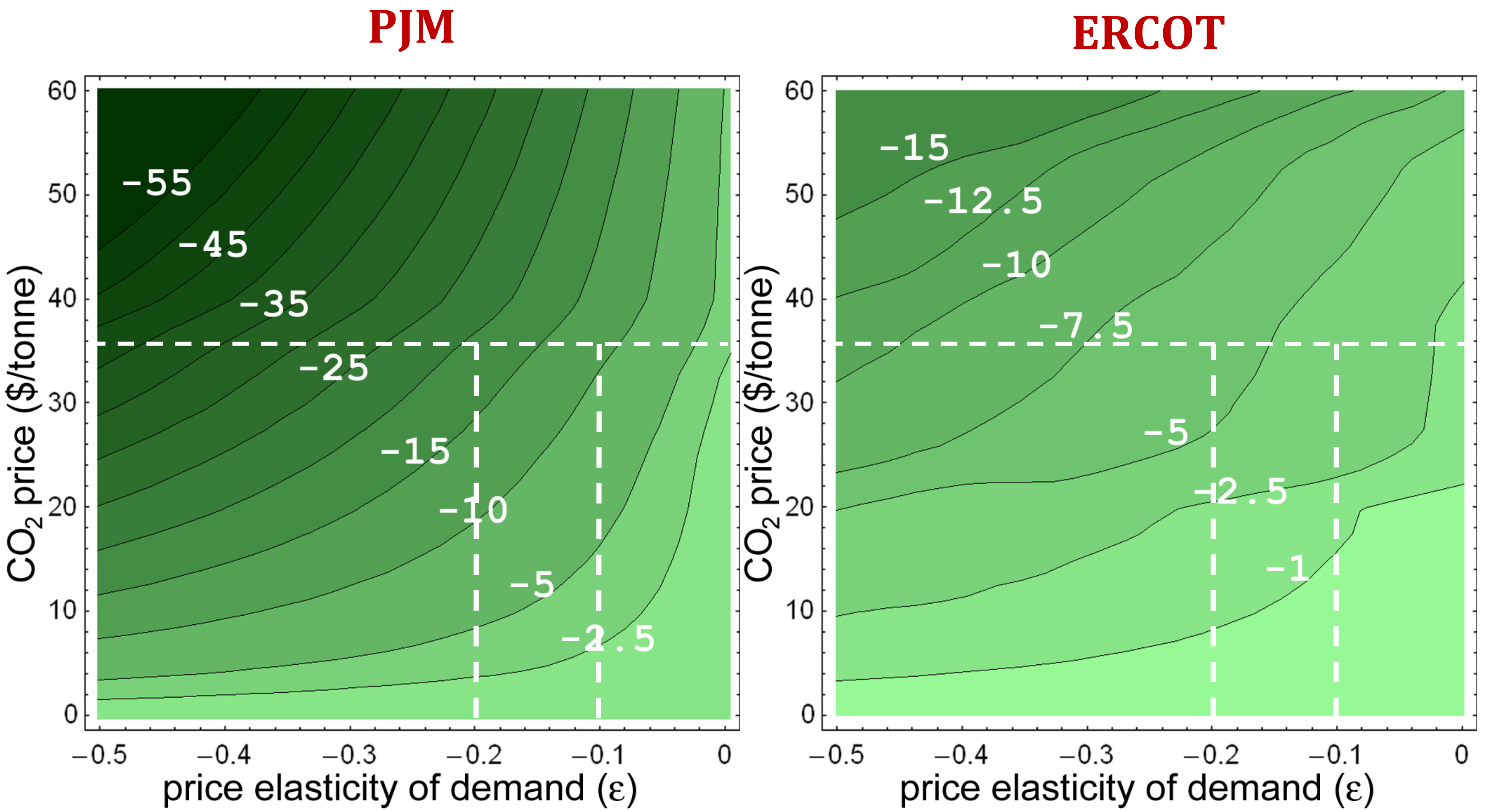
$35 / tonne CO_2

↓

10% –18%

CO_2 reductions

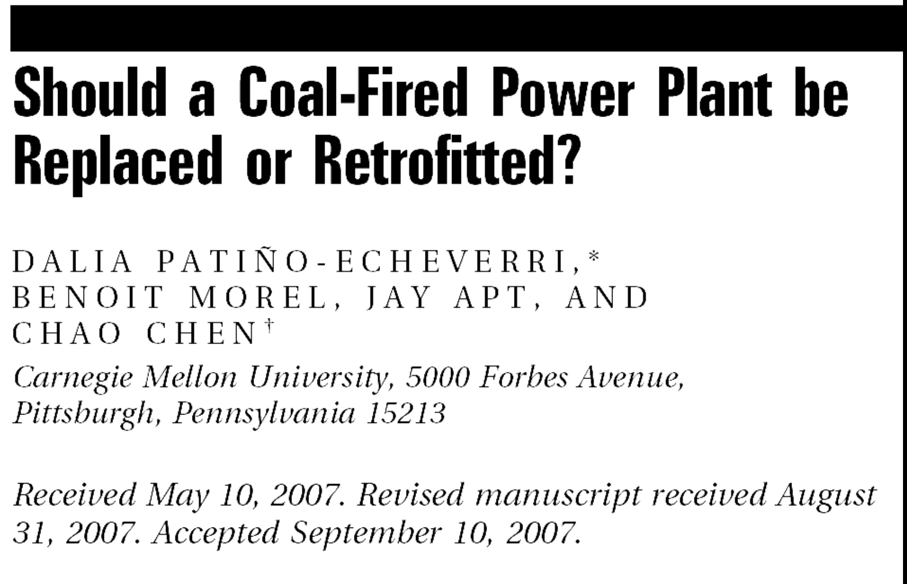
Percent CO_2 emissions reductions



$35 / tonne CO_2 → 11% –18% CO_2 reductions

3% –6% CO_2 reductions

Environmental Science & Technology



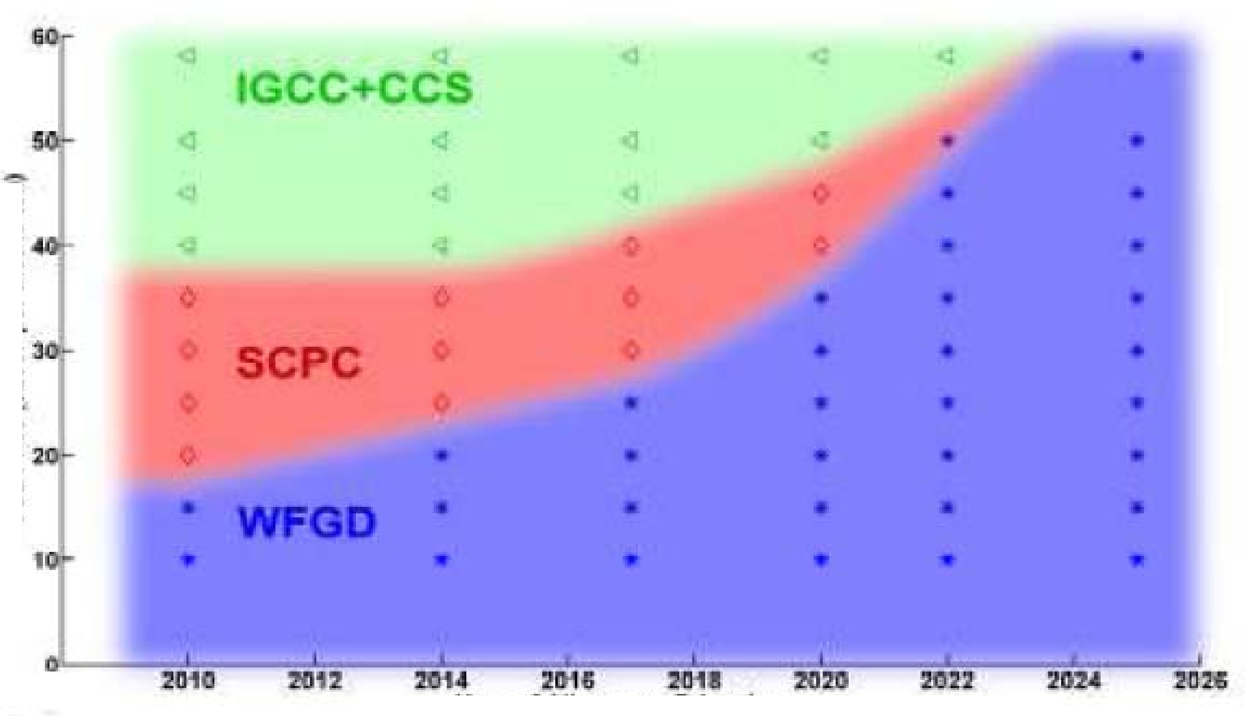
Should a Coal-Fired Power Plant be Replaced or Retrofitted?

DALIA PATIÑO-ECHEVERRI,*
BENOIT MOREL, JAY APT, AND
CHAO CHEN†
*Carnegie Mellon University, 5000 Forbes Avenue,
Pittsburgh, Pennsylvania 15213*

Received May 10, 2007. Revised manuscript received August 31, 2007. Accepted September 10, 2007.

Mathematical real options analysis for CO2 under cap-and-trade (planning horizon 20 years)

CO2 Price ($2007 per metric ton)



Year of allowance price jump

www.CMU.EDU/Electricity

Thanks to all our funders, including:

- EPRI
- The A.P. Sloan Foundation
- U.S. National Science Foundation, U.S. Environmental Protection Agency, U.S. Department of Energy, Tennessee Valley Authority, the U.S. Office of Naval Research, McDermott Technology, the ABB Group, Allegheny Conference on Community Development, Alliant Energy, Carnegie Bosch Institute, R.K. Mellon Foundation, National Rural Electric Cooperative Association, the Commonwealth of Pennsylvania Office of Energy and Technology Development, Pew Center on Global Climate Change, Team Pennsylvania Foundation, and others.

Special thanks to our CEIC Corporate Members and Associate Corporate Members:

- APPA
- Blue Source
- Bonneville Power Authority
- E3
- Eastman Chemical
- ELCON
- FPL
- Gasification Technologies Council
- GE
- JP Morgan Public Power Group
- NRECA
- Salt River Project
- Southern Company