# Establishing the Economic Impacts of Space Weather: The Case of Electricity

Kevin F. Forbes
The Catholic University of America
Washington, DC 20064 USA
Forbes@CUA.edu

O.C. St. Cyr
Department of Physics
The Catholic University of America
and NASA-Goddard Space Flight Center

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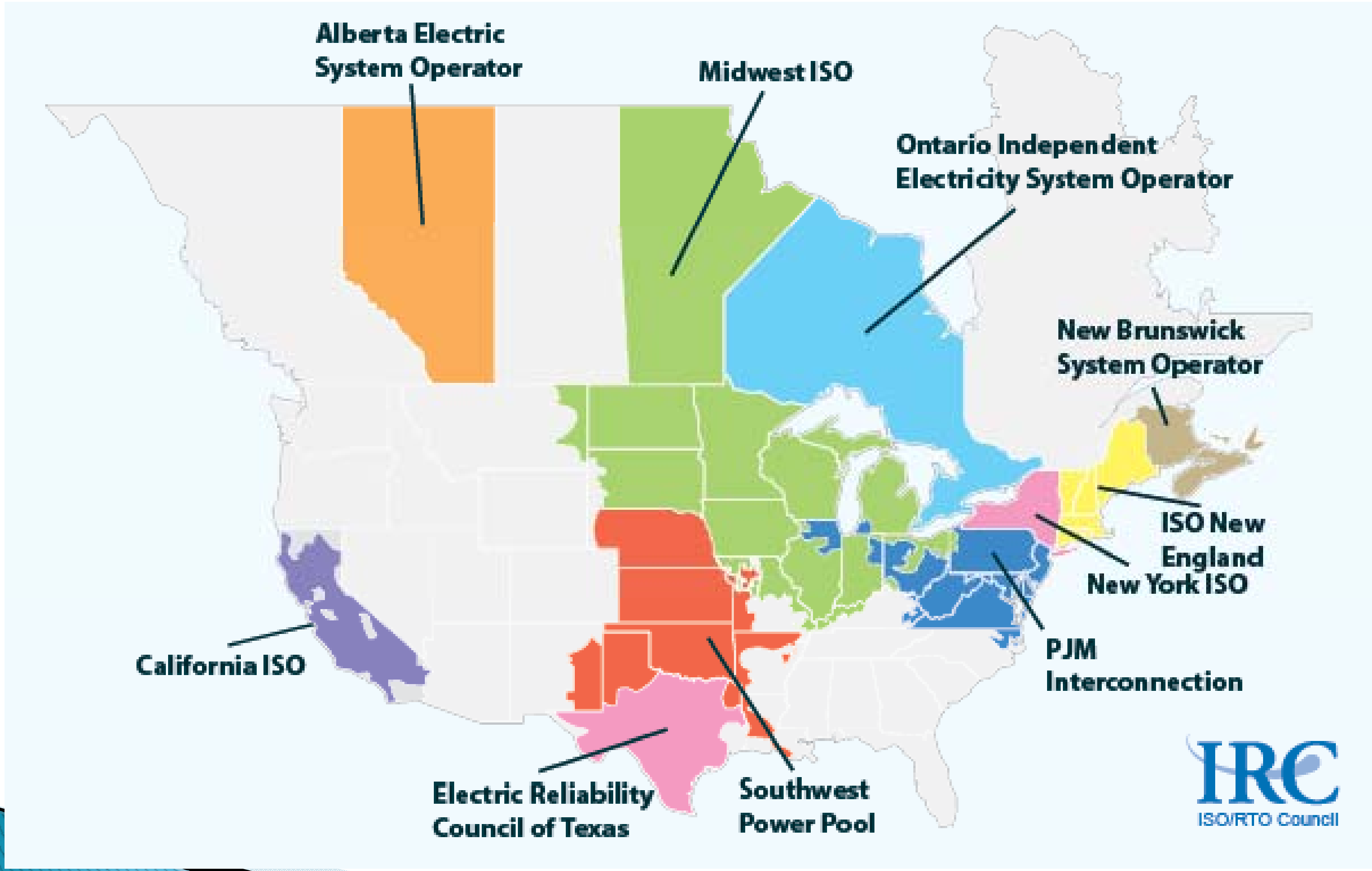
# Organization of this Talk

1. Background on Electricity Markets, Power Grid Operations, and the Goal of Electric Power Reliability
2. Geomagnetically Induced Currents and Prices in the PJM RTO
3. Why are the prices affected?
4. Can anything done about this?

## 1. Background on Electricity Markets, Power Grid Operations, and the Goal of Electric Power Reliability

- A substantial portion of electricity generation in the United States is now coordinated using electricity markets
- These markets are operated by organizations known as regional transmission organizations (RTOs) or independent system operators (ISOs)
- In many cases, the RTO/ISO will operate both a day-ahead and real-time market for energy.

# RTOs and ISOs in North America



# Economic Dispatch and the Resulting Informational Efficiency of the Market Prices

- The outcomes in these markets are increasingly being recognized as being informationally efficient.
- This is believed to occur because generators are dispatched based on an auction in which the market outcomes reveal the operating conditions.

# Economic Dispatch and the Resulting Informational Efficiency of the Market Prices (Continued)

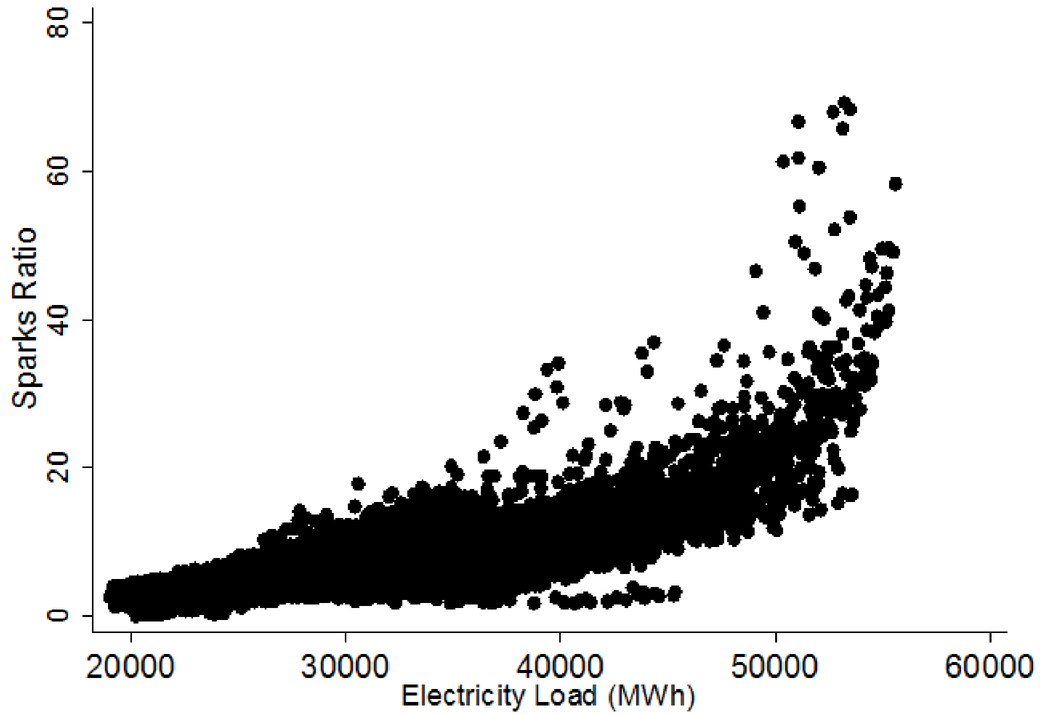
- Scheduled dispatch in the day-ahead market is based on offers to provide generation, which, in turn, are based on marginal costs.
- The offers are generally accepted beginning with the lowest-priced offers.
- Higher-priced offers are then accepted until the total amount of generation offered equals the anticipated demand for electricity.

# Economic Dispatch and the Day-Ahead Price

- The day-ahead price in each hour is determined by the expected operating characteristics of the last generating unit that is scheduled to be dispatched.

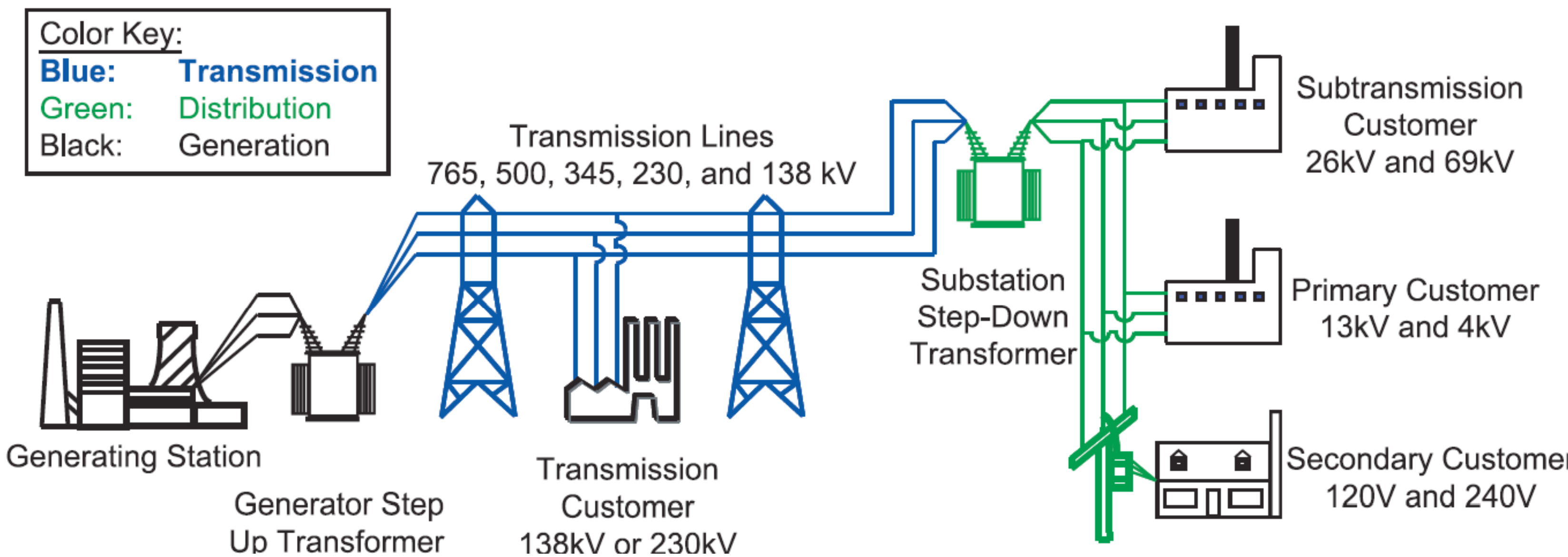
- The day-ahead price of electricity relative to the price of the fuels used to generate the electricity therefore reflects expected operating conditions.

## The Day-Ahead "Sparks Ratio" and Electricity Consumption in the PJM Control Area, 1 April 2002 – 30 April 2004




**Note: The sparks ratio is defined here as the ratio of the day-ahead system price of electricity in PJM relative to the prevailing spot price of natural gas in USD per GJ**

# The Basic Structure of the Power Industry



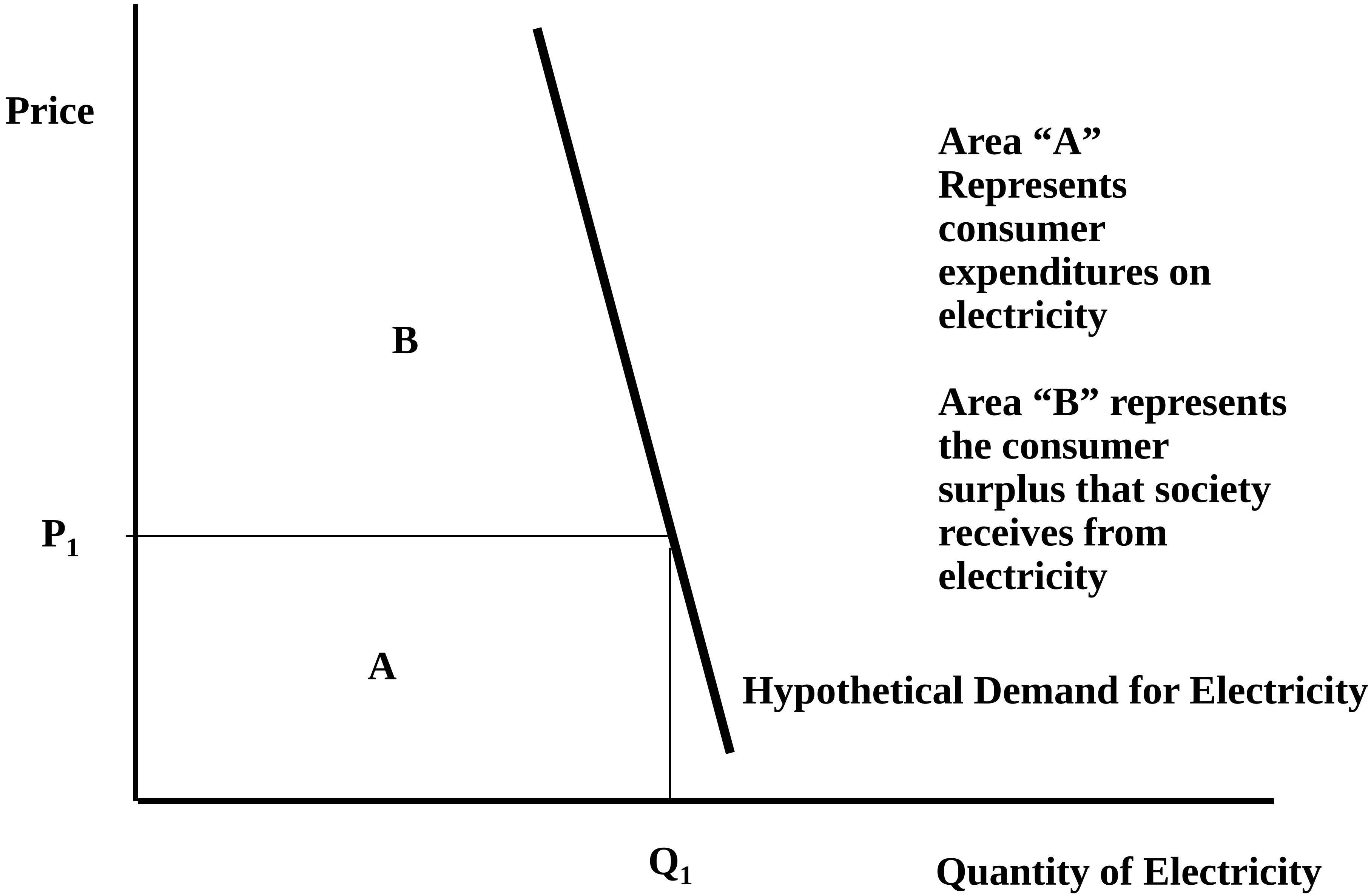

**Source: U.S.-Canada Power System Outage Task Force**

**Electricity is produced at relatively low voltages but is generally transported at high voltages so as to reduce transmission losses**

# What is the Economic Value of Electricity?

- Retail expenditures on electricity were approximately $370 billion in 2010, the most recent year for which data are available.
- The economic contribution of this industry is much higher than this because electricity is critical to almost everything we do and thus gives rise to a very large "consumer surplus"

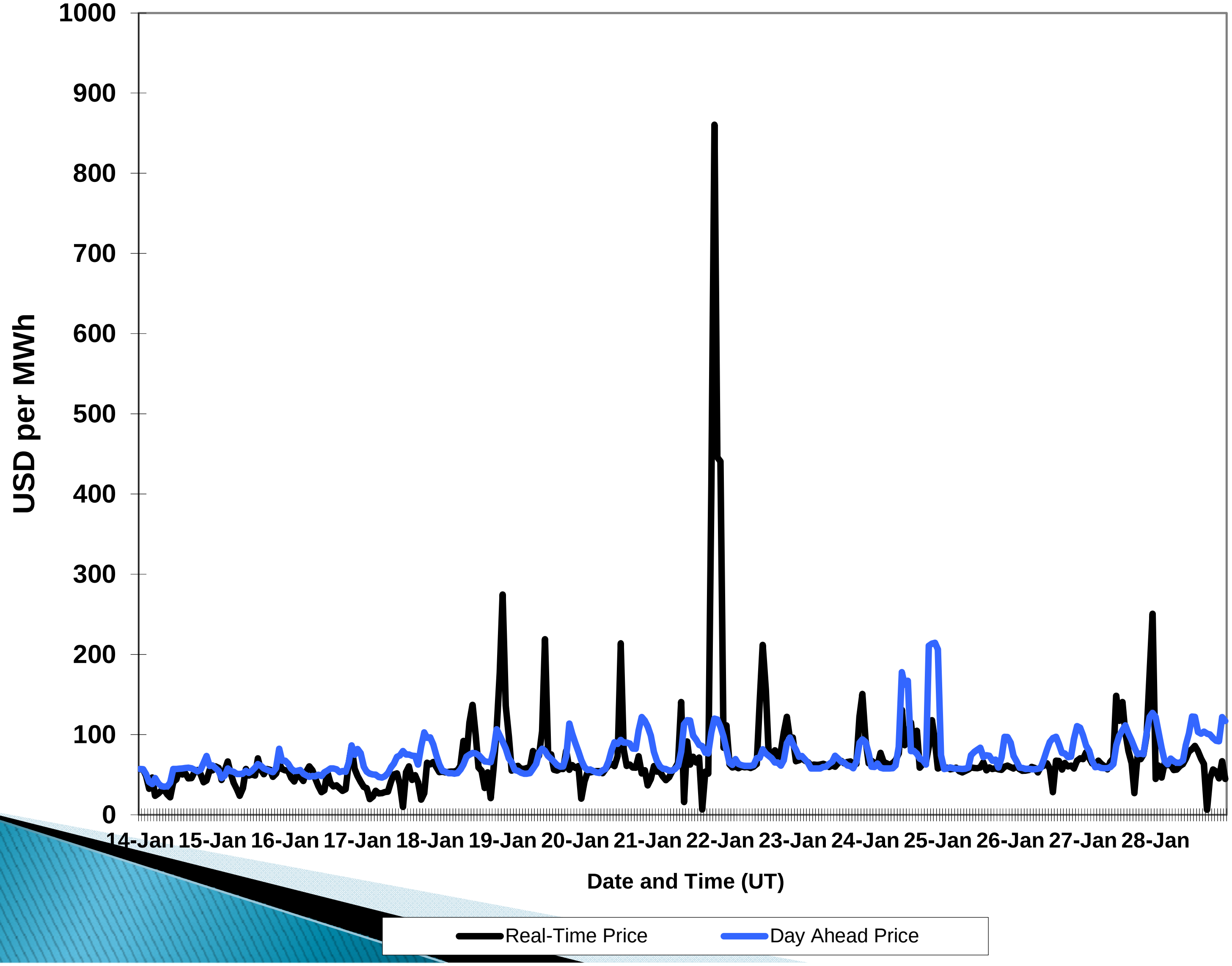
**A Hypothetical Demand Function for Electricity, Expenditures on Electricity, and the Consumer Surplus from Electricity.**



## Because the consumer surplus from electricity is very large, electricity blackouts are very costly to society

- While the wholesale price of electricity may be about $40 per megawatt-hour, the economic literature reports that the "value of lost load" is about $5,000- $10,000 per megawatt-hour
- Indicative of the high value of "lost load," it is not unheard of for the real-time price of electricity in today's restructured electricity industry to be close to $1,000 per MWh.

# The Day-Ahead and Real-Time Reference Prices of Electricity in the New York Power System, 1 – 31 January 2005



# Some Stylized Facts

- In general, electricity cannot be stored in large volumes – the power grid is not a battery.
- System operators manage the variability in demand through forecasting. While the average forecast errors tend to be modest, the distribution of the forecast errors have “fat tails.”
- Conventional generation is subject to occasional outages
- Electricity flows on a transmission system follow the laws of physics and thus the actual flow at a given interface may be quite different from the desired level

# Power systems have very stringent stability conditions

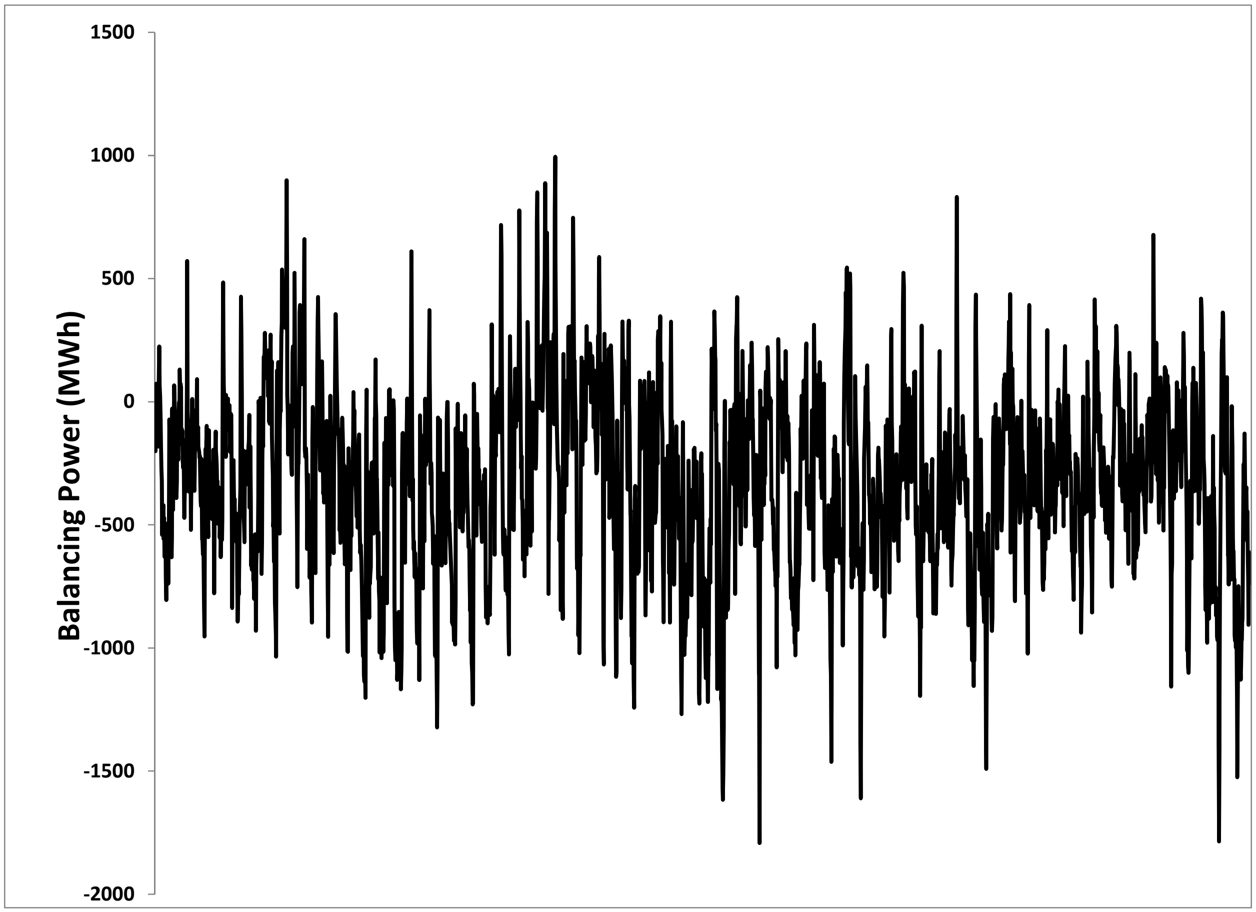
- The power system is almost exclusively an alternating current system
- There is a target level of system frequency, i.e. a desired level of voltage and current oscillations each second.
- The desired level of system frequency is 50 times per second in most of the world and 60 times per second in North America.
- Maintaining the desired levels of frequency requires that electricity supply equal demand at all times, not just on average.

# System Frequency

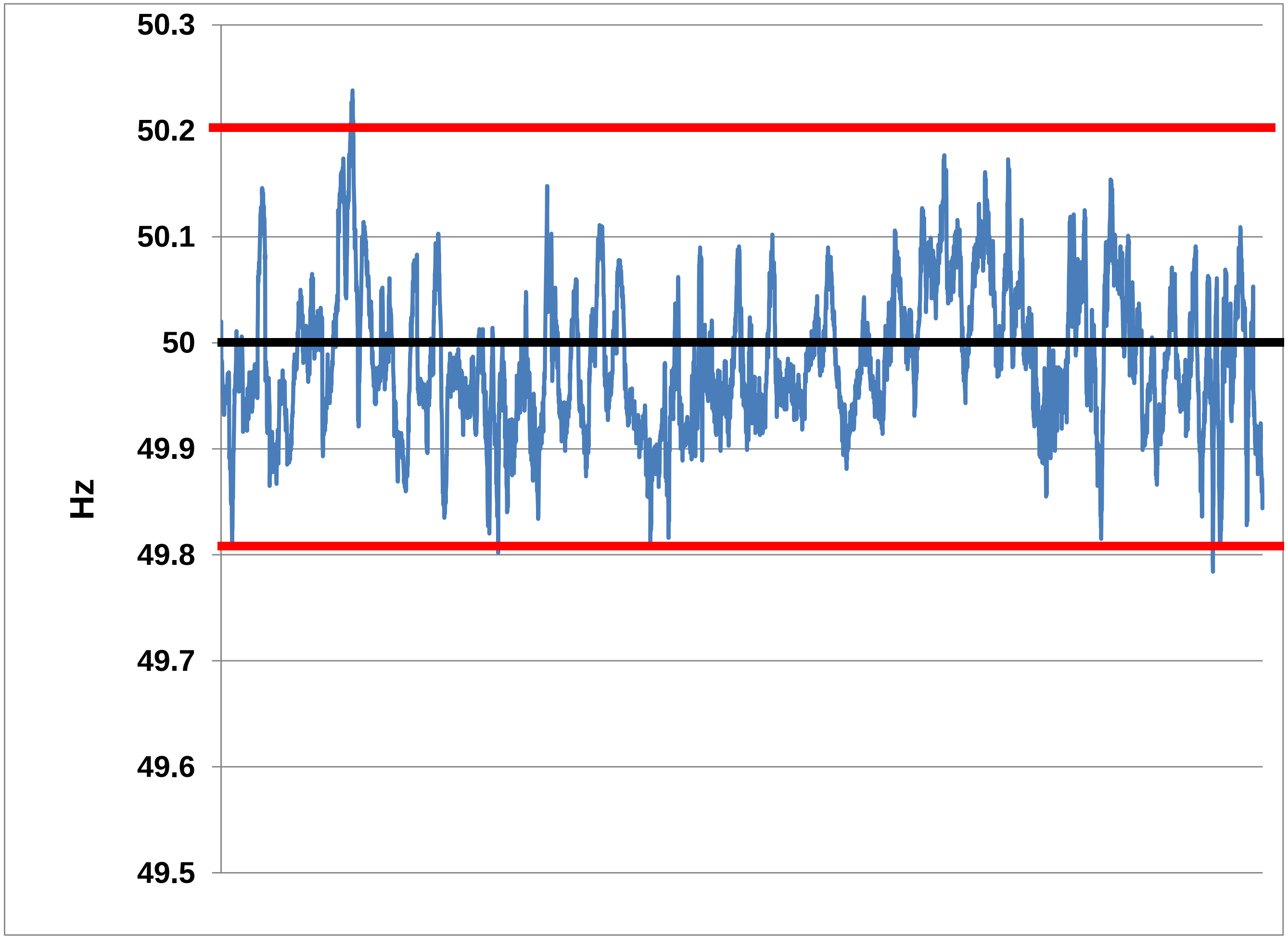
- System frequency falls when demand exceeds supply and rises when demand is less than supply. In either case, reliability is compromised.

- System operators offset these electricity imbalances by dispatching balancing power. These deployments can be large in magnitude

# The Dispatch of Balancing Power in the Power Grid that Serves England and Wales, 1 October – 30 November 2003.



# System Frequency in the UK Power Grid, 12 September 2011.



# Reactive Power and System Stability

- There is more to system stability than keeping system frequency within the stability limits.

- There are two types of power: Real and Reactive
- Real Power keeps the lights on

- Reactive power maintains the voltages required for system stability and thus is critical to the delivery of real power to consumers.

- Sources of reactive power include generators and capacitors. Reactive power is consumed by transmission lines, transformers, and motors.

# Reactive Power

- Excessive reactive power consumption has the potential to lead to voltage collapse and system instability.

- According to the Federal Energy Regulatory Commission voltage collapse due to inadequate reactive power has been a contributing factor in a number of blackouts.

# Reactive Power Deficiencies and Blackouts

- The blackouts cited by FERC include the blackout on 2 July 1996 and 10 August 1996 on the West Coast of the United States, 19 December 1978 in France, 23 July 1987 in Tokyo Japan, 28 August 2003 in London England, 23 September 2003 in Sweden and Denmark, and 28 September 2003 in Italy.

- FERC even notes that voltage collapse due to inadequate reactive power was a contributing factor to the blackout experienced by Hydro-Quebec on 13 March 1989.

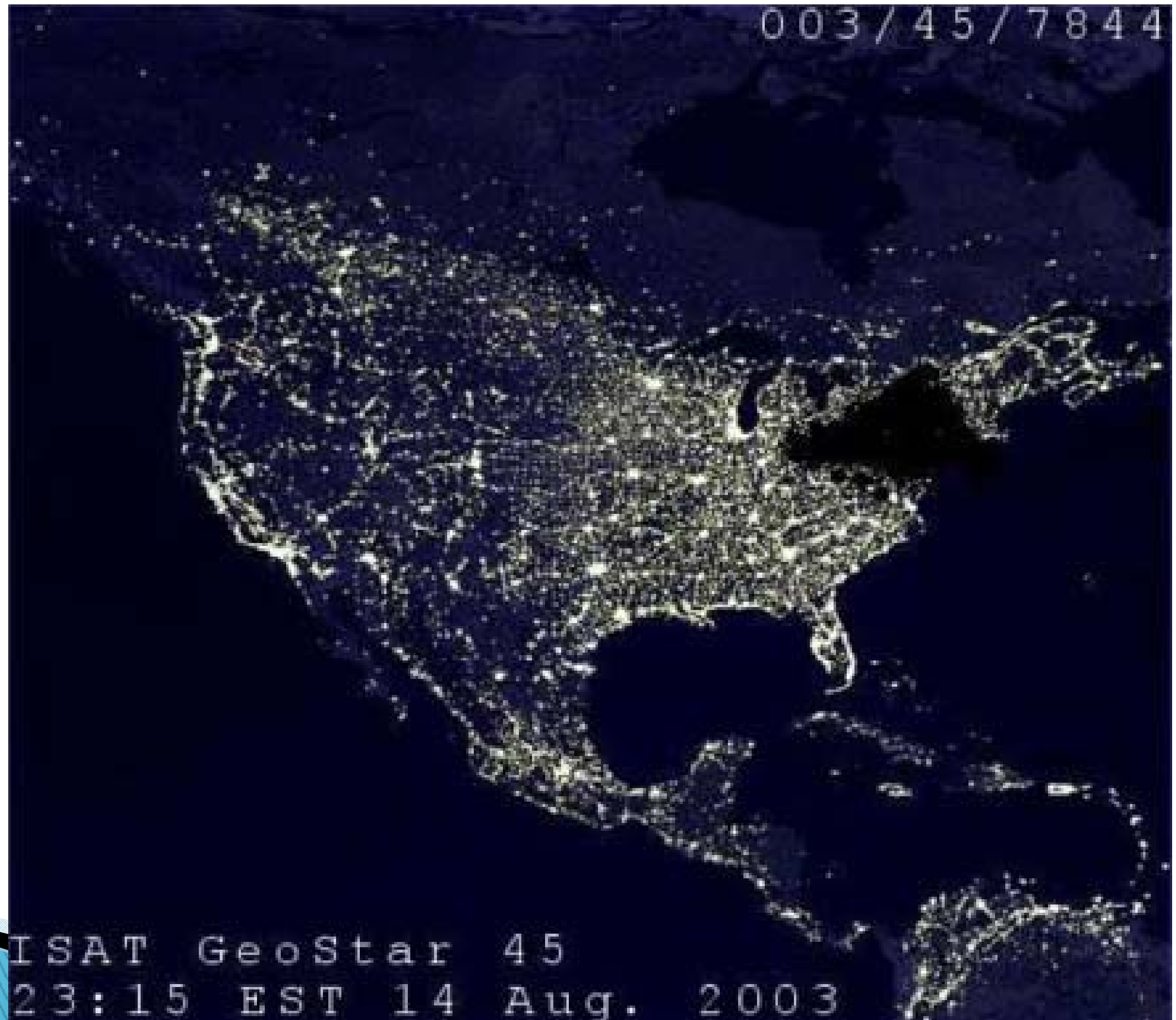
- The U.S.-Canada Power System Outage Task Force investigated the causes of the 14 August 2003 blackout in the Northeast United States and Canada and concluded that inadequate management of reactive power was a contributing factor.

# The 14 August 2003 Blackout in the Northeast United States and Canada

- The blackout originated in northeast Ohio and cascaded into an area with an estimated 50 million people.

- The lowest published estimate of the economic costs to the United States of the August 2003 blackout in North America is $4 billion

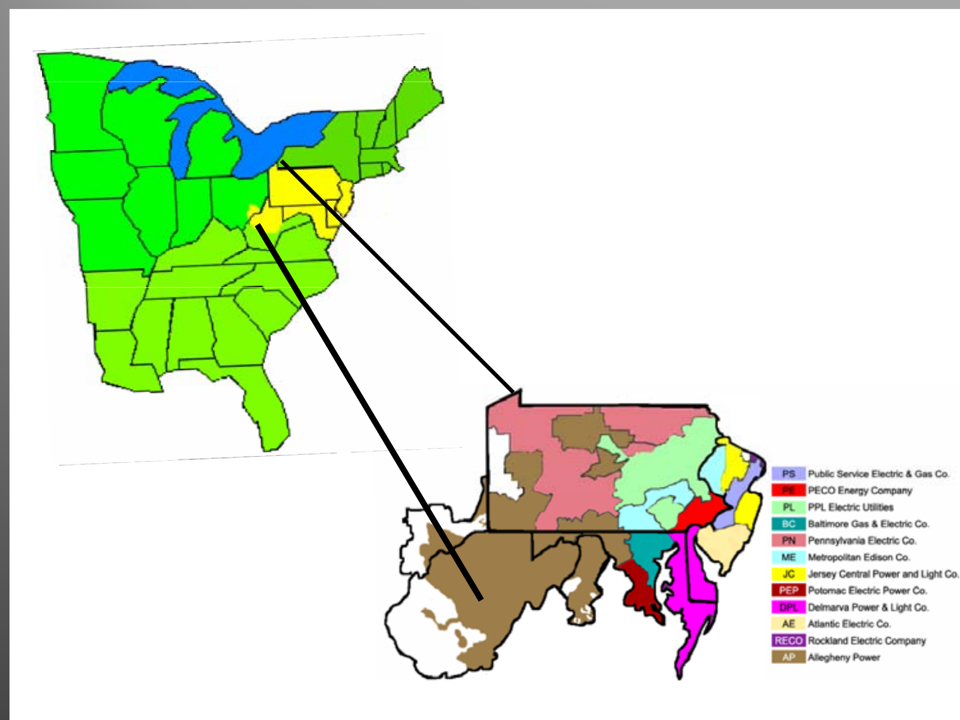
# The 14 August 2003 Blackout in the Northeast United States and Canada



# 2. Geomagnetically Induced Currents and Prices in the PJM RTO

- As of 30 April 2004, PJM coordinated the dispatch of 76,000 megawatts (MW) of generating capacity over 20,000 miles of transmission lines in all or parts of Delaware, Maryland, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia, and the District of Columbia.
- The sample period for this analysis is 1 April 2002 through 30 April 2004. The data are hourly.

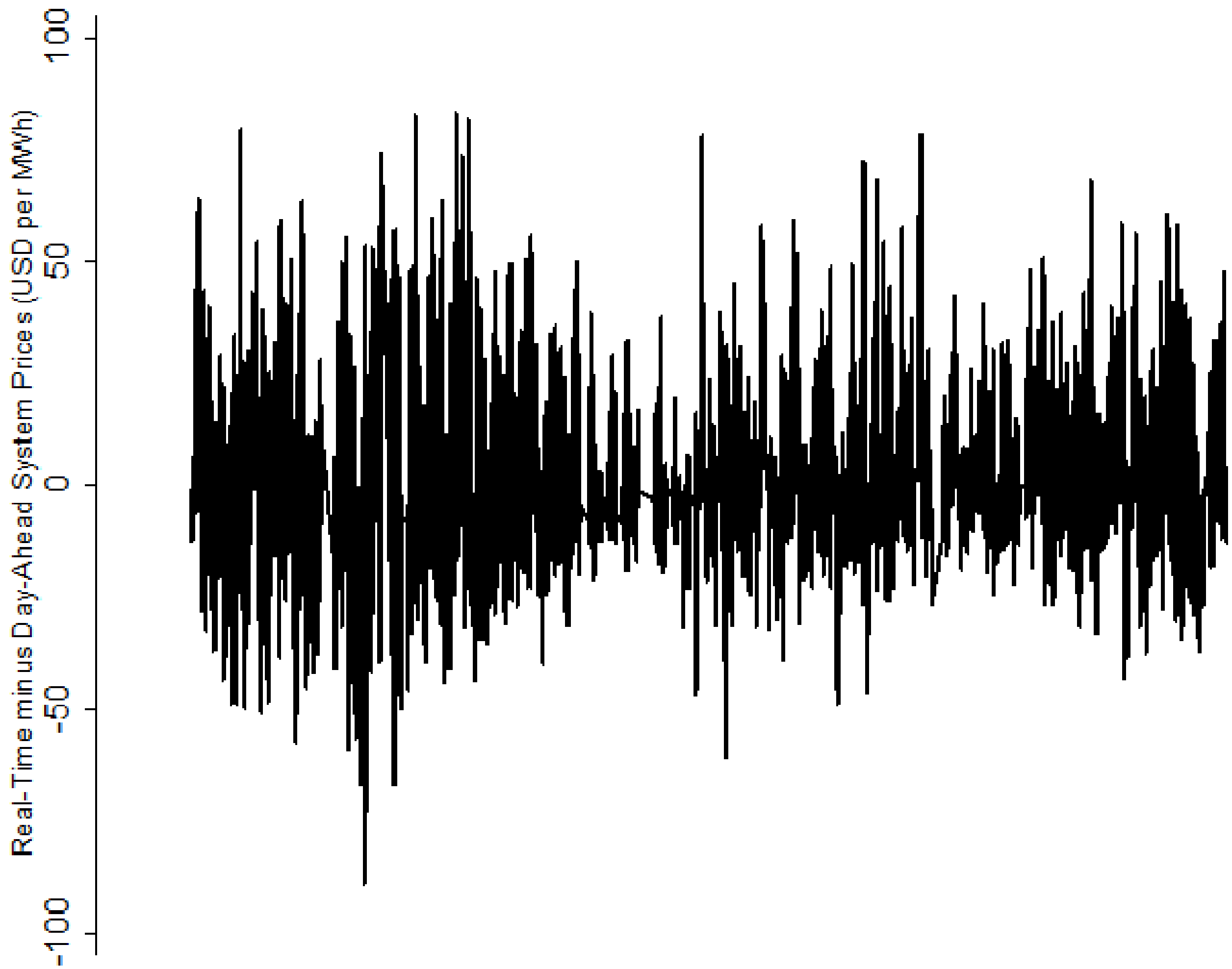
# PJM's Geographical Footprint as of 30 April 2004



# The PJM Power System

- PJM operates both real-time and day-ahead markets for energy.
- Prices are reported hourly.
- Prices in both markets are location based which means the prices will be equal across locations when the transmission system is uncongested, but can vary substantially from one location to another when there are transmission constraints.

**PJM's Hourly Real-Time System-Wide Price Minus its Hourly Day-Ahead Price, 1 January 2003 – 31 December 2003.**



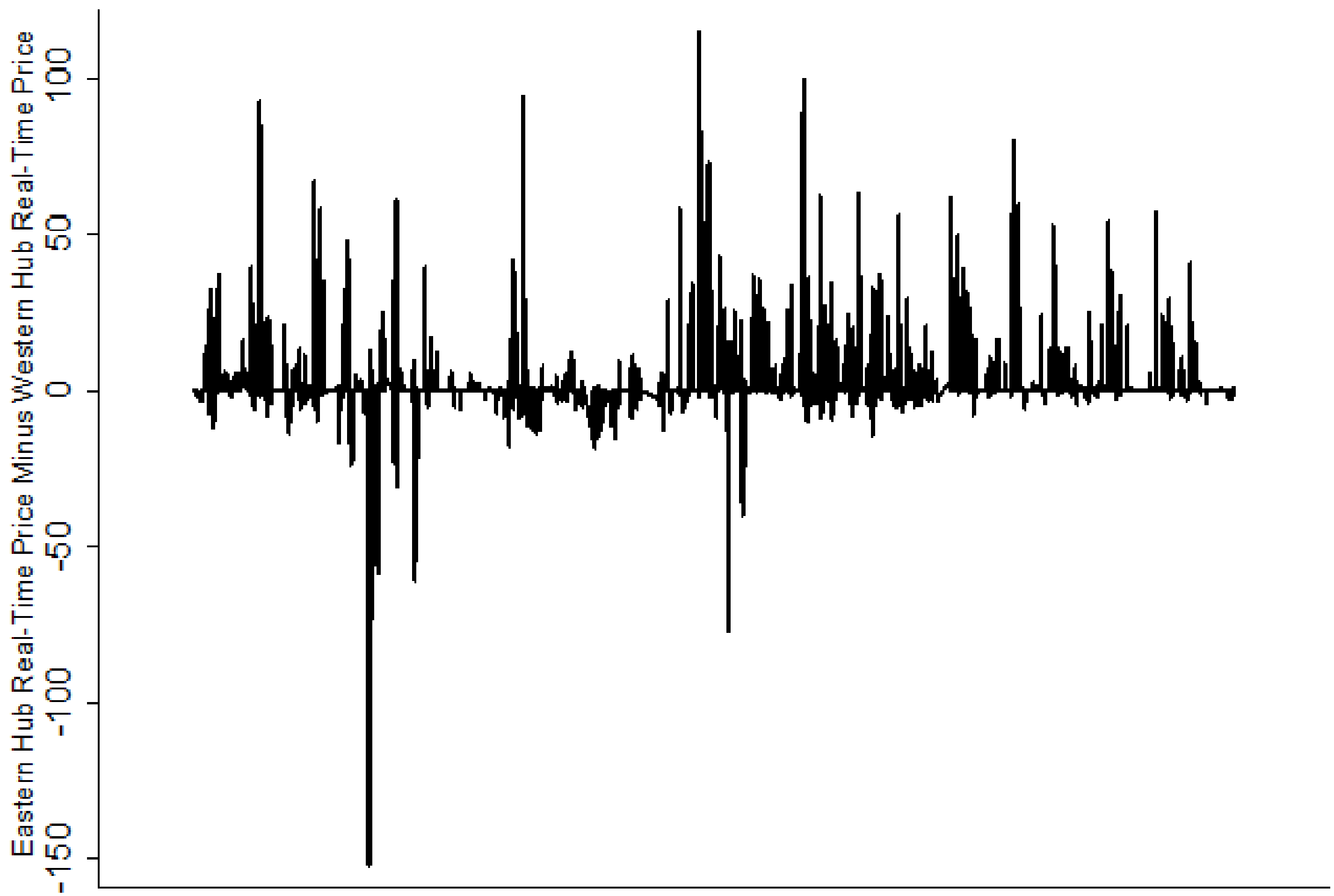
# Market Hubs

- PJM has a number of trading hubs whose economic function is to facilitate electricity trading.
- The two most important hubs over the course of the study period are its Eastern and Western hubs.
- These two hubs are located approximately 320 km apart in eastern and central Pennsylvania, respectively.
- Prices at the two hubs are equal in the absence of transmission constraints

# PJM: Highly Dependent on High Voltage Transmission

- Base load generation plants are largely in the western portion of the control area while demand centers are in the east.
- Over the sample period, the average electricity transfers from west to east averaged about 5,000 MWh per hour.
- The transfers make use of a 500 kv transmission system

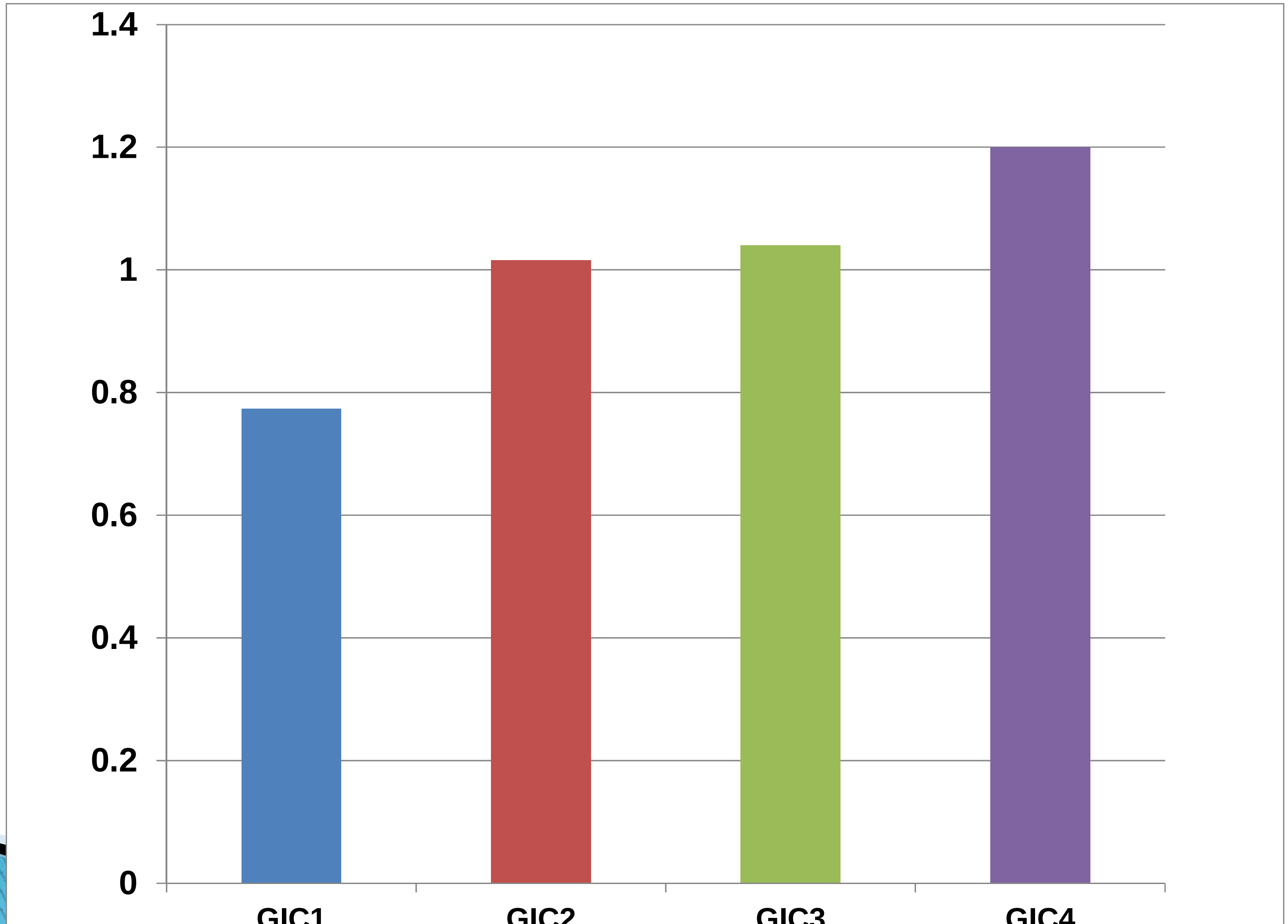
## PJM's Eastern Hub's Hourly Real-Time Minus the Hourly Real-Time at PJM's Western Hub, 1 January 2003 – 31 December 2003.



# GICs and the Differences between PJM's Real-time and Day-ahead prices

- Forbes and St Cyr (2010) organized the GIC proxy by quartile: GIC1, GIC2, GIC3, and GIC4.
- The positive differences in the prices (real-time minus day-ahead) were also arranged by quartile: P1, P2, P3, and P4.
- The observed frequencies for each cell were recorded.
- Expected frequencies for each cell were calculated under the null hypothesis of no relationship.

# The Ratio of Observed to Expected Frequencies for the Categories Representing GICs and the Fourth Quartile of the Positive Real-time/Day-Ahead Price Differences in PJM, 1 April 2002- 30 April 2004

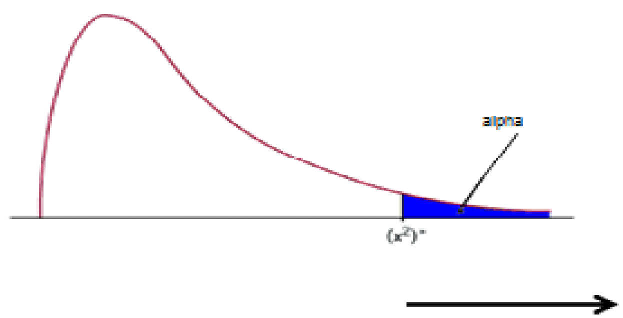


# Are the findings Statistically Signigicant ?

- Based on the differences between the observed and expected frequencies, a Chi-Squared statistic was calculated.

- This is a nonparametric test statistic that makes no assumptions about the distribution.

# Using the Chi-Squared Distribution to Test the Null Hypothesis of Statistical Independence




Reject null hypothesis if the calculated Value of the statistic exceeds $(\chi^2)^*$

# Results of the Test

- The calculated value of the test statistic was 85
- The critical value at the one percent level of statistical significance 26.2
- The null hypothesis of statistical independence was therefore rejected.

# Results of the Chi-Square Tests Between the GIC Proxy and Various Measures of Prices in the PJM Power Grid

| Price Measure | Chi-Square Statistic | P Value |
|---|---|---|
| The Difference between the Real Time and Day Ahead System Price | 85 | 4.953E-13 |
| PJM’s Eastern Hub | 113 | 1.748E-18 |
| PJM’s Western Hub | 83 | 1.213E-12 |
| Real Time Congestion Costs between the Eastern and Western Hubs as measured by the absolute value of the difference in the two real-time prices | 148 | 1.562E-25 |

# 3. Why are prices affected?

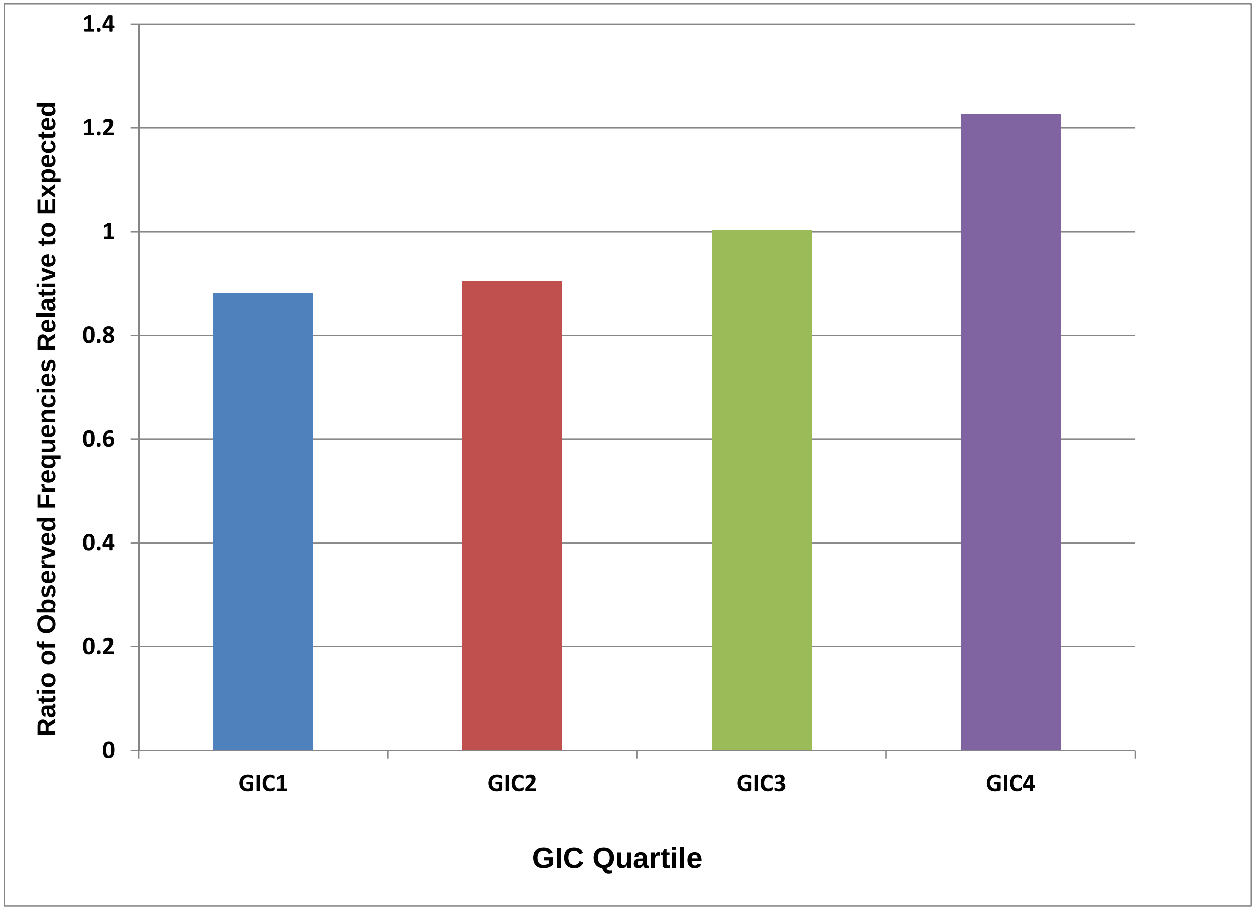
- The GICs Impair the Performance of the Transformers
- The GICs lead to adverse reactive power conditions

# GICs and PJM's 500 kv Transformers

- PJM remotely monitors these transformers for both internal temperature and flow.

- Based on these readings, transformers are determined to be unconstrained or constrained.

# The Ratio of Observed to Expected Frequencies for the Categories Representing GICs and Constrained 500 kv Transformers in PJM, 1 April 2002– 30 April 2004



# Constrained Transformers in PJM: The Results of a Multivariate Regression Analysis

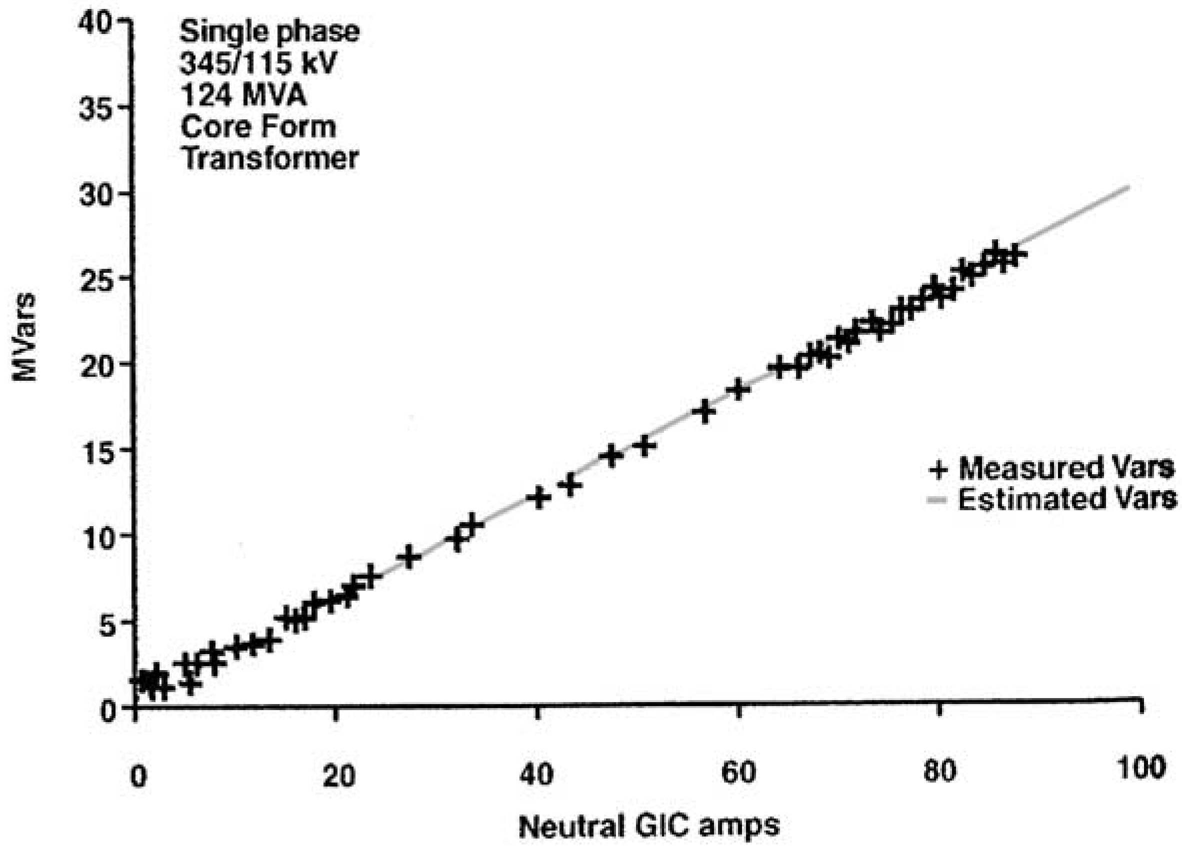
- Forbes and St. Cyr (2010) controlled for possible confounding factors by estimating a probit equation in which the binary variable representing constrained transformers was the dependent variable.
- The explanatory variables in the regression equation included ambient temperature, a GIC proxy, expected hourly load, unexpected hourly load, proxies for known transmission constraints, planned imports and exports, and proxies for unobserved hour of the day effects.
- The estimation results indicate that increases in geomagnetic activity in excess of a threshold of 1.9 nT/minute increase the probability that one or more of PJM's 500 kv transformers will be constrained.

# GICs and Reactive Power

- It is well established that GICs can lead to excessive consumption of reactive power within the transformers.
- In the words of John Kappenman,

"Though these quasi-DC currents are small compared to the normal AC current flows in the network, they have very large impacts upon the operation of transformers in the network…..The principal concern to network reliability is due to increased reactive power demands from transformers that can cause voltage regulation problems, a situation that can rapidly escalate into a grid-wide voltage collapse."

# GICs and the Consumption of "Reactive Power"




**Source: Molinski, 2002**

# Reactive Power and the 1989 Collapse of Hydro-Quebec

- According to John Kappenman, GICs increased reactive power consumption by a factor of approximately eight over the course of about six minutes on 13 march 1989.

- Minutes later, the high voltage lines needed to ensure electricity transfers to Montreal from the remote hydro generation facilities at James Bay "tripped."

- Hydro-Quebec was unable to make up the loss in transmission and the system collapsed.

# Reactive Power Issues in PJM

- The average transfers of electricity within PJM are very large, but there limits.

- Flows in excess of the limits violate the reactive power and voltage criteria.

- PJM considers adherence to the transfer limits at the internal interfaces within PJM to be critical to the reliability of its system.

- Its training materials note that "Small increase in flow or load can cause large voltage fluctuation" [*PJM*, 2008, p. 168] and that voltage collapse has potential to lead to a blackout of the system.

- In short, PJM reports that the "Reactive Transfer Limits are the <u>most critical</u> system reliability limits (emphasis not added)" because they represent the "Largest potential system impact if exceeded" [*PJM*, 2008, p. 168].

# Reactive Power Issues in PJM

- Generators in PJM are normally dispatched based on their cost with the lowest cost generators being dispatched first(e.g. coal or nuclear).

- One major exception to this "economic merit' or "on-cost" method of dispatch is when adverse reactive power conditions warrant an "out of economic merit" order dispatch.

- In PJM, this is known as a "reactive off-cost" operation. During a reactive off-cost operation, generators are redispatched in order to reduce power flows across transmission lines vulnerable to voltage collapse.

# Reactive Off-Cost Events

- The average real-time price at PJM's Eastern Hub over the sample period was about $0.70 per MWh higher than at its Western Hub when the transmission system was in reactive on-cost status.

- When reactive off-cost operations were in effect, the average real-time price at the Eastern Hub was approximately $11.36 per MWh higher than at the Western Hub.

- More importantly, a reactive off-cost event indicates that the stability of the system is challenged.

# Modeling the Reliability Challenge

- Forbes and St. Cyr(2012) modeled the status of the system as a binary variable whose value equals one if a reactive off-cost event is declared  and equals zero otherwise

- The model uses statistical controls for possible confounding factors with a focus on the inclusion of explanatory variables that reflect expected operating conditions

# The Explanatory Variables

- Ambient Temperature
- Actual Load, Forecasted Load, and the Intraday Variability in Forecasted Load
- Scheduled Imports and Exports
- The Hourly Day-Ahead Electricity Price relative to the “spot” prices of both natural gas and coal.
- Relative Fuel Prices
- The Intraday Variability in the Day-Ahead Prices

# The Explanatory Variables (Continued)

- Proxies for known transmission constraints

- Binary variables for the hour of the day and the day of the week
- A GIC Proxy. This variable is based on one minute geomagnetic data from the Fredericksburg geomagnetic observatory in Virginia.

# The Logit Model

The model was estimated using the Logit Model. This is a multivariate method of statistical analysis used by researchers in making statistical inferences with respect to the incidence of binary events.

The estimating equation:

$$Ln(p/(1-p)) = c + \delta \, GIC + \sum \beta_i \; X_i$$

Where $X_i$ is the $i^{th}$ control variable (e.g. temperature)

GIC is the value of a GIC proxy

# Results:

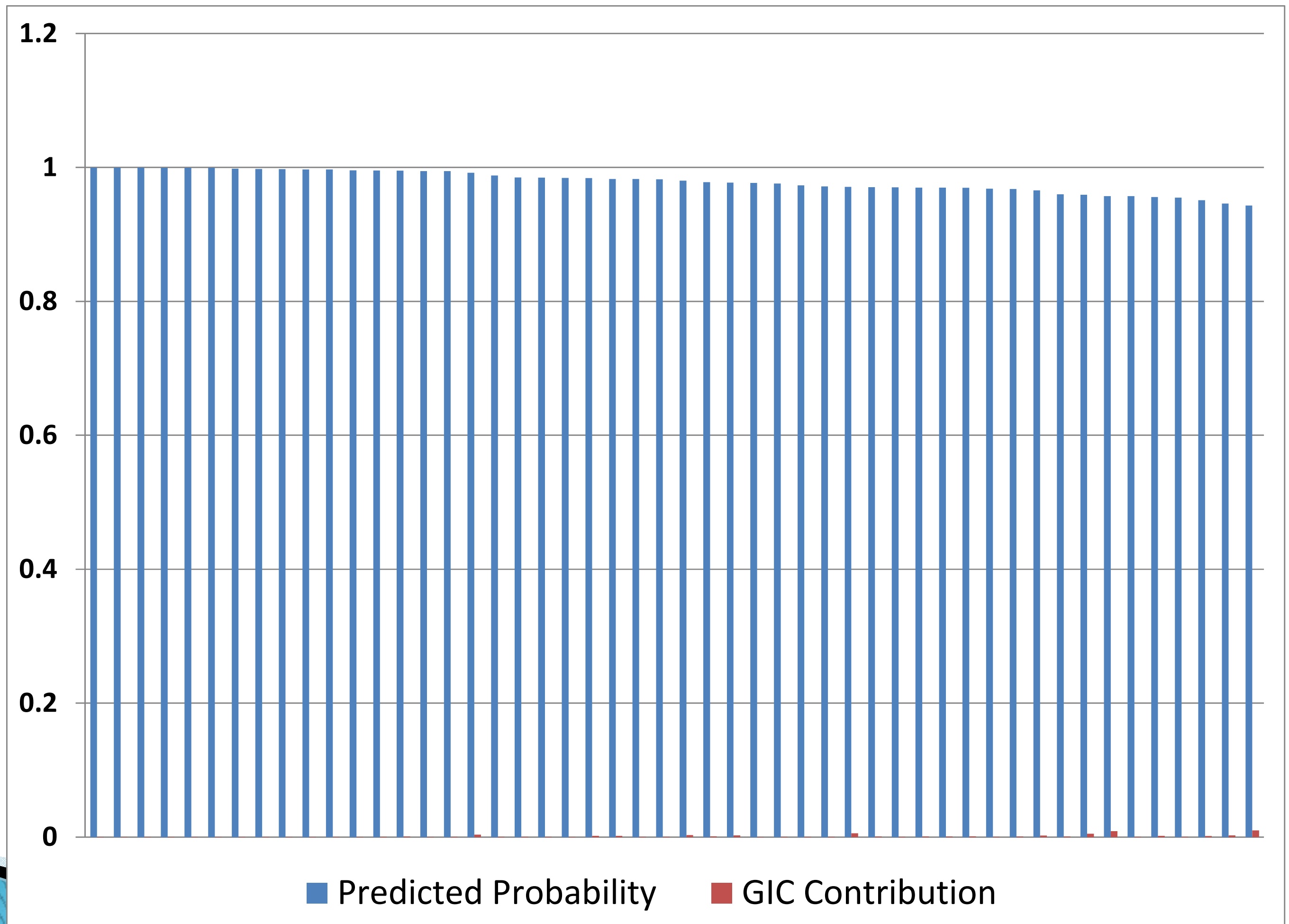
- The coefficients are highly statistically significant. For example, the coefficient on scheduled imports is positive and statistically significant.

- With respect to the GIC proxy, the coefficient is positive and statistically significant which is consistent with hypothesis that geomagnetic activity can contribute to a reliability challenge.

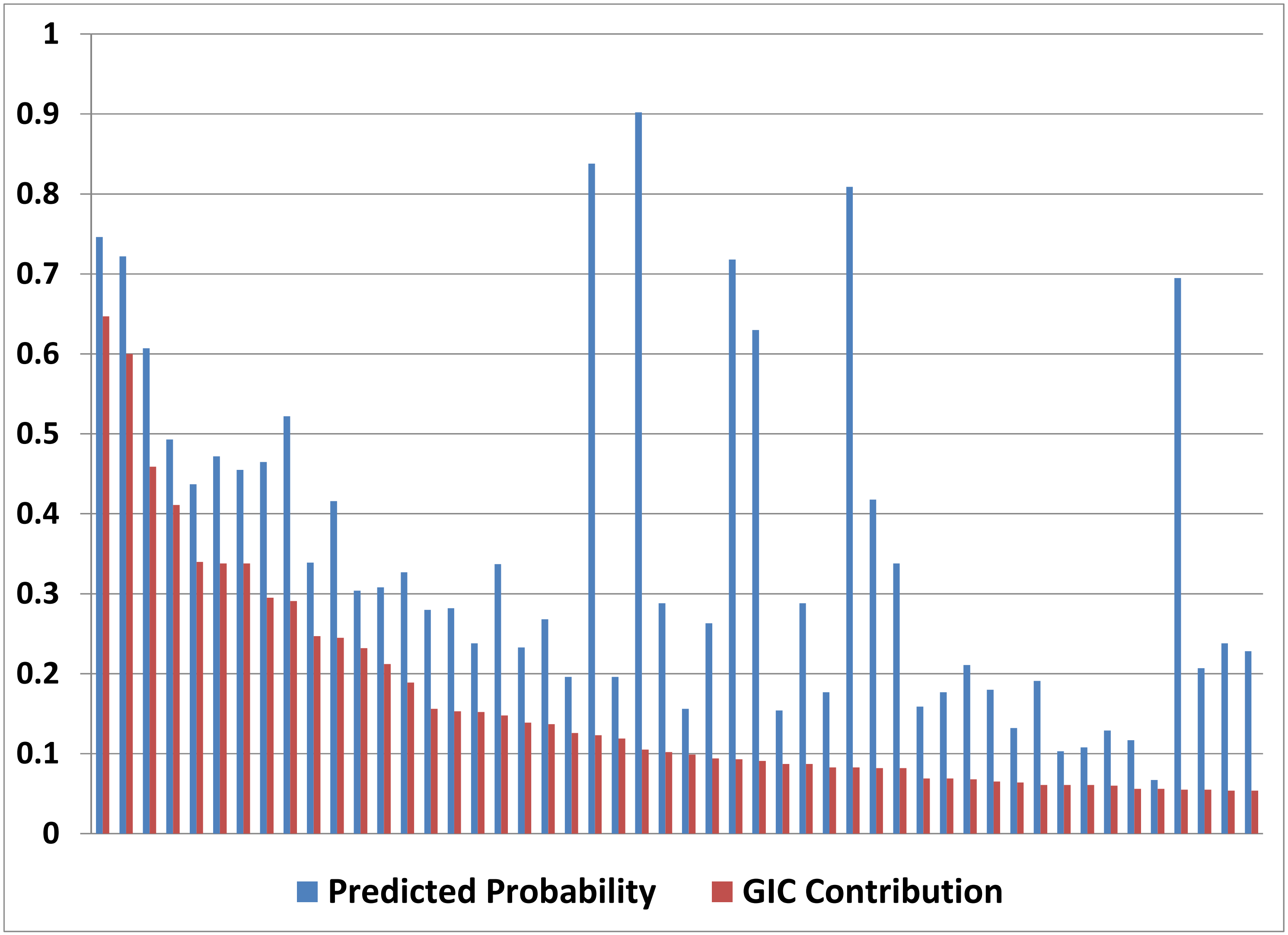
# Explanatory Power

- Percentage of correct predictions when “On-cost” status is predicted: 91%
- Percentage of correct predictions when “Off-cost” status is predicted: 70%

# Predicted Probabilities for 50 cases where the GIC Contribution is Unimportant



# Predicted Probabilities for PJM



# 4. Can anything done about this?

- Improved space weather forecasts would help a lot.

- Modeling and forecasting the vulnerability of the power system would probably also help.

# System Conditions, the GIC Proxy, and the Predicted Probability of a Reactive Off–Cost Event

| Vulnerability Percentile in the Absence of Space Weather | Probability of an Off-Cost Event in the Absence of Space Weather | Value of the GIC proxy (in nT/min) that would increase the Probability of a Reactive Off-Cost Event to 0.75 |
|---|---|---|
| 5th | 0.0055 | 342 |
| 10th | 0.0108 | 305 |
| 25th | 0.0279 | 253 |
| 50 th | 0.0643 | 205 |
| 75 th | 0.1215 | 167 |
| 90 th | 0.2110 | 131 |
| 95 th | 0.3318 | 98 |

# Conclusions

- The research reported here strongly supports the view that space weather had electricity market effects during solar cycle 23 even though there is no published evidence of a major space weather induced blackout.

- The price impacts are like “the canaries in the mine.” They inform us that the reliability of the power system is being challenged.

# Conclusions (Continued)

- The good news is that it may not insurmountable to forecast the terrestrial based vulnerability of the power system.
- Such forecasts may have the potential to enhance reliability even when the role of space weather is minor.
- Forecasts of vulnerability would also position system operators to make better use of space weather forecasts.

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