The Evolution of the Market for Wholesale Power*

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Abstract

The authors investigate the convergence in wholesale electricity day ahead spot prices over the period following the open access of transmission by FERC order 2000; specifically 2002–2012. By implementing correlation, Granger causality, and co-integration tests, as well as principal component and factor analysis the authors conclude that the regional wholesale markets have begun to converge to a national market. The authors propose the common trend test of Stock and Watson (1988) as method of determining the extent of the market. Despite this pattern of convergence, there does still appear to be constraints that segment the market along interconnections.

JEL Code: C31, C32, L94, N72, Q4

Keywords: electricity spot markets, market integration, cointegration, PCA, factor analysis

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1 Introduction

There is considerable debate over whether or not there exists a national market for wholesale electric power in the US.[1] This question has extensive implications for a wide range of public policies regarding mergers, production and imports of energy resources, electric power generation, electric power transmission, and retail electricity service. There are three major regions in the lower 48 states that have interconnected transmission grids: the Eastern Interconnect, the Western Interconnect, and the Texas Interconnect, see Figure (1).[2] Based on an analysis of electricity pricing data, we find that there is significant economic integration within the three regional wholesale power markets. In addition, we find that despite the absence of transmission interconnections between the three regions, the regional markets are becoming economically integrated with each other. We conclude that a national market for wholesale electric power is emerging.

To test the hypothesis that there is an emerging national wholesale power market, we examine monthly averages of day-ahead wholesale price data at eleven trading hubs and compare prices both within and between the three regions. We employ monthly averages to take into account the effects of market forces of duration longer than one day and shorter than one month.[3] These long-term market forces include bilateral contractual agreements and

[1] For example, The U.S. Energy Information Administration (EIA) devotes an entire section of their current Electricity Monthly Update to "[the U.S. many] regional wholesale electricity markets." The Electric Energy Market Competition Task Force (2005) asks "whether competition in wholesale markets has resulted in sufficient generation supply and transmission to provide wholesale customers with the kind of choice that is generally associated with competitive markets." The American Public Power Association (APPA) (2008) argues that: "the structural features of the electric utility industry [has made] it difficult for true competition to develop or flourish."

[2] The physical movement of electrons across interconnects due to engineering limitations is practically non-existent. The EIA recently characterized the status of the eastern and western interconnects as being: "the Eastern and Western interconnections (and a third interconnection covering most of Texas) are for most purposes electrically isolated from each other. Each interconnection is operated independently, and trade between the interconnections across the direct current ties is minimal." (EIA, 2011)

[3] In a companion paper, Butters (2013) investigates the integration of the several real-time markets at the hourly and daily frequency and finds a limited amount of integration across regions.

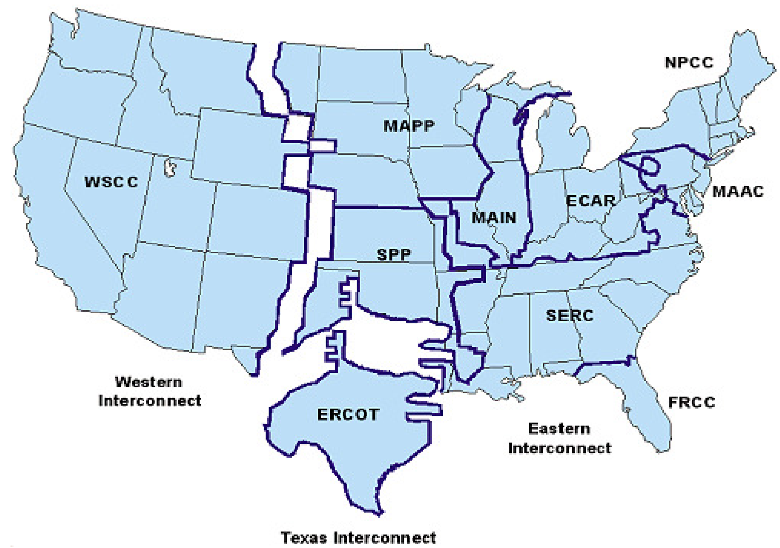


Figure 1: Map of the three interconnects throughout the United States

trades among buyers and sellers, demand adjustments by industrial and commercial buyers with multiple facilities, supply adjustments by electricity suppliers with multiple facilities, and factor price equalization in energy sources. Monthly averages reflect both direct arbitrage of electric power within regions and indirect economic arbitrage within and between regions. Thus, we examine whether a national market is emerging with an adjustment period that is less than one month.

The main results of the analysis are as follows. First, we find strong evidence of the emergence of a national market for wholesale power by comparing prices at pairs of trading hubs both within and between the three interconnect regions. Using pairwise correlations and pairwise Granger causality tests, we find substantial economic integration within the regions as well as between the regions. We find limited economic integration between the three regions in periods of high demand or capacity constraints in supply. Our results are robust to adjustment for the common influence of natural gas prices, as well as seasonality.

Second, we extend the analysis beyond pairwise comparisons by applying principal component analysis (PCA) and factor analysis methods to all of the trading hubs within the sample. This allows us to identify the historical co-movement of the price series across different trading hubs and to isolate structural patterns in the data. The first principal component among the covariance matrix of the price series explains over 55 percent of the variation in the data. Using oblique rotations of a two-factor model, we are able to identify an eastern and a western side to the market. These two sides of the market are highly correlated.

Third, we introduce a novel application of the cointegration analysis of Stock and Watson (1988) that is widely used in macroeconomics. This cointegration test contributes to the analysis of microeconomic market definition by examining whether or not the trading hubs are subject to common trends. We implement the common trend test (CTT) of Stock and Watson (1988) and find that in all of the specifications, the null hypothesis of two or more non-stationary trends can be rejected in favor of the alternative hypothesis that there is a single common trend among all of the price series; a result consistent with the emerging national market hypothesis.

Fourth, we consider the transaction costs that are associated with economic arbitrage between the three regions. Economic arbitrage exists between the three regions despite the absence of transmission connecting the regions with each other. We introduce methods used to estimate border effects in the international trade literature to determine the impact of the absence of transmission interconnections.[4] Using the volatility of price series within the same interconnect as a control for the effect of distance on the volatility of prices, we estimate the effect of being separated by a transmission interconnect on the volatility of prices between the two locations. We find that trading hubs across transmission interconnects experience

[4]On estimation of border effects in the literature on international trade, see Anderson and van Wincoop (2004) for a survey, and Coe et al. (2007), Engel and Rogers (1996).

price volatility border effects equivalent to trading hubs separated by a distance of at least 300 miles.

Finally, we consider the possibility of estimating transaction costs per-unit of electric power within and between regions using pairwise price differences between the eleven trading hubs in our data set. Using the Jarque-Bera and Lilliefor statistical tests for normality, we fail to reject the null hypothesis that the distribution of price differences between trading hubs within regions is normal for 8 of the 20 pairs. Accordingly, it is not possible to estimate the per-unit transaction costs between trading hubs as in Spiller and Huang (1986), Spiller and Wood (1988a), Spiller and Wood (1988b), and Kleit (1998), Kleit (2001) due to identification issues common in finite mixture models.[5] In order to estimate transaction costs, additional data or information about trade flows or other factors would be necessary. Absent such additional information, it is possible that transaction costs within regions are negligible or even zero. For between-region comparisons, we fail to reject the null hypothesis that the distribution of price differences between trading hubs is normal for 17 of the 35 pairs.

Our discussion builds on the classic work of Stigler and Sherwin (1985) who argue that high correlations between prices implies that goods reside within the same market, controlling for serial correlation and common influences. We extend the analysis of Doane and Spulber (1994) that examines the development of a national wholesale market for natural gas. King and Cuc (1996) utilize the Kalman filter to allow for time variation in the level of cointegration among the series, see also DeVany and Walls (1993). Evans et al. (2006) and Zachmann (2008) use principal component analysis to address the level of integration in the New Zealand and the European Union electricity context, respectively. We extend the series of multivariate

[5] The question of whether there is a unified market for electric power tends to differ from antitrust market definition under the Department of Justice's (DOJ) horizontal merger guidelines. Werden and Froeb (1993) argue that economic market definition differs from antitrust definition of the "relevant market" that is used to identify market power effects of mergers. Werden and Froeb (1993) and Coe and Krause (2008) caution against using price correlation tests for economic market definition to determine market power in merger analysis.

techniques that statistically identity the level of integration among an arbitrary amount of series; specifically oblique factor rotations and the CTT test. Furthermore, the standard pairwise tests looking at correlation and Granger causality are not robust to the presence of unit roots, a common occurrence in price series. The CTT test leverages the presence of unit roots in the multivariate series, and allows the econometrician to test the overall level of integration statistically.

We consider the emergence of a national market in wholesale electric power in the context of the restructuring of the U.S. electric markets both at the wholesale and retail level.[6] Accordingly, our data begin in 2000 with national restructuring of the industry and the introduction of hubs for wholesale electric power. Park et al. (2006) use directed graph techniques in order to motivate a particular Cholesky decomposition and explore the resulting impulse response functions, inferring the different roles hubs play in the price transmission mechanism. Our results are consistent with those of Park et al. (2006), which find that the integration of trading hubs seems strong especially amongst hubs within the same transmission interconnect. Mjelde and Bessler (2009) look at the integration of the PJM and Mid-Columbia trading hubs (both at on-peak and off-peak hours) as it pertains to the prices of their major fuel sources. Earlier studies by DeVany and Walls (1999) and Woo et al. (1997) address the issue of market integration within the Western Interconnect and find evidence that the region has developed into an integrated wholesale market using pairwise cointegration tests.

1.1 History of the Wholesale Electricity Market

This section examines the development of the wholesale power market. The section considers the effects of deregulation and industry restructuring and economic forces driving market convergence.

[6]See Holburn and Spiller (2002) and Kwoka (2006). Jamasb and Pollitt (2005) provides a review of the European experience.

The market for electricity in the United States exhibits steadily increasing geographic scope from a few city blocks to a nation-wide scale with international connections to Canada. Electricity transmission dramatically increased the distance for electric power supply, allowing electric utilities to expand their service territories. In 1882, Thomas Edison's Pearl Street Power Station served 85 customers in lower Manhattan and service was limited to one square mile. In 1895, George Westinghouse opened a hydroelectric power plant at Niagara Falls and, with the application of alternating current (AC), transported electricity for 25 miles.[7] By 1920, Samuel L. Insull's Commonwealth Edison served 500,000 customers in Chicago.[8] In the 1920s, interconnection and long-distance transmission of electric power expanded considerably.[9] During the 20th century, major electric utilities expanded their service territories to include millions of customers. Today, what is called the "world's largest machine," the U.S. electric transmission grid, has over 200,000 miles of high-voltage transmission lines.[10] Despite ever-increasing distances in electricity transmission and distribution, however, the U.S. electricity market remained fragmented at the start of the 21st century.[11] Electricity markets were limited to the local or regional service territories of incumbent electric utilities. The opening of access to transmission by the Federal Energy Regulatory Commission (FERC) under order 2000 in December 1999 was a watershed in the development of the national market for wholesale electric power.[12] The development of the wholesale markets also has depen-

[7] Berton (1992).

[8] http://www.encyclopedia.chicagohistory.org/pages/2622.html

[9] Hughes (1983).

[10] See www.eei.org/ourissues/ElectricityTransmission/Pages/default.aspx, www.theenergylibrary.com/node/647, and Biello (2008).

[11] For much of U.S. history the electrical power market resembled a patchwork quilt of localized monopoly utilities responsible for generation, transmission, and distribution serving consumers at regulated prices. See Fagan (2006) who first used the illustrative metaphor of the electricity market resembling a "patchwork quilt" in his review of the restructuring of the electrical markets.

[12] The Federal Energy Regulatory Commission (FERC) instituted open access regulation of transmission in 1996 to help establish wholesale power markets. Then, several years later, the FERC required public utilities that owned or operated transmission facilities to participate in Regional Transmission Organizations (RTOs) and guarantee open access to all third party providers. This order came at the heels of independent power producers complaining that vertically integrated utilities were discriminating against third party energy

dence on differences in regulatory policies at the state level.[13] As of late 2012, seventeen states allowed retail customers to purchase electricity directly from competitive suppliers. Most of these states are found in the northeast with the exception of Illinois, Texas, and California. Even though residential participation in the competitive market place has been low across most of the states, a sizeable amount of commercial and industrial customers have begun to purchase their power from competitive suppliers.

The FERC actions led to the development of Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) that manage transmission systems covering regional markets in over two-thirds of the US. The RTOs/ISOs for the US and Canada deliver 2.2 million gigawatt-hours of electricity annually and monitor more than 270,000 miles of high-voltage power lines.[14] The seven major RTOs/ISOs are the California ISO, the Southwest Power Pool, the Electric Reliability Council of Texas (ERCOT), PJM Interconnection, Midwest ISO (MISO), New York ISO (NYISO), and ISO New England.[15] The PJM Interconnection is an RTO that "coordinates the movement of wholesale electricity and manages the high-voltage electric grid and the wholesale electricity market" in 13 states and the District of Colombia.[16] An Independent System Operator (ISO) is an organization that manages transmission systems and power flows on the grid. MISO, an example of an ISO serves as an "independent platform for transparent regional energy markets" that "encourages wholesale electric competition in the region, and cultivates greater system reliability as well as coordinated, value-based regional planning.[17]"

producers in providing access to transmission. Since this initial order, FERC has continued with this agenda of opening up electricity generation, transmission, and distribution by way of orders 2000 and 2006.

[13] The California episode in the early 2000s have given some states pause in restructuring their wholesale/retail markets; see Borenstein and Bushnell (1999), Borenstein and Bushnell (2002). Other states, most notably Texas, have experience greater success in their restructuring efforts.

[14] http://www.caiso.com/about/Pages/OurBusiness/UnderstandingtheISO/Opening-access.aspx

[15] MISO also covers part of Canada. Canada also has the Alberta Electric System Operator, New Brunswick System Operator, and the Ontario Independent Electric System Operator.

[16] See PJM website: http://www.pjm.com/about-pjm.aspx

[17] MISO website: https://www.midwestiso.org/AboutUs/Pages/AboutUs.aspx

Following the FERCs actions, the number of power marketers and independent generation developers increased dramatically. Trade in wholesale power markets rose significantly transforming the usage of the nation's transmission grid.[18] The development of the wholesale market accompanied expansion in the size of firms through mergers and acquisitions and significant entry by startup power generation companies. Competition among electric power producers affected wholesale prices for electric power in comparison to regulated utilities. Lower wholesale prices for power resulted from greater efficiencies in power production and lower price-cost margins. Wholesale competition has already been in progress for some years and its effects can be seen in the prices for electricity offered to commercial and industrial (C&I) customers. Also, competition among retail electricity suppliers helped to reduce markups over the cost of purchased electric power by improving marketing efficiencies and lowering margins. This already is reflected in the lower prices offered to C&I customers and similar effects should be observed as competition for residential customers intensifies.

A vast amount of new generation came online, with the highest proportion of this generation coming in the form of natural gas-fired generators. Figure (2) plots the current capacity of electrical generation by initial year of operation and fuel type.[19] Since 2000, nearly 237 gigawatts of natural gas-fired generation capacity was added. This new generation was provided largely by independent power producers, who "[favor] natural gas generation due to short construction times and low capital costs." Another critical component of the shift to natural gas-fired generation is the transition from steam turbines to combined-cycle units. This transition led to higher utilization rates, as well as a relocation of the units among peaking and baseload generation.[20]

In conjunction with the new natural gas generation, wind generation also supported the

[18] Report to Congress on Competition in Wholesale and Retail Markets for Electric Energy. 2006

[19] Source: Source: U.S. Energy Information Administration (EIA).

[20] U.S. Energy Information Administration (EIA). *Today in Energy.* July 5, 2011.

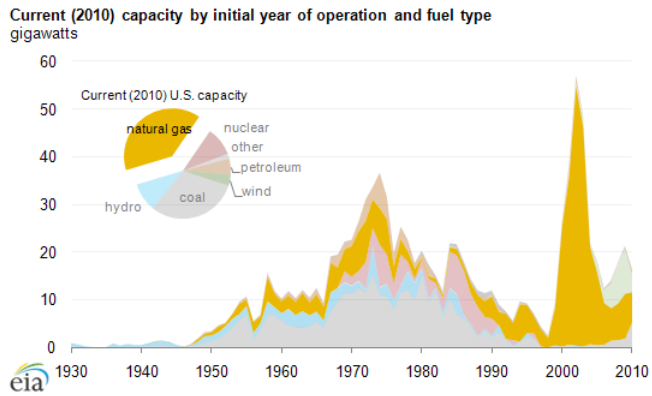


Figure 2: Electricity capacity by fuel type and vintage

overall trend in increasing the overall generation capabilities since 2000. Figure (3) plots the generation capabilities over the period 1990-2009, by resource type. From 1997 to 2007 electrical generation increased 19 percent with the most sizeable contributions to this growth coming from natural gas and wind generators.

In addition to the overall growth in electrical generation, the ownership structure of electrical generation went through a drastic transition beginning in 2000. Figure (4) plots the generation capacity of independent power producers over the period from 1990-2009. Beginning in 2000, through both new builds and divestitures the ownership of electrical generation moved from utilities to independent power producers. From a 1997 level of 28,063,532 megawatt hours, independent power producers grew generation to 1,287,751,218 megawatt hours by 2007; an increase of almost 5000 percent. While independent power producers have a diverse mix of generation by resource type, independent power producers do utilize natural gas and nuclear at much higher proportions than the levels of the electrical utilities across the country.

Clearly, restructuring access of transmission created a structural shift in who and how much generation was made available to the wholesale electricity market. As access was ensured to third party power producers, more generation came online that also happened

Figure 3: Total Electricity Generation

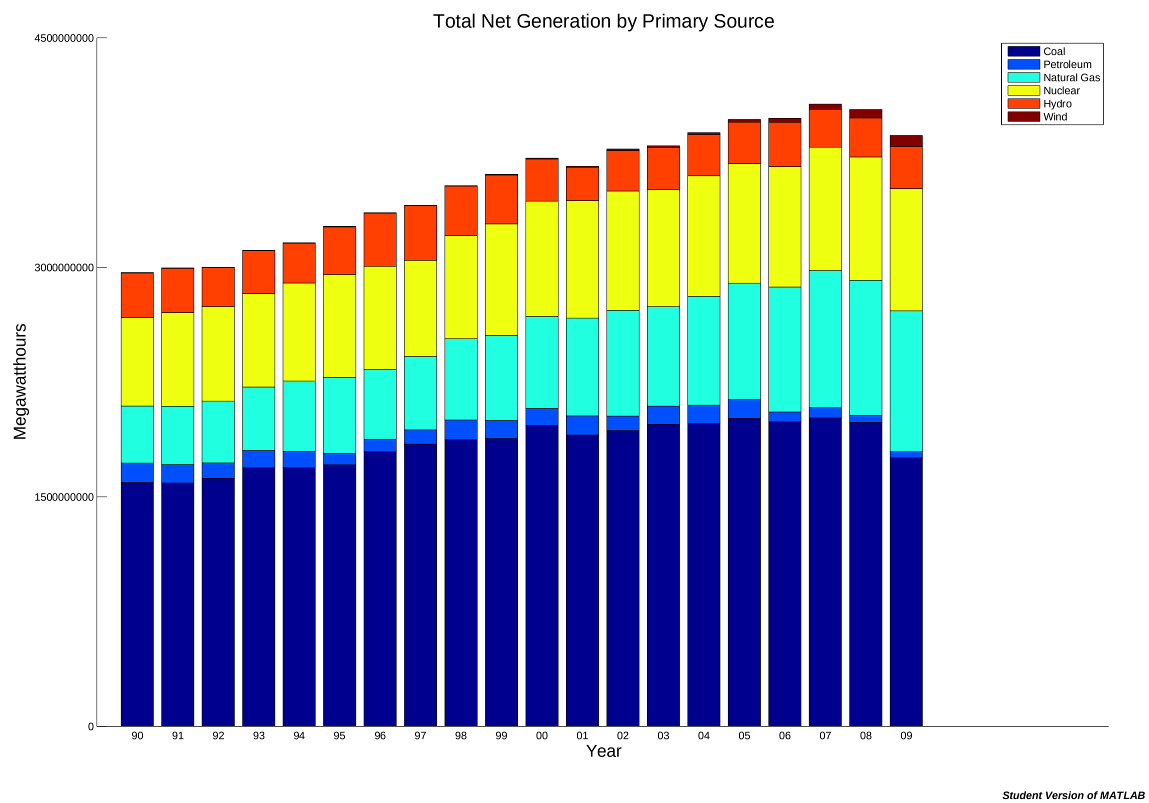
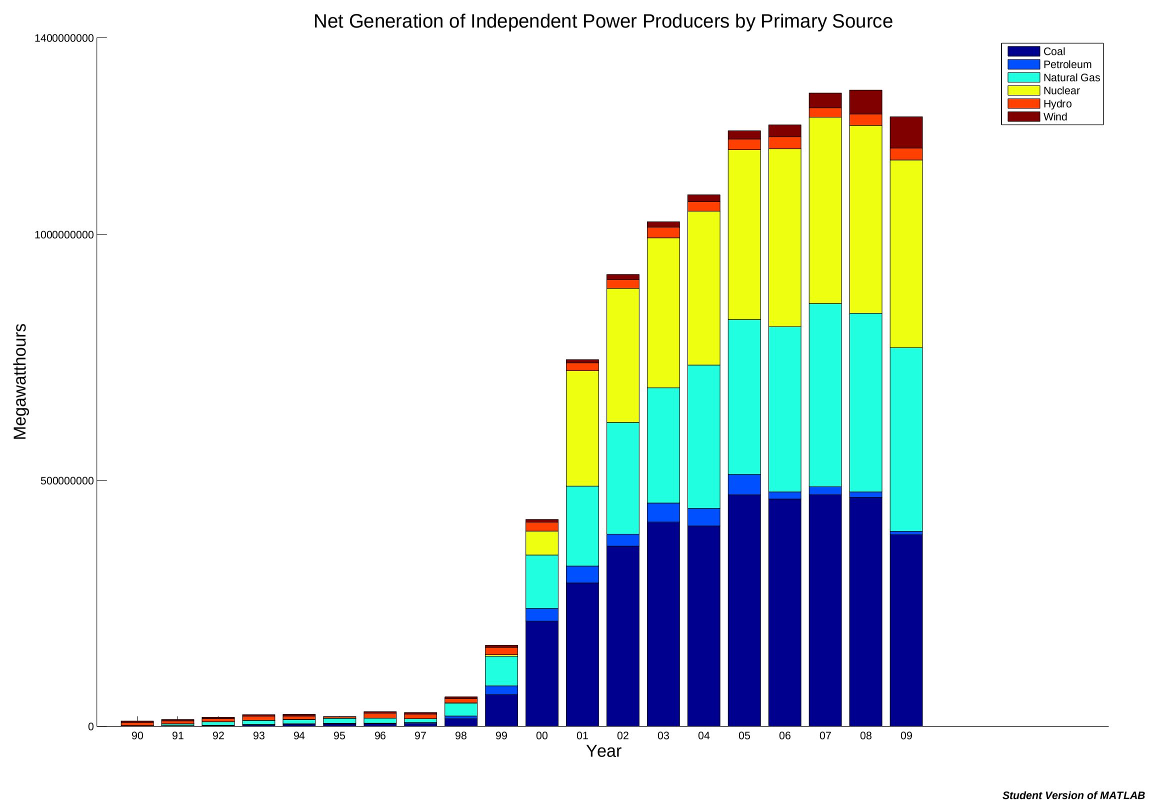


Figure 4: Electricity Generation of Independent power producers



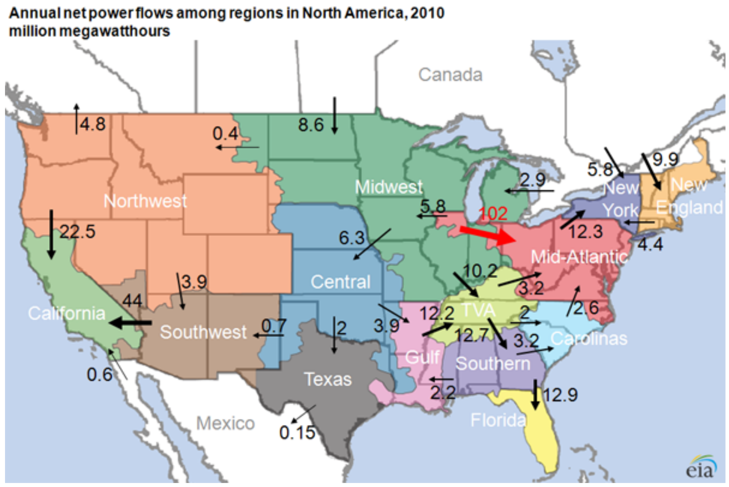


Figure 5: Annual regional trade flows within the U.S.

to be more efficient. Furthermore, a series of divestitures separating ownership rights of the generation units of legacy utilities from their transmission divisions moved more generation to independent power producers. We propose that these ancillary effects of the FERCs 2000 order created a more competitive market place for wholesale electricity as well as integrated the localized markets into a national market.

1.2 Market Convergence

Three economic forces drive convergence in wholesale electricity markets. First, trade in electric power across transmission facilities within regional markets drives market integration. Figure (5) plots the annual inter-regional trade flows across the country for 2010.

Figure (5) suggests that the international trade theory model might be a plausible explanation for the convergence result. Hydroelectric rich regions in Pacific north-west and Tennessee Valley are net exporters of electricity, while relative scarcer supply regions in California and New York are net importers. In 2010, California imported as much as 25 percent of its total electricity needs.[21] Furthermore, the abundance of nuclear generation in the northern Illinois area is exported across parts of the Midwest Independent System Operator (MISO) region to a final destination back within the PJM RTO, indicating that there is likely many instances of intraregional flows that serve a similar function to the inter-regional ones. While the pattern in figure (5) demonstrates that trade between regions is occurring, the overall electricity volume of electricity moving across regions still makes up a small percentage of the overall load.

Second, both within and between regional markets, we find evidence of economic arbitrage despite the absence of transmission interconnects. Companies that demand electric power can shift their usage across regions. Perhaps more significantly, companies that supply wholesale electric power operate in multiple regions and can shift their production across regions. This type of economic arbitrage is increased by the consolidation of firms in the electric power generation industry.[22] Following the open access to transmission an influx of new entrants entered into the market coupled with the divestiture of several generation units by legacy utilities. Since then, a series of mergers and acquisitions have dominated the national wholesale electricity industry. In just the year 2012, the merger of Duke and Progress Energy as well as the merger of Constellation and Exelon created the largest and third largest utility companies in the country. Furthermore, the proposed merger of NRG and GenOn would create a single independent power producer responsible for electricity generation in 47 Gigawatts of capacity in 21 states, across four system operators, and all three interconnections.[23]

In addition to the integration of the public utilities and independent power producers,

[21] EIA. *Today in Energy.* December 19, 2011.

[22] Firms almost always face the tradeoff of offering differentiated products or capturing scale economies. Krugman (1980) shows as the boundaries of firms cross over boundaries, the arbitrage and movement of scarce resources can be internalized within the firm absent any physical movement of the final product.

[23] E.I.A. *Today in Energy.* September 6, 2012.

the ISOs and RTOs are consolidating. Entergy announced that they will be joining the MISO independent system operator. In addition to the region controlled by Entergy, MISO works closely with PJM to manage the largest span of transmission lines in the Eastern interconnect.

Third, market integration reflects factor price equalization across geographic locations. Stigler and Sherwin (1985) explain that merely "[the] competition of [buyers] can bring about equality in the [price of a good], allowing for [transportation] costs, in the various areas where [the good is sold].... and is well known in trade theory as the factor equalization theorem." Energy resource supplies, notably natural gas and coal can be traded and transported across regions. Saravia (2003) found the forward premium in the New York wholesale electricity market fell upon the introduction of non-generating buyers into the wholesale market. In the particular case of wholesale electricity the natural application of this idea would be to relate how the competition in the retail markets for electricity may affect the wholesale market.

2 Data

The primary data set used in the analysis consists of daily day-ahead spot market prices data from eleven of the major trading hubs across the country. Each individual price series is publicly available from the Intercontinental Exchange, a platform for wholesale power transactions that issues approximately 70 percent of next day trading activity.[24] The price series for each trading hub are volume weighted averages for all the transactions completed by the end of that trading day. Our data set ranges from January 2001 to May 2012, and includes the trading hubs: AEP Dayton,[25] California-Oregon Border (COB), Entergy, ERCOT, Mid-Columbia (Mid-C), NEPOOL, NP-15, Palo Verde, PJM-West, SP-15, and

[24] www.eia.gov/electricity/wholesale.

[25] Due to transitions in the major trading hub in the Ohio area, the Cinergy trading hub is substituted in for the AEP Dayton hub for the January 2001-January 2005 part of the sample.

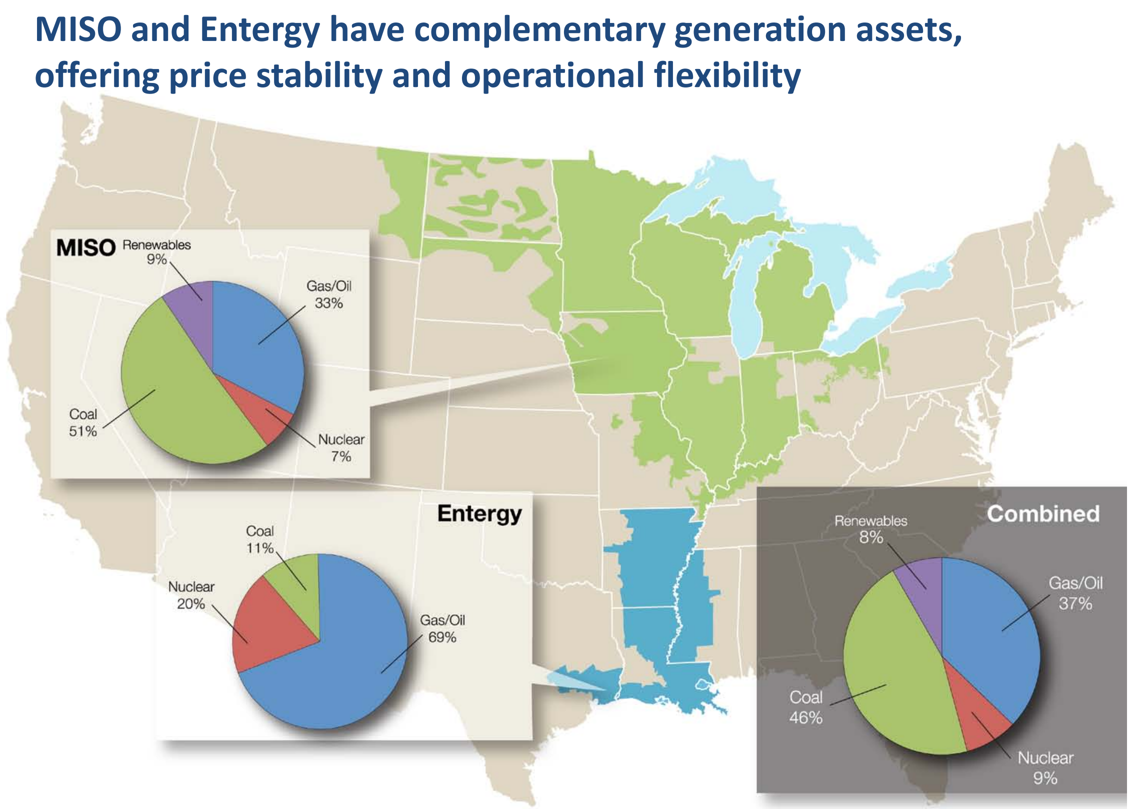


Figure 6: MISO footprint assuming integration with Entergy region as well generation source mix.
Source: Midwest Independent System Operator

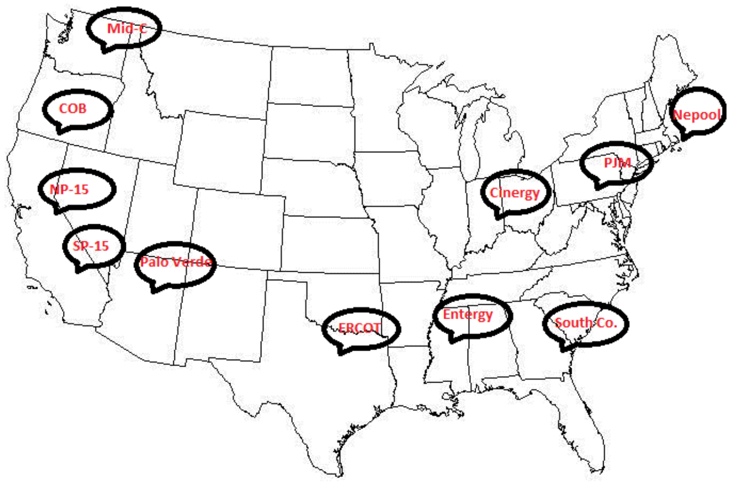


Figure 7: Map of the eleven trading hubs throughout the United States

Southern Company (SOCO). Figure (7) provides the geographic location of these eleven trading hubs. These trading hubs not only represent a nice span geographically, but also represent the majority of day ahead trading in wholesale power.

For most of the analysis, the daily price series will be averaged to the monthly level. Table (1) presents the summary statistics of the eleven series. On average wholesale prices tend to be higher in the northeast (NEPOOL), and more volatile in Texas (ERCOT). Figure (8) plots the average monthly price over time, while the eastern trading hubs and western trading hubs are separately plotted in figure (9). From these figures, it is clear that correlation among the series is present throughout the sample. During the early part of the sample, wholesale electricity prices trend upwards until the peak of business cycle. In the latter part of the sample, factors including the recession and lower natural gas prices led to lower wholesale electricity prices across all of the trading hubs. Each of these series is expected to have some amount of serial-correlation, that could bias some of the empirical results as noted by

	Cinergy	COB	Entergy	ERCOT	Mid-C	Nepool	NP15	PaloVerde	PJM	South Co	SP15
Mean	47.60	48.81	47.63	51.61	44.21	63.97	52.96	49.65	57.39	48.80	53.31
Std.	15.38	17.89	17.21	25.01	17.26	21.35	19.18	17.58	19.26	16.85	19.10
Min	19.68	21.25	19.35	18.46	9.75	28.13	23.76	22.43	23.54	23.71	23.84
Max	95.89	114.69	107.69	225.67	111.13	131.30	113.97	107.55	127.42	107.50	113.89
DF	-3.02	-2.93	-2.64	-4.29	-2.61	-3.18	-2.50	-2.92	-3.37	-3.06	-2.55
DF-LD	-9.53	-7.05	-8.21	-8.31	-7.62	-8.59	-6.86	-7.06	-8.78	-8.61	-6.80

Table 1: Summary statistics of the monthly averages of price ($/Mega-watt hour) series across all eleven trading hubs. Red denotes Dickey-Fuller test statistic significant at the 1% level.

Stigler and Sherwin (1985). Figure (10) plots the percent log difference of each series to account for any serial correlation. Figure (10) provides evidence that all the series are I(1) as the transformed series all appear close to stationary. To investigate this result formally we implement the augmented Dickey-Fuller test to identify whether we can reject the null hypothesis that the series are I(1). The augmented Dickey-Fuller test statistics for both the prices series in levels as well as log first differences are reported in table (1). We fail to reject the null hypothesis that the price series possesses a unit root for all of the series except Texas trading hub ERCOT.[26] When the price series are transformed to log differences, we are able to reject the null hypothesis of a unit root at the 1% significance level for all of the series. Given this evidence is does appear that all of the series are I(1).

3 Empirical Results

In this section, we empirically test the hypothesis that there is a national market for wholesale electric power. First, we look at the pairwise correlations among all the trading hubs. High price correlation among trading hubs within the same transmission inter-connect are found, and is robust to alternative explanations involving common influences. Next, we implement the Granger causality test among all the pairs of trading hubs. In these tests, evidence of

[26] In order to implement our test for common trends it is necessary for all of the series to be I(1). Though, the Dickey-Fuller test statistic did reject the null hypothesis of a unit root, we include the ERCOT series in the co-integration results presented in section (3). We find no substantial differences in the results if we drop ERCOT from the sample.

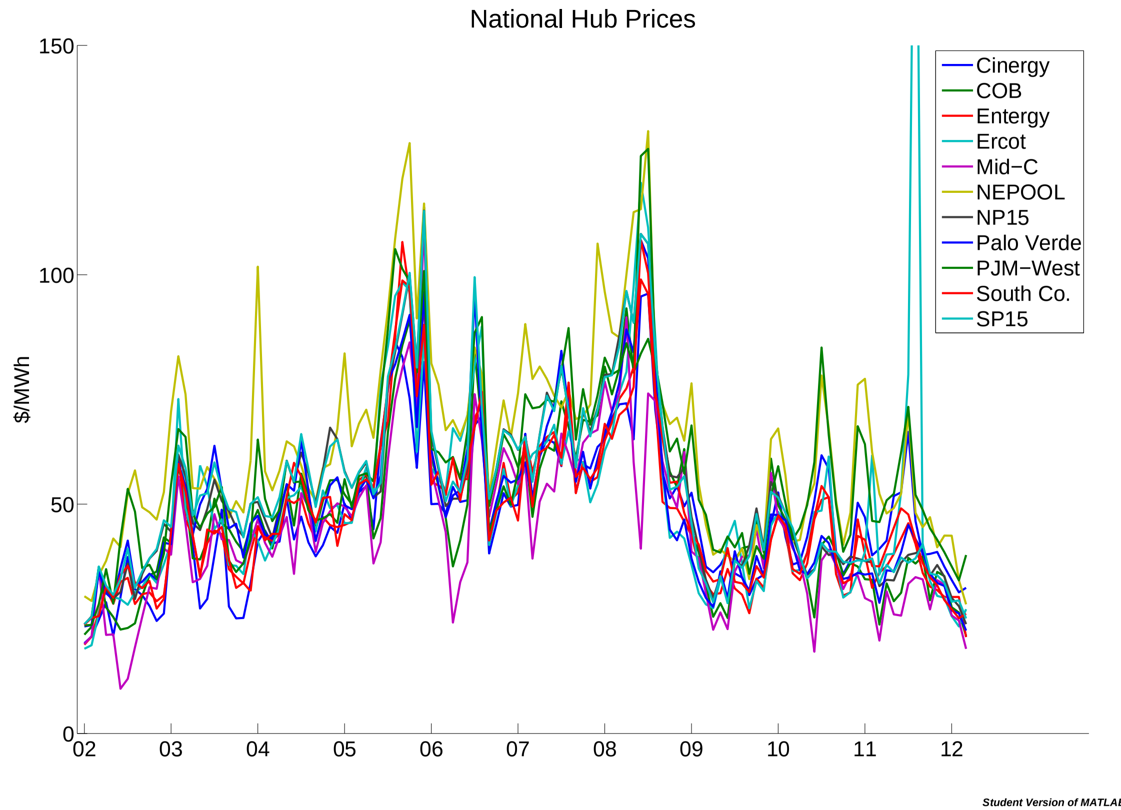


Figure 8: Average Monthly Prices at several trading hubs across the country

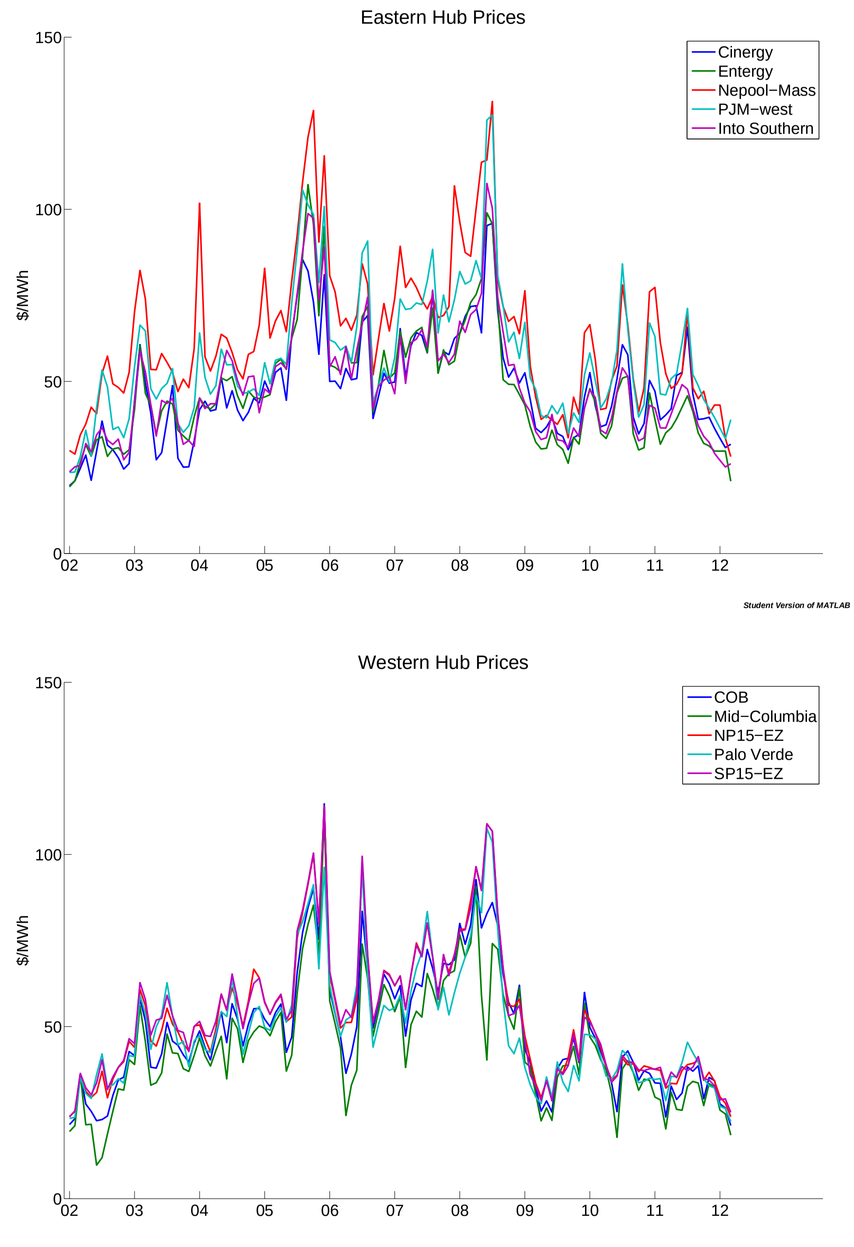


Figure 9: Average Monthly Prices at Eastern (top panel) and Western (bottom panel) trading hubs

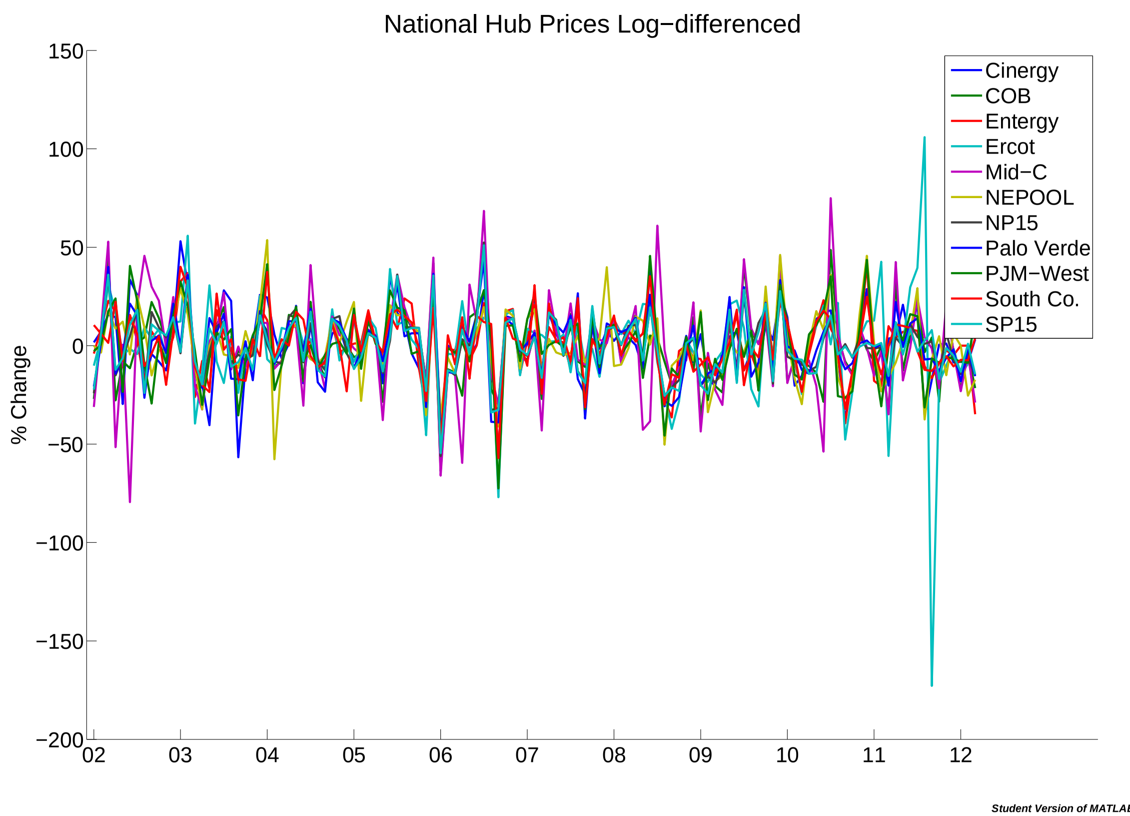


Figure 10: Log difference of average monthly prices at several trading hubs across the country

pairwise causality is found for all of the trading hubs combinations, except one, at all natural significance levels. Each of these tests provide evidence that trading hubs' prices are tied together, with increasing propensity as they are closer geographically.

In order to test the level of integration amongst all the price series simultaneously, we implement principle component analysis, factor analysis and the common trend test. By looking at the loadings of the first principle component, we are able to non-parameterically estimate the relative importance of each trading hub in explaining the variance of the other series, as well as how much variance of each series can be explained by the comovement of all the series. Next, we investigate the hypothesis of the markets being segmented along the interconnections using factor analysis. By implementing oblique rotations, we find interpretable factors and are able to determine the level of integration amongst the eastern and western segments of the market.

Lastly, we implement the common trend test (CTT) of Stock and Watson (1988) to test the national market hypothesis. The common trend test identifies whether a group of series possess a co-integrating vector that links the otherwise non-stationary series from diverging too far from each other. This co-integrating vector often has the interpretation as a long-run equilibrium and structural relationship that governs the comovement of the series. In each of these tests strong evidence is found for the presence of one lone national market.

3.1 Tests of Correlation

Our first test involves looking at the correlations of the prices series across different trading hubs. Stigler and Sherwin (1985) suggest that examining the correlation of price series of the same good can be successful in distinguishing different geographical markets. More specifically, price series of the same commodity sold at different locations with higher levels of correlation are likelier to be within the same (geographical) market. Electricity traded at the wholesale level is a homogenous product, and is generated by many utility and independent power producers across the country. Wholesale electricity trading hubs with prices series that tend to move together suggest that, absent common influences, the electricity sold at each has some measure of substitutability and are likely to be within the same market.

Given the high levels of serial correlation amongst all of the series that could bias the results, each series is first transformed by taking log differences. Table (2) and figure (11) summarize the pairwise price correlations in log first differences and how they relate to the distance separating the trading hub pair. A clear pattern emerges: trading hubs closer together geographically tend to have more highly correlated price series. For trading hubs pairs co-located within the eastern or western transmission interconnects correlations tend to be high, with the lowest correlation at 0.57 and most correlations well above 0.7. Interestingly, the correlations within the western interconnect are all high with exception to the ones involving the Mid-Columbian trading hub. The Mid-Columbian hub hosts the wholesale trading for the north-west region of the country which has abundant amounts of cheap hydroelectric generation during the spring and early summer months.[27]

Aside from serial correlation, common influences amongst the series could provide an alternative explanation to the high levels of correlation amongst prices series from still distinct geographical markets. To rule out these alternative explanations, we regress each price series on the producer price index for electricity generation and natural gas as well as the 3 month moving average of the production and income group of the Chicago Fed National Activity Index (CFNAI) as well as quarter dummies, and examine the pairwise correlations amongst residuals of these regressions.[28] Table (3) and figure (12) summarize the correlations of the

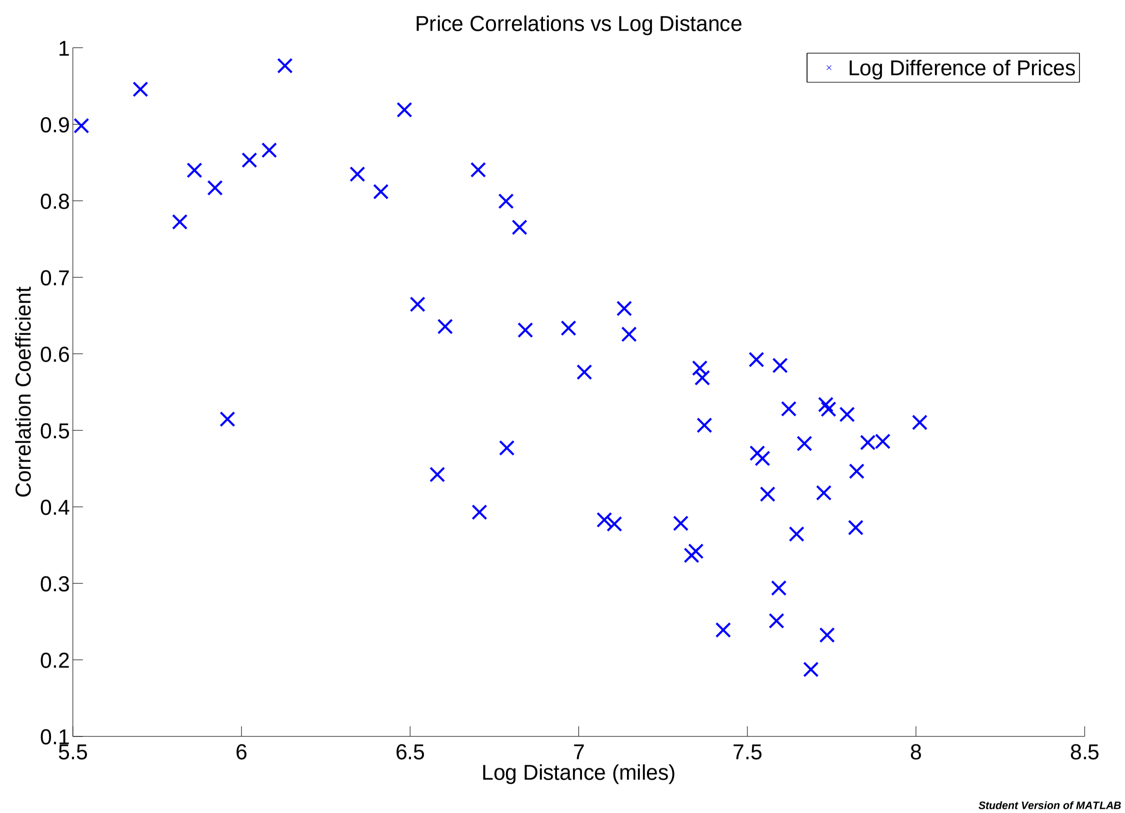
[27] "Hydroelectric generation in the Pacific Northwest is typically highest in the late winter and spring when river flows are high because of snowpack melt. This low-cost energy contributed to an average 18% decline in wholesale electricity prices compared to prices in 2010 at Mid-Columbia, a major Northwest wholesale pricing hub near the Washington-Oregon border." EIA. *Today in Energy.*

[28] We used the production and income group from the CFNAI because we wanted to isolate the production side of the economy, the most likely source of electricity demand fluctuations, from the national aggregate of

Table 2: Correlation Coefficients: First Difference of Logarithms

		02–12
cinergy	cob	0.41661
cinergy	entergy	0.83489
cinergy	ercot	0.393
cinergy	midc	0.25094
cinergy	nepool	0.63568
cinergy	np15	0.52812
cinergy	paloverde	0.56862
cinergy	pjmwest	0.85321
cinergy	soco	0.81697
cinergy	sp15	0.51037
cob	entergy	0.47017
cob	ercot	0.33661
cob	midc	0.89814
cob	nepool	0.44651
cob	np15	0.86624
cob	paloverde	0.7995
cob	pjmwest	0.41826
cob	soco	0.36433
cob	sp15	0.8405
entergy	ercot	0.51464
entergy	midc	0.29385
entergy	nepool	0.65932
entergy	np15	0.59246
entergy	paloverde	0.62562
entergy	pjmwest	0.76538
entergy	soco	0.83992
entergy	sp15	0.58127
ercot	midc	0.23902
ercot	nepool	0.34196
ercot	np15	0.37844
ercot	paloverde	0.47702
ercot	pjmwest	0.37765
ercot	soco	0.44223
ercot	sp15	0.38294
midc	nepool	0.37291
midc	np15	0.66475
midc	paloverde	0.57608
midc	pjmwest	0.2324
midc	soco	0.18744
midc	sp15	0.63359
nepool	np15	0.48561
nepool	paloverde	0.52769
nepool	pjmwest	0.77244
nepool	soco	0.63104
nepool	sp15	0.48403
np15	paloverde	0.91894
np15	pjmwest	0.52076
np15	soco	0.48276
np15	sp15	0.97657
paloverde	pjmwest	0.58481
paloverde	soco	0.50666
paloverde	sp15	0.94586
pjmwest	soco	0.81199
pjmwest	sp15	0.53362
soco	sp15	0.46329

Figure 11: Total Electricity Generation



residuals for each pair of trading hubs. Although the correlations amongst the residuals generally are lower, a similar picture emerges. As before, trading hubs that are in close proximity still have high price correlations.

3.2 Granger Causality

Moving beyond the static framework of correlation, we next implement the Granger Causality test. Granger (1969) empirically evaluates the predictive quality of contemporaneous and past values of another series in predicting the current level of the series of interest. Formally, the Granger Causality test involves computing the F-statistic characterized by the null hypothesis that information of the series is not predictive of the other (contemporaneously or at any lag). A statistically significant F-statistic allows one to reject the null hypothesis in favor of the alternative that the series "Granger causes" the other. As noted by Sims et al. (1990), unit roots can affect the accuracy of the Granger causality test. Given that Dickey-Fuller test statistics do not allow us to reject the null hypothesis of a unit root in any of the price series, each series is log first differenced before the Granger causality test is conducted. Unlike the correlation tests where the order of P_1 and P_2 is irrelevant, the Granger causality test is run twice for each pair; P_1 *causing* P_2 does not imply P_2 *causes* P_1.

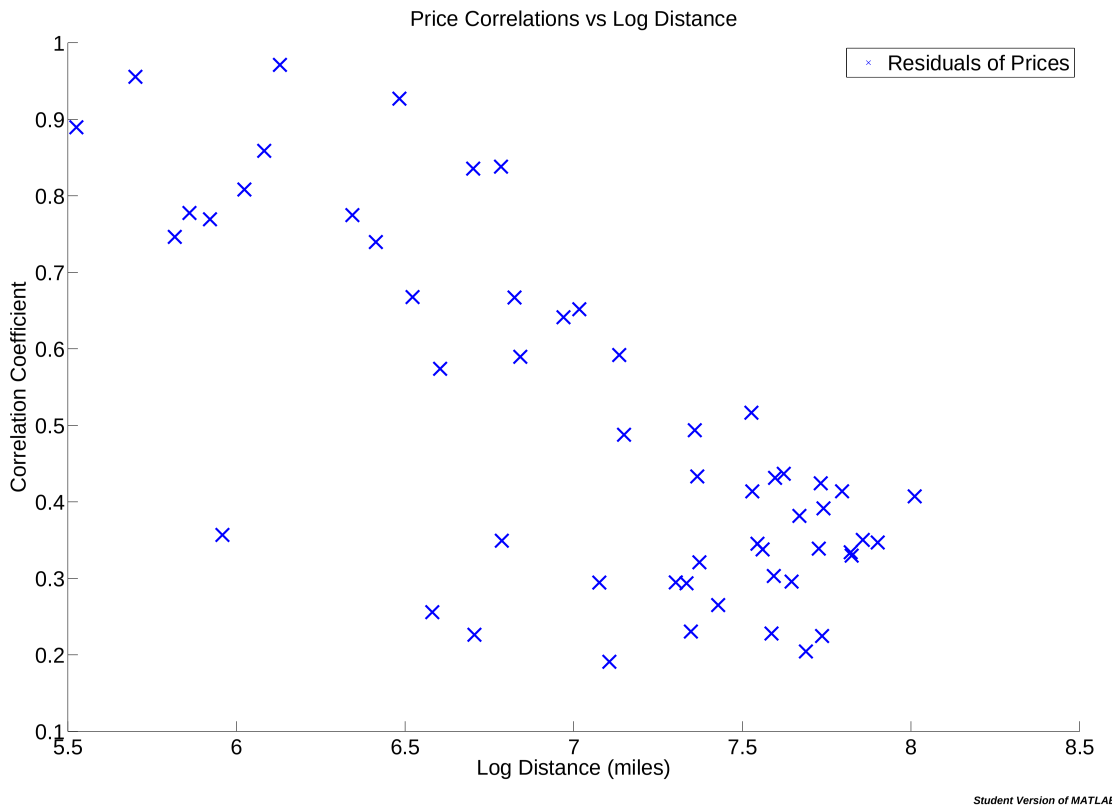
Table (4) presents the results of all 110 of the Granger causality tests. The results presented in table (4) mirror those from the correlation tests. All of the price series "Granger cause" all of the other series at statistically significant levels, except one pair. The Southern Company trading hub does not Granger cause the Mid-C trading hub. While these results occur across the trading hubs nationally, the test statistics tend to be higher for pairs of series that reside within the same interconnect. In the Granger causality tests, all of the pairwise tests display an interconnectedness suggestive of an integrated national market, with the

activity. For more information on the CFNAI see Brave and Butters (2010).

Table 3: Correlation Coefficients: Regression residuals

		02–12
cinergy	cob	0.33775
cinergy	entergy	0.7748
cinergy	ercot	0.22618
cinergy	midc	0.22791
cinergy	nepool	0.57386
cinergy	np15	0.43668
cinergy	paloverde	0.43312
cinergy	pjmwest	0.8082
cinergy	soco	0.76929
cinergy	sp15	0.40709
cob	entergy	0.41371
cob	ercot	0.29347
cob	midc	0.88956
cob	nepool	0.32959
cob	np15	0.85878
cob	paloverde	0.83813
cob	pjmwest	0.33888
cob	soco	0.29576
cob	sp15	0.83548
entergy	ercot	0.35667
entergy	midc	0.30305
entergy	nepool	0.59188
entergy	np15	0.51652
entergy	paloverde	0.4877
entergy	pjmwest	0.6671
entergy	soco	0.77761
entergy	sp15	0.49355
ercot	midc	0.2651
ercot	nepool	0.23044
ercot	np15	0.29472
ercot	paloverde	0.34916
ercot	pjmwest	0.19087
ercot	soco	0.25577
ercot	sp15	0.29445
midc	nepool	0.33407
midc	np15	0.66765
midc	paloverde	0.6517
midc	pjmwest	0.22463
midc	soco	0.20438
midc	sp15	0.64123
nepool	np15	0.34681
nepool	paloverde	0.39144
nepool	pjmwest	0.74627
nepool	soco	0.58954
nepool	sp15	0.35018
np15	paloverde	0.92701
np15	pjmwest	0.41373
np15	soco	0.38159
np15	sp15	0.97114
paloverde	pjmwest	0.43132
paloverde	soco	0.32096
paloverde	sp15	0.95557
pjmwest	soco	0.73959
pjmwest	sp15	0.42423
soco	sp15	0.34526

Figure 12: Total Electricity Generation



P^1	P^2 Cinergy	COB	Entergy	ERCOT	Mid-C	NEPOOL	NP-15	Palo Verde	PJM-West	South Co.	SP-15
Cinergy	x	$9^{\star\star}$	$124^{\star\star}$	$12^{\star\star}$	$5^{\star\star}$	$34^{\star\star}$	$8^{\star\star}$	$14^{\star\star}$	$148^{\star\star}$	$105^{\star\star}$	$10^{\star\star}$
COB	$8^{\star\star}$	x	$13^{\star\star}$	$8^{\star\star}$	$187^{\star\star}$	$10^{\star\star}$	$224^{\star\star}$	$132^{\star\star}$	$7^{\star\star}$	$10^{\star\star}$	$196^{\star\star}$
Entergy	$123^{\star\star}$	$12^{\star\star}$	x	$22^{\star\star}$	$6^{\star\star}$	$38^{\star\star}$	$14^{\star\star}$	$22^{\star\star}$	$68^{\star\star}$	$144^{\star\star}$	$16^{\star\star}$
Ercot	$17^{\star\star}$	$10^{\star\star}$	$26^{\star\star}$	x	$5^{\star\star}$	$12^{\star\star}$	$8^{\star\star}$	$17^{\star\star}$	$17^{\star\star}$	$17^{\star\star}$	$10^{\star\star}$
MidC	$5^{\star\star}$	$187^{\star\star}$	$6^{\star\star}$	$4^{\star}$	x	$7^{\star\star}$	$47^{\star\star}$	$36^{\star\star}$	$3^{\star}$	$3^{\star}$	$45^{\star\star}$
Nepool	$34^{\star\star}$	$11^{\star\star}$	$39^{\star\star}$	$8^{\star\star}$	$7^{\star\star}$	x	$14^{\star\star}$	$18^{\star\star}$	$59^{\star\star}$	$32^{\star\star}$	$14^{\star\star}$
NP15	$8^{\star\star}$	$230^{\star\star}$	$14^{\star\star}$	$8^{\star\star}$	$45^{\star\star}$	$13^{\star\star}$	x	$316^{\star\star}$	$8^{\star\star}$	$19^{\star\star}$	$1069^{\star\star}$
PV	$13^{\star\star}$	$129^{\star\star}$	$23^{\star\star}$	$16^{\star\star}$	$34^{\star\star}$	$16^{\star\star}$	$318^{\star\star}$	x	$15^{\star\star}$	$30^{\star\star}$	$529^{\star\star}$
PJM	$151^{\star\star}$	$11^{\star\star}$	$75^{\star\star}$	$15^{\star\star}$	$5^{\star\star}$	$60^{\star\star}$	$11^{\star\star}$	$20^{\star\star}$	x	$99^{\star\star}$	$16^{\star\star}$
SoCo.	$107^{\star\star}$	$9^{\star\star}$	$149^{\star\star}$	$14^{\star\star}$	3	$36^{\star\star}$	$20^{\star\star}$	$31^{\star\star}$	$106^{\star\star}$	x	$20^{\star\star}$
SP15	$10^{\star\star}$	$190^{\star\star}$	$16^{\star\star}$	$10^{\star\star}$	$42^{\star\star}$	$14^{\star\star}$	$997^{\star\star}$	$528^{\star\star}$	$12^{\star\star}$	$20^{\star\star}$	x

Table 4: Granger Causality test F-statistics and significance levels $\star$-indicates significant at the 5% level, $\star\star$-indicates significant at the 1% level

P^1	P^2 Cinergy	COB	Entergy	ERCOT	Mid-C	NEPOOL	NP-15	Palo Verde	PJM-West	South Co.	SP-15
Cinergy	x	$9^{\star\star}$	$112^{\star\star}$	$10^{\star\star}$	$6^{\star\star}$	$33^{\star\star}$	$7^{\star\star}$	$11^{\star\star}$	$129^{\star\star}$	$102^{\star\star}$	$9^{\star\star}$
COB	$7^{\star\star}$	x	$11^{\star\star}$	$9^{\star\star}$	$189^{\star\star}$	$6^{\star\star}$	$200^{\star\star}$	$146^{\star\star}$	$7^{\star\star}$	$14^{\star\star}$	$179^{\star\star}$
Entergy	$112^{\star\star}$	$12^{\star\star}$	x	$18^{\star\star}$	$8^{\star\star}$	$35^{\star\star}$	$11^{\star\star}$	$15^{\star\star}$	$61^{\star\star}$	$131^{\star\star}$	$12^{\star\star}$
Ercot	$14^{\star\star}$	$10^{\star\star}$	$21^{\star\star}$	x	$8^{\star\star}$	$12^{\star\star}$	$7^{\star\star}$	$13^{\star\star}$	$14^{\star\star}$	$13^{\star\star}$	$9^{\star\star}$
MidC	$5^{\star\star}$	$190^{\star\star}$	$8^{\star\star}$	$6^{\star\star}$	x	$5^{\star\star}$	$47^{\star\star}$	$47^{\star\star}$	$3^{\star}$	$5^{\star\star}$	$49^{\star\star}$
Nepool	$33^{\star\star}$	$7^{\star\star}$	$33^{\star\star}$	$8^{\star\star}$	$6^{\star\star}$	x	$8^{\star\star}$	$12^{\star\star}$	$64^{\star\star}$	$33^{\star\star}$	$8^{\star\star}$
NP15	$7^{\star\star}$	$203^{\star\star}$	$11^{\star\star}$	$8^{\star\star}$	$47^{\star\star}$	$9^{\star\star}$	x	$302^{\star\star}$	$7^{\star\star}$	$22^{\star\star}$	$873^{\star\star}$
PV	$11^{\star\star}$	$138^{\star\star}$	$15^{\star\star}$	$13^{\star\star}$	$44^{\star\star}$	$12^{\star\star}$	$297^{\star\star}$	x	$12^{\star\star}$	$24^{\star\star}$	$561^{\star\star}$
PJM	$130^{\star\star}$	$11^{\star\star}$	$62^{\star\star}$	$11^{\star\star}$	$7^{\star\star}$	$63^{\star\star}$	$8^{\star\star}$	$15^{\star\star}$	x	$81^{\star\star}$	$13^{\star\star}$
SoCo.	$105^{\star\star}$	$13^{\star\star}$	$128^{\star\star}$	$10^{\star\star}$	$5^{\star\star}$	$37^{\star\star}$	$21^{\star\star}$	$23^{\star\star}$	$87^{\star\star}$	x	$18^{\star\star}$
SP15	$8^{\star\star}$	$169^{\star\star}$	$12^{\star\star}$	$9^{\star\star}$	$45^{\star\star}$	$9^{\star\star}$	$805^{\star\star}$	$559^{\star\star}$	$10^{\star\star}$	$21^{\star\star}$	x

Table 5: Granger Causality test F-statistics and significance levels with exogenous controls $\star$-indicates significant at the 5% level, $\star\star$-indicates significant at the 1% level

regional markets at a more mature level of integration. As is the case in looking at correlation, controlling for common influences is important in implementing Granger Causality tests. Table (5) reports the Granger causality F-statistics controlling for natural gas prices and seasonality effects. Again, all of the test statistics are statistically significant, and display a similar pattern of higher connectedness amongst trading hubs within the same interconnect.

As in the case of the correlation tests, the test for "Granger causality" is limited to only looking at pairs of price series and its usefulness is limited given its sensitivity to the presence of unit roots in the series. While both tests presented evidence of the null hypothesis of a national market, neither was able to test the null hypothesis simultaneously among all eleven price series, and both required us to first difference the data. In order to jointly test the null hypothesis among all the trading hubs' price series principal component analysis (PCA) and factor analysis will he used.

3.3 Principle Component Analysis (PCA)

In order to move the investigation beyond the pairwise comparisons used thus far, we employ the techniques of principal component analysis to uncover the co-movement of all of the series simultaneously. PCA "is a multivariate technique in which a number of related variables are transformed to (hopefully, a smaller) set of uncorrelated variables.[29]" By finding the *orthogonal regression* line that minimizes the deviations perpendicular to the line itself, PCA generates scores that explain the most variance within the series as possible. A typical issue when using PCA is determining the number of principal components to estimate. At one extreme, the fewer principal component used the easier the interpretation. At the other extreme, one could estimate the set of principal components that *explains all the variation in the data*. Clearly, a delicate balance is required in order to successfully characterize the underlying variation of the data in the most appropriate way.

Several methods within the PCA literature have been suggested to determine the number of useful principal components. Some of the most illustrative methods come from simple plots of both the characteristic root for each principal component, and the amount of variation cumulatively explained by each principal component. Figure (13) includes both of these plots for the log difference of prices. In the top panel of figure (13) the characteristic roots of each principal component are plotted, a plot commonly known as a SCREE plot. Cattell and Jaspers (1967) suggest finding the "elbow" of the plot and include all the principal components up to that point. In our case, this seems to suggest the use of three or four principal components. An alternative way to determine the number of principal components, is by examining the cumulative amount of variance explained by adding each subsequent principle component. The bottom panel of figure (13) plots the cumulative variance explained for each additional principal component. While no standard cutoff rule exists, it is clear

[29] Jackson (1991)

from the plot that a sizeable amount of variance is explained with as few as three principal components.

With a sense as to the relevant number of principal components to look at, estimation can take place. Figure (14) plots the first three principal components and the scores. Figure (14) provides insight as to how the prices series are clustered. Immediately, it is clear that the hubs with the same interconnection tend to move together. Given that ERCOT trading hub has the largest loading on the third principal component, it is clear that the previous analysis suggestive of including a third principal component was sensitive to the variance of the ERCOT trading hub left unexplained by the first two principal components. Due to the relatively small loadings that the other series have on this third principal component, for the remainder of this section we will focus our attention on just the first two principal components.

Figures (15) plots the first two principal components and the scores. Figure (15) is simply a replication of figure (14) reduced down to two dimensions, to make the visualizations easier. Two key features emerge from the figure: (i) all price series load heavily (positively) onto the first principal component, (ii) the loadings of the second principle component are less systematic and seem to be in two groups. The hubs within the western interconnect all tend to load positively onto the second principal component, while the hubs within the eastern (and Texas) interconnect tend to load negatively onto the second principal component. Though the first principal component is clearly a weighted average of all of the price series and could be interpreted as "National wholesale electricity price index" much like the activity indices commonly found in the macro literature.[30] The second principal component clearly represents whatever divergence exists among the trading hubs across the interconnects.

Another perspective that one can take when evaluating the success of a few principal com-

[30]See Stock and Watson (1999) for a discussion of the methodology.

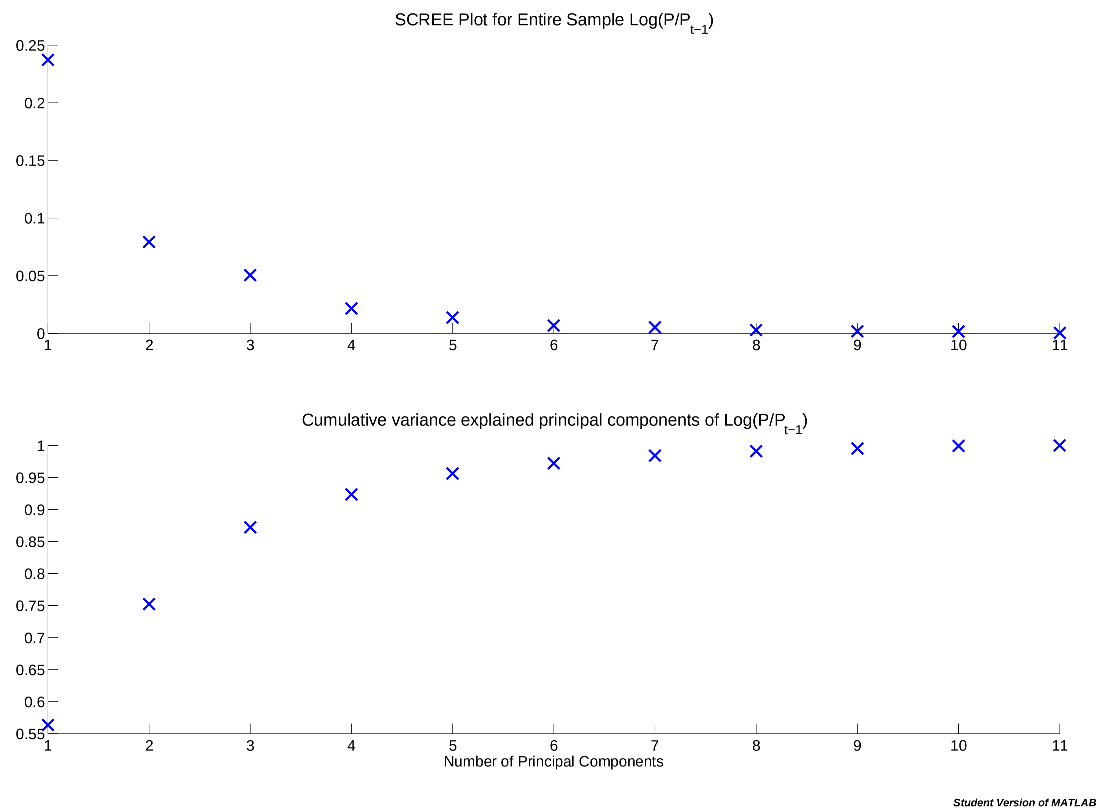


Figure 13: Diagnostic plots for Principal Component Analysis

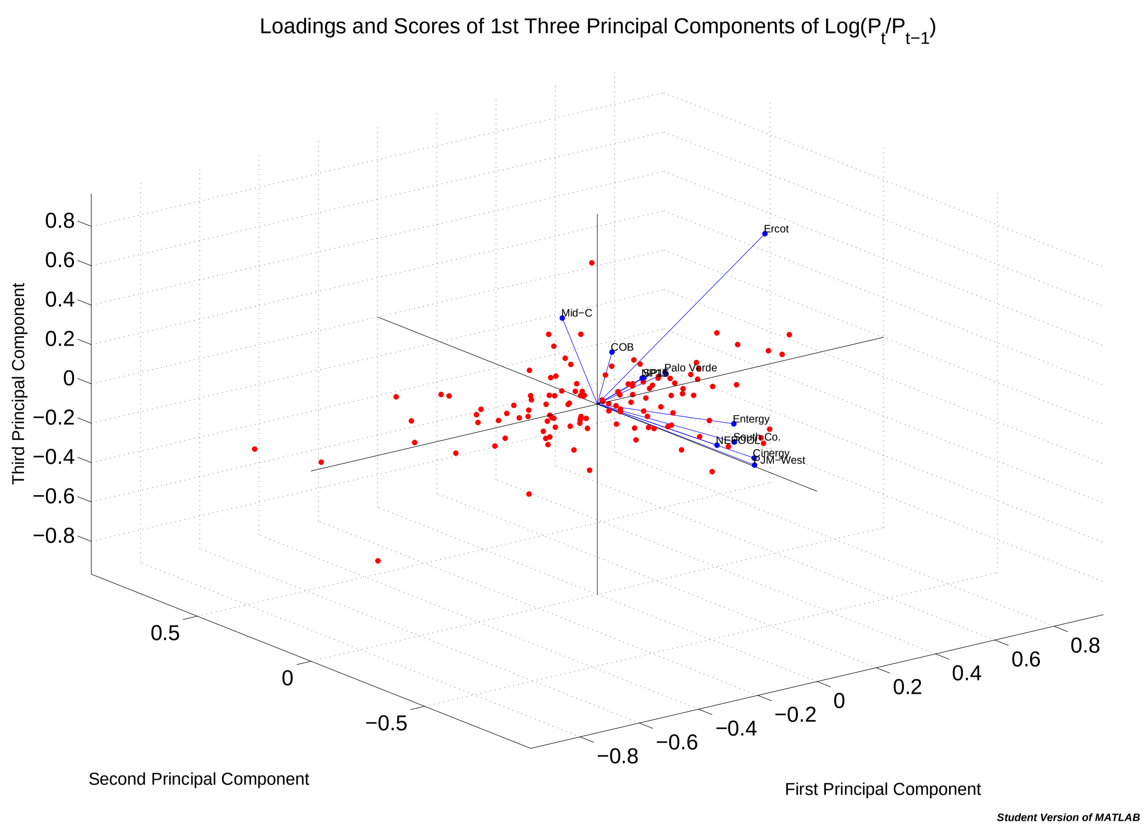


Figure 14: Plot of Loadings and Scores for first three principal components of Log Prices

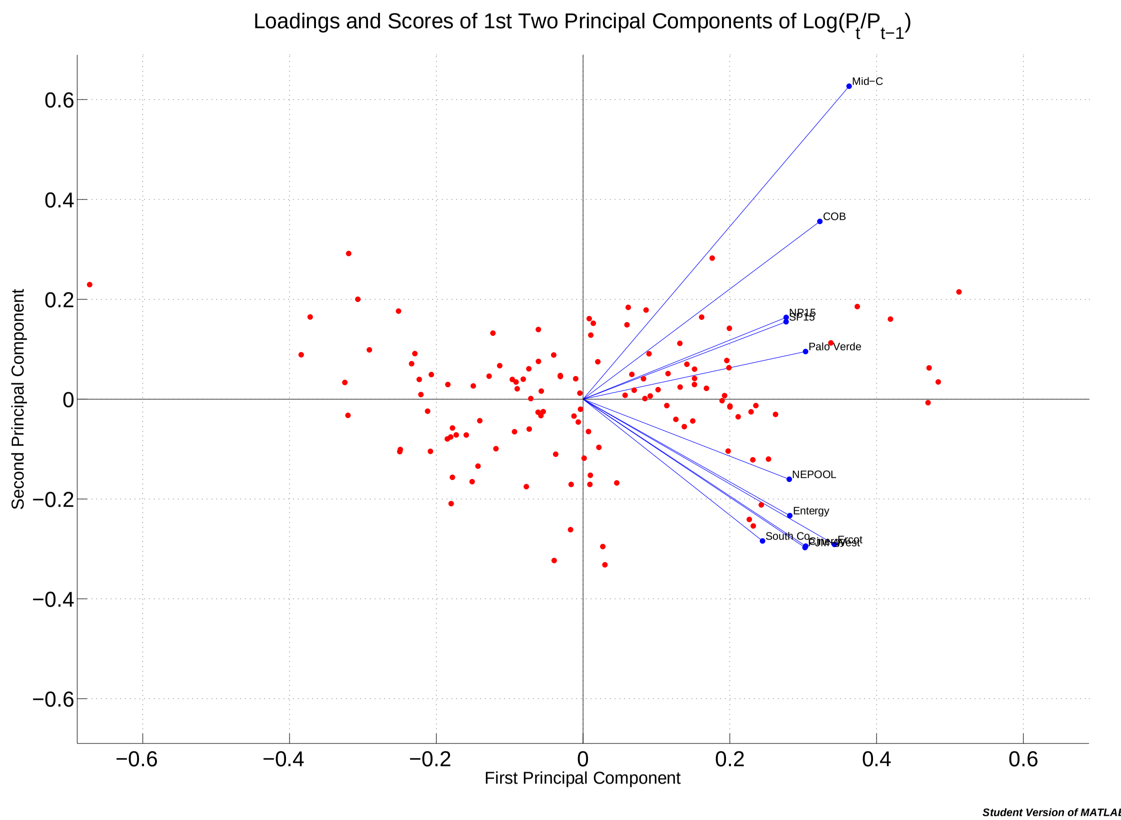


Figure 15: Plot of Loadings and Scores for first two principal components of Log Prices

Table 6: Variance Decomposition of Log Difference series on 1st Principal Component

P_i	1st PC	Idiosyncratic
Cinergy	0.59	0.41
COB	0.68	0.32
Entergy	0.66	0.34
Ercot	0.38	0.62
Mid-C	0.45	0.55
NEPOOL	0.53	0.47
NP15	0.74	0.26
Palo Verde	0.76	0.24
PJM-West	0.60	0.40
South Co.	0.54	0.46
SP15	0.72	0.28

ponents in explaining the data, is by examining the decomposition of the variance explained by the principal components as well as the variation left unexplained (if not all principal components are used) across all the series. Table (6) displays this decomposition of the variances for each of the price series in the data. In general, the first principal component does a very good job of explaining most of the variation in the data across all series. The first principal component explains at least 50 percent of the variation in every series except ERCOT and Mid-C, while explaining close to 70 percent for several. From this table it is clear that a large amount of the variation each series displays could be explained by one component. Put differently, all of the series display a high level of co-movement.

PCA offers a non-parametric method of testing whether a transformation of the data allows for a reduction in the number of variables necessary to explain a large portion of the original variation. To identify structural patterns in the data, we move the analysis to the more parametric factor analysis.

3.4 Factor Analysis

While the evidence from the PCA analysis suggested that one principle component could be used to explain the model most of the variation, adding a second principle component did appear to capture the divergence between the eastern and western trading hubs. Estimating a two factor model and implementing oblique rotations will create readily interpretable factors: the eastern and the western segments of the market. With interpretable factors, we can assess the level of correlation among the two sides of the market. This should provide a robustness check to the alternative hypothesis that there are two isolated segments to the markets.

We implement an oblique rotation known as the “promax” rotation on a two factor model to provide a better interpretation for the estimated factors. Figure (16) plots the rotated loadings and the estimates of the factors. After examining the loadings for each price hub the interpretation of the two factors becomes clear; one factor represents the eastern market while the other factor represents the western market. Even within interconnect groups, the loadings are closer among trading hubs closer in distance.[31] Distance does appear to be an important factor in governing integration of the market. ERCOT, the lone hub within the Texas interconnect, appears isolated and does not have high loadings on either factor.

Another critical insight that can be drawn from the rotated factors is the degree of correlation between the two factors. In figure (16) the factor scores are plotted as well. A high degree of correlation between the two factors is present; the factors have a correlation of 0.57. Even with slight deviations the two factors are highly correlated and resemble the integration of a lone market. Up until this point we have been limited to the form of transformation used in the empirical specifications due to the sensitivity of unit roots. Under the null hypothesis that all of the series belong to a common market and that the dynamics

[31] Both NP-15 and SP-15 are in California, COB and Mid-C are in the north west, PJM-west and Cinergy are in the rust belt, and Southern Co and Entergy are in the south east.

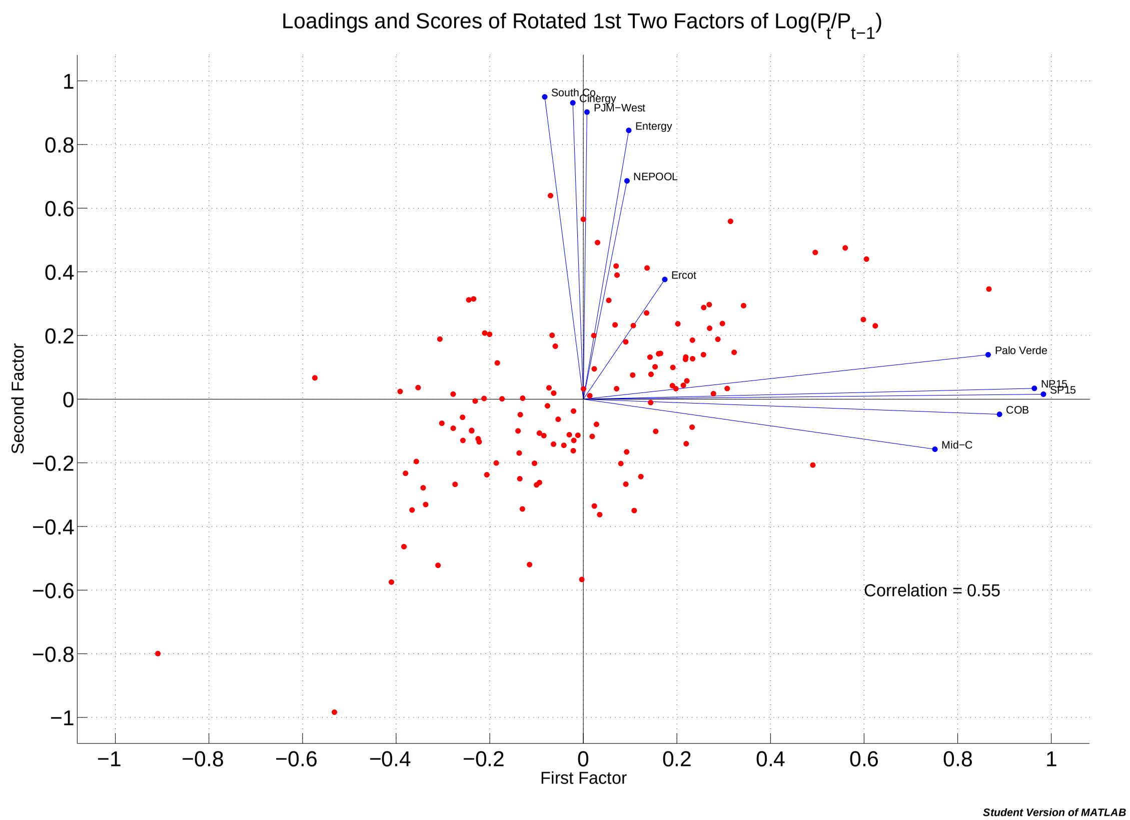


Figure 16: Plot of Loadings and Scores for first two factors of Log Differences

of that market are non-stationary, log differencing the series pre-test could be creating overly conservative tests. To ameliorate this concern we consider the common trend test of Stock and Watson (1988).

3.5 Common Trend Test

The final test rooted in principal component analysis will be that of Stock and Watson (1988); an empirical test used to test for the number of common trends among a group of non-stationary data. In their setting, X_t denote an $n \times 1$ vector times series in which each series is integrated of order 1. Formally, the vector time series has the moving average representation:

$$\Delta X_t = \mu + C(L)\varepsilon_t, \quad \sum_{j=1}^{\infty} j|C_j| < \infty \tag{1}$$

The motivation for the test will be that among these n integrated series there are k common trends and a $n \times r(r = n - k)$ matrix α, in which $\alpha' X_t$ results in a stationary process. Specifically, it will be assumed that there exists a matrix A such that the common trends representation for X_t exists as follows:

$$X_t = X_0 + A\tau_t + a_t \tag{2}$$

$$\tau_t = \pi + \tau_{t-1} + v_t \tag{3}$$

where X_t now is represented as a linear combination of k random walks (τ_t) with drift π, plus some stationary components a_t.

	02–12
$k = 11$	$-98.93^{\star\star}$
$k = 2$	$-133.33^{\star\star}$

Table 7: Stock and Watson (1988) test statistics and significance values for different samples and values of k. k represents the null hypothesis number of common trends. $\star$-indicates significant at the 5% level, $\star\star$-indicates significant at the 1% level

Formally, the Stock and Watson (1988) common trend test (CT) proceeds by setting up a null hypothesis that there are k common stochastic trends against the alternative that it has $m < k$ common trends. Stock and Watson (1988) show that although the limiting distribution of the test statistic does not have a closed form solution, it can be easily approximated by simulation.

Table (7) presents the test statistics for the CT test over under the null hypothesizes of both $k = 11$ and the more restrictive $k = 2$. In both specifications the test rejects the null hypothesis in favor of the alternative of one common trend in the vector time series at all statistic levels. Given that this test can be performed on non-stationary series, and can simultaneously test the level of integration across any number of time series, we conclude that the test of Stock and Watson (1988) is the most natural and suggestive evidence of the presence of a lone national market for wholesale electricity. Throughout all of the analysis, we have seen suggestive evidence that the interconnections seem to be affecting the level of integration between trading hubs. Specifically, trading hubs within interconnects tend to be more integrated than trading separated by interconnection regions.

3.6 How much do the transmission interconnections matter?

In testing the empirical importance of the US/Canadian border, Engel and Rogers (1996) propose a method to empirically sort out the border effects controlling for distance. In a similar way, our goal is to determine the effect being separated by an interconnect system has on the volatility of prices between two trading hubs controlling for the distance between the two hubs. For this empirical exercise, we take the standard deviation of the relative price ratio (in log first differences) over the entire sample for each of the 55 possible pair of trading hubs. For each pair, the distance between the two trading hubs was gathered. Lastly, we build a dummy variable that indicates whether the particular pair of trading hubs lies in different transmission interconnects. Our preferred empirical specification is characterized by the regression equation given by:

$$V(P_{ij}) = \beta_1 distance_{ij} + \beta_2 distance_{ij}^2 + \gamma Interconnect_{ij} + \sum_{m=1}^{n} \alpha_m D_m + u_{ij} \tag{4}$$

where D_m is a hub level dummy, and u_{ij} is assumed by distributed normally. Given the assumed concave effect distance will have on volatility, our hypothesis is that $\beta_1 > 0$ and $\beta_2 < 0$. We prefer the specification above from other concave transformations like the logarithm, because we can empirically test the hypothesis of distance having a concave effect on volatility. Likewise, if being across transmission interconnects has a meaningful impact on the relative volatility of prices then we would expect $\gamma > 0$.

Table (8) presents the regression results for the specification given by equation (4).[32] As expected distance has a positive effect while squared distance has a negative effect on the volatility of prices, supporting the hypothesis that distance's effect on volatility is concave. Interestingly, this decreasing effect of distance, while statistically significant, is economically negligible. This result likely comes from the physical and engineering restraints governing electricity transmission.[33] While the effect of distance seems to be constant, their does appear

[32]Bootstrap standard errors are reported.

[33]The EIA estimate that the electricity loss due to transmission is about 7 percent.

to be a statistically and economically strong effect on the volatility of prices coming from being across interconnects. In fact with the estimated coefficient on the interconnect dummy variable of 2.48, it can be imputed that two trading hubs would need to be separated by over 300 miles in order to create the same level of volatility that being across interconnects creates.

Table 8: Estimation results: Quadratic distance specification

Variable	Coefficient	(Std. Err.)
Distance	0.009**	(0.002)
Distance^2	-1.96e-6**	(5.87e-7)
Interconnection	2.482*	(1.398)

Significance levels: $*$: 10% $**$: 1%

3.7 Estimating Per-Unit Transaction Costs

Limited to only price data, a structural model of arbitrage similar to Spiller and Huang (1986) must be used to estimate the per-unit transaction costs between trading hub pairs. In principle, it is possible to decompose the variation in the prices between two hubs into three regimes: (1) autarky (2) arbitrage binding in one direction or (3) arbitrage binding in the other direction. The task of the model will then be to classify the observed price difference between two hubs $P_{i,t} - P_{j,t}$ as belonging to the one of the three regimes:

$$P_{i,t} - P_{j,t} = \alpha + \epsilon_{1,t} \quad (5)$$

$$P_{i,t} - P_{j,t} = \overline{T}_2 + \nu_{2,t} \quad (6)$$

$$P_{i,t} - P_{j,t} = -\overline{T}_3 - \nu_{3,t} \quad (7)$$

where (5) represents the state of autarky (transaction costs not binding), (6) represents the state of transaction costs in one direction are binding, and (7) represents the state where the transaction costs in the other direction are binding. Typically, $\epsilon_{1,t}$ is assumed to be distributed normally, while $\nu_{2,t}$ and $\nu_{3,t}$ are distributed as a truncated normal distribution to prevent transaction costs from being negative. By making these distributional assumptions, the model becomes a standard finite mixture model with parameters $(\alpha, \overline{T}_2, \overline{T}_3, \sigma_1, \sigma_2, \sigma_3)$ to be estimated by maximum likelihood.[34] Unfortunately, large variations are required in order to have estimates robust to the distributional assumptions. Furthermore, the model suffers from an identification problem in regions of the parameter space that yield price differences that appear normally distributed. To gauge how serious this identification problem is for our setting, we use the Jarque-Bera and Lilliefor hypothesis tests to determine how plausible it is that each of the 55 pairs of price differences are distributed normally. In close to half of the pairs either within the three interconnects or across the interconnects, we fail to reject the null hypothesis that the price difference between the trading hubs is distributed normally.[35] Consequently, we caution the use of structural arbitrage models in recovering per-unit transaction costs in the wholesale electricity markets.

4 Conclusion

A national market for wholesale electric power in the US has emerged following industry restructuring in 2000. Tests for correlation and Granger Causality between trading hubs support the presence of a national market. Going beyond pairwise analysis, we introduce an array of multivariate techniques capable of addressing the national market hypothesis, including the common trend test. Although there is strong evidence of integration between the series, the analysis suggests a division between the eastern and western parts of the market. We also find border effects of 300 miles between the three interconnects.

[34] The parameters σ_1, σ_2, and σ_3 are the spread parameters in the normal or truncated normal distributions.
[35] These results hold for either of the statistical tests we chose to use.

The absence of transmission between the interconnects and significant border effects suggests that the national market is not yet fully integrated, even within the one-month horizon. Construction of transmission facilities between the interconnects would complete the development of the US wholesale market for electric power. Our analysis suggests that transmission facilities connecting the three regions would result in substantial gains from trade.

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