Bi-directional causality in California's electricity and natural-gas markets

Chi-Keung Woo[a,b,*], Arne Olson[a], Ira Horowitz[c,d], Stephen Luk[d]

[a] *Energy and Environmental Economics, Inc., 353 Sacramento Street, Suite 1700, San Francisco, CA 94111 USA*

[b] *Hong Kong Energy Studies Centre, Hong Kong Baptist University, Hong Kong*

[c] *Department of Decision and Information Sciences, Warrington College of Business Administration, University of Florida, Gainesville, FL 32611-7169*

[d] *School of Accounting and Finance, Hong Kong Polytechnic University, Hong Kong*

Abstract

The Granger instantaneous-causality test is applied to explore the potential causal relationships between wholesale electricity and natural-gas prices in California. The test shows these relationships to be bi-directional, and reveals California's electricity and natural gas markets to be as inextricably intertwined as casual observation and theoretical considerations would suggest they ought to be. This meshing of markets exacerbated the effects of California's natural gas crisis on the contemporaneous electricity crisis, while concurrently the electricity crisis may have contributed to the dysfunction in the national-gas market and helped to precipitate the natural-gas crisis. The finding supports an integrated approach, as opposed to a piecemeal approach, for formulating energy policy recommendations, not just in California but in the world at large.

Keywords: Electricity crisis; Natural gas crisis; Causality

* Corresponding author. Tel: +1-415-391-5100; Fax: +1-415-391-6500.

Email address: ck@ethree.com (C.K. Woo).

1. Introduction

Targets abound for those seeking to point the finger of blame for the California energy crisis that extended from May 2000 to June 2001, with the most noteworthy candidates being extreme weather, the failure of electricity deregulation, capacity shortages in electricity generation, abuses of market power by electric generators, "gaming" and price manipulation by electricity and natural-gas marketers, and high emissions-credit prices. Indeed, the crisis has spawned a veritable cottage industry for the production of studies exploring its various aspects, including the attribution of blame and the impact of deregulation — and that industry is still in its growth stage (Faruqui *et al*. 2001; Woo, 2001; Blumenstein *et al*. 2002; Borenstein, 2002; Borenstein *et al*., 2002; Joskow and Khan, 2002; Kolstad and Wolak, 2003; Weare, 2003; Woo *et al*., 2003; Wolak, 2003a, 2003b; Lee, 2004; Woo, *et al*., 2005).

Figure 1 shows what all the fuss is about. Three sets of California wholesale electricity prices are on display: California Power Exchange (PX) day-ahead unconstrained clearing prices and bilateral, volume-weighted average prices for next-day on-peak (06:00-22:00, Monday-Saturday) delivery at the major pricing points in Northern California (NP-15) and Southern California (SP-15). The NP-15 and SP-15 zones are connected by "Path 15", an 84-mile stretch of electrical transmission lines in the Central Valley connecting Southern California with Northern California. The figure also shows the California Independent System Operator's (CAISO's) declared emergency hours of operating reserve shortfall by month.

Consistent with FERC (2003a), Figure 1 reveals three distinct periods: (1) a pre-crisis period from April 1998 through April 2000; (2) a crisis period from May 2000 through June 2001; and (3) a post-crisis period that began in July 2001 and persists to this day. During the pre-crisis period day-ahead electricity prices were low and emergency hours were few. During the crisis period (with the PX shutting down on February 1, 2001), electricity prices were high and volatile, and there were many emergency hours. After the crisis, electricity prices were once again low and emergency hours were few.

As indicated by the spot natural-gas prices in Figure 2, the electricity-crisis period overlapped the one in natural gas that lasted from November 2000 through May 2001. In a previous paper (Woo *et al*., 2004a), we developed a model designed to (1) test whether the integration of natural-gas markets in North America since open access and deregulation in the mid-1980s resulted in efficient markets that would permit accurate long-term forecasts of California natural-gas prices, and to (2) isolate the individual impacts of both the electricity crisis and the natural-gas crisis on California natural-gas prices. The finding that the electricity *crisis* influenced California natural-gas prices in 2000-2001 begs the question whether electricity markets *in general* can do so, especially in light of the importance of natural gas as an input in electricity generation.

The present paper explores whether this *demand pull* impact can be demonstrated to exist alongside the well-documented *supply-push* impact of natural-gas prices on electricity prices. If there is a bi-directional relationship between electricity and natural-gas prices, such abnormalities as apparently occurred in the electricity market in the May 2000 to June 2001 period would affect the otherwise efficient natural-gas market and contribute to any tendencies it might have to dysfunction under stress, as was apparently the case during the November 2000 to May 2001 period. That dysfunction would in turn exacerbate the problems in the electricity market, etc., etc., and so forth.

But is there such a bi-directional relationship? With a couple of rare exceptions (Serletis and Herbert, 1999; Rothwell, 2002), the possibility has been subjected to almost pointed neglect, beyond mention *en passant*. Here we rectify that neglect by applying the Granger instantaneous-causality test (Granger, 1969; Pierce and Haugh, 1977) to formally explore the potential causal relationships between wholesale electricity and natural-gas prices. The test shows that the relationship is indeed bi-directional and that the electricity and natural-gas markets are inextricably intertwined. This meshing of markets exacerbated the effects of California's natural-gas crisis on its contemporaneous electricity crisis. Our results also suggest that, conversely, the electricity crisis may have contributed to the dysfunction of the natural-gas market and helped to precipitate the natural-gas crisis. This finding supports an integrated approach, rather than one that is piecemeal, for formulating energy-policy recommendations.

2. California's electricity market

At present, there are spot electricity markets for next-day delivery at two locations inside California: CAISO Zone NP-15 in Northern California, and CAISO Zone SP-15 in Southern California. The NP-15 and SP-15 zones are connected by Path 15 that sometimes becomes congested, causing prices on either side to diverge. The trading in these markets is bilateral: buyers and sellers contract directly with each other, or perhaps through intermediaries such as power brokers and marketers, rather than transacting through a centralized exchange such as the Pennsylvania-Jersey-Maryland (PJM) market in the northeastern U.S. Both on-peak and off-peak contracts are traded, with the on-peak period being 06:00-22:00, Monday through Saturday, and the off-peak period comprising the remaining hours. Useful for managing spot-price risks (Woo, *et al*., 2004b, 2004c, 2004d), forward contracts are traded up to 36 months into the future.

In addition to these two bilateral spot electricity markets, the CAISO operates daily auction markets to acquire ancillary services such as operating reserves and imbalance energy for reliable operation of the California grid. The auction uses incentive-compatible scoring and settlement rules to induce suppliers to truthfully reveal their private cost information, which permits the CAISO to implement least-cost procurement and dispatch (Chao and Wilson, 2002).

The current market organization is the result of several key events. First, the Federal Public Utilities Regulatory Policy Act of 1978 sparked the rapid growth of small, non-utility generation and cogeneration facilities, which sold to investor-owned utilities in California under avoided-cost pricing (Woo, 1988). These high-priced contracts contributed to California's relatively high electricity rates, which formed part of the rationale cited by Governor Pete Wilson and others in support of electricity deregulation in the mid-1990s (Woo, 2001; Blumenstein *et al*. 2002; Jeruwitz, 2002; Woo *et al*., 2003; Lee, 2004).

Second, the Federal Energy Policy Act of 1992 created a new class of "exempt wholesale generators" that were allowed to sell at market prices, rather than at cost-based rates. The Act also granted the Federal Energy Regulatory Commission (FERC) broad authority to mandate open access to utility-owned transmission. FERC Orders 888 and 889, issued in 1996, required jurisdictional utilities to provide open and comparable access to third parties desiring to use their systems for wheeling (Woo, *et al*. 1998). The result of these federal actions was an explosion of wholesale electricity trading and the emergence of integrated electricity markets with converging prices (Woo, *et al*., 1997; De Vany and Walls, 1996).

Third, in 1996 the California legislature passed Assembly Bill (AB) 1890 which deregulated the California electric sector, creating both the PX to operate day-ahead and hour-ahead electricity markets and the CAISO to run the transmission grid and to operate markets for ancillary services and real-time imbalance energy. The bill provided utilities with substantial incentives to divest their generation assets. Combined with the California Public Utilities

Commission's "must-buy" requirement that utilities use PX markets to procure the electricity needed to serve their retail loads, this created heavy reliance on spot markets for the vast majority of California's daily electricity requirements.

The first two years after the market opening on April 1, 1998, were relatively uneventful, but the price spike in May 2000 kicked off a 13-month excursion of extremely high and volatile prices. The crisis produced many victims, including electricity consumers, shareholders of financially ruined utilities, and the PX itself (Faruqui *et al*., 2001; Woo, 2001; Jeruwitz, 2002; Blumenstein *et al*., 2002; Weare, 2003; Woo, *et al*., 2003; Lee, 2004). The latest is Governor Gray Davis, who was recalled from office in November 2003 due in part to his failure to address the crisis before it spiraled out of control in late 2000.

Finally, 2002 saw California utilities return to the role of forward procurement with the passage of Assembly Bill 57 (AB57), which directed the CPUC to "review each electrical corporation's procurement plan in a manner that assures creation of a diversified procurement portfolio, assures just and reasonable electricity rates, [and] provides certainty." (Section 1(c)). The three large utilities, Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E) now procure energy in the spot and forward markets to cover their residual net short (RNS) positions. Each utility's RNS is the utility's retail load obligation less retained generation and its allocated share of the long-term contracts signed by the California Department of Water Resources during the crisis.

3. California's natural-gas market

As with electricity, there are two key wholesale natural-gas markets in California: Pacific Gas and Electric (PG&E) Citygate serving Northern California and Southern California Gas

(SoCal Gas) serving Southern California. The physical ties evolving from the pipeline grid both directly and indirectly link the California markets to those throughout North America, including Canada. As a buyer of natural gas, City of Palo Alto Utilities (Palo Alto), for example, purchases its gas at PG&E Citygate where PG&E's local distribution system interconnects with its California Gas Transmission pipeline. Palo Alto then pipes the gas to its distribution network for delivery to its end-use customers: industrial buyers, residences, and commercial outlets.

Electric power generation accounts for approximately 25 percent of natural-gas consumption in the United States, up from less than 20 percent five years ago. This increase in natural-gas-fired generation accounts for virtually all of the increase in natural-gas consumption during that period. The rising natural-gas demand is alarming because "after more than three decades of development, …almost every major conventional source of natural gas supply in the U.S. and the Albertan field in Canada has been in rapid decline" (Weissman, 2002, p. 2). The issue is particularly salient for electricity production in California, since "[a]bout half of in-state generating capacity consists of natural-gas-fired steam and peaking units and these units are the marginal supply sources during most hours in the summer when electricity demand in California is highest" (Joskow and Kahn, 2002, p. 5). But the winter is not necessarily immune, as evidenced by the fact that both the electricity and natural-gas crises reached their apex in December 2000.

Beyond the physical ties, an array of financial instruments, including futures contracts, swaps, and options, form the economic ties that directly bind the California markets to the important markets at Henry Hub. Located on the Sabine Pipeline in Louisiana, Henry Hub is the physical delivery point for the nation's largest natural-gas spot and futures markets, including the monthly natural-gas futures contracts traded on the New York Mercantile Exchange (NYMEX) since April 1990. NYMEX also offers clearing services and calculates settlement prices for natural-gas basis swap contracts, providing a method for managing spot-price differences (also known as basis differentials) between Henry Hub and local markets, including PG&E Citygate and SoCal Gas. The extensive North American pipeline network allows gas to flow from region to region based on price movements, effectively integrating virtually all of the individual natural-gas markets.

These economic and physical ties led us to posit that California's natural-gas spot markets are integrated with out-of-state markets, with the ensuing outcome of price convergence (Woo *et al*., 2004a). The implied hypothesis was supported by earlier empirical evidence in Doane and Spulber (1994), NEB (1995), King and Cuc (1996), and Cuddington and Wang (2003), which we were able to update and reaffirm. That affirmation notwithstanding, Figure 2 shows that California's natural-gas price skyrocketed from $5 per million British thermal units (MMBtu) to over $25 from November to December 2000, a five-fold increase that far exceeded the contemporaneous rise in spot prices at Henry Hub. This natural-gas price spike has been attributed to dysfunction in the natural-gas market that "fed off misconduct, including gas transaction misreporting and wash trading" (FERC, 2003a). Since June 2001, however, California's natural-gas spot markets have once again been relatively calm, save for a brief price spike in February 2003 attributed to extremely cold weather in the eastern half of the country (FERC, 2003b).

Looking forward, Americans (including Californians) are under constant and looming threat of a natural-gas crisis. The rising tide of natural-gas-fired generation and economic recovery, unmatched by the discovery of new reserves and the expansion of transportation and storage infrastructure, threatens to swamp existing supplies and leads to ominous predictions of supply shortage and high prices in the coming years (Barlett and Steele; 2003; Francis, 2003; Hebert, 2003; Hulse, 2003; Gilpin, 2003; Wald, 2003). Potential solutions include exploiting "frontier gas" reserves in the Arctic regions of Alaska and Canada, increasing liquefied natural gas (LNG) imports, easing drilling restrictions on federal lands, streamlining the permitting process, providing incentives for production and new technologies (e.g., extracting methane hydrates from deep ocean floors), implementing renewable portfolio standards, and improving energy efficiency efforts (HR, 2003; CEC, 2003a).

4. Causal relationships between California's natural-gas and electricity markets

In order to develop sensible and coordinated policies for California's natural-gas and electricity markets, it is necessary to understand how the demand-and-supply relationships in one market, and the resultant prices, influence the demand-and-supply relationships, and the resulting prices, in the other market. In particular, we posit a bi-directional causal relationship, which would lend support to the March 5, 2001 remark by California Assembly Republican Leader Bill Campbell (Villa Park) that "California's natural gas crisis is completely intertwined with its electricity crisis … [and] … [a]ny plan to deal with our electricity crisis must have a natural gas component or Californians are going to pay unacceptably high prices for both" (California State Assembly Republican Caucus, 2001).

Consider, for example, a random increase in electricity demand that is triggered by hot weather. That increase will, *ceteris paribus*, drive up the price of electricity and widen the "spark-spread" - the per MWh profit margin approximated by the positive difference between the electricity price minus the per MWh fuel cost of a natural-gas-fired power plant. The widening spark-spread will raise the demand for natural gas by (a) increasing the willingness-to-pay of natural-gas-fired generators, and (b) inducing less efficient plants to begin operating. This manifests itself in higher bids for spot gas in bilateral trading and higher realized natural-gas prices. On the one hand, then, we can anticipate that movements in electricity prices will ultimately be reflected in corresponding movements in natural-gas prices. Moreover, inasmuch as natural-gas suppliers look to the summer as a period in which they can restock reserves that have declined during the winter season when natural gas is in particularly high demand, their best intentions are thwarted under the pressure of above-normal summer demand from generators.

Alternatively, suppose a random burst of cold weather increases the demand for natural gas on the part of the residential users and commercial outlets that account for about 40 percent of natural-gas usage nationally. When natural gas is under tight (inelastic) supply, that demand increase can be expected to result in higher natural-gas prices. Those higher prices raise the operating cost, and bids, of the natural-gas-fired electricity generation that serves a large proportion of California electricity demand. That is, "[c]hanges in natural-gas prices shift the supply curve up or down, and other things being equal, competitive [electricity] market prices would move up or down along with the changes in the gas prices" (Joskow and Kahn, 2002, p. 5). In essence, generator owners will pass natural-gas price increases on to electricity distributors, and these increases will reverberate in an end-user market that is typically characterized by inelastic short-term demand. On the other hand, then, we can anticipate that movements in natural-gas prices will ultimately be reflected in corresponding movements in both wholesale and retail electricity prices. Moreover, the end-users' problem will be compounded when the same cold weather that increased the demand for natural gas simultaneously increases their demand for electricity.

Finally, market-power abuse can further magnify the natural-gas price effect on the electricity price (Borenstein *et al*., 2002; Joskow and Kahn, 2002; Kolstad and Wolak, 2003; Wolak, 2003a, 2003b).

4.1 Causality test

Let P_{Et} denote the wholesale volume-weighted average electricity price on day *t* and let P_{Gt} denote the comparable natural-gas price. The assertion that "movements in natural-gas prices will ultimately be reflected in corresponding movements in electricity prices" can be framed as a hypothesis that can be tested via a Granger instantaneous-causality test (Granger, 1969; Pierce and Haugh, 1977). Granger causality is established when at least one of the coefficients for a set of lagged and contemporaneous natural-gas prices that enter a linear regression as independent variables along with a set of lagged electricity prices is a statistically significant factor in explaining the current electricity price. The contemporaneous natural-gas price is included and is relevant here, because generator owners arbitrage natural gas and electricity prices in real time.

So long as one is not concerned with the magnitude of the impact of natural-gas prices on electricity prices, as opposed to simply establishing causality, the appropriate test of the hypothesis is an *F* test on the statistical significance of the *set* of natural-gas prices, rather than a *t* test, on each of the individual coefficients.

Implementing the *F* test entails estimating the parameters of the following linear regression (Berndt, 1991, pp. 380-383):

$$P_{Et} = \alpha + \Sigma_j \beta_j P_{E(t-j)} + \Sigma_k \gamma_k P_{G(t-k)} + \varepsilon_t. \qquad (1)$$

Here, ε_t is a random-error term with the usual normality properties, and α, β_j (j = 1, …, J) and γ_k (k = 0, …, K) are parameters that will be estimated using ordinary least squares (OLS).

Equation (1) asserts that the price of electricity on day t depends on both previous electricity prices that date as far back as day $t - J$ and on the current and previous natural-gas prices dating as far back as day $t - K$. Although values for J and K are often set in advance and somewhat arbitrarily, they are best determined empirically in the estimation process so as to satisfy two criteria. First, the parameter estimates for β_J and γ_K must be significantly different from zero. Second, the residuals from the estimated regression for that pair of J and K must not be serially correlated to any (statistically) significant extent, thus not rejecting the white-noise hypothesis for the random-error term. When after applying the appropriate F test our estimated regression coefficients allow us to reject the null hypothesis H_0: $\gamma_k = 0$ for *all* k = 0, …, K, the natural-gas price is said to Granger-cause the electricity price.

Reversing the roles of the electricity and natural-gas prices allows us to test the intuitively appealing assertion that movements in electricity prices will ultimately be reflected in corresponding movements in natural-gas prices. This is done through OLS estimates of the parameters of equation (2), which is the companion piece to equation (1):

$$P_{Gt} = \eta + \Sigma_j \kappa_j P_{G(t-j)} + \Sigma_k \lambda_k P_{E(t-k)} + \mu_t. \qquad (2)$$

When, after applying the appropriate F test, our estimated regression coefficients allow us to reject the null hypothesis H_1: $\lambda_k = 0$ for *all* k = 0, …, K, the electricity price is said to Granger-cause the natural-gas price.

Finally, when both of these null hypotheses are rejected by the F test, Granger causality is said to be bi-directional, which is the empirical result that our theoretical arguments and institutional observations would lead us to expect.

4.2 Data

To implement the causality tests before, during, and after the electricity crisis, we construct a data sample containing the following price series:

- The wholesale, daily, volume-weighted average electricity prices reported by Platts for on-peak (06:00-22:00, Monday-Saturday), next-day delivery to CAISO Zone NP-15 in Northern California and CAISO Zone SP-15 in Southern California.
- The wholesale, daily, volume-weighted average natural-gas prices reported by Platts for next-day delivery to PG&E Citygate in Northern California and Southern California Gas (SoCal Gas) in Southern California.

The sample period begins on April 20, 1999 and concludes on December 30, 2004, encompassing the most recent data available at this time of writing. The choice of April 20, 1999 as a starting point was dictated by the fact that NP-15 and SP-15 price data first became available in January 1999, but there are glaring gaps in the data prior to the April date.[1] We did not use the PX hourly price data, because the PX ended its operation at the end of January 2001, thus precluding tests based on a set of consistently collected data that cover the pre-crisis, crisis, and post-crisis periods.

---

[1] The several missing observations during our sample period were filled in via a three-step process:

(1) Find the immediately preceding and following data points of a missing observation,

(2) Estimate a regression of the entire series of NP-15 (SP-15) prices against the same-day SP-15 (NP-15) prices and the immediately preceding and following NP-15 (SP-15) prices as regressors, and

(3) Use the estimated regression to estimate the missing prices.

Table 1 reports the summary statistics for the daily wholesale natural-gas and electricity prices. The statistics offer compelling, if partial, evidence that the relatively high and volatile prices for the full sample period are largely due to the very high and volatile prices during the electricity-crisis period.

Table 2 reports the pair-wise correlations between the daily wholesale natural gas and electricity prices. It shows that PG&E Citygate and SoCal Gas natural-gas prices are highly correlated, with a correlation coefficient of at least $r = 0.9$ for the entire sample period and the sub-periods. The natural-gas prices, however, are only moderately correlated with the electricity prices. Except for the crisis period, the NP-15 and SP-15 electricity prices are highly correlated.

4.3 Results

As presaged in Tables 1 and 2, our intention was to establish or reject Granger causality over the entire sampling period, as well as in the three individual periods. In order to assure the validity of the Granger test, however, we first had to establish that all four price series were stationary in all four periods. The stationarity test that we employed was the augmented Dickey-Fuller unit-root test with drift and trend (Enders, 2004, pp. 181-184). In the cases of the two natural-gas prices during the pre-crisis period, we were able to reject the unit-root hypothesis at the $p = 0.10$ level; in all other cases the unit-root hypothesis was rejected at the $p \leq 0.01$ level.

Having settled the stationarity issue, we next sought to determine the maximum lags that will fix values for J and K. In this regard, we allowed the data to speak for themselves through a preliminary analysis that estimated regressions with what in this context are rather long lags of $J = K = 4$ days. In each causal direction the only estimated regression coefficients that were uniformly statistically insignificant were those attached to the lagged variables for periods $t - 3$ and $t - 4$, which had p-values close to unity. Thus, we set $J = K = 2$ for all our final estimations.

Table 3 reports the F statistics with (3, N) degrees of freedom because the F-test applies to $K + 1 = 3$ parameters under the causality hypothesis and N is the number of observations in the sample, adjusted for the six parameters being estimated. The first panel in Table 3 reports results for the pre-crisis period. We are unable to reject three of the hypotheses: the PG&E Citygate natural-gas price does not Granger-cause the NP-15 electricity price, and the SoCal natural-gas price does not Granger-cause either electricity price. The F-statistics for the other five cases are statistically significant, but suggest bi-directional causality in the pre-crisis period only in case of the PG&E Citygate natural-gas price and SP-15 electricity.

The second panel in Table 3 reports results for the electricity-crisis period of May 2000 through June 2001. The first half of the panel indicates that NP-15 prices, but not SP-15 prices, Granger-cause PG&E Citygate and SoCal gas prices, though both NP-15 inferences are borderline. This result reflects the fact that NP-15 prices were higher than SP-15 prices during the electricity crisis and therefore NP-15 prices (not SP-15 prices) were the primary driver of spark spreads in California. The second half of the panel indicates that natural-gas prices Granger cause electricity prices.

The third panel in Table 3 reports results for the post-electricity-crisis period. Without exception, the F-statistics of seven of the eight cases are highly significant, with the SP-15 natural-gas price causing the PG&E electricity price being the exception at $p = 0.07$, implying bi-directional causality in the post-electricity-crisis period. Finally, and most tellingly, the fourth panel in Table 3 establishes bi-directional causality at virtually any standard of statistical significance, in all eight cases.

Taken as a whole, then, the Granger causality test results provide strong affirmation of bi-directional causality between wholesale natural-gas and electricity prices in California.[2]

5. Natural gas and the California energy crisis

Natural-gas traders, whether at PG&E Citygate or SoCal Gas, may have the option of locking in a future price through the concurrent purchase of a NYMEX futures contract at Henry Hub and a basis swap contract between Henry Hub and the local market. Woo *et al*. (2004a) affirm the feasibility of this option via the maximum-likelihood parameter estimates of a single-equation, partial-adjustment regression model. The model is fitted to data for each of the two California markets individually, and for three alternative orders of an autoregressive process. In all, then, there were six estimated regressions. Although there are minor differences in the specific estimates, the overall implications are the same: notably, that the natural-gas spot markets operate efficiently and that it is only a matter of a few days, rather than a few months, before each market will regain any perturbed local equilibrium price. Thus, it is feasible for traders to use NYMEX natural-gas futures prices to forecast prices for an extended period of time.

During the 13-month California energy-crisis period that began in May 2000, however, things were markedly different and the model isolated the differences. In particular, during the

---

[2] At the suggestion of a referee, we also ran all of the unit-root tests and estimated the 16 regressions with the data in logarithms. For the pre-crisis period, we were unable to reject the unit-root hypothesis for the PG&E Citygate prices, and for the crisis period we were unable to reject the unit-root hypothesis for the PG&E Citygate and the SoCal natural gas prices. With those three exceptions, the data passed the stationarity test and the bi-directional causality hypothesis was, in the main, supported for the logged data, too.

overlapping natural gas crisis of November 2000 to May 2001, the three alternative estimates for PG&E Citygate imply a statistically significant (p = 0.05) increase of $5.30/MMBtu in the daily price of natural gas, while those for SoCal Gas imply a statistically significant increase of $7.80/MMBtu, attributable to natural gas market dysfunction. These estimates corroborate the corresponding FERC (2003a) figures of $4.18/MMBtu and $7.03/MMBtu. Assuming a conservative marginal fuel-conversion efficiency (heat rate) of 10,000 Btu per kilowatt hour, the excess above normally expected natural-gas price levels could have contributed anywhere from $50 to $70 per MWh to the electricity-price spike, notwithstanding the previously cited targets of blame.

6. Conclusion

Natural gas and electricity are energy sources whose prices, more often than not, will be driven by a common set of demand considerations. Beyond that, however, the two markets and their prices are inextricably intertwined, because natural gas is a significant input for electricity generation. Indeed, it is a commonly held belief, one that is solidly grounded in casual institutional observation and sound theoretical considerations, that one consequence of this intertwining is a bi-directional causal relationship between natural-gas and electricity prices. The fact that it is commonplace notwithstanding, this belief has not heretofore been subjected to rigorous empirical testing. In providing that rigorous test we have verified the convergence of the markets for these two critical energy sources, at least in California and doubtless anyplace in the world with substantial natural-gas-fired generation.

The linkage of the two markets exacerbated the effects of California's natural-gas crisis on its contemporaneous electricity crisis. In addition, California may well have had the electricity crisis aiding and abetting any dysfunction in the natural gas market, thus precipitating the natural gas crisis. The empirical evidence provided herein argues in favor of an integrated approach that will mitigate both the demand-pull impact from electricity to natural gas and the supply-push impact from natural gas to electricity. It opposes a piecemeal approach for formulating energy-policy recommendations, not in California but in the world at large.

The integrated approach would first and foremost entail reducing the demand for electricity and over-reliance on natural gas generation. This would require such actions as replacing inefficient natural-gas-fired generators with newer facilities and promoting renewable energy (CEC, 2003a, p. 18; CEC, 2003b, p. 69; WA-OTED, 2001, pp. 53-55; Besant-Jones and Tenenbaum, 2001, p. 8; Weare, 2003, p. ix). A second imperative is to assure a steady and adequate supply of natural gas by preventing bottlenecks in natural-gas pipelines and the monopolization of natural-gas pipelines, and assuring adequate natural gas storage capacity, (Navarro and Shames, 2003, p. 34; Weare, 2003, p. ix).

Moreover, the bi-directional causality documented herein may have implications for other closely related markets. For instance, Kolstad and Wolak (2003) postulate that NOx emissions-credit prices in the South Coast Air Quality Management District's Regional Clean Air Incentives Market (RECLAIM), were manipulated in order to allow generators to "cost-justify" prices above competitive levels in California's electricity markets. The Granger instantaneous-causality test could be applied to test whether electricity prices influence emissions-credit prices, or vice-versa.

Finally, our results point to yet another instance of how California's experience should serve as a cautionary example for other regions and countries embarking on or considering a course of market reforms and deregulation. Electricity restructuring may not achieve the desired result of competitive pricing if key input markets are not sufficiently competitive to resist demand shocks emanating from electricity markets. If California's electricity crisis could shock a mature and liquid natural-gas market, less developed markets would surely be even more vulnerable. This supports the use of alternatives to full-blown restructuring with generation divestiture, such as regulatory reform with performance-based ratemaking, to achieve efficiencies in places like Hong Kong and Israel that do not have competitive fuel markets (Woo *et al*., 2005; Woo, *et al*., 2003; Tishler, *et al*, 2002).

References

Barlett, D.L., Steele, J.B., 2003. Why the US is running out of gas. Time Magazine, July 21.

Berndt, E.R., 1991. The Practice of Econometrics. Addison Wesley, New York.

Besant-Jones, J.E., Tenenbaum, B.W., 2001. The California Power Crisis: Lessons for Developing Countries. The World Bank, Washington D.C.

Borenstein, S., 2002. The trouble with electricity markets: understanding California's restructuring disaster. Journal of Economic Perspectives 16 (1), 191-211.

Borenstein, S., Bushnell, J.B., Wolak, F.A., 2002. Measuring market inefficiencies in California's restructured wholesale electricity market. American Economic Review 92 (5) 1376-1405.

Blumstein, C., Friedman, L., Green, R.J., 2002. The history of electricity restructuring in California. Journal of Industry and Competition and Trade 2 (1/2) 9-38.

California State Assembly Republican Caucus, 2001. GOP moves natural gas to front burner. Press release, March 5.

CEC, 2003a. 2003 Integrated Energy Policy Report, 100-03-019D, Docket No.02-IEP-1. California Energy Commission, Sacramento (CA).

CEC, 2003b. Preliminary Natural Gas Market Assessment, 100-03-006SR, Docket No.02-IEP-1. Sacramento: California Energy Commission.

Chao, H-P., Wilson, R., 2002. Multi-dimensional procurement auctions for power reserves: robust incentive-compatible scoring and settlement rules. Journal of Regulatory Economics 22 (2), 161-183.

Cuddington, J.T., Wang, Z., 2003. Assessing the integration of U.S. natural gas spot markets: evidence from daily price data. Economics Department Working Paper, Georgetown University, Washington, D.C.

De Vany A., Walls, W.D., 1996. Price dynamics in a network of decentralized power markets. Journal of Regulatory Economics 15, 123-140.

Doane, M.J., Spulber, D.F., 1994. Open access and the evolution of the U.S. spot market for natural gas. Journal of Law and Economics 37 (2), 477-517.

Enders, W., 2004. Applied Econometric Time Series. John Wiley & Sons, New York.

Faruqui, A., Chao, H-P., Niemeyer, V., Platt, J., Stahlkopf, K., 2001. Analyzing California's power crisis. Energy Journal 22 (4), 29-52.

FERC, 2003a. Final Report on Price Manipulation in Western Markets, Docket No.PA02-02-000. Federal Energy Regulatory Commission, Washington, D.C.

FERC, 2003b. Report on The Natural-Gas Price Spike of February 2003. Federal Energy Regulatory Commission, Washington, D.C.

Francis, M., 2003. Natural-gas prices seen rising further. CNBC TV, September 17.

Gilpin, K.N., 2003. Assessing the price surge in natural gas. New York Times, July 20.

Granger, C.W.J., 1969. Investigating causal relations by econometric models and cross spectral methods. Econometrica 37 (3), 424-438.

Hebert, H.J., 2003. Natural gas crisis looms ahead. CBSNEWS.com, October 1.

HR, 2003. Speaker's Task Force Report on Affordable Natural Gas. U.S. House of Representatives, Washington, D.C.

Hulse, C., 2003. Natural gas outlook troubling Greenspan, *New York Times*, June 11.

Jurewitz, J.L., 2002. California electricity debacle: a guided tour. Electricity Journal 15(4), 10-29.

Joskow, P.L., Kahn, E., 2002. A quantitative analysis of pricing behavior in California's wholesale electricity market during Summer 2000. Energy Journal 23 (4), 1-35.

King, M., Cuc, M., 1996. Price convergence in North American natural gas spot markets. Energy Journal 17 (2), 17-42.

Kolstad, J., Wolak, F.A., 2003. Using environmental emissions permit prices to raise electricity prices: evidence from the California electricity market," Working Paper 113, Center for the Study of Energy Markets, University of California Energy Institute, Berkely.

Lee, W.W., 2004. US lessons for energy industry restructuring: based on natural gas and California electricity incidences. Energy Policy 32 (2), 237-259.

Navarro, P., Shames, M., 2003. Electricity deregulation: lessons from California. Energy Law Journal 24 (1), 33-64.

NEB, 1995. Price Convergence in North American Natural Gas Markets. National Energy Board, Calgary.

Pierce, D.A., Haugh, L.D., 1977. Causality in temporal systems, Journal of Econometrics 5, 265-293.

Rothwell, G., 2002. Lessons from the California crisis for the restructuring of Russia's UES. XII Research Conference, Russian Economic and Political Institutions in Transition, New Economics School, Moscow.

Serletis, A., Herbert, J., 1999. The message in North American energy prices. Energy Economics 21 (5), 471-483.

Tishler, A., Woo, C.K., Lloyd, D., 2002. Reforming Israel's electric sector. Energy Policy 30(4), 347-353.

Wald, M.L., 2003. In natural gas's future, experts see more high prices and growing imports. New York Times, June 27.

WA-OTED, 2001. Convergence: Natural Gas and Electricity in Washington. Washington State Office of Trade and Economic Development, Olympia, Washington.

Weare, C., 2003. The California Electricity Crisis: Causes and Policy Options. Public Policy Institute of California, San Francisco, California.

Weissman, A., 2002. Natural gas supply, demand and pricing. Energy Ventures Group, Washington, D.C.

Wolak, F.A., 2003a. Measuring unilateral market power in wholesale electricity markets: the California market, 1998-2000. American Economic Review 93 (2), 425-430.

Wolak, F.A., 2003b. Lessons from the California electricity crisis. Working Paper 110, Center for the Study of Energy Markets, University of California Energy Institute, Berkeley.

Woo, C.K., 1988. Inefficiency of avoided cost pricing of cogenerated power. Energy Journal 9(1), 103-113.

Woo, C.K., Lloyd-Zannetti, D., Horowitz, I., 1997. Electricity market integration in the Pacific Northwest. Energy Journal 18 (3), 75-101.

Woo, C. K., Horowitz, I., Martin, J., 1998. Reliability differentiation of electricity transmission. Journal of Regulatory Economics 13, 277-292.

Woo, C.K., 2001. What went wrong in California's electricity market? Energy - The International Journal 26 (8), 747-758.

Woo, C.K., Lloyd, D., Tishler, A., 2003. Electricity market reform failures: UK, Norway, Alberta and California. Energy Policy 31 (11) 1103-1115.

Woo, C.K., Olson, A., Horowitz, I., 2004a. Market efficiency, cross hedging and price forecasts: California's natural-gas markets. Energy and Environmental Economics, San Francisco.

Woo, C.K., Horowitz, I., Horii, B., Karimov, R., 2004b. The efficient frontier for spot and forward Purchases: an application to electricity, Journal of the Operational Research Society 55 (11) 1130-1136.

Woo, C.K., Horowitz, I., Horii, B., Karimov, R., 2004c. Managing electricity procurement cost and risk by a local distribution company, Energy Policy 32(5), 635-645.

Woo, C.K., Horowitz, I., Olson, A., Horii and, B., Baskette, C. 2004d. Efficient frontiers for electricity procurement by an LDC with multiple purchase options. OMEGA, forthcoming

Woo, C.K., Chow, L.C.H., Lior, N. (Ed.), 2005. Special Issue on Electricity Deregulation, Energy-The International Journal, forthcoming.

Table 1: Summary statistics for California's wholesale daily volume-weighted average on-peak (06:00-22:00, Monday-Saturday) electricity prices and daily volume-weighted average gas prices (Monday-Saturday).

Sample period	PG&E Citygate gas price ($/MMBtu)		SoCal gas price ($/MMBtu)		NP-15 electricity price ($/MWh)		SP-15 electricity price ($/MWh)	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Full: 04/99-12/04	4.88	3.22	5.21	4.28	72.7	77.9	69.9	69.6
Before the electricity crisis: 04/99-04/00	2.71	0.28	2.6	0.27	36.4	11.2	34.5	7.2
Electricity crisis: 05/00-06/01	8.04	5.44	9.99	7.2	187.9	109	172.8	96.9
After the electricity crisis: 07/01-12/04	4.44	1.42	4.34	1.36	44.3	13.3	45.4	13.4

Table 2: Pair-wise correlation between California's wholesale daily volume-weighted average on-peak (06:00-22:00, Monday-Saturday) electricity prices and daily volume-weighted average gas prices (Monday-Saturday).

Sample period	Variable	PG&E Citygate gas price ($/MMBtu)	SoCal gas price ($/MMBtu)	NP-15 electricity price ($/MWh)	SP-15 electricity price ($/MWh)
Full: 04/99-12/04	PG&E Citygate gas price ($/MMBtu)	1			
	SoCal gas price ($/MMBtu)	0.93	1		
	NP-15 electricity price ($/MWh)	0.69	0.79	1	
	SP-15 electricity price ($/MWh)	0.66	0.75	0.98	1
Before the electricity crisis: 04/99-04/00	PG&E Citygate gas price ($/MMBtu)	1			
	SoCal gas price ($/MMBtu)	0.97	1		
	NP-15 electricity price ($/MWh)	0.45	0.39	1	
	SP-15 electricity price ($/MWh)	0.42	0.4	0.74	1
Electricity crisis: 05/00-06/01	PG&E Citygate gas price ($/MMBtu)	1			
	SoCal gas price ($/MMBtu)	0.9	1		

	NP-15 electricity price ($/MWh)	0.55	0.65	1	
	SP-15 electricity price ($/MWh)	0.46	0.57	0.95	1
After the electricity crisis: 07/01-12/04	PG&E Citygate gas price ($/MMBtu)	1			
	SoCal gas price ($/MMBtu)	0.99	1		
	NP-15 electricity price ($/MWh)	0.77	0.81	1	
	SP-15 electricity price ($/MWh)	0.83	0.87	0.98	1

Table 3: Tests of causality (“→”) relationships between California’s wholesale daily volume-weighted average on-peak (06:00-22:00, Monday-Saturday) electricity prices and daily volume-weighted average natural-gas prices (Monday-Saturday). “*” = “Significant at $p < 0.05$”

Null hypothesis for the pre-electricity-crisis period (04/99-04/00)		*F* statistic (degrees of freedom) for testing the null hypothesis
Electricity price → Gas price	NP-15 price → PG&E Citygate gas price	8.34* (3, 292)
	SP-15 price → PG&E Citygate gas price	13.77* (3, 292)
	NP-15 price → SoCal gas price	12.44* (3, 292)
	SP-15 price → SoCal gas price	15.78* (3, 292)
Gas price → Electricity price	PG&E Citygate gas price → NP-15 price	2.01 (3, 292)
	SoCal gas price → NP-15 price	1.20 (3, 292)
	PG&E Citygate gas price → SP-15 price	3.21* (3, 292)
	SoCal gas price → SP-15 price	2.02 (3, 292)

Null hypothesis for the electricity-crisis period (05/00-06/01)		*F* statistic (degrees of freedom) for testing the null hypothesis
Electricity price → Gas price	NP-15 price → PG&E Citygate gas price	2.51* (3, 347)
	SP-15 price → PG&E Citygate gas price	1.33 (3, 347)
	NP-15 price → SoCal gas price	2.22 (3, 347)
	SP-15 price → SoCal gas price	0.44 (3, 347)
Gas price → Electricity price	PG&E Citygate gas price → NP-15 price	14.22* (3, 347)
	SoCal gas price → NP-15 price	21.27* (3, 347)
	PG&E Citygate gas price → SP-15 price	9.03* (3, 347)
	SoCal gas price → SP-15 price	16.29* (3, 347)

Null hypothesis for the post-electricity-crisis period (07/01-12/04)		*F* statistic (degrees of freedom) for testing the null hypothesis
Electricity price → Gas price	NP-15 price → PG&E Citygate gas price	8.12* (3, 1052)
	SP-15 price → PG&E Citygate gas price	2.70* (3, 1052)
	NP-15 price → SoCal gas price	8.44* (3, 1052)
	SP-15 price → SoCal gas price	3.34* (3, 1052)
Gas price → Electricity price	PG&E Citygate gas price → NP-15 price	45.92* (3, 1052)
	SoCal gas price → NP-15 price	47.63* (3, 1052)
	PG&E Citygate gas price → SP-15 price	60.79* (3, 1052)
	SoCal gas price → SP-15 price	62.52* (3, 1052)

Null hypothesis for the full period (04/99-12/04)		*F* statistic (degrees of freedom) for testing the null hypothesis
Electricity price → Gas price	NP-15 price → PG&E Citygate gas price	17.47* (3, 1707)
	SP-15 price → PG&E Citygate gas price	11.32* (3, 1707)
	NP-15 price → SoCal gas price	20.81* (3, 1707)
	SP-15 price → SoCal gas price	10.99* (3, 1707)
Gas price → Electricity price	PG&E Citygate gas price → NP-15 price	61.08* (3, 1707)
	SoCal gas price → NP-15 price	94.54* (3, 1707)
	PG&E Citygate gas price → SP-15 price	45.23* (3, 1707)
	SoCal gas price → SP-15 price	79.70* (3, 1707)

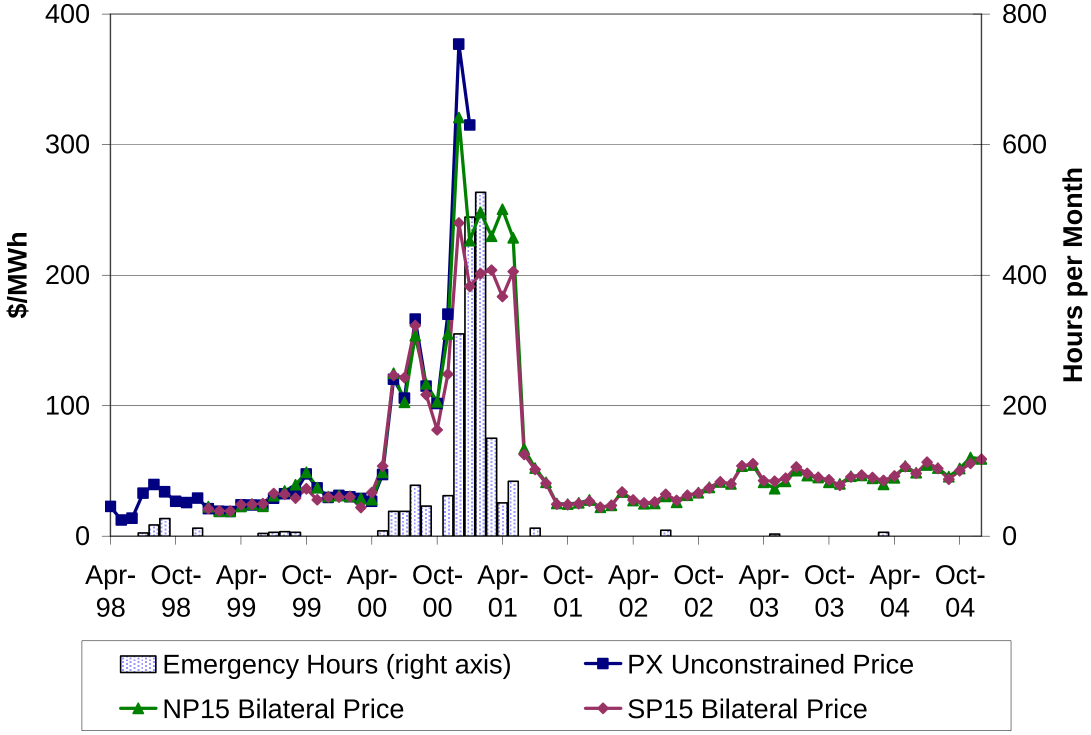

Figure 1. California electricity market history: monthly average day-ahead prices and ISO declared emergency hours, April 1998 – December 2004. Source: Platts and www.caiso.com.

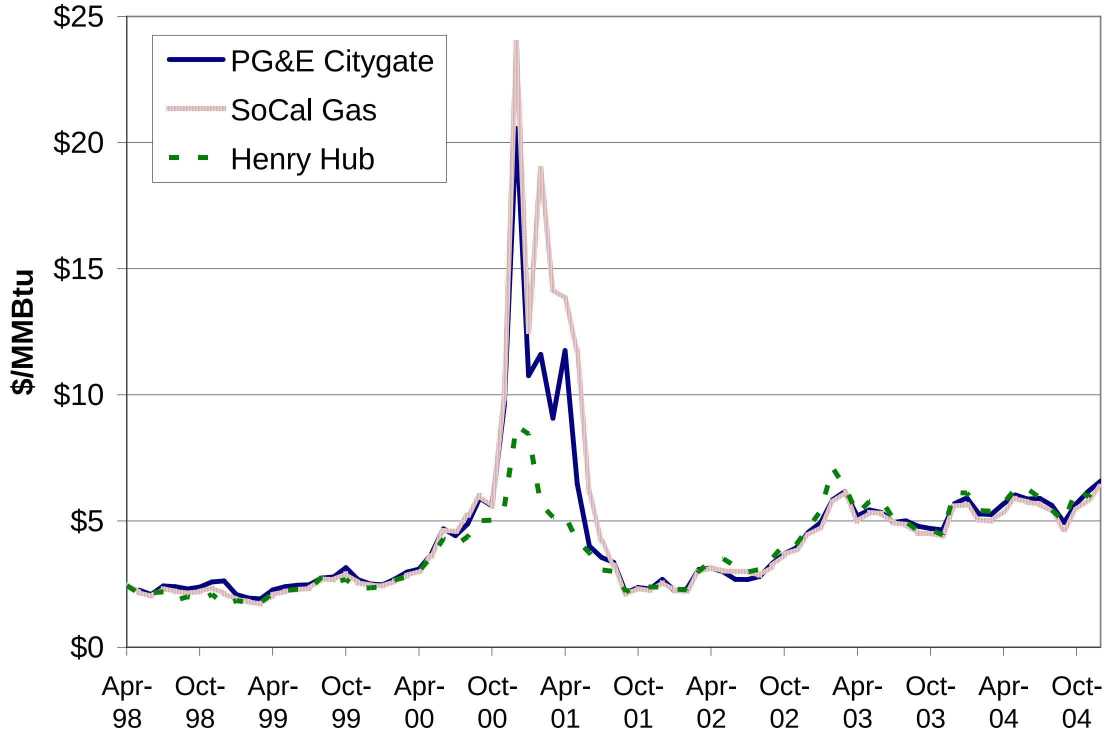

Figure 2: Monthly average spot-natural-gas prices for Henry Hub, SoCal Gas, and PG&E Citygate, April 1998 to December 2004. Source: Platts.