Influence of Natural Gas Price and Other Factors on ISO-NE Electricity Price

Final Report for Undergraduate Research Opportunities Program

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SUMMARY

This report is motivated by the need to expose driving forces behind volatile prices of electricity at the time scales of day-ahead market and shorter. The winter of 2013-2014 has revealed high sensitivity of day-ahead and real-time electricity price in ISO-NE to the availability in supply of natural gas. Although these electricity prices tend to follow the pattern of the natural gas price, their relative dependence has to be quantified as a first step in building appropriate interdependency models. In addition, the relative impact of factors other than natural gas price has to be considered. Under or over predicted renewable generation, together with erroneous load forecast and unpredicted emergency operational scenarios carry a certain level of uncertainty, and could therefore, cause a peculiar behavior of electricity prices. In this report, we quantify the interdependence between day-ahead and real-time electricity prices and various factors that affect them to some extent. Statistical approach to data analysis is used and results are presented in terms of statistical indicators. Finally, based on the obtained results a set of conclusions and recommendations is made.

Contents

Motivation

Independent System Operator – New England (ISO-NE) wholesale electricity market is organized as a combination of several markets with different purposes and timelines. Energy markets, namely day-ahead and real-time electricity markets, accommodate the trade of energy as commodity between suppliers (generation companies - GenCos) and consumers (consumer companies - ConCos). Contracts made at the day-ahead market are due for delivery the next day (thus the name day-ahead). Contracts made at the real-time market are due for delivery in the x number of hours. According to the old market rules, $x \geq 6$ hours.

Winter 2014-2015 is the first season under new rules of market operations in ISO-NE. The newly adopted changes should accommodate closer to real time decision making by different market players. This desired effect is achieved by modifying supply and demand bidding timeline. According to the new rules[1], the real-time electricity market bids are accepted until 30 minutes prior to the operating hour ($x = 0.5$ hours). The 30 minute interval between market closing time and the actual dispatch of generation and consumption is much shorter than the same interval under the old market rules.

One benefit of adopting new rules is that the natural gas-fired generators are able to submit their supply bids (cost curves) with higher certainty in the amounts of gas at their disposal. During winter season, when the supply of gas could become scarce, higher certainty in gas availability results in more accurate supply bids of natural gas-fired generators at the real-time electricity market. Presumably, higher accuracy should result in smaller price variations.

Typical variation of real-time electricity price on an ordinary winter day is shown in Figure 1.

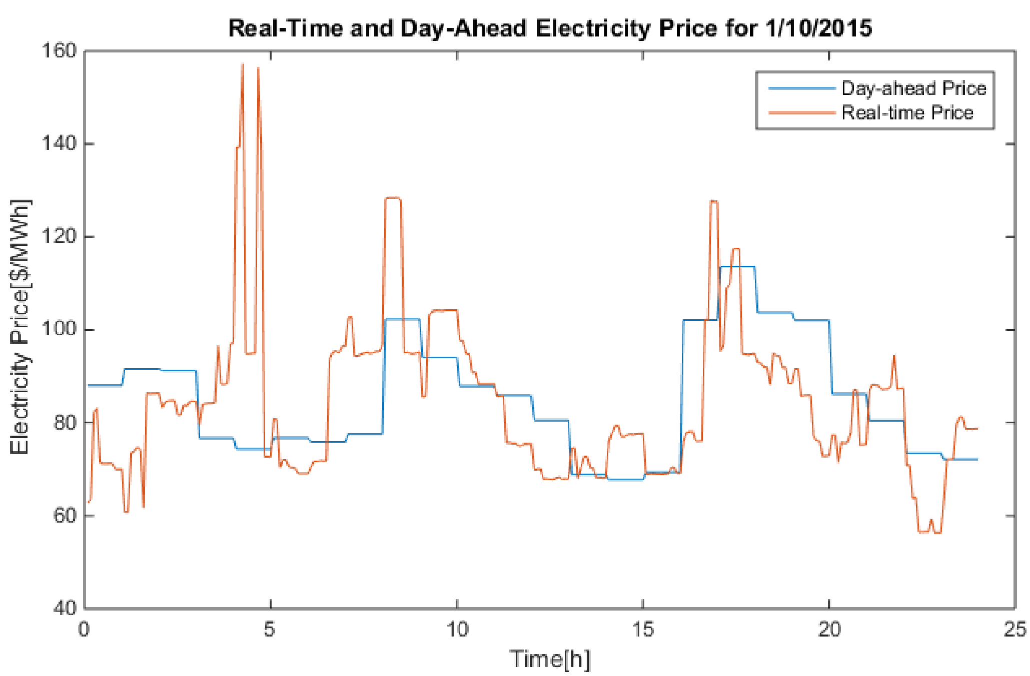


Figure 1: The electricity price for both the real-time and day-ahead markets fluctuates significantly over the course of a day.

[1] http://www.iso-ne.com/aboutiso/fin/annl_reports/2000/2014_reo.pdf

However, the real-time market electricity price depends on many other factors among which the following few are quantifiable using publically available data:

1) Natural gas prices at the natural gas spot market
2) Locational effect of gas pipeline distribution
3) Demand pattern deviations from day-ahead predictions
4) Demand response events (if any)
5) Renewable (wind) power penetration level and its prediction accuracy
6) Day-ahead electricity market prices

Each of the listed factors affects the price of electricity at the real-time market to some extent.

Project Description

The goal of the project is to understand and quantify the main drivers of volatility of day-ahead and real-time electricity price. To this end, we compute statistical correlation between the day-ahead and real-time electricity market prices and the factors listed above for the period of December 2014 - January 2015 (new market rules).

The electricity price data is obtained from the online ISO-NE data repository[2]. Day-ahead electricity price is given as locational marginal price for 24 hours at all the nodes in the grid. Real-time electricity price is given as locational marginal price for 12*24 5-minute interval points for a day at all nodes in the grid. In this initial comparison, topology of the grid is omitted from the list of factors since its effect is tractable through the congestion and loss components of the electricity price. Thus, only the electricity price at the hub location (location of ISO-NE) is considered.

One of the main factors we considered was natural gas price. Since natural gas price data for the New England region was not available to us at the time of this analysis, publically available gas price data for the Henry Hub in Alabama[3] is used to develop the necessary analysis methods and conduct an initial comparison. This market does not trade gas on weekends or holidays. The gas needed on those days is purchased on the preceding day. In the case of holidays and weekends, the electricity price is correlated with the most recent gas price, either the Friday before the weekend or the day before the holiday.

Next, we analyzed the correlation of the electricity price (day-ahead and/or real-time) and the error in load and wind forecasts. Load forecast error is the difference between the actual demand and the predicted demand for electricity in the entire New England region, as reported by ISO. The actual demand is recorded every five-minutes while the predicted demand is reported every hour. Wind forecast error is the difference between the actual amount of electricity produced from wind and the predicted amount of electricity produced in the entire New England region, as reported by ISO. The actual amount of electricity produced from wind is recorded daily while the predicted wind energy is reported every hour.

[2] http://www.iso-ne.com/isoexpress/
[3] http://www.eia.gov/dnav/ng/hist/rngwhhdd.htm

Due to the length of the UROP project, data starting December 5th 2014 to January 18th 2015 is used for comparison. Since interdependency between prices can vary throughout the day, comparison has been done on different time intervals. The morning hours between 6 and 9 AM represent a time interval at which the morning demand for electricity rises steeply. This period could potentially introduce difficulties in operations due to misalignments in predicted and realized values of demand and renewable power resulting in a higher volume of trade at the real-time electricity market. The higher quantity of electricity traded in the real-time market could potentially impact the volatility in the price. The evening hours between 3 and 9 PM see a steep increase in the electricity demand up to the daily peak values and rapid decrease towards base load. As with the morning hours, steep change in demand in evening hours could potentially cause higher volatility of prices. We compared these time periods to determine whether correlation is significantly different during different times of the day.

Besides looking at different periods throughout the day, we made distinction when analyzing data during contingency events and during normal operation. Contingency (or constraint) events are time periods for which the ISO has issued a warning flag due to unanticipated operating conditions. Some of these codes results in activation of generation reserves. Each hour the ISO reports whether, yes, there was a constraint event, or, no, there was no constraint event. The ISO also reports a code identifying the type of constraint event. In this initial investigation we did not make distinction between different types of constraint events.

Finally, to determine how various factors impact day-ahead and real-time electricity price during the time periods mentioned, the correlation coefficient relating electricity prices and different factors is computed. To identify when the system is most stressed, the variance of real-time electricity price during constraint events and normal operation is compared. Also, compared are the variances during the entire day, during morning hours, and during evening hours.

Specifically, the following comparisons are made:

A. Correlation between day-ahead electricity price and:
   1. Natural gas price
   2. Natural gas price using the extended dates of October 1st to January 18th
   3. Natural gas price using the extended dates of October 1st to January 18th but not including values for weekends or holidays when no data was recorded

B. Correlation between real-time electricity price and:
   4. Day-ahead electricity price
   5. Day-ahead electricity price during constraint event and non-constraint event time periods
   6. Day-ahead electricity price for morning hours
   7. Day-ahead electricity price during constraint event and non-constraint event time periods for morning hours
   8. Day-ahead electricity price for evening hours
   9. Day-ahead electricity price during constraint event and non-constraint event time periods for evening hours
   10. Demand forecast error
   11. Demand forecast error during constraint event and non-constraint event time periods
   12. Demand forecast error for morning hours

13. Demand forecast error during constraint event and non-constraint event time periods for morning hours
14. Demand forecast error for evening hours
15. Demand forecast error during constraint event and non-constraint event time periods for evening hours
16. Wind forecast error
17. Wind forecast error during constraint event and non-constraint event time periods
18. Natural gas price
19. Natural gas price for morning hours
20. Natural gas price for evening hours
21. Variance of real-time electricity price during constraint event and non-constraint event time periods
22. Variance of real-time electricity price during constraint event and non-constraint event time periods for morning hours
23. Variance of real-time electricity price during constraint event and non-constraint event time periods for evening hours

In the next section, methods for calculating the above-mentioned correlation coefficients and variance are described. The following two sections present the results of these comparisons and discuss their significance.

Methods

MATLAB functions and scripts are developed to: (i) calculate the correlation coefficient relating day-ahead and real-time electricity price to natural gas price, wind production forecast error, demand forecast error, and each other; and (ii) calculate the variance of real-time electricity price during constraint events and non-constraint-event time periods. These scripts considered data recorded during the entire day, morning hours, evening hours, constraint events, non-constraint-event time periods, constraint events for just morning or evening hours, and non-constraint-event time periods for just morning or evening hours.

In what follows, depending on the context we denote a vector of points for day-ahead and/or real-time electricity price by y. We use x to denote vector of points for load forecast error, wind prediction error, natural gas price, and/or day-ahead electricity price depending on the particular case study. Scalar n denotes the size of the data vectors and varies from one case to another. Coefficients β_1 and β_2 represent first and second coefficient of the best fit line. Correlation coefficient is denoted by r, while σ_x^2 and σ_y^2 denote the variance of data vectors x and y.

Best fit line

Coefficients of the least squares best fit line $y = \beta_1 x + \beta_2$ relating electricity price and various factors are computed by simultaneously solving

$$\sum_{i=1}^{n} y_i = n\beta_1 + \beta_2 \sum_{i=1}^{n} x_i$$

$$\sum_{i=1}^{n} x_i y_i = \beta_1 \sum_{i=1}^{n} x_i + \beta_2 \sum_{i=1}^{n} x_i^2$$

Resulting coefficients in each of the cases 1-20 are given in the next section.

Variance

Variance of the real-time electricity price is computed as

$$\sigma_x^2 = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2$$

$$\sigma_y^2 = \frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y})^2$$

where $\sigma_x^2 \geq 0$ and $\sigma_y^2 \geq 0$. The value of variance equal to zero indicates that all the values within the data set x are identical. A small variance indicates that the data is close to the mean value. A large variance indicates higher separation of data points from the mean value. Resulting variances for cases 21-23 and presented in the following section.

Correlation coefficients

Correlation coefficients revealing interdependence between electricity price and various factors are calculated using following equations

$$S_{xy} = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})$$

$$r = \beta_2 \sqrt{\frac{\sigma_x^2}{\sigma_y^2}} = \frac{S_{xy}}{\sqrt{\sigma_x^2 \sigma_y^2}}$$

where correlation coefficient takes values in the range $-1 \leq r \leq 1$. The value of correlation coefficient $r = 1$ indicates maximum positive correlation between two datasets, and thus, the two datasets are considered strongly interdependent. The value of correlation coefficient $r = -1$ indicates maximum negative correlation between two datasets. Finally, the value of correlation coefficient $r = 0$ indicates no correlation between two datasets.

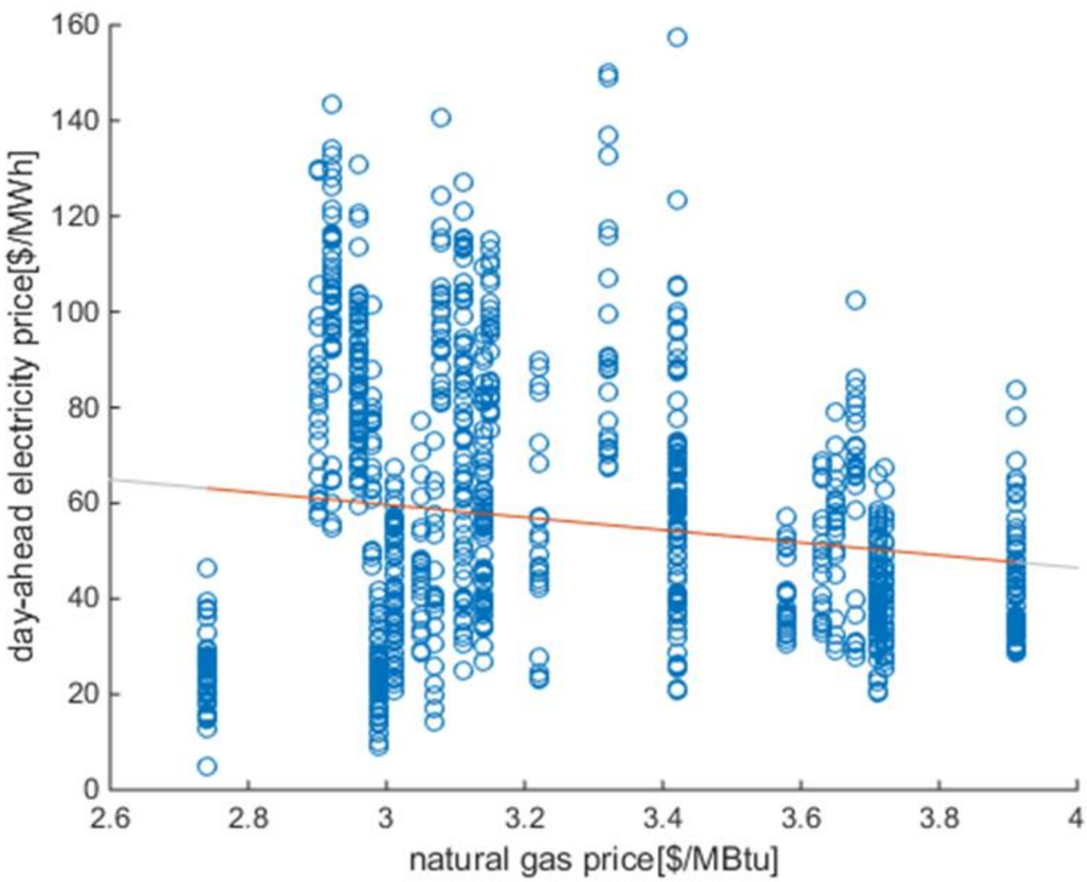
Results

In this section, we present the results for previously described cases 1-23.

1. Correlation between day-ahead electricity price and natural gas price

We start by looking at the correlation between day-ahead electricity price and natural gas spot price.

Results:
β_1 =-13.1992
β_2 = 99.2545
r = -0.1602
n = 1080



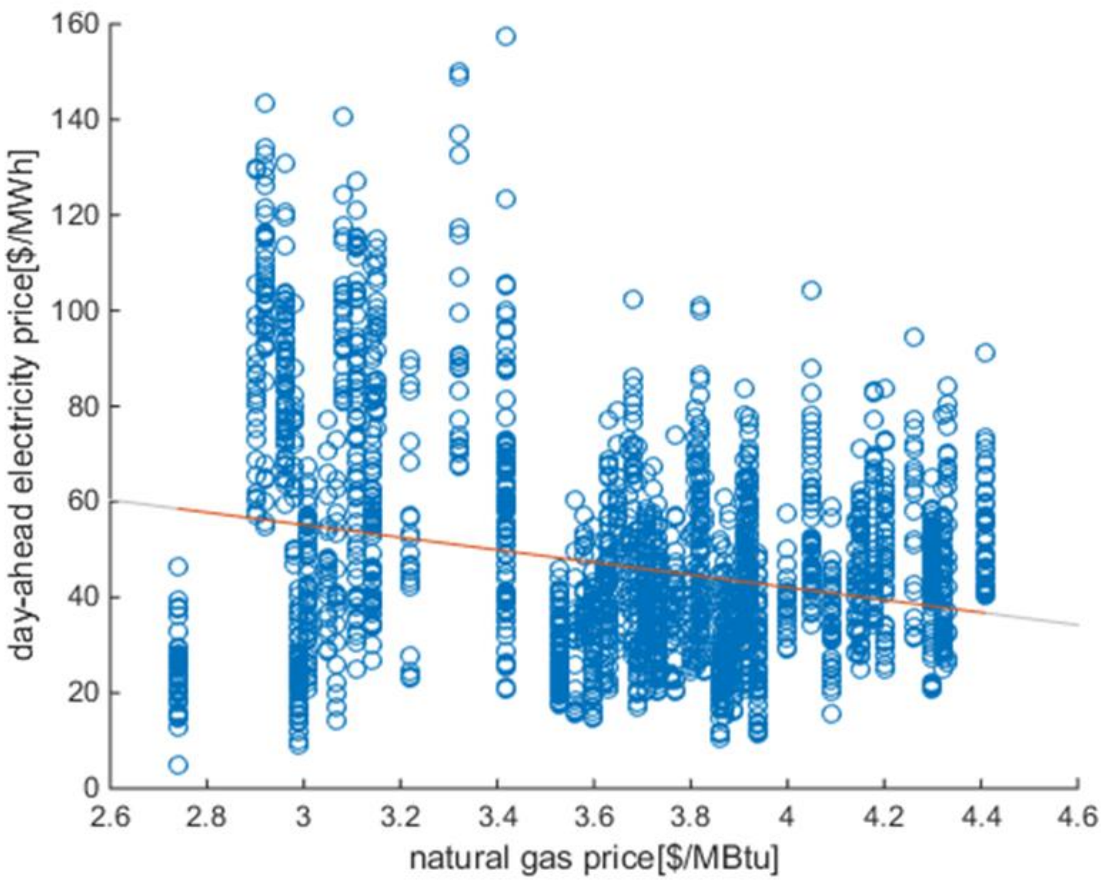
Plot 1. Dependence between day-ahead electricity price and natural gas price

The small magnitude of the correlation coefficient indicates there is little correlation between the electricity price and natural gas price. Its negative value indicates that an increase in gas price will be accompanied by a decrease in electricity price.

2. Correlation between day-ahead electricity price and natural gas price using the extended set of data for dates of October 1st to January 18th

To make sure our data set was large enough to give statistically meaningful results, the dataset is increased to include dates of October 1st to January 18th. The change in market operations that ISO-NE made in December 2014 applies only to the real-time electricity market and thus should not affect the results for day-ahead electricity price. Using the extended dataset the number of data points increased from 1080 to 2640 points. The correlation coefficient became more negative.

Results:
β_1 = -13.0905
β_2 = 94.4384
r = -0.2543
n = 2640



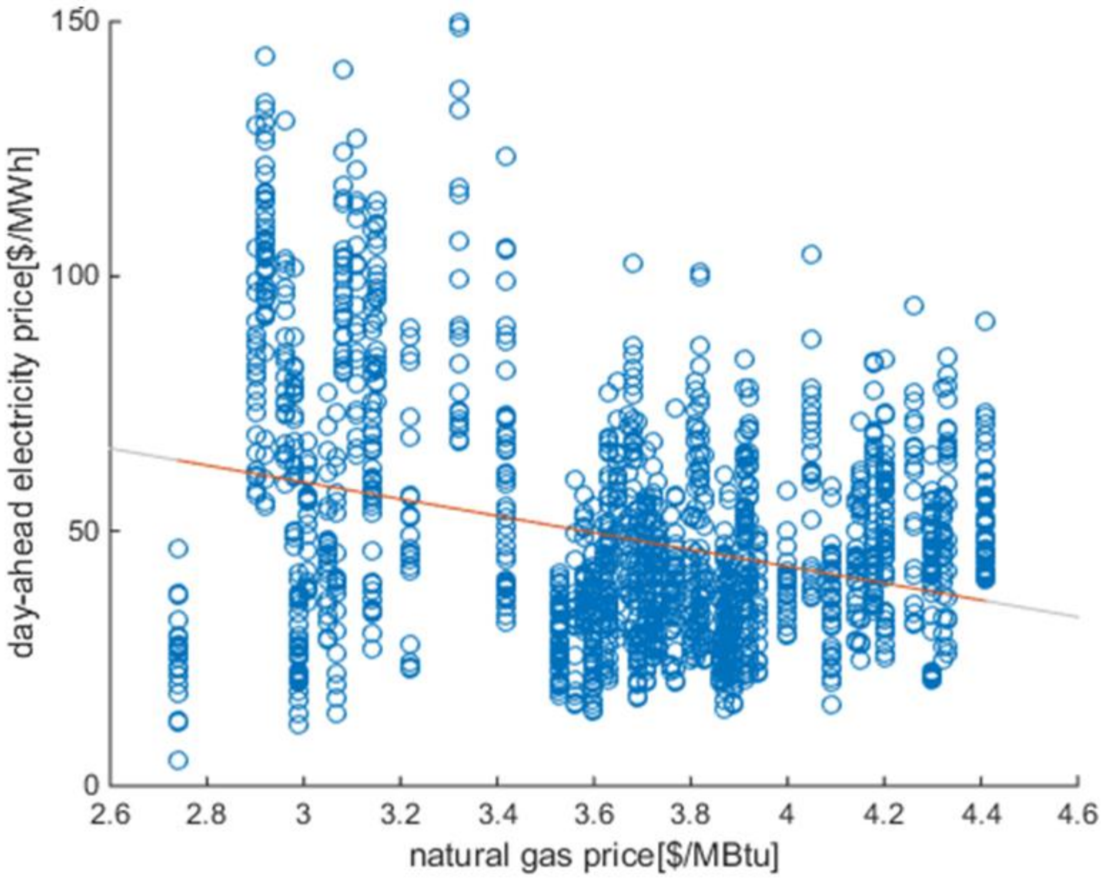
Plot 2. Dependence between day-ahead electricity price and natural gas price for the extended dataset

3. Correlation between day-ahead electricity price and natural gas price using the extended dataset of dates from October 1st to January 18th but excluding values for weekends or holidays when no data was recorded

The extended date range provided enough data points to consider the data without including weekends and holidays when natural gas was not actually traded.

Results:
β_1 = -16.5308
β_2 = 109.2018
r = -0.3029
n = 1800

Not including values for weekends or holidays the number of data points decreased from 2640 to 1800 points. The correlation coefficient became more negative.



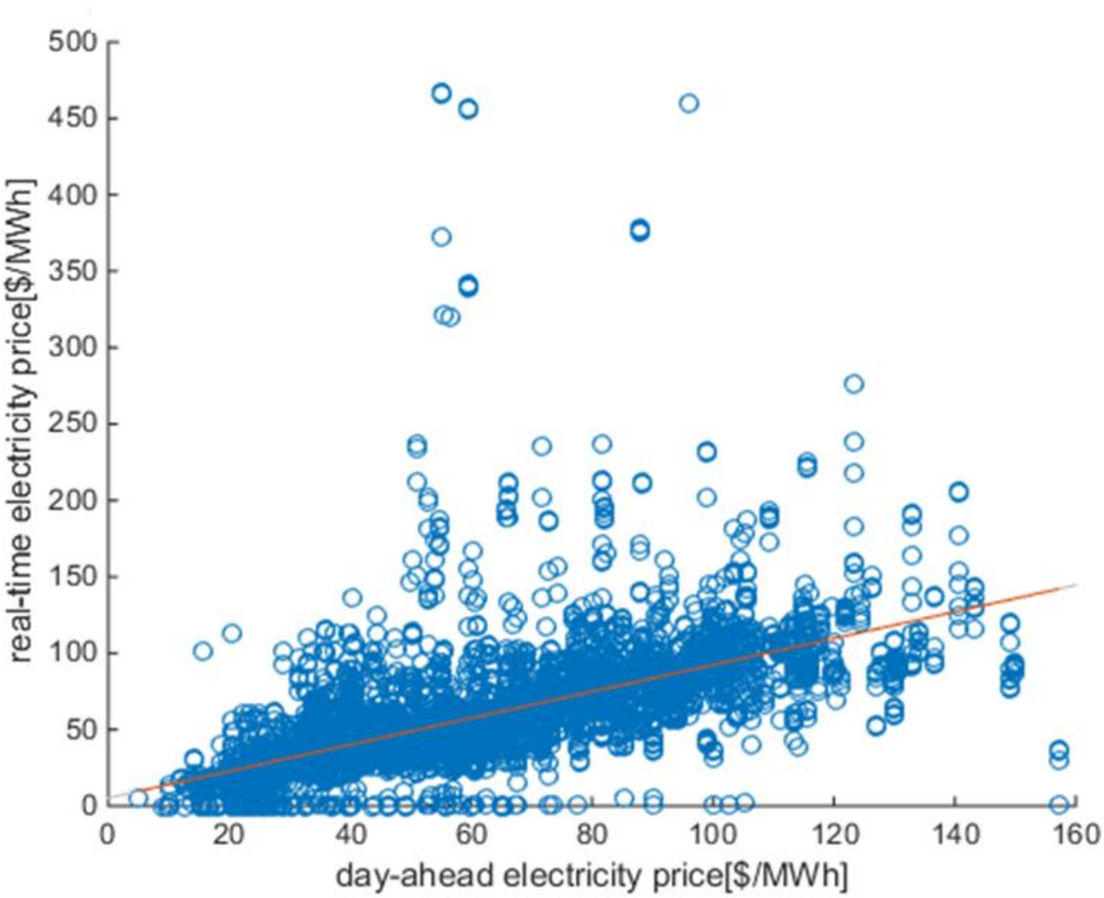
Plot 3. Dependence between day-ahead electricity price and natural gas price for the extended dataset excluding holidays and weekends

4. Correlation between real-time electricity price and day-ahead electricity price

The dependency of real-time electricity price is analyzed next.

Results:
$\beta_1 = 0.8704$
$\beta_2 = 5.2662$
$r = 0.6598$
$n = 12{,}718$

The large positive correlation coefficient indicates that an increase in day-ahead electricity price will be accompanied by an increase in real-time electricity price.



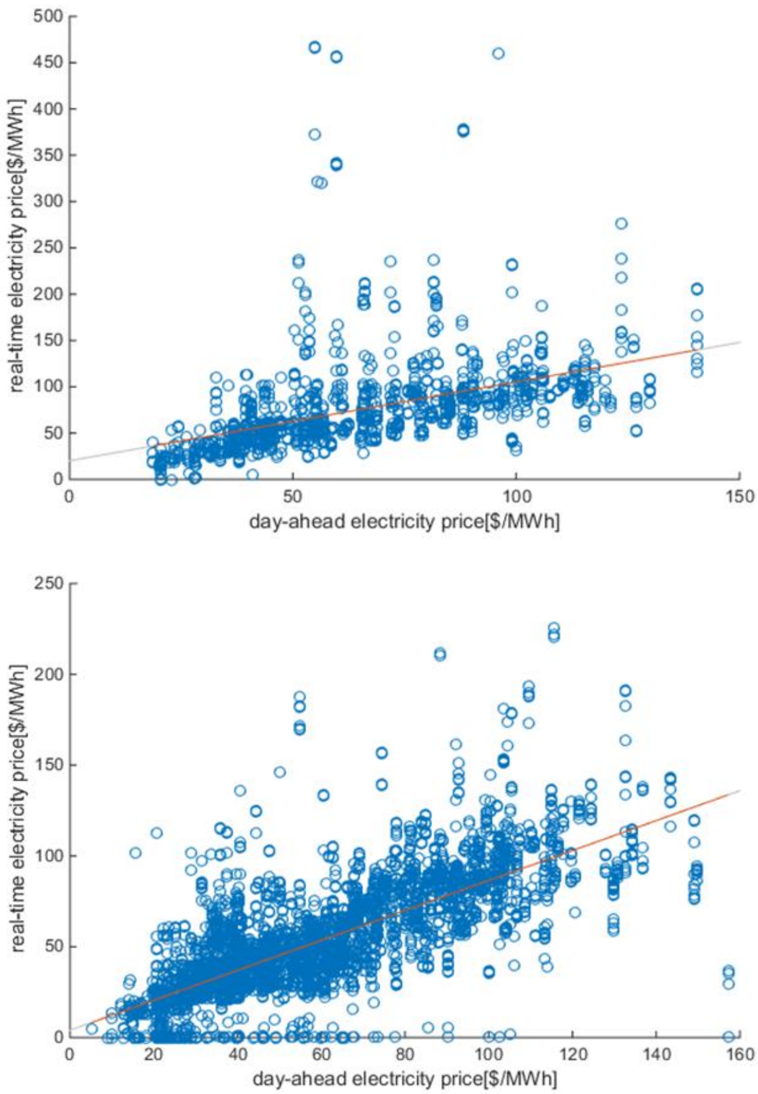
Plot 4. Dependence between real-time electricity price and day-ahead electricity price

5. Correlation between real-time electricity price and day-ahead electricity price during constraint event and non-constraint event time periods

Results during constraint event periods:
$\beta_1 = 0.8517$
$\beta_2 = 20.1141$
$r = 0.4769$
$n = 2729$

Results during non-constraint event periods:
$\beta_1 = 0.8245$
$\beta_2 = 4.0486$
$r = 0.7581$
$n = 9989$

During constraint events the correlation coefficient is lower. This indicates that during constraint events the real-time electricity price depends less on day-ahead electricity price and more on other factors.

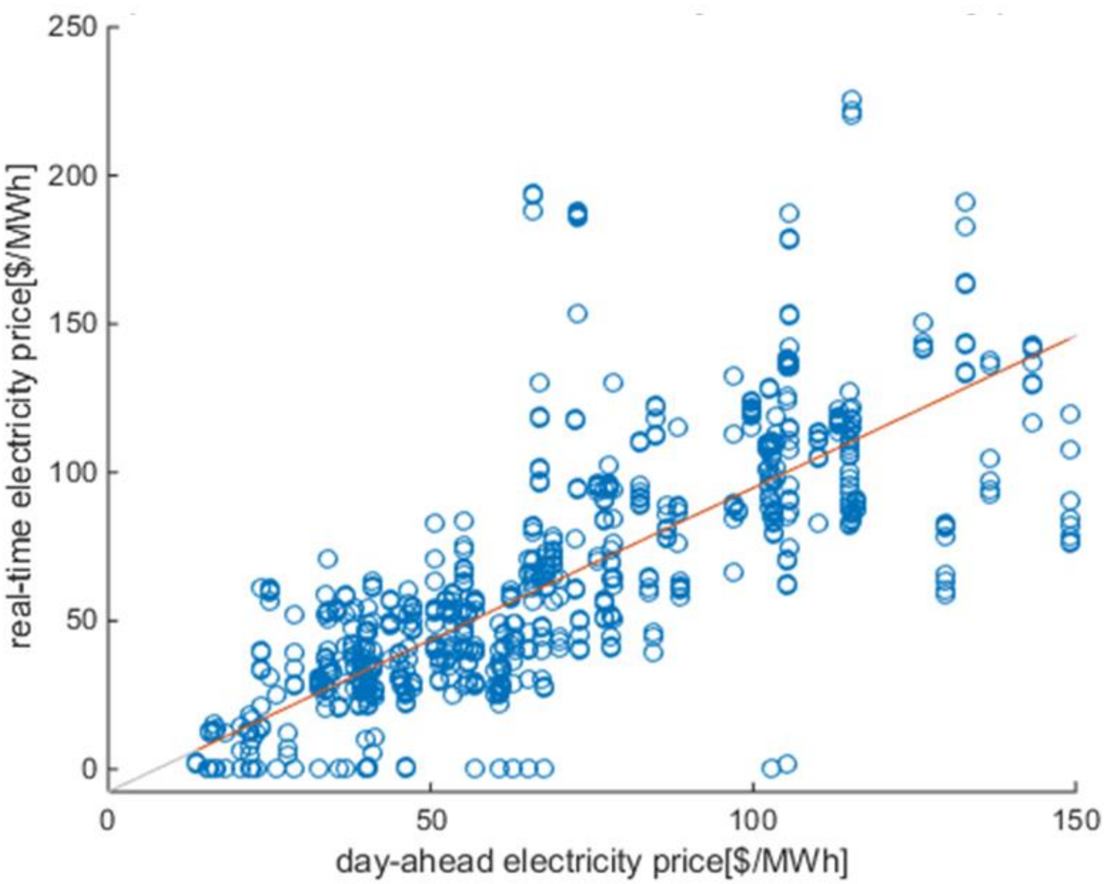


Plot 5. Dependence between real-time electricity price and day-ahead electricity price a) during constraint event periods b) during non-constraint event periods

6. Correlation between real-time electricity price and day-ahead electricity price for morning hours

Results:
$\beta_1 = 1.0240$
$\beta_2 = -7.5821$
$r = 0.8110$
$n = 1550$

The correlation coefficient increased from .6598 to .8110 when considering the entire day versus the morning hours. This indicates that during morning hours the real-time electricity price correlates more closely with day-ahead electricity price.



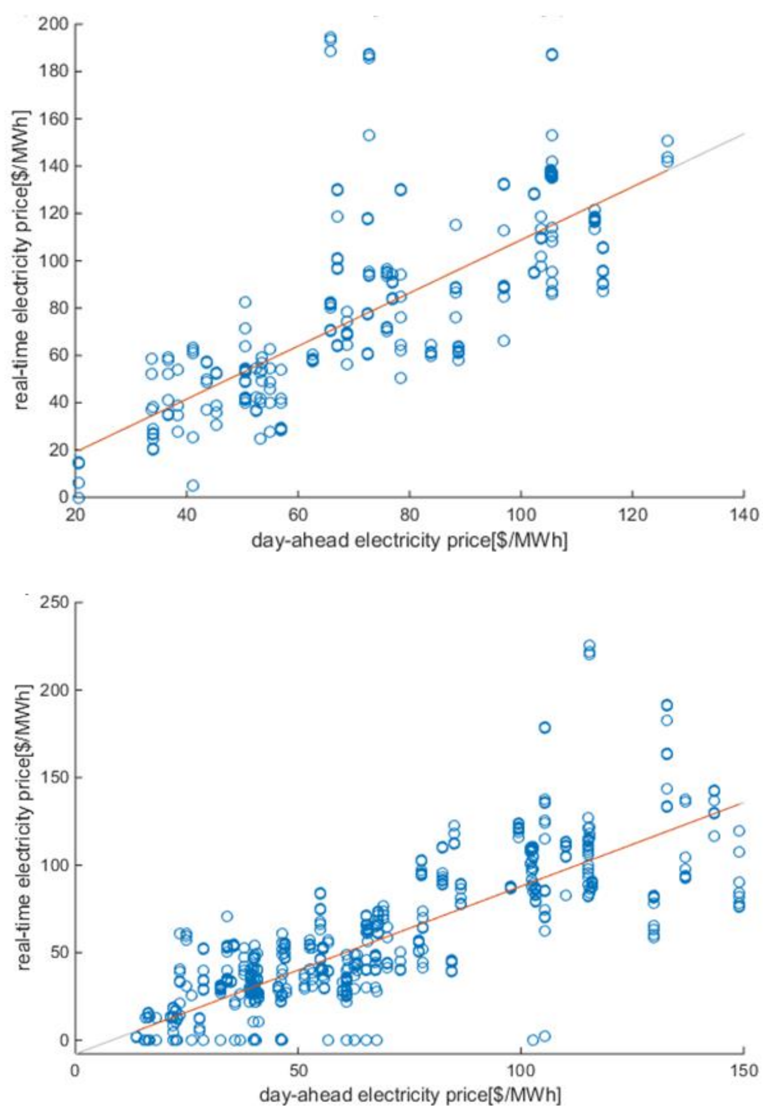
Plot 6. Dependence between real-time electricity price and day-ahead electricity price for morning hours

7. Correlation between real-time electricity price and day-ahead electricity price during constraint event and non-constraint event time periods for morning hours

Results during constraint event periods:
$\beta_1 = 1.1216$
$\beta_2 = -3.3610$
$r = 0.7700$
$n = 432$

Results during non-constraint event periods:
$\beta_1 = .9573$
$\beta_2 = -7.8247$
$r = 0.8331$
$n = 1118$

During constraint events the correlation coefficient is lower. This indicates that during constraint events the real-time electricity price depends less on day-ahead electricity price and more on other factors. However, there are only 432 data points for constraint event time periods during morning hours so results for this comparison are more doubtful.

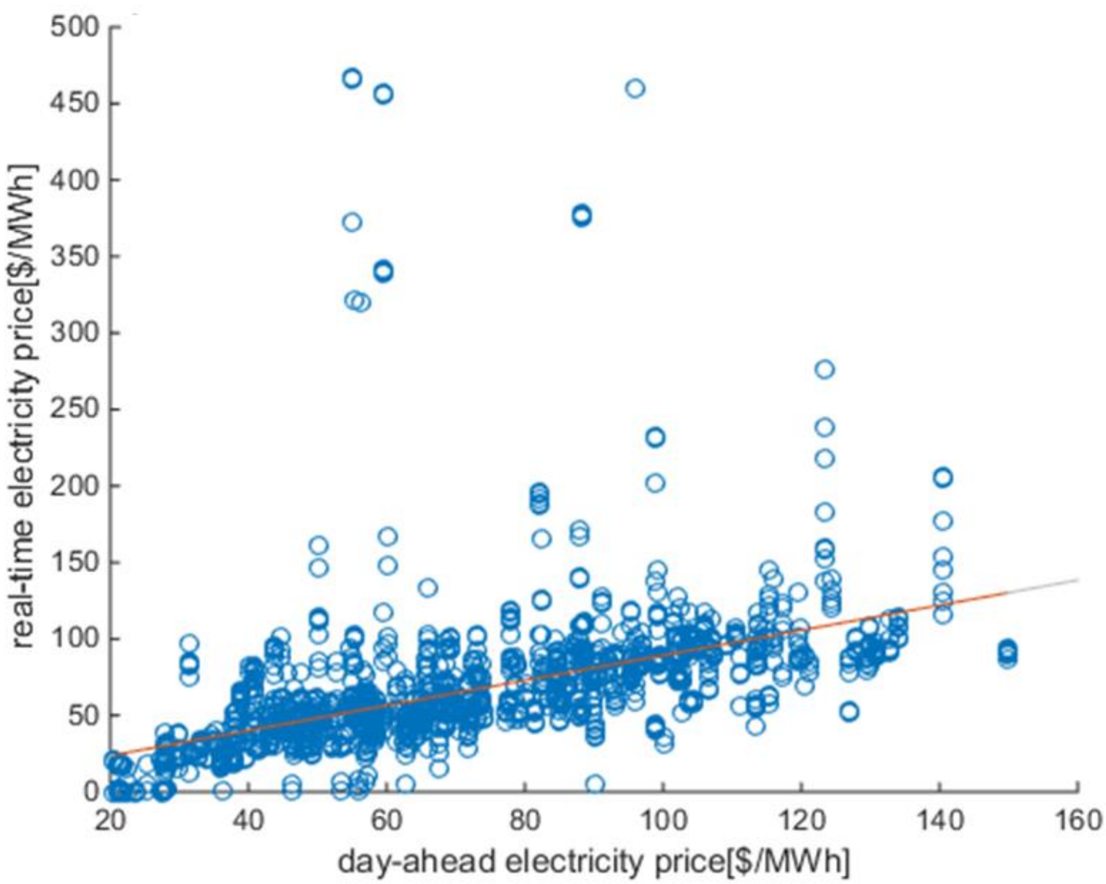


Plot 7. Dependence between real-time electricity price and day-ahead electricity price for morning hours a) during constraint event periods b) duing non-constraint event periods

8. Correlation between real-time electricity price and day-ahead electricity price for evening hours

Results:
$\beta_1 = 0.8195$
$\beta_2 = 7.3317$
$r = 0.5229$
$n = 3201$

The correlation coefficient decreased from .6598 to .5229 when considering the entire day versus the evening hours. This indicates that during evening hours the real-time electricity price correlates less closely with day-ahead electricity price.



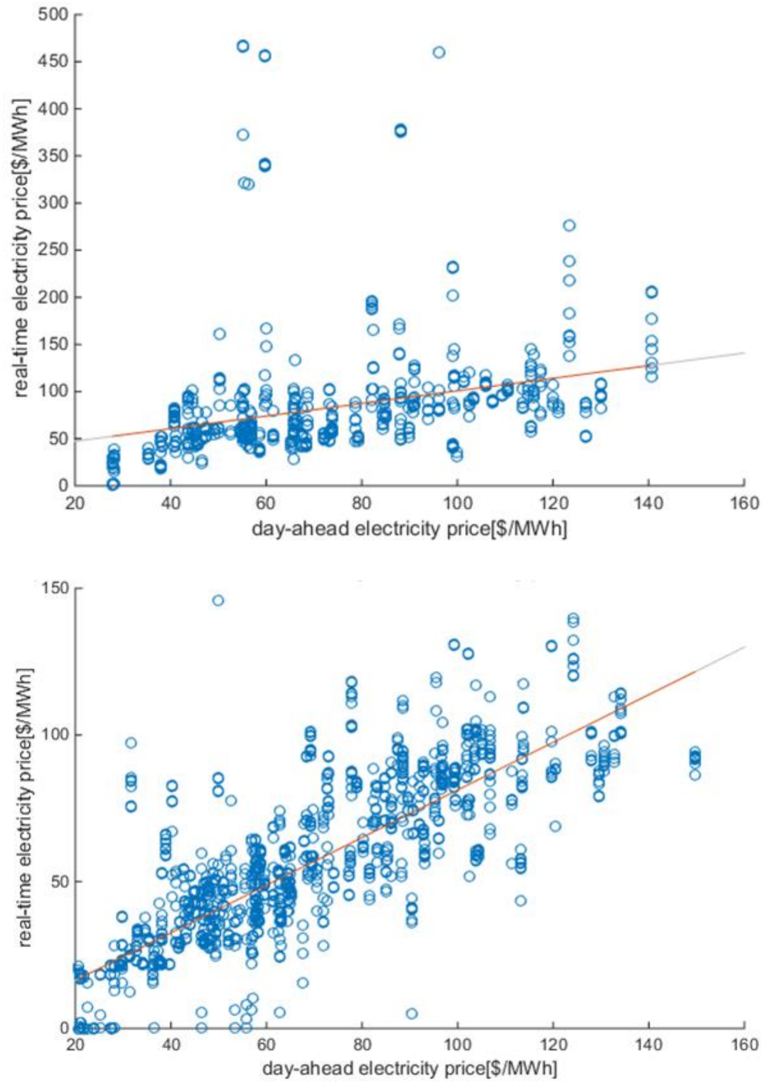
Plot 8. Dependence between real-time electricity price and day-ahead electricity price for evening hours

9. Correlation between real-time electricity price and day-ahead electricity price during constraint event and non-constraint event time periods for evening hours

Results during constraint event periods:
$\beta_1 = 0.6686$
$\beta_2 = 33.8693$
$r = 0.3009$
$n = 1073$

Results during non-constraint event periods:
$\beta_1 = 0.8115$
$\beta_2 = .1210$
$r = 0.8221$
$n = 2128$

During constraint events the correlation coefficient is lower. This indicates that during constraint events the real-time electricity price depends less on day-ahead electricity price and more on other factors.

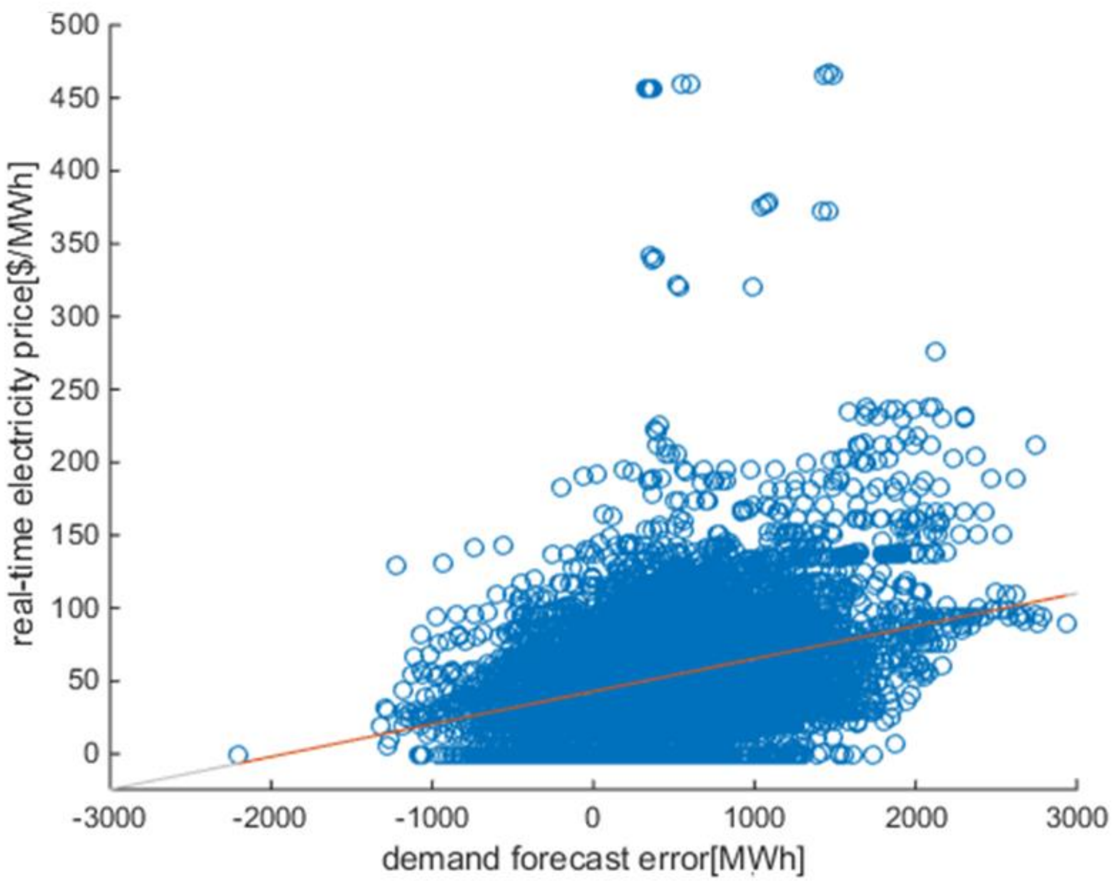


Plot 9. Dependence between real-time electricity price and day-ahead electricity price for evening hours a) during constraint event periods b) during non-constraint event periods

10. Correlation between real-time electricity price and demand forecast error

Results:
$\beta_1 = 0.0224$
$\beta_2 = 42.8772$
$r = 0.3287$
$n = 12{,}718$

The large positive correlation coefficient indicates that an increase in demand forecast error will be accompanied by an increase in real-time electricity price.



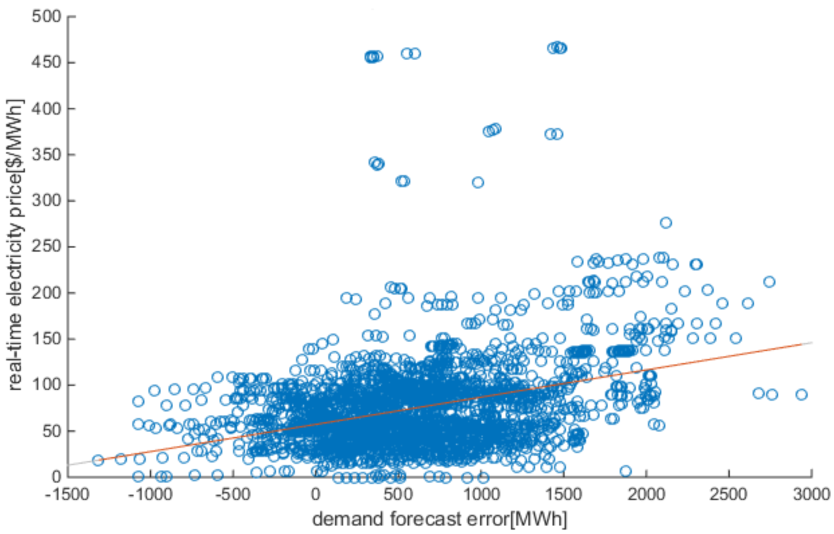
Plot 10. Dependence between real-time electricity price and demand forecast error

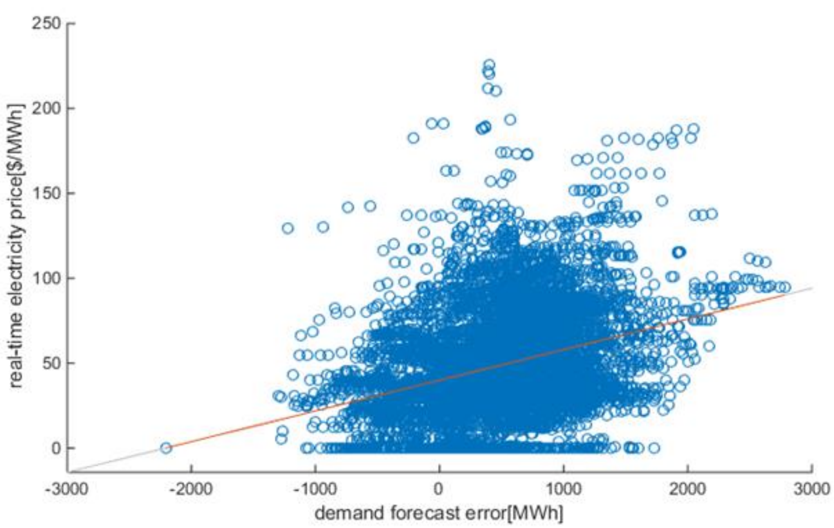
11. Correlation between real-time electricity price and demand forecast error during constraint event and non-constraint event time periods

Results during constraint event periods:
$\beta_1 = 0.0296$
$\beta_2 = 57.3459$
$r = 0.3419$
$n = 2729$

Results during non-constraint event periods:
$\beta_1 = 0.0181$
$\beta_2 = 39.9316$
$r = 0.3183$
$n = 9989$

The correlation coefficient is very similar during constraint event and non-constraint event time periods.



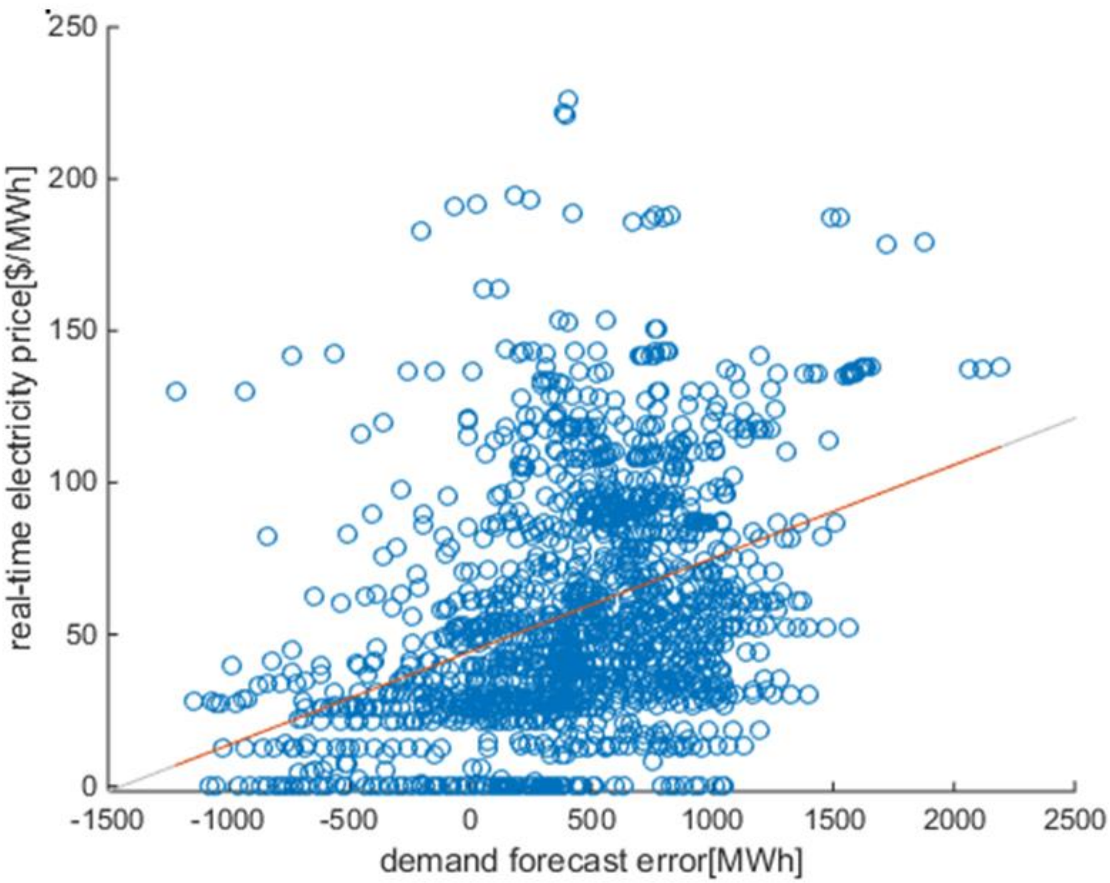


Plot 11. Dependence between real-time electricity price and demand forecast error a) during constraint event periods b) during non-constraint event periods

12. Correlation between real-time electricity price and demand forecast error for morning hours

Results:
$\beta_1 = 0.0307$
$\beta_2 = 44.3825$
$r = 0.3834$
$n = 1550$

The correlation coefficient changes very little, increasing from .3287 to .3834, between the full day and morning hours.



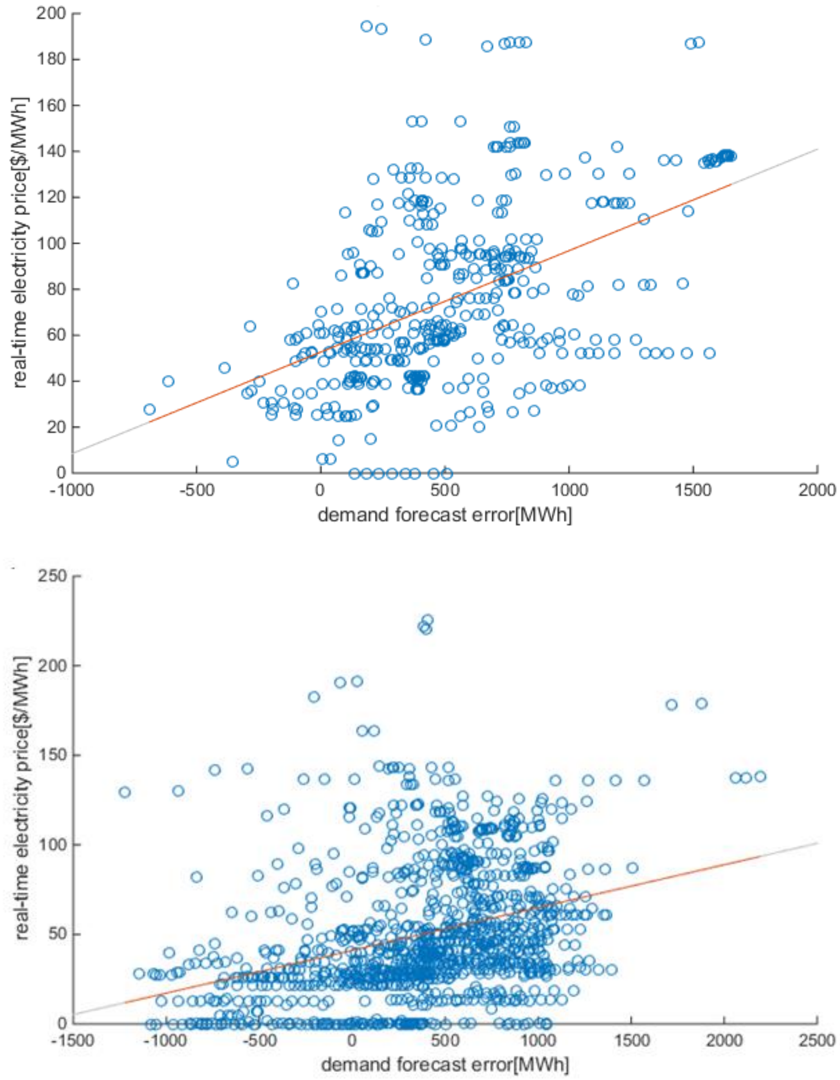
Plot 12. Dependence between real-time electricity price and demand forecast error for morning hours

13. Correlation between real-time electricity price and demand forecast error during constraint event and non-constraint event time periods for morning hours

Results during constraint event periods:
$\beta_1 = .0441$
$\beta_2 = 52.6901$
$r = 0.4823$
$n = 432$

Results during non-constraint event periods:
$\beta_1 = .0239$
$\beta_2 = 41.0914$
$r = 0.3277$
$n = 1118$

The correlation coefficient is very similar during constraint event and non-constraint event time periods for morning hours.

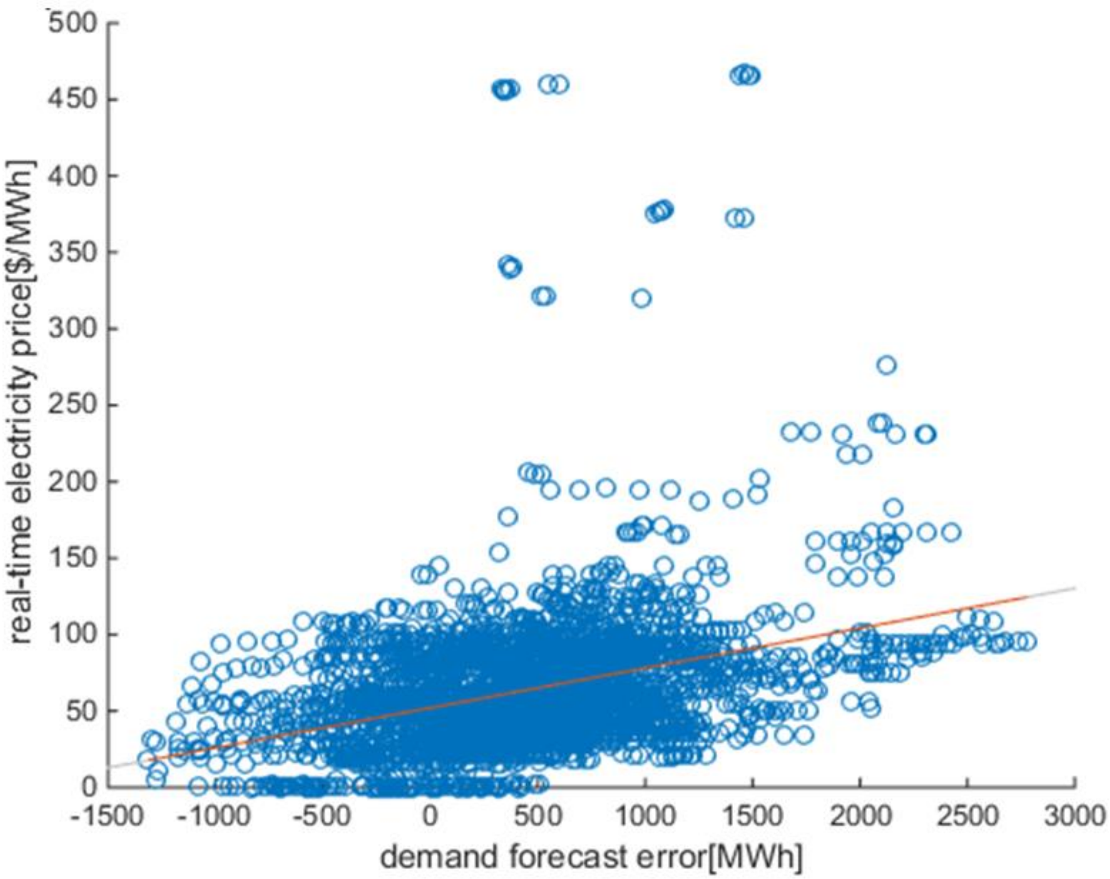


Plot 13. Dependence between real-time electricity price and demand forecast error for morning hours a) during constraint event periods b) during non-constraint event periods

14. Correlation between real-time electricity price and demand forecast error for evening hours

Results:
$\beta_1 = 0.0261$
$\beta_2 = 52.0202$
$r = 0.3477$
$n = 3201$

The correlation coefficient changes very little, increasing from .3287 to .3477, between the full day and evening hours.



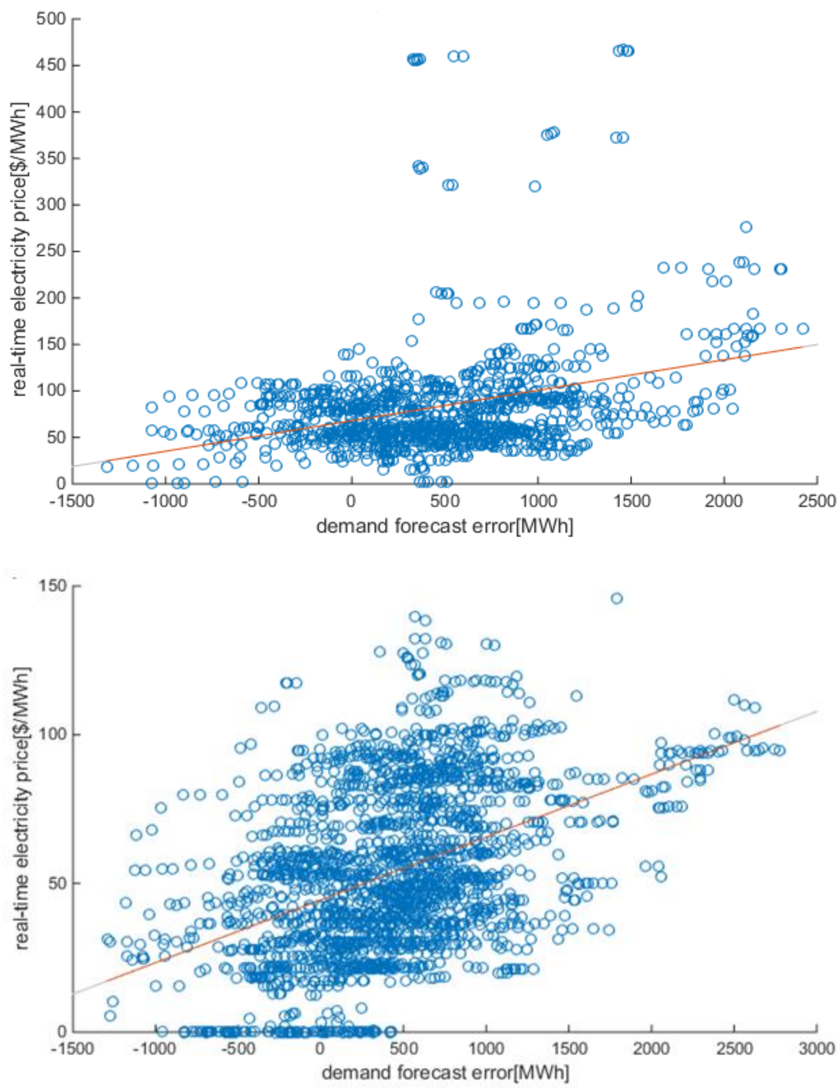
Plot 14. Dependence between real-time electricity price and demand forecast error for evening hours

15. Correlation between real-time electricity price and demand forecast error during constraint event and non-constraint event time periods for evening hours

Results during constraint event periods:
$\beta_1 = 0.0328$
$\beta_2 = 67.9086$
$r = 0.3217$
$n = 1073$

Results during non-constraint event periods:
$\beta_1 = 0.0211$
$\beta_2 = 44.5012$
$r = 0.4435$
$n = 2128$

The correlation coefficient is very similar during constraint event and non-constraint event time periods for evening hours.

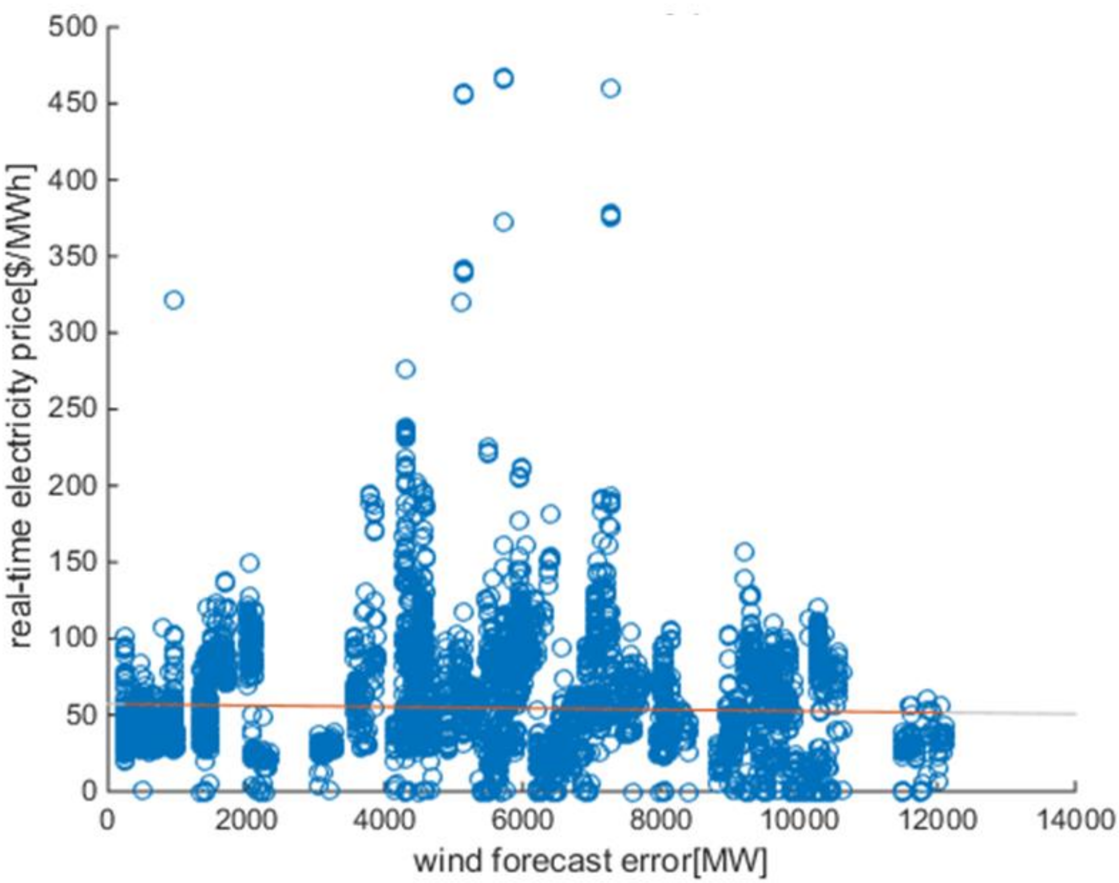


Plot 15. Dependence between real-time electricity price and demand forecast error for evening hours a) during constraint event periods b) during non-constraint event periods

16. Correlation between real-time electricity price and wind forecast error

Results:
β_1 = -4.6302e-04
β_2 = 57.1906
r = -0.0403
n = 12,718

The correlation coefficient relating real-time electricity price to wind forecast error is very close to zero. This suggests there is little correlation between electricity price and wind forecast error.



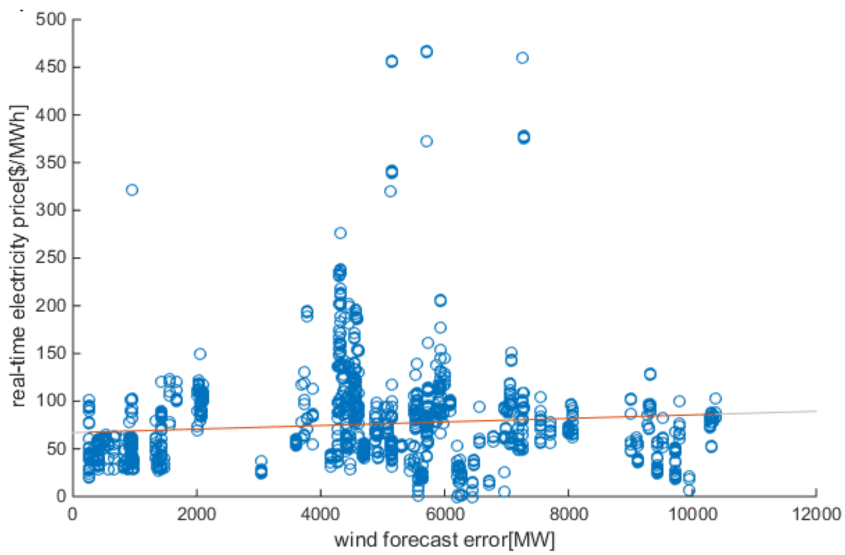
Plot 16. Dependence between real-time electricity price and wind forecast error

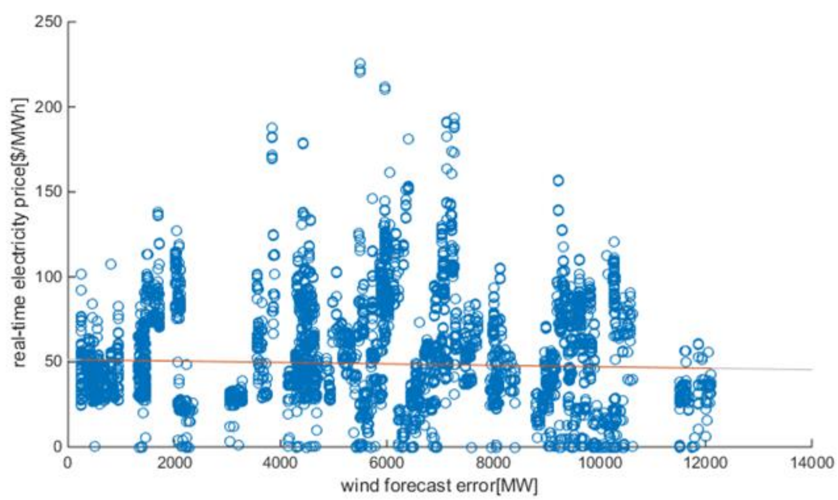
17. Correlation between real-time electricity price and wind forecast error during constraint event and non-constraint event time periods

Results during constraint event periods:
β_1 = 0.0019
β_2 = 66.9547
r = 0.1049
n = 2729

Results during non-constraint event periods:
β_1 = -4.2376e-04
β_2 = 51.4042
r = -0.0465
n = 9989

The correlation coefficient is greater during constraint events than non-constraint event time periods. This suggests that during constraint events an increase in wind forecast error would be accompanied by an increase in electricity price.



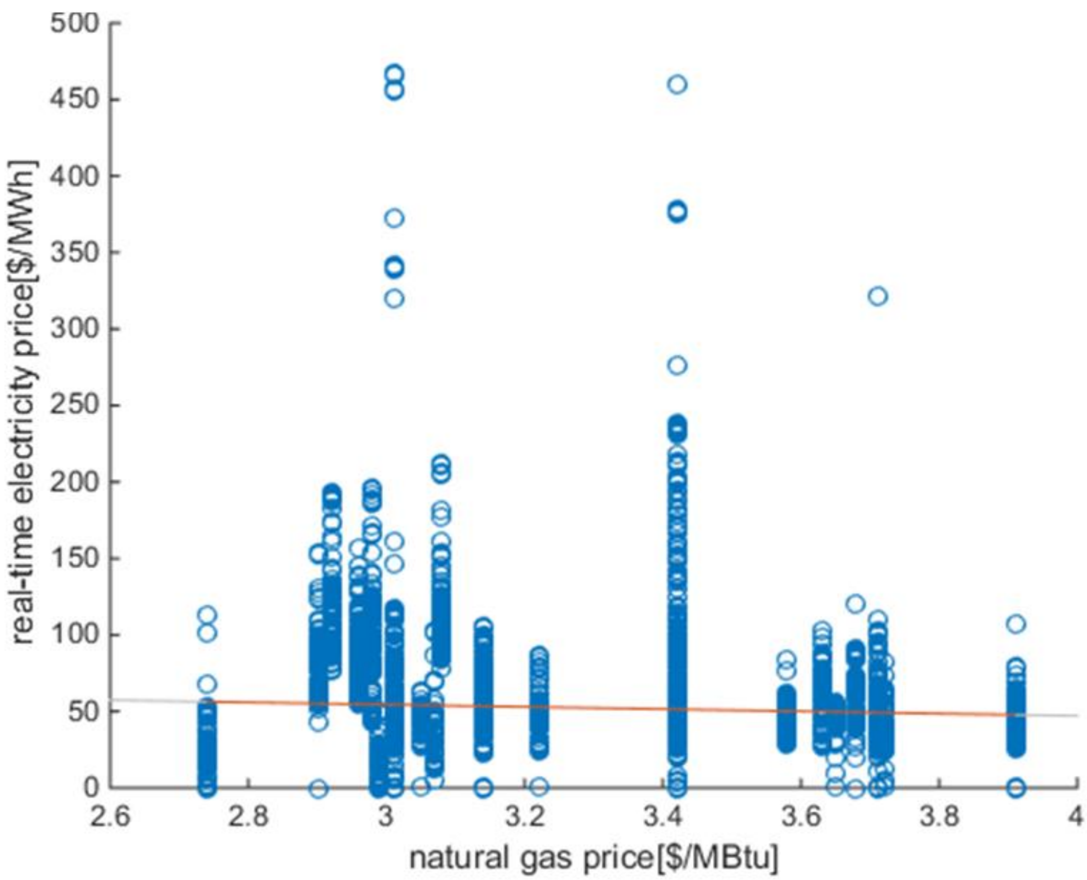


Plot 17. Dependence between real-time electricity price and wind forecast error a) during constraint event periods b) during non-constraint event periods

18. Correlation between real-time electricity price and natural gas price

Results:
β_1 = -7.3191
β_2 = 76.3982
r = -.0705
n = 10,994

The small, negative correlation coefficient indicates that an increase in natural gas price will be accompanied by a decrease in electricity price.

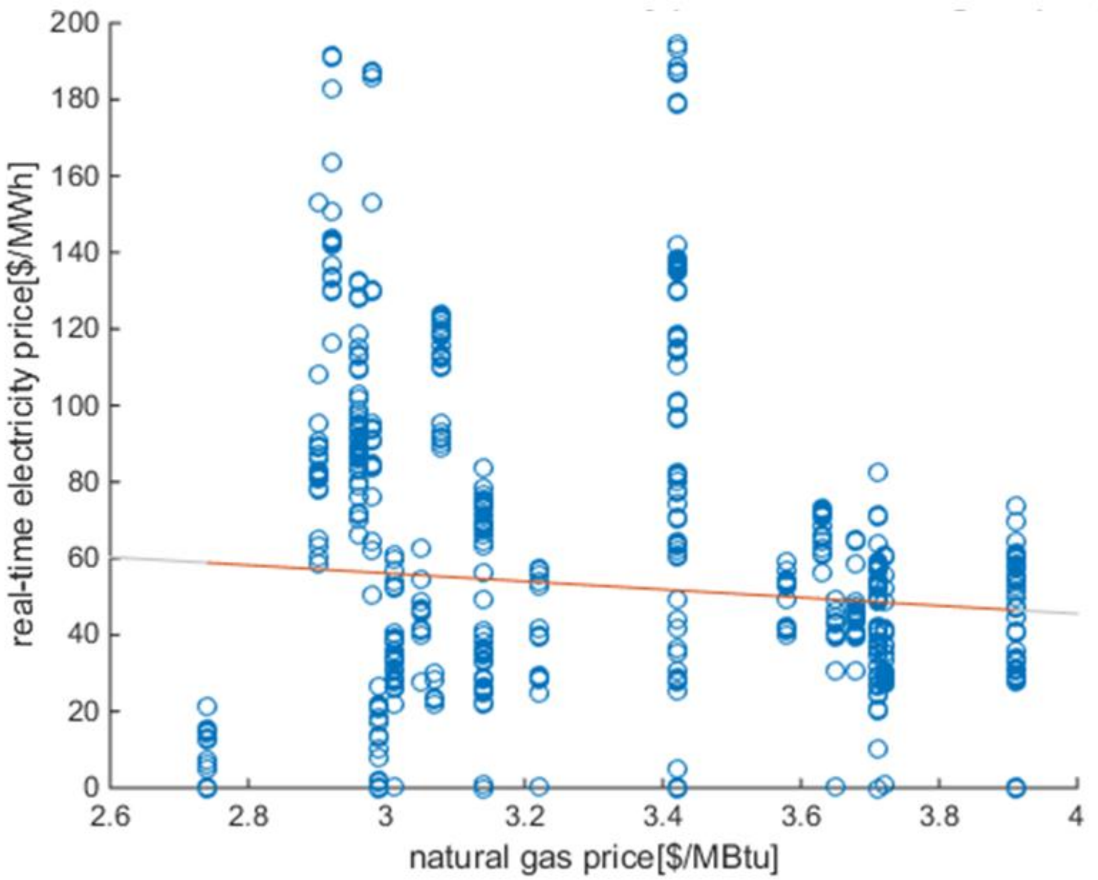


Plot 18. Dependence between real-time electricity price and natural gas spot price

19. Correlation between real-time electricity price and natural gas price for morning hours

Results:
β_1 = -10.5929
β_2 = 87.9095
r = -.0995
n = 1334

The correlation coefficient does not differ significantly, decreasing in value from -.0705 to -.0995, when considering the entire day versus the morning hours.

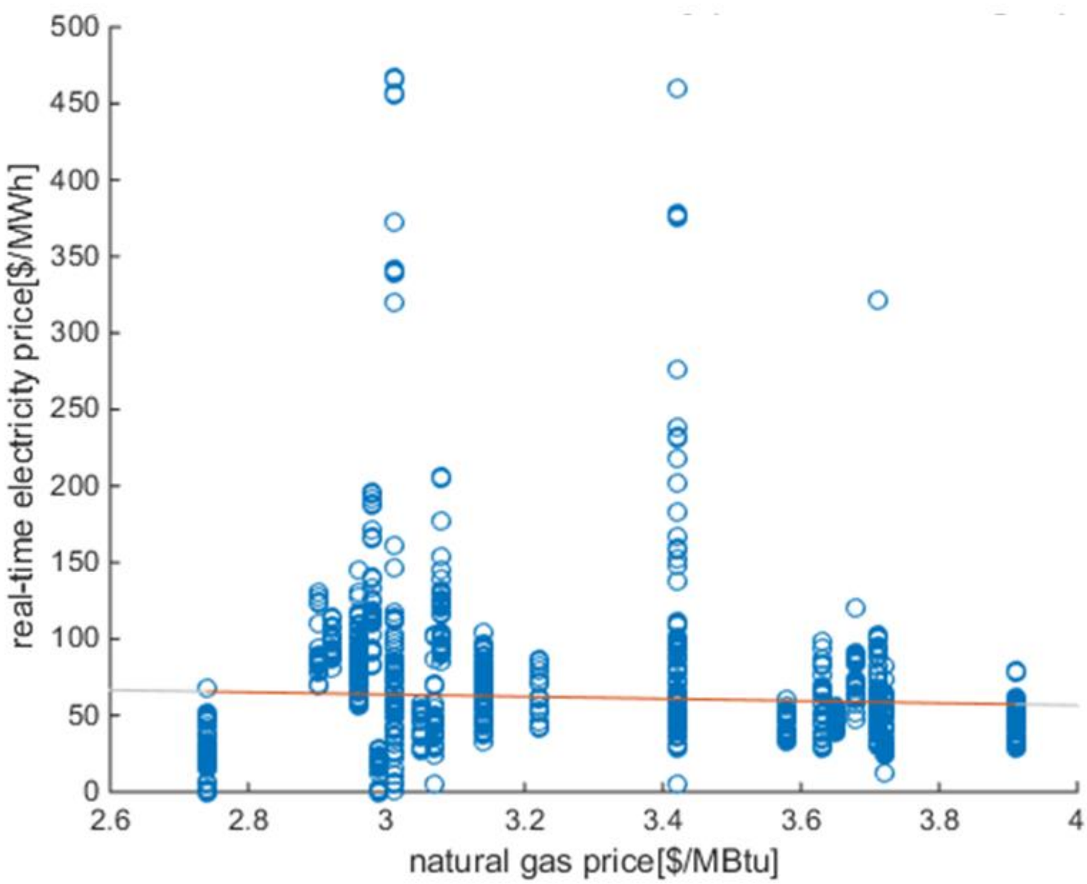


Plot 19. Dependence between real-time electricity price and natural gas spot price for morning hours

20. Correlation between real-time electricity price and natural gas price for evening hours

Results:
$\beta_1 = -7.1169$
$\beta_2 = 85.0805$
$r = -.0549$
$n = 2769$

The correlation coefficient does not differ significantly, increasing in value from -.0705 to -.0549, when considering the entire day versus the evening hours.



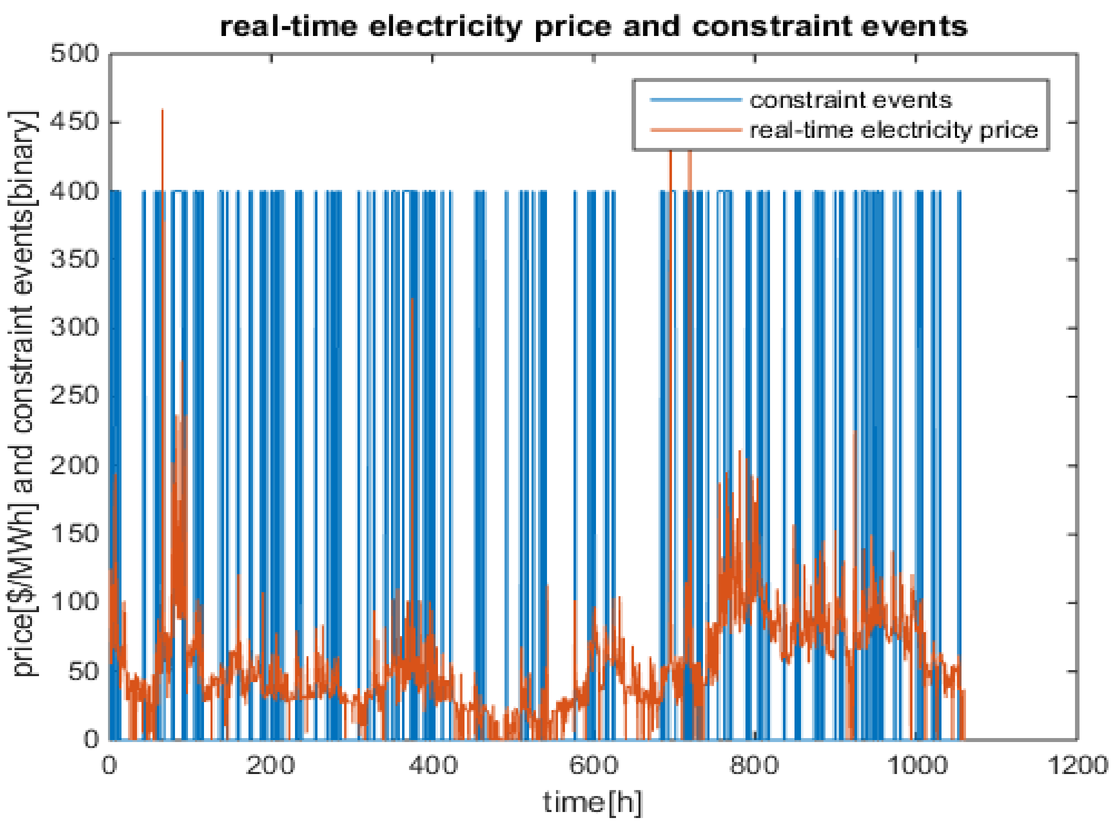
Plot 20. Dependence between real-time electricity price and natural gas spot price for evening hours

21. Variance of real-time electricity price during constraint event and non-constraint event time periods

Results during constraint event time periods
σ_y^2 = 2.5127e+03
n = 2729

Results during non-constraint-event time periods
σ_y^2 = 893.8456
n = 9989

The variance of the real-time electricity price was over 2.5 times greater during constraint events than non-constraint-event time periods. This indicates electricity price is more volatile during constraint events.



Plot 21. Dependence between real-time electricity price and constraint event periods

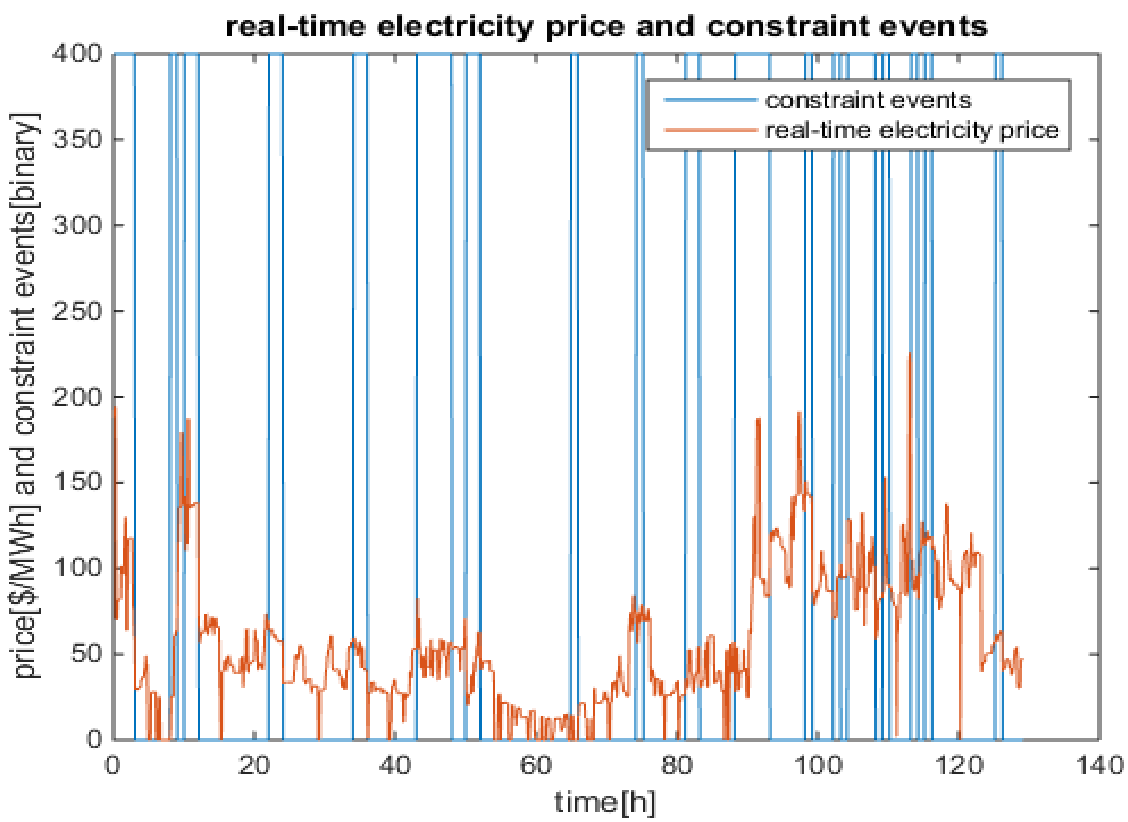
In Plot 21 the constraint events are represented by the value 400 and non-constraint event time periods are represented by the value 0 rather than the binary values of 1 and 0 to make constraint events visible on the graph of electricity price over time. The x-axis corresponds to all the days from December 5th to January 18th, measured in hours. Close inspection reveals that nearly all of the spikes in electricity price occur during constraint events.

22. Variance of real-time electricity price during constraint event and non-constraint event time periods for morning hours

Results during constraint event time periods
σ_y^2 = 1.5438e+03
n = 432

Results during non-constraint-event time periods
σ_y^2 = 1.3794e+03
n = 1118

The variance of the real-time electricity price was very similar during constraint events and non-constraint-event time periods for morning hours. However, there are only 432 data points for constraint event time periods during morning hours so the results for this comparison are more doubtful.



Plot 22. Dependence between real-time electricity price and constraint event periods for morning hours

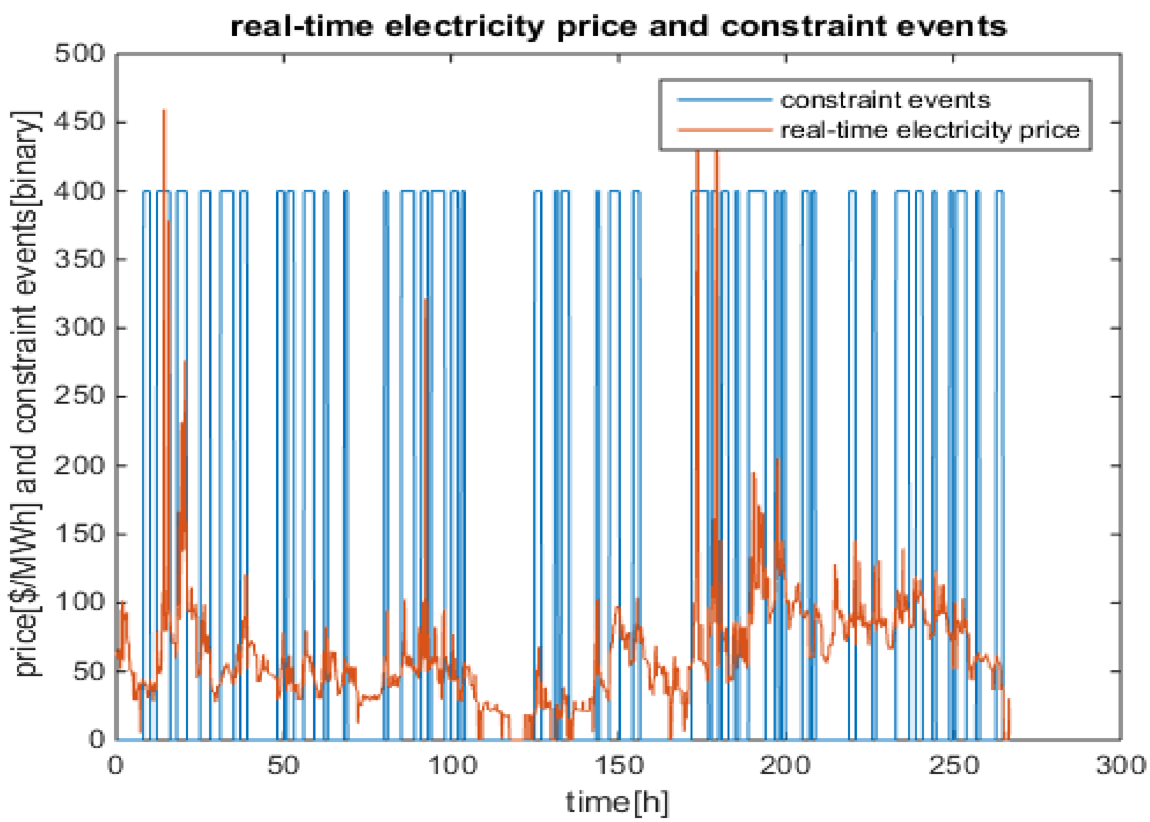
In Plot 22 the variance constraint events are represented by the value 400 and non-constraint event time periods are represented by the value 0 rather than the binary values of 1 and 0 to make constraint events visible on the graph of electricity price over time.

23. Variance of real-time electricity price during constraint event and non-constraint event time periods for evening hours

Results during constraint event time periods
σ_y^2 = 3.8420e+03
n = 1073

Results during non-constraint-event time periods
σ_y^2 = 800.2938
n = 2128

The variance of the real-time electricity price was over 4.5 times greater during constraint events than non-constraint-event time periods. This indicates electricity price is much more volatile during constraint events and evening hours than any other time period.



Plot 23. Dependence between real-time electricity price and constraint event periods for evening hours

In Plot 23 the variance constraint events are represented by the value 400 and non-constraint event time periods are represented by the value 0 rather than the binary values of 1 and 0 to make constraint events visible on the graph of electricity price over time. Close inspection reveals that nearly all of the spikes in electricity price occur during constraint events.

Discussion

Table 1: The correlation coefficient values relating day-ahead electricity price to various sets of natural gas price listed in decreasing order.

Independent Variable	Correlation Coefficient	Number of data points
Natural Gas Price	-.1602	1080
Natural Gas Price -Including data for October and November-	-.2543	2640
Natural Gas Price -Including data for October and November excluding several missing days-	-.3029	1800

The small, negative correlation coefficient across all three versions of the natural gas price data is surprising. It suggests that an increase in the natural gas price will correspond with a decrease in day-ahead electricity price. Since natural gas is used to produce electricity, one would expect that an increase in natural gas price will correspond with an increase in electricity price. These unexpected results could have been caused by comparing natural gas and electricity prices for the same day. Electricity producers actually purchase natural gas a day or more ahead of time. Therefore, more accurate results could be expected when comparing the electricity price for one day and the natural gas price for one of the preceding days. Using the natural gas price for the New England region rather than for the Henry Hub in Alabama would also result in a more meaningful comparison.

Table 2: The correlation coefficient values relating real-time electricity price to factors of interest listed in decreasing order.

Independent Variable	Correlation Coefficient	Number of data points
Day-ahead Electricity Price -for morning hours during non-constraint-event time periods-	.8331	1118
Day-ahead Electricity Price -for evening hours during non-constraint-event time periods-	.8221	2128
Day-ahead Electricity Price -for morning hours-	.8110	1550
Day-ahead Electricity Price -for morning hours during constraint events-	.7700	432
Day-ahead Electricity Price -during non-constraint-event time periods-	.7581	9989
Day-ahead Electricity Price	.6598	12,718
Day-ahead Electricity Price -for evening hours-	.5229	3201
Day-ahead Electricity Price -during constraint events-	.4769	2729
Demand Forecast Error -for morning hours during constraint events-	.4823	432
Demand Forecast Error -for evening hours during non-constraint-event time periods-	.4435	2128
Demand Forecast Error -for morning hours-	.3834	1550
Demand Forecast Error -for evening hours-	.3477	3201
Demand Forecast Error -during constraint events-	.3419	2729
Demand Forecast Error	.3287	12,718
Demand Forecast Error -for morning hours during non-constraint-event time periods-	.3277	1118
Demand Forecast Error -for evening hours during constraint events-	.3217	1073
Demand Forecast Error -during non-constraint-event time periods-	.3183	9989
Day-ahead Electricity Price -during evening hours for constraint-event time periods-	.3009	1073
Wind Production Forecast Error -during constraint events-	.1049	2729
Wind Production Forecast Error	-.0403	12,718
Wind Production Forecast Error -during non-constraint-event time periods-	-.0465	2128
Natural Gas Price -for evening hours-	-.0549	2769
Natural Gas Price	-.0705	10,994
Natural Gas Price -for morning hours-	-.0995	1334

The largest correlation coefficients are those relating real-time electricity price and day-ahead electricity price. This was expected. Higher day-ahead electricity prices mean that the less expensive resources are already in use. Therefore any additional electricity required will also be more expensive, driving up real-time electricity prices. During constraint events the correlation coefficient decreased. This was also expected. During constraint events the price is driven less by relatively constant factors such as the day-ahead electricity price and is more sensitive to other factors. The correlation coefficient was higher during morning hours and lower during evening hours. This suggests that the critical time for the grid occurs during evening hours since the price depends less on relatively constant factors such as day-ahead electricity price and is more sensitive to other factors.

The next largest correlation coefficients were those relating real-time electricity price and demand forecast error. A large, positive difference between the actual demand and the predicted demand will result in a sudden surge in demand for electricity, driving real-time prices up. There was no significant change in the correlation coefficient during constraint events, morning hours, or evening hours. This suggests that the dependence of real-time electricity price on demand forecast error does not depend on the time of day.

The correlation coefficients relating real-time electricity price to wind forecast error was close to zero indicating there is little correlation between the two. This result was somewhat unexpected. If more wind energy is produced than anticipated then one would expect the price of electricity to decrease. During constraint events the correlation actually became positive. This suggests that if additional wind energy is produced then the price of electricity will increase, which is somewhat counterintuitive. Further investigation is required to fully understand implications of this result.

The small correlation coefficient relating real-time electricity price and natural gas price indicates there is little correlation between the two. The correlation coefficient remained close to zero when considering morning or evening hours. Since natural gas is used to produce electricity, one would expect that an increase in natural gas price will correspond with an increase in electricity price. As explained for Table 1, these unexpected results may have been caused by comparing natural gas and electricity prices for the same day and the use of natural gas price data from an Alabama hub and not a New England one.

As expected, the variance of the real-time electricity price was greater during constraint event than non-constraint-event time periods. During constraint event periods the system operator might have limited options in terms of available resources. This leads to solving constrained economic dispatch problem which usually results in dispatch of units with higher costs. Therefore, we observe higher variance of real-time price and lower correlation between day-ahead electricity price and real-time electricity price.

The factors with larger correlation coefficients could potentially be used to design predictive models for the behavior of prices. The factors with lower correlation coefficients will not be very informative for this purpose.

Conclusions

This report investigates the factors that are potentially causing the fluctuations in electricity price. Several relevant relationships between various factors and electricity price have been identified. First, a strong positive correlation between real-time and day-ahead electricity prices exists. Second, a moderate positive correlation between real-time electricity price and demand forecast error exists. Third, there is no evidence of a correlation between real-time electricity price and wind forecast error or natural gas price.

The second objective of the conducted analysis was to identify the critical conditions for significant price volatility. The results suggest that conditions under which price volatility is particularly pronounced are periods during constraint events for evening hours. During these periods the real-time electricity price depends less on the day-ahead electricity price and is more sensitive to other factors.

Going forward it will be informative to compare electricity price for one day with natural gas price for the preceding days. It will also be useful to repeat this study with the natural gas price data for the New England region rather than the Henry Hub in Alabama once that data becomes available following winter 2014-2015. These modifications should result in more credible results.

Additionally, incorporating different constraint event codes and calculating the variance and dependencies for each code should help identify the most relevant codes for electricity price deviation. Ultimately, the goal is use the conclusions of this study to develop critical scenarios for grid operation with insufficient supply of natural gas.

Appendix: List of Correlation Coefficients and Variances

This appendix summarizes the results for each of the 23 comparisons considered. In the following two tables *DAM LMP* refers to day-ahead electricity price, *RTM LMP* refers to real-time electricity price, *NG spot* refers to natural gas spot price, *D-error* refers to demand forecast error, *W-error* refers to wind forecast error, *Morning* refers to morning hours, *Evening* refers to evening hours, *CEV* refers to constraint event periods and *nonCEV* refers to non-constraint event periods.

Table 3. Summary of results – Part I.

Test case	Electricity price	Factors	Correlation coefficient
1	DAM LMP	NG spot	-0.1602
2	DAM LMP	NG spot, extended	-0.2543
3	DAM LMP	NG spot, extended cut	-0.3029
4	RTM LMP	DAM LMP	0.6598
5a	RTM LMP	DAM LMP, CEV	0.4769
5b	RTM LMP	DAM LMP, nonCEV	0.7581
6	RTM LMP	DAM LMP, morning	0.8810
7a	RTM LMP	DAM LMP, morning, CEV	0.7700
7b	RTM LMP	DAM LMP, morning, nonCEV	0.8331
8	RTM LMP	DAM LMP, evening	0.5229
9a	RTM LMP	DAM LMP, evening, CEV	0.3009
9b	RTM LMP	DAM LMP, evening, nonCEV	0.8221
10	RTM LMP	D-error	0.3287
11a	RTM LMP	D-error, CEV	0.3419
11b	RTM LMP	D-error, nonCEV	0.3183
12	RTM LMP	D-error, morning	0.3834
13a	RTM LMP	D-error, morning, CEV	0.4823
13b	RTM LMP	D-error, morning, nonCEV	0.3277
14	RTM LMP	D-error, evening	0.3477
15a	RTM LMP	D-error, evening, CEV	0.3217
15b	RTM LMP	D-error, evening, nonCEV	0.4435
16	RTM LMP	W-error	-0.0403
17a	RTM LMP	W-error, CEV	0.1049
17b	RTM LMP	W-error, nonCEV	-0.0465
18	RTM LMP	NG spot	-0.0705
19	RTM LMP	NG spot, morning	-0.0995
20	RTM LMP	NG spot, evening	-0.0549

Table 4. Summary of results – Part II.

Test case	Electricity price	Factors	Variance
21a	RTM LMP	CEV	2512.7
21b	RTM LMP	nonCEV	893.8
22a	RTM LMP	Morning, CEV	1543.8
22b	RTM LMP	Morning, nonCEV	1379.4
23a	RTM LMP	Evening, CEV	3842.0