Integrated Economic, Environmental, and Reliability Modeling of Power System Growth

Final Report

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1. Overview

We are pleased to report on the results attained by our research team for the project, “Integrated Economic, Environmental, and Reliability Modeling of Power System Growth.” As noted in our proposal, the ultimate objective of this research is to develop and apply linked state-of-the-science models for complex power systems describing electricity supply and demand in a deregulated market, the functioning and reliability of transmission systems, and the impacts of power plant emissions on air quality and health (Figure 1). While complete achievement of that overall objective will require work beyond this initial year, funding from the Shell Center for Sustainability has enabled our multi-disciplinary research team to make significant progress toward our research objectives. The research team, consisting of the project scientists as well as graduate and undergraduate research assistants, has met approximately monthly to coordinate the research efforts. Those discussions have proven to be valuable to integrating the multiple disciplinary perspectives that are being brought to bear on this project. The significant progress that the team has made in implementing each component of the integrated modeling is detailed in the subsequent sections.

Figure 1. Schematic of integrated economic, reliability, and environmental analysis of power systems.
The research team has striven to leverage the Shell Center funding to obtain external research funding and to extend the efforts beyond the 1-year scope of the project. Research conducted for this project laid the groundwork for Dr. Cohan to successfully obtain a $41,494 research grant from Texas Business for Clean Air, titled “A Roadmap to Clean Air and Sustainable Energy in Texas.” That study generated a white paper exploring options for advancing clean energy and air quality in Texas. Dr. Cohan has also submitted a CAREER proposal, pending review by the National Science Foundation, which would build upon the air quality modeling of the current project to conduct advanced atmospheric chemistry studies. In addition, the Shell Center project team has discussed options for applying for funding from the National Science Foundation or other sources to extend the electricity systems research beyond the term of the current project. Those funding opportunities will continue to be pursued in the coming year.

The following sections describe specific progress made in each component of the research for this project.

2. Air Quality component

Air quality modeling and analysis has been conducted by Prof. Daniel Cohan (Civil & Environmental Engineering) and graduate research assistant Wei Zhou.

2.1 Motivation

Power plants are responsible for 11% of the state’s nitrogen oxide (NO\textsubscript{x}) and 70% of the state’s sulfur dioxide (SO\textsubscript{2}) emissions. For air quality, the most critical aspect of the Texas electricity system is the emissions of the 37 coal-fired power plants, which generate about one-third of the state’s electricity. While power plants are located throughout the state (Figure 2), geospatial mapping using Platts power system data purchased for this project and EPA emissions data shows that most of the heavily polluting coal facilities reside in the eastern half of the state (Figures 3-4).
Figure 2. Locations of power plants in Texas

Figure 3. NOx emissions from power plants
2.2 Accomplishments to date

Initial efforts at air quality modeling for this project were conducted with the Community Multi-scale Air Quality model using emissions data produced by the CENRAP regional planning organization. However, as the project progressed, we shifted course to use the Comprehensive Air Quality Model with Extensions (hereafter CAMx, Environ Corp) to capitalize upon detailed emissions inventories and meteorological modeling developed by the Texas Commission on Environmental Quality (TCEQ). CAMx is a broadly used, state-of-the-science photochemical model for simulating air quality on urban and regional scales.

The modeling domain on which CAMx was applied, with nested grids of resolution 36, 12, 4, and 2 km, corresponds with the domain used by TCEQ for ozone attainment planning and is shown in Figure 5. Texas is an apt testbed for air quality studies because both the Houston and Dallas-Fort Worth regions have long violated federal standards for ground-level ozone, and several other regions may be designated in non-attainment as the U.S. EPA tightens the ozone standards. Houston is also near the threshold for violating ambient standards for fine particulate matter (PM$_{2.5}$, denoting particles with aerodynamic diameter smaller than 2.5 microns), a pollutant that many epidemiological studies have identified as the leading cause of air pollution related morbidity and mortality. Power plant NO$_x$ could contribute to ozone pollution, and both NO$_x$ and SO$_2$ can serve as precursors for PM$_{2.5}$. 

Figure 4. SO$_2$ emission from power plants
As an initial air pollution episode for study, CAMx modeling was conducted for May 31 – June 15, 2006, a period containing several days of warm temperatures high ozone levels in multiple Texas cities. To evaluate the performance of CAMx for representing pollutant formation and transport, model results were compared with observed concentration of ozone and its precursors (Figures 6-9). At C81, the model well captures diurnal patterns, daily variations, and peak levels for ozone (Figure 6). At Deerpark, CAMx has also performed satisfactorily for the overall ozone patterns, even though modeling peak ozone values were lower than the observed ones on some days. Model performance for two ozone precursors (isoprene and NO2) was also examined (Figures 8-9). Figure 10 shows ozone concentrations on the afternoon of June 14, 2006 to provide an example of spatial patterns of pollution during the episode.
Figure 7. Observed vs. modeled ozone at Deerpark (suburban site, blue dot: observed, black line: modeled)

Figure 8. Observed vs. modeled NO\textsubscript{2} at Deerpark (blue dot: observed, black line: modeled)

Figure 9. Observed vs. modeled isoprene at Deerpark (blue dot: observed, black line: modeled)
A key output of the air quality modeling for the overall integrated modeling will be the relative impact of each power plant on air quality and population exposure. Modeling has so far been conducted to quantify the impacts of six power plants that are among the largest emitting sources in Texas: Pirkey, Parish, Deepwater, Martin Lake, Monticello, and Limestone. Base case simulated ozone concentrations were differenced from a series of simulations in which the NO\textsubscript{x} emissions of one of these facilities was removed to quantify the “zero-out” source contribution of each facility. As can be seen in Figures 11-13, the impacts of the NO\textsubscript{x} emissions generally extend over tens of counties to a distance of 100-200 km.

Figure 11. Impact of Martin Lake power plant emissions on ozone concentrations, averaged over all hours of the episode.
To quantitatively evaluate the air quality impacts of power plants, three impact metrics were developed as defined below. Each of these metrics can be evaluated on a per-ton or per-MWh basis. For the purposes of this preliminary analysis, results were processed over all hours of the episode, excluding two model initialization days.

Metric 1 represents the spatially integrated ozone impact of each power plant (Eq. 1), where \( \text{ozone}_{\text{base}} \) and \( \text{ozone}_{\text{zero out}} \) refer to surface layer ozone concentrations in the base and zero-out cases, respectively.
\[ \sum_{\text{All cells}} (O_{\text{base}} - O_{\text{zrout}}) \quad (\text{Metric 1}) \]

Metric 2 is identical to Metric 1 except that it only considers grid cells in which the base case concentration was above 85 ppb. This threshold corresponds to the current ambient 8-hour ozone standard and allows us to focus on results at times when ozone levels were modeled to be high.

\[ \sum_{O_{\text{base}} > 85 \text{ ppb}} (O_{\text{base}} - O_{\text{zrout}}) \quad (\text{Metric 2}) \]

Metric 3 weights the results by the population of each affected grid cell in order to provide a measure of population exposure to air pollution caused by each power plant. This reflects the dual goals of air quality planners, who must both attain ambient air quality standards throughout their targeted regions but also seeks ways to reduce the human health impacts of air pollution.

\[ \sum_{O_{\text{base}} > 85 \text{ ppb}} (O_{\text{base}} - O_{\text{zrout}}) \times \text{Population} \quad (\text{Metric 3}) \]

The population data was processed in three steps. The gridded population data was created by ArcGis. Data source of “Population group” was downloaded from U.S. census bureau and interpolated for each grid cell (Figure 14).

Figure 14. Population in the 12-km resolution modeling domain.
Final results of ozone impacts from each single power plant are shown in Table 1. The units for the metrics are arbitrary and depend on the number of grid cells and hours for the particular episode, but the comparisons across power plants indicate the relative impacts of each facility. On each metric, Martin Lake power plant had the largest impact for this episode on a total and per-ton basis. Deepwater had a high level of NOx emissions relative to its small level of electricity generation, and thus caused the greatest impacts on a per-MWh basis.

Table 1. Characteristics and ozone impacts for selected power plants in Texas. Bold indicates the power plant with the greatest impact for that metric.

<table>
<thead>
<tr>
<th></th>
<th>Deepwater</th>
<th>Limestone</th>
<th>Martin Lake</th>
<th>Monticello</th>
<th>Parish</th>
<th>Pirkey</th>
</tr>
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<tbody>
<tr>
<td>NOx (Tons/day)</td>
<td>11.6</td>
<td>40.9</td>
<td>33.8</td>
<td><strong>48.5</strong></td>
<td>16.6</td>
<td>13.6</td>
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<td>Electricity Generation (GWh/year)</td>
<td>1209</td>
<td>14411</td>
<td><strong>19460</strong></td>
<td>16432</td>
<td>20483</td>
<td>5171</td>
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<tr>
<td>Metric 1 (average spatial impact)</td>
<td>20423</td>
<td>145227</td>
<td><strong>178625</strong></td>
<td>102578</td>
<td>42609</td>
<td>45925</td>
</tr>
<tr>
<td>Metric 1/EmisNOx</td>
<td>1760</td>
<td>3546</td>
<td><strong>5284</strong></td>
<td>2115</td>
<td>2566</td>
<td>3376</td>
</tr>
<tr>
<td>Metric 1/MWh</td>
<td><strong>0.440</strong></td>
<td>0.263</td>
<td>0.239</td>
<td>0.163</td>
<td>0.054</td>
<td>0.232</td>
</tr>
<tr>
<td>Metric 2 (spatial impact w/threshold)</td>
<td>794</td>
<td>2758</td>
<td><strong>11275</strong></td>
<td>2558</td>
<td>964</td>
<td>2596</td>
</tr>
<tr>
<td>Metric 2/EmisNOx</td>
<td>68</td>
<td>67</td>
<td><strong>333</strong></td>
<td>52</td>
<td>58</td>
<td>190</td>
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<td>Metric 2/MWh (×100)</td>
<td><strong>1.71</strong></td>
<td>0.50</td>
<td>1.51</td>
<td>0.41</td>
<td>0.12</td>
<td>1.31</td>
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<td>Metric 3 (population weighted w/threshold)</td>
<td>23402</td>
<td>96698</td>
<td><strong>255207</strong></td>
<td>83376</td>
<td>18407</td>
<td>68828</td>
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<td>Metric 3/EmisNOx</td>
<td>2017</td>
<td>2361</td>
<td><strong>7550</strong></td>
<td>1719</td>
<td>1108</td>
<td>5060</td>
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<tr>
<td>Metric 3/MWh</td>
<td><strong>0.50</strong></td>
<td>0.17</td>
<td>0.34</td>
<td>0.13</td>
<td>0.02</td>
<td>0.35</td>
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</table>

2.3 Next Steps: Air quality component

Current research has explored the ozone impacts of single facilities through several predefined indicators. As the research is going on, the power plant plume variation and the atmospheric chemistry of plumes will be investigated. Tracking the trace of power plant plume, reactive nitrogen budget could help find the ozone production efficiency. Furthermore, atmospheric chemistry of SO2 and aerosol formation from SO2 oxidation are the other significant aspect of air quality impact caused by power plant, which will be investigated next.

3. Power System Flow and Reliability component

Power system flow and reliability modeling has been conducted by Prof. Leonardo Duenas-Osorio (Civil & Environmental Engineering) and undergraduate research assistant Olufemi Oke.
3.1 Accomplishments to date

After the development of two Matlab-based algorithms for solving simplified versions of the power flow problem, the power system reliability team initiated an exploration of software platforms to solve the full alternating current (AC) power flow problem. This full power flow problem requires a solution of a system of simultaneous nonlinear equations in order to account for real and reactive power flow as well as system losses. The two simplified Matlab models that were initially developed by the team did not account for power losses, and included a few assumptions about power system operation to enable a decoupling of the system of simultaneous equations and facilitate the power flow problem solution. However, for the Texas power grid study region a realistic modeling of power losses is critical due to the significant length of transmission lines in the state and the prevalent heat conditions during several months of the year.

A generic power transmission grid consists of complex impedances between buses and from the buses to the ground. Buses correspond to power generation sources, and loads or power consumption points. The objective of the power flow model is to determine the amount of power flowing through the transmission lines, and the optimal amount of power to be delivered by the generation points. The solution also includes the optimal voltages and phase angles at the buses of the system to ensure power flow stability. A working power flow computer model allows for exploration of the impacts of system reconfigurations. For instance, the impacts of change in load patterns, siting of new generation buses, and natural hazard occurrence can be reliably quantified via power flow analysis.

The selected platform to perform the full AC power flow analysis of electric systems in this research is WinIGS-F. Specifically, this program allows modeling any multiphase power system together with its neutral and ground wires, analyzes the performance of the system under steady state normal and fault conditions, and evaluates system performance against industry-standard criteria. The power system may include any number of symmetric three phase devices as well as asymmetric elements. Presently, the program supports power systems comprising any combination of devices, such as power generation sources, transmission lines, transformers, and loads.

The WinIGS-F platform is a graphical interface in which the network topology, connectivity, and geographical coordinates are provided as initial input. A sample electric power system used in this study to gain insight about the full AC power flow problem solution is displayed in Figure 15.
Figure 15. Small power system with generation buses, transmission lines, and load buses.

Once the topological layout of the power system is in place, electrical details are needed to complete a working power model. In particular, WinIGS-F requires information about the voltage schedule in generation buses, the real and reactive power at load buses, and the resistance and reactance of every transmission line. Additional details about equipment brands and technical specifications for cables can be customized as well. The power flow analysis is performed based on the topological and electrical input, and the output contains voltages at the load buses, power generation values at the swing bus, power flow along transmission lines, and quantification of power losses.

Although the team has already performed full AC power flow on small electric systems, the required input data to develop a model of the Texas power grid is still being collected. In particular, the team is in the process of obtaining the electrical characterization of the system and associated component states for normal operation conditions. The team has already obtained access to the ERCOT planning and operations information portal, which offers some degree of detail about the base-line power system and its operation. However, access to comprehensive information about bus voltages, and resistances and reactances at transmission lines is pending approval from the state estimation support team at ERCOT.

Regarding topological input data, the team has already completed the data collection task and processed the raw data to obtain a GIS-based representation of the grid (Figure 16). This georeferenced topology has been constructed by integrating individual data sets maintained by Platts\textsuperscript{\textsuperscript{iii}}, which include generation, transmission and substation system elements. Detailed
information associated with the power plants includes fuel types, operational and financial statistics, and descriptions about utility and non-utility ownership. Also, all generation facilities with least 4.5 MW of demonstrated capacity, plus many smaller power plants, are included in the data set. Regarding the electric substation data, it contains electric transmission, sub-transmission, and some distribution substations. These substations are fed by electric transmission and sub-transmission lines, which are also included in the data set. The line voltages typically range from 110 kV to 765 kV for transmission cables, and 33 kV to 100 kV for sub-transmission cables. These transmission and sub-transmission lines include both overhead and underground types.

Figure 16. Geospatial representation of the Texas power transmission and sub-transmission network.

3.2 Next Steps: Power flow component

The power flow and reliability team will continue assembling the database with input information to run a full AC power flow model of the state of Texas. Specifically, the team will gather information from ERCOT’s secure documents library about power system states for base-line operation. Also, the team will attend a training session on WinIGS-F at the Georgia
Institute of Technology during the first quarter of 2009 to refine the initial conditions of the Texas power grid model. After successful construction of the electric power system model of Texas, the team will implement a Matlab-based program to run in batch mode the WinIGS-F tool, and explore the effects of faults triggered by aging and natural hazards, siting of new power plants, decommissioning of old generation buses, and general stability of the system to fluctuating loads and demand patterns. This coupled power flow and contingency analysis tool will provide a critical link to the integrated economic, environmental and reliability power system growth study.

4. Economics Market Modeling component

The economics component of the research was conducted by Prof. Peter Hartley, Dr. Kenneth Medlock, and graduate research assistant Ozgur Inal.

4.1 Accomplishments to date
We have developed a duopoly model to explain how the bidding process in Texas electricity markets works. Although our model includes only two firms, the objective of each firm is to maximize its profits in its ‘residual’ market. Hence, without loss of generality, we can assume that a given firm may treat its competitors as a single firm.

We can summarize this idea as follows:

Let \( N=\{1,2,\ldots,n\} \) denote the set of firms competing in the spot market. If we let \( D(p) \) denote the market demand function, \( s_j(p) \) denote firm \( j \)'s supply function, and \( S_{-i} \) denote the sum of the supply functions of every firm but \( i \). The residual demand, \( RD_i : P \rightarrow Q \), firm \( i \) will face then will be

\[
RD_i(p) = D(p) - S_{-i}(p).
\]

Firm \( i \) will act as a monopolist in this residual market it faces. That is, it will solve the problem \( MR_i(q_i^*) = MC_i(q_i^*) \) (where \( MR_i \) and \( MC_i \) are the marginal revenue and marginal cost of firm \( i \), respectively) to find the profit maximizing quantity \( q_i^* \) to offer to the
market. The price it will charge will be given by \( RD(q^i) \), for a particular realization of market demand, \( D(p) \).

Most of the successful applications in the literature that we are aware of use linear or piecewise linear models to explain bidding behavior in electricity markets. As we described in more detail in our previous report, we diverge from the existing literature at this point and do not assume linearity of the supply functions. Our approach is to approximate each firm’s supply stack with a piecewise cubic polynomial. The main advantage of this approach is that since the resulting residual demand curve the firm faces is differentiable, its marginal revenue curve will be continuous. Continuity is crucial since discontinuities in a firm’s marginal revenue curve will in turn lead to discontinuities in its supply function. In turn, the market supply function would be discontinuous. As can be seen from the picture below, where the blue line is the market demand and the red lines are the discontinuous market supply, it is not clear at what price and quantity the market will clear. This is problematic since it creates uncertainty as to what the market clearing price and quantity will be. It also would not allow the researcher to predict equilibrium outcomes, which in turn is crucial for our overall modeling exercise.

![Figure 17. Jumps in the market supply function will lead to uncertainty.](image)

Note that, now, the residual demand is a function from quantity to price.
Another potential problem that we came across during our simulations is illustrated in the following picture. For some profiles of the residual supply curve, marginal revenue can be increasing over some ranges. Most of the time, this case is ignored in the literature but we believe this case will be observed more often than not. Increasing marginal revenue is problematic since it may lead to multiple profit maximizing points for a firm and hence an uncertainty as to how much quantity this firm will supply to the market. This, in turn, may cause an imbalance between supply and demand, which will cause deviations from the standard frequency of 60 Hz\(^2\), if not a fall in voltage below required levels. We can easily solve for the optimum quantity in case of increasing marginal revenue. However, we are yet to come up with a solution in case where a firm faces multiple profit maximizing quantities. One idea we are exploring is using the second derivative of the profit function at those points to measure the sensitivity of profits to a deviation in marginal revenue. The firm is likely to prefer an output level where profits vary less as marginal revenue fluctuates.

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Figure 18. Another cause of uncertainty is non-monotone marginal revenue curve.
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\(^2\) As Stoft\(^\text{'}\) puts it, “Frequency is very precisely maintained as indicated by the following report … “In late July 1999… system frequency on the Eastern Interconnection dipped to one of its lowest levels in history (59.93 Hertz).”
4.1 Next Steps: Economics component

We are still trying to improve our model. Ultimately, we would like to come up with a model as general as possible. An immediate question to be answered, as briefly mentioned above, is what will happen if there are multiple profit maximizing equilibria for a firm. After the model is complete, we will use data from the ERCOT market to simulate optimal bidding behavior. In the absence of transmission constraints, this bidding behavior would in turn determine those firms that are called upon to supply output at any given time. In practice, however, the system operator may depart from the dispatch pattern that minimizes the costs of procuring a given supply of electricity. In addition, the expectation of transmission constraints can alter the optimal bidding behavior of the firms. We therefore need to alter the model to accommodate the effects of transmission constraints.

Another issue we need to address is the effect of long-term contracts on the bidding behavior of the firms. These are especially important in the ERCOT market because firms have to submit “balanced” supply schedules, which effectively mean that the majority of their output is sold at long-term contract prices rather than the spot market price determined through bidding behavior.

The next phase will be developing a demand function for electricity in Texas. We will use the demand relationship to examine a number of factors including the effect of projected population and economic growth in Texas on the electricity demand and how will this demand respond to a change in the structure of prices to more closely reflect costs of supply.
5. References


