# ENVIRONMENTAL REGULATION AND THE ELECTRIC POWER INDUSTRY: THEORETICAL AND NUMERICAL ANALYSES OF INTERSECTING MARKETS WITH MULTIPLE PUBLIC GOODS

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ENVIRONMENTAL REGULATION AND THE ELECTRIC POWER INDUSTRY: THEORETICAL AND NUMERICAL ANALYSES OF INTERSECTING MARKETS WITH MULTIPLE PUBLIC GOODS

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The reliable supply of electricity over an electrical network is essential for modern societies. The electrical network is a complex grid connecting electric generation units, or generators, with the consumers who use the energy to meet their daily needs. In order to successfully provide electric energy to consumers each day, certain regulations are implemented by the regional dispatcher of electricity to ensure its uninterrupted delivery even if a mild contingency occurs. Unlike the electric energy consumed by each individual consumer, which is a private good because consumers use and pay for exactly what they use, the electric reliability supplied over the network is a public good. This is because all consumers in a region receive the same level of electric reliability, no matter how much electricity is individually consumed.

While the reliable supply of electricity is crucial, there is also serious concern about the negative environmental impacts of the air pollution created by these generators. Depending on the type of air pollutant, it can have either a uniform or localized impact, called global or criteria pollutants, respectively. Though global and criteria pollutants impact the environment differently, both have properties of public goods because all consumers in the region affected by the pollutant receive the same level of air pollution, no matter how much electricity is individually consumed. Further complicating the layering of environmental regulation on top of electric reliability regulation is that the path of electricity over the network, the dispersion of global pollutants through the air, and

the dispersion of criteria pollutants through the air generally differ.

In order to explore the interactions of electric reliability and environmental regulation, both a theoretical and numerical simulation framework is built. The main exploration of the theoretical model is to compare, while considering electric reliability and environmental pollution, the social welfare maximizing solution to the competitive market solution. This is done to determine if competitive markets for electricity and either global or criteria air pollutants can achieve the socially optimal solution.

In addition to the theoretical analysis, numerical simulations of a highly simplified electricity network and airshed for Northeastern North America are built. The model is exercised under varying combinations of variables in order to test the practical significance of the theoretical results. The adjustment of the model variables allows for meaningful research in two primary areas. The first area is understanding the policy impacts of environmental regulation, such as the Regional Greenhouse Gas Initiative (RGGI), when faced with various constraints on the electric grid, such as a required reserve margin. The second area is to study varying methodological practices for modeling the electric grid by comparing alternating current (AC) and direct current (DC) simulation results and the effect of their different estimates of line constraints based upon both thermal load and voltage level.

The results of the theoretical analysis lead to the conclusion that after assuming a central planner has set variables surrounding the transmission grid, complicating interdependencies in markets for criteria pollutants make achieving the socially optimal solution unlikely. Markets for global pollutants can more easily achieve the socially optimal solution due to the lack of these interdependencies.

The numerical simulations demonstrate a major issue that can arise in attempts to regulate air pollution on a regional basis in a policy such as the RGGI. "Leakage" occurs when the cost of generating electricity to pollution emitting generators in the regions where air pollution regulation applies is increased, inducing larger imports of electricity from external unregulated regions that do not face the same emission cost. The resulting outcome may diminish the effectiveness of the regulation in reducing pollution or, in the worst case, increase total emissions. The outcome of the simulations shows that leakage is a major concern for the RGGI's ability to reduce net emissions.

The numerical simulations also demonstrate that the outcomes critically depend on the methodology used in solving the system. Both a DC approximation of the actual AC system (flows are modeled by linear equations in a DC network) and the more realistic non-linear AC network that includes constraints on voltage levels (a public good that in reality must be kept within bounds) are modeled. In addition, the electric transmission power constraints are relaxed to examine their importance. The difference in complexity between AC modeling and DC modeling as well as transmission constraints become especially important when the network is operated at high prices for the regulated air pollutants, causing significant changes to the mix of the fuel type used by dispatched generators.

## BIOGRAPHICAL SKETCH

Douglas Christopher Mitarotonda grew up in Pittsburgh, Pennsylvania and graduated from Mount Lebanon High School in 1998. He attended college at Cornell University, which included spending a semester abroad in Nepal where his interest in energy and environmental issues was piqued. Douglas graduated with his Bachelor of Arts degree in Computer Science, Mathematics, and Asian Studies in 2002. Before commencing his doctoral studies in Economics at Cornell, Douglas completed his Master of Engineering degree in Computer Science, also from Cornell, in 2003.

To my mother, Carol Ann Crowley.

## ACKNOWLEDGMENTS

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | alternating current |
| ACESA | American Clean Energy and Security Act of 2009 |
| CAIR | Clean Air Interstate Rule |
| DC | direct current |
| EPA | United States Environmental Protection Agency |
| GHG | greenhouse gas |
| IESO | Independent Electricity System Operator |
| IPM® | Integrated Planning Model® |
| ISO-NE | Independent System Operator – New England |
| LMP | locational-based marginal price |
| MW | megawatt |
| MWh | megawatt-hour |
| NERC | North American Electric Reliability Corporation |
| NYISO | New York Independent System Operator |
| OPF | optimal power flow |
| PJM | PJM Interconnection |
| RGGI | Regional Greenhouse Gas Initiative |
| RTO | regional transmission organization |

## LIST OF SYMBOLS

| | |
|---|---|
| $CO_2$ | Carbon dioxide |
| $NO_x$ | Nitrogen oxides |
| $SO_2$ | Sulfur dioxide |

CHAPTER 1

# INTRODUCTION

The consumption of electricity is an essential part of everyday modern life. Unfortunately, most large electric generation units, or generators, use a fuel source that emits pollutants, such as carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$), and nitrogen oxides ($NO_x$), as well as fine particulate matter that are not completely captured by existing emission reduction technologies. $CO_2$ is a heat-trapping greenhouse gas (GHG) contributing to global climate change [21]. The emission of a GHG acts like a pure public "bad" because no matter where it is emitted, the adverse effect on the planet's atmosphere is more or less equal. Therefore, GHG pollutants are global pollutants.

$SO_2$ and $NO_x$ are two of the six air pollutants the United States Environmental Protection Agency (EPA) call criteria pollutants [26]. $SO_2$ contributes to respiratory illness, aggravates existing heart and lung diseases, the formation of acid rain, and atmospheric particulate matter that causes reduced visibility [25]. $NO_x$ are a main ingredient in ground level ozone, which causes adverse respiratory effects [22]. Because, the emission of these criteria pollutants are dispersed non-uniformly according to weather and topographic conditions, thereby affecting humans differently at different locations, they are local public "bads." Nevertheless, the varying levels of potential harm to people can be predicted, given the specific generator information (e.g. location, stack height, and pollutant emissions), weather patterns, and topography.

The electric power industry has been a major contributor to the production of all of these pollutants. In 2007, the generation of electricity was the single largest source of $CO_2$ emissions in the United States, representing 40 percent of all $CO_2$ emissions [27]. In 2002, the fuel combustion of electric utilities created 70 percent of the $SO_2$ emissions (the largest source) and 20 percent of the $NO_x$ emissions (the second largest source) produced in the United States [24, 23].

To date, efforts to reduce $CO_2$ emissions in the United States have been left for individual states to implement, as the federal government has not taken a leadership role beyond deliberations in the legislature. Multiple regional programs have been discussed across the country, including the Western Climate Initiative and the Midwestern Greenhouse Gas Reduction Accord. The only state-led program to become a reality has been the Regional Greenhouse Gas Initiative (RGGI), a cap and trade program developed by ten Northeastern and mid-Atlantic states. The most current federal legislation being considered is the American Clean Energy and Security Act of 2009 (ACESA).

Efforts to reduce $SO_2$ and $NO_x$ emissions were made by the federal government with the 1990 Clean Air Act Amendments. This legislation created an Acid Rain program that authorized a cap and trade system of $SO_2$ emissions as well as placed a limit on generation unit emissions of $NO_x$. The EPA issued the Clean Air Interstate Rule (CAIR) in early 2005 as an effort to better control and further reduce pollution that crosses state borders. Though the more stringent proposed CAIR regulation was vacated in 2008,[1] both $SO_2$ and $NO_x$ are currently regulated by cap and trade programs.

In addition, the infrastructure that transports electricity to each consumer is essential to its reliable delivery. Due to economies of scale for the generation of electricity, there is an incentive to build large generation units. Because of the difficulty in situating those large generators near residential consumers, the electricity must be shipped long distances. But, the electric lines, each with its own scale economies and carrying capacity, limit the routes electricity can flow from each generator to reach customers. The lack of efficient storage of electricity amplifies these limitations. Furthermore, to maintain service reliability, parallel routes are usually established for transmission lines.

[1] A similar program focusing on mercury emissions, the Clean Air Mercury Rule, was also vacated in 2008.

The path electricity takes along the network is governed solely by the laws of physics, not by contracts for generation and delivery. The ability for electricity to be supplied without surprised interruption, in other words electric reliability, is also a public good even though the consumption of electricity is a private good. Electric reliability is a public good because all consumers in a region receive the same level of electric reliability, no matter how much electricity is individually consumed. No single consumer has the incentive to honestly reveal his or her desire for reliable service, which is provided by installing redundant and excess capacity. Each individual can "free-ride" on the spare capacity demanded by others. In addition, the drastic over- or under-consumption of electricity by any individual would cause the electric grid to go down for everyone. Nevertheless, electric reliability has a value to all consumers, which is likely different for each consumer, making demand revelation difficult.

The interaction of environmental and electric reliability regulation is further complicated because often the geographical responsibilities of these two regulatory agencies do not completely intersect. Thus, the challenge to set optimal standards is increased as more parties are involved. There is a growing importance in the relationship between environmental and electric reliability agencies, as evidenced by a statement by the North American Electric Reliability Corporation (NERC)[2] in late 2008.

> The NERC Planning Committee (PC) has identified initiatives currently underway to address climate change and reduce GHG emissions as among the most important emerging issues facing the reliability of the bulk power system over the coming years [15].

The relationships between global impacts of GHG emissions, locational impacts of criteria pollutants, and the physical constraints of the electrical grid have been well-

[2]The entity that sets electric reliability standards in North America.

studied by others, such as Talaq et al. [18]. However, unlike other work on this topic, the theoretical model presented here includes electric reliability as a variable in the model and takes a utility function-based approach. The main exploration of the theoretical model is to compare, while considering electric reliability and environmental pollution, the social welfare maximizing solution to the competitive market solution. This is done to determine if competitive markets for electricity and either global or criteria air pollutants can achieve the socially optimal solution.

In addition to the theoretical analysis, numerical simulations of a highly simplified electricity network and airshed for Northeastern North America are built. The model is exercised under varying combinations of variables in order to test the practical significance of the theoretical results. The adjustment of the model variables allow for meaningful research in two primary areas. The first area is understanding the policy impacts of environmental regulation, such as the RGGI, when faced with various constraints on the electric grid, such as a required reserve margin. The second area is to study varying methodological practices for modeling the electric grid by comparing alternating current (AC) and direct current (DC) simulation results as well as to examine line constraints.

The primary policy focus in the numerical simulations is the RGGI. Scenarios are created to compare, for example, electricity prices, industry profits, and the use of each major fuel type, both with and without the RGGI imposed on generators. One of the main focuses of these RGGI simulations is to examine the amount of emissions "leakage" that will occur. Leakage refers to the increased emissions from generators outside of a regulated region as a result of the increased marginal operating cost for generators inside a regulated region. This is of particular concern because leakage could potentially partially, or completely, offset the emission reductions from inside the regulated area with increased emissions from outside the regulated area. Furthermore, numerical simulations considering the presence of a drought and operating reserve margins in light of the RGGI are also considered. The purpose in modeling a drought is to examine the potential for permit price volatility under a cap and trade program. A drought reduces hydropower, therefore increasing the need for $CO_2$-emitting generation and the price of emission permits. Operating reserves are important because they provide electric reliability, a crucial feature to any modern electric power system.

Numerical simulations are also conducted to explore methodological practices for modeling the electric grid. Actual power systems are AC networks. Thousands of constraints on flow, voltage, stability, and power production, many of which are non-linear, govern the operation of such a network. However, realistic modeling of power networks is challenging. Because of the complexity of creating and solving a realistic AC power system model, simpler models have been used instead, including DC models that are linear approximations of the AC model. Therefore, both AC and DC models are simulated in order to draw comparisons between the two models.

Furthermore, the characteristics of an electric power network can strongly influence the effects of environmental policies that are applied to the power sector. The flows in such a network do not follow the shortest or most under-utilized route from where power is generated to where it is consumed, rather flows follow laws of physics known as Kirchoff's Laws. So, scenarios both enforcing and relaxing transmission line constraints are executed in order to examine the importance of such constraints.

Chapter 2 reviews the RGGI because it is a major driver for both the theoretical model and numerical simulations. Chapter 3 presents the theoretical model and results. Section 3.1 provides an overview of the theoretical analysis. Section 3.2 sets up the model by outlining the variables that are used. In order to isolate the impacts of each pollutant with reliability, the global and criteria pollutants are modeled separately with reliability. Section 3.3 begins the theoretical modeling by considering only electric reliability. Section 3.4 summarizes the results of Section 3.3. Section 3.5 builds on Section 3.3 by adding a global pollutant to the model. Section 3.6 replaces the global pollutant from Section 3.5 with a criteria pollutant. Section 3.7 summarizes the results from both Sections 3.5 and 3.6.

Chapter 4 presents the numerical simulation model and results. Section 4.1 provides an overview of the numerical simulations. Section 4.2 sets up the model by outlining the variables that are used. Section 4.3 discusses the underlying consumer demand, transmission line data characteristics, and generator characteristics used in the numerical simulations. Section 4.4 outlines the optimization formulation solved in each of the numerical simulations. Section 4.5 examines the policy and methodology results of the numerical simulations. Chapter 5 summarizes the key points of the theoretical model and numerical simulations and outlines areas for future research.

CHAPTER 2

# REGIONAL GREENHOUSE GAS INITIATIVE

The RGGI is a cap and trade regulation on $CO_2$ emissions that has been approved by and is operative in ten Northeastern and mid-Atlantic states: Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Maryland, and Delaware, as shown in Figure 2.1 [13].


Figure 2.1: RGGI participating states

In this study, the RGGI is the focus for four primary reasons. First, an existing network model is available for the electricity system in Northeastern North America that can be used to explore many issues that have been raised concerning $CO_2$ regulation. Second, the RGGI is the only of the state-driven initiatives to come to fruition. Third, the

RGGI only regulates a portion of the United States and the boundaries of the regulated area do not exactly coincide with electric reliability control areas. Fourth, the RGGI has borders with portions of the United States and Canada that do not have $CO_2$ regulations currently in place.

The ten states in the RGGI contain 16 percent of the United States population [9], but emit only ten percent of United States GHG emissions. This is in part because the RGGI area's electricity generation mix uses relatively more natural gas and less coal than some other areas, such as Pennsylvania, a state not participating in the RGGI.

The objective of the RGGI is to reduce electric power sector $CO_2$ emissions by ten percent from a baseline level, calculated to be four percent more than the average regional emissions during the period of 2000–2004, by 2018. This reduction is achieved by capping emissions at the baseline level for the first six years of the program, 2009–2014, and then reducing the cap by 2.5 percent of the baseline in each of the next four years.

The main highlight of the RGGI is that each of the states participating in the program has agreed to auction a large fraction of the $CO_2$ allowances. This is unlike other $CO_2$ cap and trade programs like the European Union's Emission Trading Scheme that distributed the vast majority of $CO_2$ allowances without charge to emitting generators. Though 25 percent of a state's allocation of $CO_2$ allowances is the minimum agreed upon number of $CO_2$ allowances to auction, multiple states are on track to sell nearly 100 percent of their $CO_2$ allowances via auction. As a group, approximately 80 percent of the annual budget of roughly 188 million $CO_2$ allowances are projected to be sold via auction. Furthermore, each of the auctions conducted has a reserve price — a minimum price for which a $CO_2$ allowance will be sold (set to be $1.86 per $CO_2$ allowance at the start of the program).

The first four of the quarterly scheduled auctions have been completed and all $CO_2$ allowances were sold. In particular, $CO_2$ allowances from the 2009 allocation year have had the following auction results [17].

- 12,565,387 sold at \$3.07 per $CO_2$ allowance (September 25, 2008)
- 31,505,898 sold at \$3.38 per $CO_2$ allowance (December 17, 2008)
- 31,513,765 sold at \$3.51 per $CO_2$ allowance (March 18, 2009)
- 30,887,620 sold at \$3.23 per $CO_2$ allowance (June 17, 2009)

The proceeds of the $CO_2$ allowance auctions will be used for consumer benefit, as determined by each of the participating states, by funding projects and programs for energy efficiency and clean energy technology.

Another feature of the RGGI is that generators only have to demonstrate that they hold enough $CO_2$ allowances to meet their $CO_2$ emissions every three years. Also, offsets that are of the RGGI's specified type and geographic scope can be used to fulfill up to 3.3 percent of a compliance obligation. The RGGI does have provisions in place that allow the control period to be extended (to a fourth year) and the offset amount (ten percent) and geographic scope to be expanded if the per $CO_2$ allowance price is above \$10 (in 2005 dollars) for a long enough period of time. Lastly, an unlimited number of $CO_2$ allowances can be banked for future use (though $CO_2$ allowances cannot be borrowed from future years) as the $CO_2$ allowances in the RGGI do not expire.

Though the RGGI is the only cap and trade program for $CO_2$ emissions to be implemented in the United States, other programs are currently in discussion. At the Federal level, United States Representatives Henry Waxman (D-CA) and Edward Markey (D-MA) propose to reduce United States GHG emissions via the ACESA. This bill passed

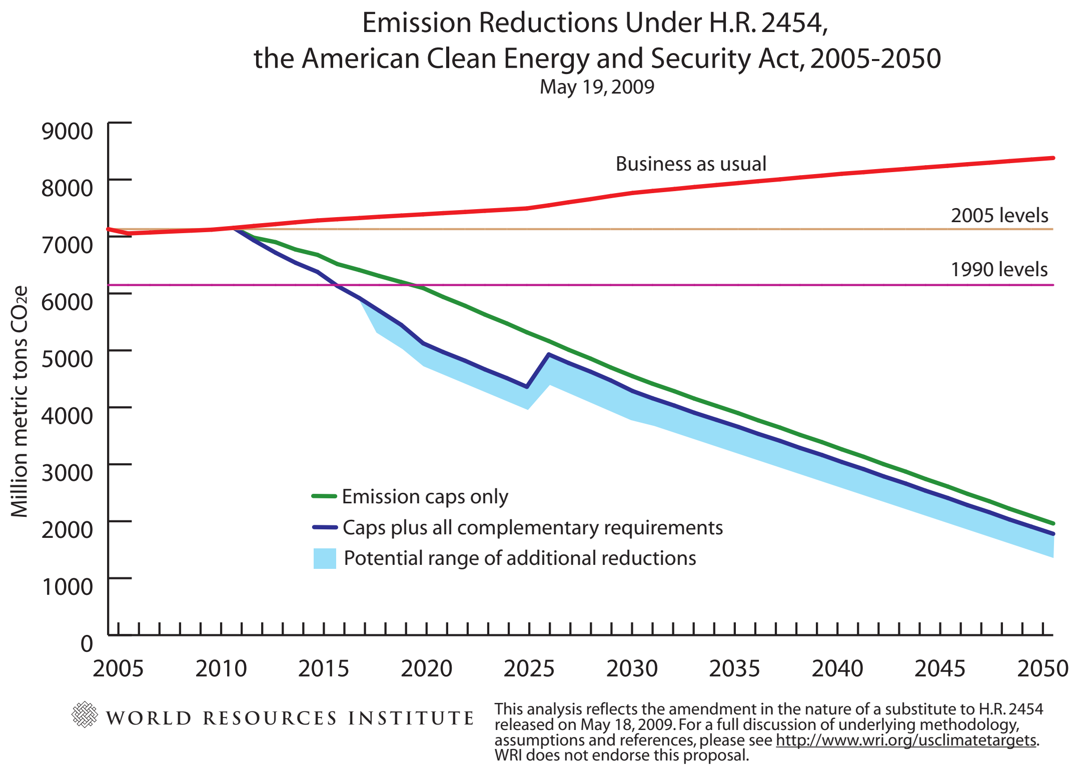


Figure 2.2: ACESA target GHG emissions

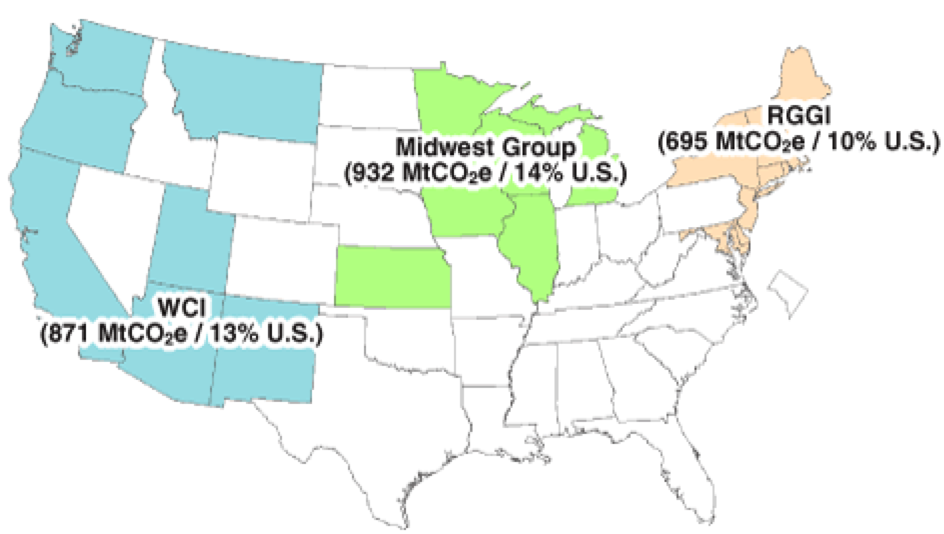


Figure 2.3: GHG emissions of regional cap and trade initiatives

the House of Representatives by a vote of 219 to 212 on June 26, 2009 [19]. The proposed emission reductions of the ACESA are shown in Figure 2.2 [11].

In addition to the proposed Federal legislation, state-driven initiatives to reduce GHG emissions are also underway in the Western Climate Initiative and Midwestern Greenhouse Gas Reduction Accord. In total, the states participating in each of the three programs depicted in Figure 2.3 [5][1] comprise 37 percent of United States emissions.

[1] "[Greenhouse gas] emissions from Canadian Provinces participating in the Midwest Accord and [Western Climate Initiative] are not included here. $MtCO_2e$ is million metric tons of carbon dioxide equivalent per year. Percentages are total of U.S. emissions."

CHAPTER 3

# WHEN THE TRANSPORT PATHS OF COMMODITIES AND THE EXTERNALITIES THEY GENERATE DIVERGE: ELECTRICITY AS AN EXAMPLE

## 3.1 Overview of Theoretical Analysis

The theoretical model presented in this chapter closely examines the interrelationship between electric reliability and environmental pollution to determine if competitive markets for electricity and either global or criteria air pollutants can achieve the socially optimal solution.

The methodology chosen to examine this question is to compare the solution reached by a social planner who maximizes a generalized social welfare function to the optimal result reached by each individual consumer if faced with a competitive market. This methodology is executed three times. The first use of the methodology compares the socially optimal outcome to the market solution while solely focusing on electric reliability. The second and third uses of the methodology include global and criteria air pollutants, respectively.

## 3.2 Description of the Model

There are $i = 1, \ldots, I$ locations, or buses, where each location is a node or connection point in the transmission system. The physical relationship of these locations is assumed to be small enough that each location faces the same electric reliability and that each location has its own air quality due to criteria pollutant emissions and distribution patterns.

An example of such a model size would be the New York City or Boston metropolitan areas.

There is a single resource in the economy, with maximum availability $G$, that can be used to produce electricity for consumption, electricity for electric reliability, mitigate pollution, or produce all other goods that consumers value. When using the resource to produce electricity for either consumption or electric reliability, both global and criteria air pollutants are created.

At each location, there is one representative consumer, who is the aggregate representation of all consumers at location $i$. Each representative consumer has utility function $u_i$ that is dependent upon five variables: individual real electric power consumption $x_i$, individual consumption of all other goods $y_i$ (a use of $G$), the air quality at all locations due to a global pollutant $\alpha$, the air quality at the consumer's location due to a criteria pollutant $\gamma_i$, and the electric reliability of the bulk power electric system $\beta$. Each consumer's utility is increasing in all of these variables. There is a social welfare function $W$ that weights each consumer's utility.

Also at each location, there is at most one fossil-fired generation unit that produces electricity. Each generation unit transforms the resource used to generate electricity for consumption, $z_i^g$ (a use of $G$), into electricity, $g_i$, by the function $R_i$, so $g_i = R_i(z_i^g)$. Similarly, each generation unit transforms the resource used to be able to generate additional electricity for electric reliability, $z_i^r$ (a use of $G$), into electricity, $r_i$, by the same function $R_i$, so $r_i = R_i(z_i^r)$.

Electric reliability, $\beta$, is modeled by requiring each generation unit to provide electric generation in addition to that which is needed to satisfy consumer demand. So, if generation unit $i$ is scheduled to produce $g_i$ units of electricity for consumers to use, it is required to produce an additional $r_i = \beta g_i$ units of electricity to satisfy electric reliability. It is assumed that $\beta \geq 0$. Unlike the units of electricity created for consumption, the units of electricity created for electric reliability do not flow over the transmission lines. This construction of electric reliability is a simplifying qualitative assumption compared to reality, where generators are paid in a separate market for making additional generating capacity available, not additional electricity.

The exogenous variables $P_i^{min}$ and $P_i^{max}$ denote each generator's upper and lower electricity production bounds. The sum of generation of electricity used for consumption and electric reliability must fall within these bounds.

At each generation unit, the emissions of the global pollutant are produced according to the function $e_i^\alpha = E_i^\alpha(g_i, r_i, w_i^\alpha)$, where $w_i^\alpha$ (a use of $G$) is the amount of the resource used to reduce emissions of the global pollutant of the generator at location $i$. The emissions of the criteria pollutant are produced according to the function $e_i^\gamma = E_i^\gamma(g_i, r_i, w_i^\gamma)$, where $w_i^\gamma$ is the amount of the resource used to reduce emissions of the criteria pollutant of the generator at location $i$. The air quality at all locations caused by the global pollutant is defined by the function $\alpha = Q^\alpha(e_1^\alpha, \ldots, e_I^\alpha)$ while the air quality at each location caused by the criteria pollutant is defined by the $I$ functions $\gamma_i = Q_i^\gamma(e_1^\gamma, \ldots, e_I^\gamma)$. By substitution, functions $A$ and $\Gamma_i$ are defined as follows:

$$\alpha = A(z_1^g, z_1^r, w_1^\alpha, \ldots, z_I^g, z_I^r, w_I^\alpha) \equiv Q^\alpha(E_1^\alpha(g_1, r_1, w_1^\alpha), \ldots, E_I^\alpha(g_I, r_I, w_I^\alpha)) \quad (3.1)$$

$$\gamma_i = \Gamma_i(z_1^g, z_1^r, w_1^\gamma, \ldots, z_I^g, z_I^r, w_I^\gamma) \equiv Q_i^\gamma(E_1^\gamma(g_1, r_1, w_1^\gamma), \ldots, E_I^\gamma(g_I, r_I, w_I^\gamma)),\ \forall\, i \quad (3.2)$$

The $L$ electric transmission lines are modeled as a lossless DC system. Each of the transmission lines has a maximum carrying capacity of electricity of $M_l$. The bus susceptance matrix, $B$, is a linear approximation of net power injections (from demand and generation) at each bus as a function of voltage phase angles. The branch susceptance matrix, $C$, is a linear approximation of power flows on each line as a function of voltage phase angles. In the definitions of both $B$ and $C$, voltage angle refers to the difference in the phase of the sinusoidal voltage at a bus, relative to the reference bus (bus 1 is assumed to be the reference bus in this model).

It is assumed that the exogenously defined consumer, generation, and transmission line variables are defined so that the electric grid operates competitively. Thus, it is assumed that all prices are not subject to monopolist manipulation.

## 3.3 Electric Reliability

To begin, $\beta$, the level of electric reliability provided for the entire electric system, is considered as a variable in the model while environmental pollution is added in subsequent sections. Appendix A.1 provides the detailed mathematical results that are summarized in this section.

### 3.3.1 Social Planner

The social planner solves the following social welfare maximization problem:

$$\max_{\substack{x_i, y_i, \beta, \\ g_i, r_i, z_i^g, z_i^r, \theta_i}} \quad W(u_1(x_1, y_1, \beta), \ldots, u_I(x_I, y_I, \beta)) \tag{3.3}$$

$$\ni \quad g_i = R_i(z_i^g), \; \forall \, i \tag{3.4}$$

$$r_i = R_i(z_i^r), \; \forall \, i \tag{3.5}$$

$$x_i - g_i = \sum_{j=1}^{I} B_{ij}\theta_j, \; \forall \, i \tag{3.6}$$

$$r_i = \beta g_i, \; \forall \, i \tag{3.7}$$

$$\sum_{j=1}^{I} y_j + \sum_{j=1}^{I} z_j^g + \sum_{j=1}^{I} z_j^r \leq G \tag{3.8}$$

$$P_i^{min} \leq g_i + r_i \leq P_i^{max}, \; \forall \, i \tag{3.9}$$

$$\sum_{j=1}^{I} C_{lj}\theta_j \leq |M_l|, \; \forall \, l \tag{3.10}$$

$$\theta_1 = 0 \tag{3.11}$$

Objective function (3.3) is a generalized welfare function that accounts for the utility of each consumer in the model. The utility of each consumer $i$ is a function of their consumption of electricity $x_i$, all other goods $y_i$, and the level of electric reliability provided to all consumers in the model, $\beta$.

Constraint (3.4) describes how the single resource in the economy is transformed into electricity generated for consumption for each generation unit. Constraint (3.5) describes how the single resource in the economy is transformed into electric reliability for each generation unit. Constraint (3.6) specifies that the net power injection due to demand and generation for consumption (but not for electric reliability) at each bus $i$ must be equal to the sum of all of the power injections used for electricity consumption coming from all other buses in the model to bus $i$. Constraint (3.7) defines the relationship between the level of electric reliability chosen and the number of units of electricity generated to meet that standard. Constraint (3.8) is the resource constraint, requiring that total amount of the resource consumed for the generation of electricity for consumption, generation of electricity for electric reliability, and all other goods does not exceed the total availability of the resource. Constraint (3.9) requires that the sum of electricity generated for consumption and electric reliability must be within each generation unit's physical operating constraints. Constraint (3.10) requires that the amount of electricity traveling over each transmission line does not exceed the physical carrying capacity of that line. The maximum carrying capacity of each transmission line, $M_l$, is expressed in an absolute value because electricity can flow over a transmission line in either direction between two buses, $i$ and $j$. By construction of the model, one direction of flow is the "positive" direction (i.e. from bus $i$ to bus $j$) and the other direction of flow is the "negative" direction (i.e. from bus $j$ to bus $i$). Finally, constraint (3.11) sets the voltage angle at bus 1, the reference bus, to a reference value of zero.

The results of this maximization yield that the following results must hold at an optimal solution (an endogenous variable evaluated at its optimal solution is noted by $\cdot^*$), where $\lambda_i^*$ are the $I$ Lagrange multipliers for constraint (3.6), $\kappa_i^*$ are the $I$ Lagrange multipliers for constraint (3.7), $\rho^*$ is the Lagrange multiplier for constraint (3.8), $\mu_i^*$ and $\tau_i^*$ are the $2I$ Langrange multipliers for constraint (3.9), and $\delta_l^*$ and $\sigma_l^*$ are the $2L$

Langrange multipliers for constraint (3.10):

$$\frac{\frac{\partial u_i(\cdot)}{\partial x_i}}{\frac{\partial u_i(\cdot)}{\partial y_i}} = \frac{\lambda_i^*}{\rho^*},\ \forall\, i \tag{3.12}$$

$$\sum_{j=1}^{I} \frac{\frac{\partial u_j(\cdot)}{\partial \beta}}{\frac{\partial u_j(\cdot)}{\partial y_j}} = \frac{\sum_{j=1}^{I} \kappa_j^* R_j(z_j^{g*})}{\rho^*} \tag{3.13}$$

$$\frac{R_i'(z_i^{g*})}{R_i'(z_i^{r*})} = \frac{\kappa_i^* + \mu_i^* - \tau_i^*}{\lambda_i^* - \kappa_i^*\beta^* + \mu_i^* - \tau_i^*},\ \forall\, i \tag{3.14}$$

$$\sum_{j=1}^{I} \lambda_j^* B_{ji} = \sum_{l=1}^{L} \delta_l^* C_{li} - \sum_{l=1}^{L} \sigma_l^* C_{li},\ \forall\, i \tag{3.15}$$

### 3.3.2 Individual Consumer

Consider the individual consumer's perspective of a competitive market. Each individual consumer at location $i$ solves the following utility maximization problem:

$$\max_{x_i, y_i, \beta} \quad u_i(x_i, y_i, \beta) \tag{3.16}$$

$$\ni \quad \lambda_i x_i + \rho y_i + \kappa_i \beta \leq m_i \tag{3.17}$$

Objective function (3.16), is consumer $i$'s utility function. Constraint (3.17) is consumer $i$'s budget constraint, where $\lambda_i$ is the price of electricity used for consumption to consumer $i$, $\rho$ is the cost of all other goods to all consumers, $\kappa_i$ is the price of electric reliability for consumer $i$, and $m_i$ is consumer $i$'s wealth allocation, where $m_i$ is defined in terms of consumer $i$'s allocation of all other goods, $\bar{y}_i$, so that $m_i \equiv \rho \bar{y}_i$.

In order for endogenous variables $x_i^*$, $y_i^*$, and $\beta^*$ to be optimal, the following first order conditions must be satisfied:

$$\frac{\frac{\partial u_i(\cdot)}{\partial x_i}}{\frac{\partial u_i(\cdot)}{\partial y_i}} = \frac{\lambda_i}{\rho} \tag{3.18}$$

$$\frac{\frac{\partial u_i(\cdot)}{\partial \beta}}{\frac{\partial u_i(\cdot)}{\partial y_i}} = \frac{\kappa_i}{\rho} \tag{3.19}$$

## 3.4 Electric Reliability Results

This section summarizes the results from the optimization problem that considers electric reliability, but not environmental pollutants.

### 3.4.1 Electricity Consumption and All Other Goods

Equations (3.12) and (3.18) are the same and require that, at an optimal solution, each consumer's marginal rate of substitution between the consumption of electricity and all other goods must be equal to the price ratio of electricity produced for consumption and all other goods. Each consumer's optimal marginal rate of substitution is matched pairwise with its own price ratio. Therefore, consumption of electricity and all other goods are private goods and a competitive market will yield the socially optimal outcome, provided the socially desired allocation of welfare is given by an initial allocation of income to each individual resulting in the desired outcome.

### 3.4.2 Electric Reliability

Equations (3.13) and (3.19) are not the same. Equation (3.13), the result from the social planner's maximization, requires that in order to set the optimal level of electric reliability that each consumer receives, the sum of each consumer's marginal rate of substitution between electric reliability and all other goods must be equated to the marginal cost of its efficient production.

On the other hand, equation (3.19), the result from an individual consumer's utility maximization, requires that each consumer's marginal rate of substitution between electric reliability and all other goods must be equal to the price ratio of electric reliability and all other goods. Because a particular consumer's marginal rate of substitution is generally less than that of its sum over all consumers, too little electric reliability will tend to be provided by a market mechanism without further government adjustment. Therefore, electric reliability is a public good and a competitive market will not yield the socially optimal outcome.

### 3.4.3 Electricity Generation

Equation (3.14) outlines the marginal rate of transformation between using the resource for the production of electricity for consumption and electric reliability. The optimal solution for each generator is dependent on the prices it faces for the production of electricity and electric reliability, as well as the cost of transmission congestion and the units' physical limitations. Each generator's optimal marginal rate of transformation is matched pair-wise with its own prices. Therefore, electricity generation for both consumption and reliability are private goods and a competitive market will yield the socially optimal outcome, given that a regulatory authority establishes the optimal level of electric reliability that generation units must provide.

### 3.4.4 Voltage Angles and the Transmission Grid

Equations (3.13), (3.14), and (3.15) all support the importance of a central planner, such as a regional transmission organization (RTO), in dispatching the electric grid.

As described in Section 3.4.2, equation (3.13) highlights the public good nature of electric reliability. The optimal provision of electric reliability will not be achieved when left to a competitive market, hence the need of a central planner to estimate the optimal value for all consumers.

The cost of producing electricity, as outlined in equation (3.14), includes the physical limitations of each generation unit. Whenever a unit is operating at its upper or lower physical limit, the coinciding Lagrange multiplier is strictly positive. This cost of the physical limitation is important for a central planner to take into consideration when dispatching the electric grid as it limits the amount of electricity and electric reliability available at each particular location in the network.

The transmission line constraints outlined in equation (3.15) would not be considered without a central planner. In particular, because the price of electricity at each bus, $\lambda_i^*$, is the same $\forall\, i$ only when $\delta_l^* = \sigma_l^* = 0,\ \forall l$. These Langrage multipliers are only all equal to zero when none of the transmission lines are operating at their physical carrying capacity limit. If the amount of electricity generated exceeded the line limits, a blackout might ensue.

In total, these results demonstrate the importance of a "smart market" that gives different prices at different nodes, provided in real-time to all buyers and sellers of electricity that reflect existing transmission constraints. Thus, the more efficient price signals will optimally alleviate transmission line congestion, further reducing the overall cost of providing a reliable electricity supply to consumers.

## 3.5 Global Pollutant and Electric Reliability

Now, both $\beta$, the level of electric reliability provided for the entire electric system, and $\alpha$, the air quality at all locations due to the global pollutant, are included in the model. Appendix A.2 provides the detailed mathematical results that are summarized in this section.

### 3.5.1 Social Planner

The social planner solves the following social welfare maximization problem:

$$\max_{\substack{x_i, y_i, \alpha, \beta, \\ g_i, r_i, z_i^g, z_i^r, w_i^\alpha, \theta_i}} \quad W(u_1(x_1, y_1, \alpha, \beta), \ldots, u_I(x_I, y_I, \alpha, \beta)) \tag{3.20}$$

$$\ni \quad g_i = R_i(z_i^g), \ \forall\, i \tag{3.21}$$

$$r_i = R_i(z_i^r), \ \forall\, i \tag{3.22}$$

$$e_i^\alpha = E_i^\alpha(g_i, r_i, w_i^\alpha), \ \forall\, i \tag{3.23}$$

$$\alpha = Q^\alpha(e_1^\alpha, \ldots, e_I^\alpha) \tag{3.24}$$

$$x_i - g_i = \sum_{j=1}^{I} B_{ij}\theta_j, \ \forall\, i \tag{3.25}$$

$$r_i = \beta g_i, \ \forall\, i \tag{3.26}$$

$$\sum_{j=1}^{I} w_j^\alpha + \sum_{j=1}^{I} y_j + \sum_{j=1}^{I} z_j^g + \sum_{j=1}^{I} z_j^r \leq G \tag{3.27}$$

$$P_i^{min} \leq g_i + r_i \leq P_i^{max}, \ \forall\, i \tag{3.28}$$

$$\sum_{j=1}^{I} C_{lj}\theta_j \leq |M_l|, \ \forall\, l \tag{3.29}$$

$$\theta_1 = 0 \tag{3.30}$$

Objective function (3.20) is identical to objective function (3.3) except objective function (3.20) now includes $\alpha$ as a variable in each consumer's utility function.

Constraints (3.23) and (3.24) are new relative to the social planner's optimization problem from Section 3.3.1. Constraint (3.23) specifies how much of the global pollutant is created from each generator, given the output of electricity generated for consumption, electricity generated for electric reliability, and the amount of the resource dedicated to global pollutant emission reductions. Constraint (3.24) specifies how global pollutant emissions from each generator aggregate into a single air quality that all individuals consume. Constraints (3.27) and (3.8) are identical except that constraint (3.27) now includes the use of the resource for reducing global pollutant emissions via $w_i^{\alpha}$.

Constraints (3.21), (3.22), (3.25), (3.26), (3.28), (3.29), and (3.30) are identical to constraints (3.4), (3.5), (3.6), (3.7), (3.9), (3.10), and (3.11), respectively.

The results of this maximization yield that the following equations must hold at an optimal solution, where $\psi^*$ is the Lagrange multiplier for the combination of constraints (3.23) and (3.24) as defined by (3.1) and all other Lagrange multipliers are the same as in Section 3.3.1:

$$\frac{\frac{\partial u_i(\cdot)}{\partial x_i}}{\frac{\partial u_i(\cdot)}{\partial y_i}} = \frac{\lambda_i^*}{\rho^*}, \ \forall\, i$$
$$\sum_{j=1}^{I} \frac{\frac{\partial u_j(\cdot)}{\partial \alpha}}{\frac{\partial u_j(\cdot)}{\partial y_j}} = \frac{\psi^*}{\rho^*} \tag{3.31}$$
$$\sum_{j=1}^{I} \frac{\frac{\partial u_j(\cdot)}{\partial \beta}}{\frac{\partial u_j(\cdot)}{\partial y_j}} = \frac{\sum_{j=1}^{I} \kappa_j^* R_j(z_j^{g*})}{\rho^*}$$
$$\frac{R_i'(z_i^{g*})}{R_i'(z_i^{r*})} = \left(\frac{\rho^* - \psi^* \frac{\partial A(\cdot)}{\partial z_i^{g*}}}{\lambda_i^* - \kappa_i^* \beta^* + \mu_i^* - \tau_i^*}\right)\left(\frac{\kappa_i^* + \mu_i^* - \tau_i^*}{\rho^* - \psi^* \frac{\partial A(\cdot)}{\partial z_i^{r*}}}\right), \ \forall\, i \tag{3.32}$$
$$\frac{\partial A(\cdot)}{\partial w_i^{\alpha}} = \frac{\rho^*}{\psi^*}, \ \forall\, i \tag{3.33}$$
$$\sum_{j=1}^{I} \lambda_j^* B_{ji} = \sum_{l=1}^{L} \delta_l^* C_{li} - \sum_{l=1}^{L} \sigma_l^* C_{li}, \ \forall\, i$$

### 3.5.2 Individual Consumer

Consider the individual consumer's perspective of a competitive market. Each individual consumer at location $i$ solves the following utility maximization problem:

$$\max_{x_i, y_i, \alpha, \beta} \quad u_i(x_i, y_i, \alpha, \beta) \tag{3.34}$$

$$\ni \quad \lambda_i x_i + \rho y_i + \psi \alpha + \kappa_i \beta \leq m_i \tag{3.35}$$

Objective function (3.34) is consumer $i$'s utility function, which, compared to objective function (3.16), now includes $\alpha$. Constraint (3.35) is consumer $i$'s budget constraint, which, compared to constraint (3.17), now includes the cost to improve the global pollutant air quality.

In order for endogenous variables $x_i^*$, $y_i^*$, $\alpha^*$, and $\beta^*$ to be optimal, the following first order conditions must be satisfied:

$$\begin{aligned}
\frac{\frac{\partial u_i(\cdot)}{\partial x_i}}{\frac{\partial u_i(\cdot)}{\partial y_i}} &= \frac{\lambda_i}{\rho} \\
\frac{\frac{\partial u_i(\cdot)}{\partial \alpha}}{\frac{\partial u_i(\cdot)}{\partial y_i}} &= \frac{\psi}{\rho} \qquad (3.36) \\
\frac{\frac{\partial u_i(\cdot)}{\partial \beta}}{\frac{\partial u_i(\cdot)}{\partial y_i}} &= \frac{\kappa_i}{\rho}
\end{aligned}$$

## 3.6 Criteria Pollutant and Electric Reliability

Instead of including a global pollutant as is done in Section 3.5, this section replaces $\alpha$ with $\gamma_i$, the air quality at each location due to the criteria pollutant. Appendix A.3 provides the detailed mathematical results that are summarized in this section.

### 3.6.1 Social Planner

The social planner solves the following social welfare maximization problem:

$$\max_{\substack{x_i, y_i, \gamma_i, \beta, \\ g_i, r_i, z_i^g, z_i^r, w_i^\gamma, \theta_i}} \quad W(u_1(x_1, y_1, \gamma_1, \beta), \ldots, u_I(x_I, y_I, \gamma_I, \beta)) \tag{3.37}$$

$$\ni \quad g_i = R_i(z_i^g), \; \forall\, i \tag{3.38}$$

$$r_i = R_i(z_i^r), \; \forall\, i \tag{3.39}$$

$$e_i^\gamma = E_i^\gamma(g_i, r_i, w_i^\gamma), \; \forall\, i \tag{3.40}$$

$$\gamma_i = Q_i^\gamma(e_1^\gamma, \ldots, e_I^\gamma), \; \forall\, i \tag{3.41}$$

$$x_i - g_i = \sum_{j=1}^{I} B_{ij}\theta_j, \; \forall\, i \tag{3.42}$$

$$r_i = \beta g_i, \; \forall\, i \tag{3.43}$$

$$\sum_{j=1}^{I} w_j^\gamma + \sum_{j=1}^{I} y_j + \sum_{j=1}^{I} z_j^g + \sum_{j=1}^{I} z_j^r \le G \tag{3.44}$$

$$P_i^{min} \le g_i + r_i \le P_i^{max}, \; \forall\, i \tag{3.45}$$

$$\sum_{j=1}^{I} C_{lj}\theta_j \le |M_l|, \; \forall\, l \tag{3.46}$$

$$\theta_1 = 0 \tag{3.47}$$

Objective function (3.37) is identical to objective function (3.20) except objective function (3.37) now includes $\gamma_i$ as a variable in each consumer's utility function instead of $\alpha$.

Constraints (3.40) and (3.41) are very similar to constraints (3.23) and (3.24). Constraint (3.40) specifies the how much of the criteria pollutant is created for each generator, given the output of electricity generated for consumption, output of electricity generated for electric reliability, and the amount of the resource dedicated to criteria pollutant emission reductions. Constraint (3.41) specifies how criteria pollutant emissions from each generator aggregate into an air quality for each location, which each individual consumer in that location consumes. Constraint (3.44) is identical to constraint (3.27) except constraint (3.44) now includes the use of the resource for reducing criteria pollutant emissions via $w_i^\gamma$.

Constraints (3.38), (3.39), (3.42), (3.43), (3.45), (3.46), and (3.47) are identical to constraints (3.4), (3.5), (3.6), (3.7), (3.9), (3.10), and (3.11), respectively.

The results of this maximization yield that the following equations must hold at an optimal solution, where $\phi_i^*$ are the $I$ Lagrange multipliers for the combination of constraints (3.40) and (3.41) as defined by (3.2) and all other Lagrange multipliers are the same as in Section 3.3.1:

$$\frac{\frac{\partial u_i(\cdot)}{\partial x_i}}{\frac{\partial u_i(\cdot)}{\partial y_i}} = \frac{\lambda_i^*}{\rho^*}, \ \forall \, i$$

$$\frac{\frac{\partial u_i(\cdot)}{\partial \gamma_i}}{\frac{\partial u_j(\cdot)}{\partial y_j}} = \frac{\phi_i^*}{\rho^*}, \ \forall \, i \tag{3.48}$$

$$\sum_{j=1}^{I} \frac{\frac{\partial u_j(\cdot)}{\partial \beta}}{\frac{\partial u_j(\cdot)}{\partial y_j}} = \frac{\sum_{j=1}^{I} \kappa_j^* R_j(z_j^{g*})}{\rho^*}$$

$$\frac{R_i'(z_i^{g*})}{R_i'(z_i^{r*})} = \left( \frac{\rho^* - \sum_{j=1}^{I} \phi_j^* \frac{\partial \Gamma_j(\cdot)}{\partial z_i^g}}{\lambda_i^* - \kappa_i^* \beta^* + \mu_i^* - \tau_i^*} \right) \left( \frac{\kappa_i^* + \mu_i^* - \tau_i^*}{\rho^* - \sum_{j=1}^{I} \phi_j^* \frac{\partial \Gamma_j(\cdot)}{\partial z_i^r}} \right), \ \forall \, i \tag{3.49}$$

$$\sum_{j=1}^{I} \phi_j^* \frac{\partial \Gamma_j(\cdot)}{\partial w_i^\gamma} = \rho^*, \ \forall \, i \tag{3.50}$$

$$\sum_{j=1}^{I} \lambda_j^* B_{ji} = \sum_{l=1}^{L} \delta_l^* C_{li} - \sum_{l=1}^{L} \sigma_l^* C_{li}, \ \forall \, i$$

### 3.6.2 Individual Consumer

Consider the individual consumer's perspective of a competitive market. Each individual consumer at location $i$ solves the following utility maximization problem:

$$\max_{x_i, y_i, \gamma_i, \beta} \quad u_i(x_i, y_i, \gamma_i, \beta) \tag{3.51}$$

$$\ni \quad \lambda_i x_i + \rho y_i + \phi_i \gamma_i + \kappa_i \beta \leq m_i \tag{3.52}$$

Objective function (3.51) is consumer $i$'s utility function, which, compared to objective function (3.34), now includes $\gamma_i$, the criteria pollutant, instead of $\alpha$, the global pollutant. Constraint (3.52) is consumer $i$'s budget constraint, which, compared to constraint (3.35), now includes the cost to improve the criteria pollutant air quality rather than the global air quality.

In order for endogenous variables $x_i^*$, $y_i^*$, $\gamma_i^*$, and $\beta^*$ to be optimal, the following first order conditions must be satisfied:

$$\begin{aligned} \frac{\frac{\partial u_i(\cdot)}{\partial x_i}}{\frac{\partial u_i(\cdot)}{\partial y_i}} &= \frac{\lambda_i}{\rho} \\ \frac{\frac{\partial u_i(\cdot)}{\partial \gamma_i}}{\frac{\partial u_i(\cdot)}{\partial y_i}} &= \frac{\phi_i}{\rho} \\ \frac{\frac{\partial u_i(\cdot)}{\partial \beta}}{\frac{\partial u_i(\cdot)}{\partial y_i}} &= \frac{\kappa_i}{\rho} \end{aligned} \tag{3.53}$$

## 3.7 Environmental Pollution and Electric Reliability Results

This section summarizes the new results beyond those presented in Section 3.4 from the optimization problems that consider electric reliability with global and criteria air pollutants, Sections 3.5 and 3.6, respectively.

### 3.7.1 Global Pollutant

Similar to the result for electric reliability in Section 3.4.2, equations (3.31) and (3.36) are not the same. Equation (3.31), the result from the social planner's maximization, requires that in order to set the optimal level of global air quality that each consumer receives, the sum of each consumer's marginal rate of substitution between global air quality and all other goods must be equated to the marginal cost of its efficient production. On the other hand, equation (3.36), the result from an individual consumer's utility maximization, requires only that each individual's marginal rate of substitution between global air quality and all other goods must be equated to the marginal cost of its efficient production.

Because a particular consumer's marginal rate of substitution is generally less than that of its sum over all consumers, too little global air quality will generally be provided by a market mechanism without further government adjustment. Therefore, global air quality is a public good and a competitive market will not yield the socially optimal outcome.

### 3.7.2 Criteria Pollutant

Equations (3.48) and (3.53) are the same, making it look like the criteria pollutant is a private good. This mathematical result is due to the model's assumption of a single representative consumer at each location. The use of a single consumer is a representative aggregation of many consumers at each node. If the model considered individual consumers at each location, instead of one representative consumer, it would be clear that the consumption of a single local air quality at each location would be a public good from the perspective of the consumers at that each location. For example, suppose that in each of the $I$ locations, there are $N$ consumers, not one. All $N$ consumers at location $i$ will consume a criteria pollutant air quality of $\gamma_i$.

This is very similar to how all consumers at each of the $I$ locations consume the same air quality due to the global pollutant, $\alpha$. Hence, a similar result to the global air pollutant will follow, such that the optimal provision of the public good from the social planner's perspective will take into the consideration the sum of each consumer's marginal rates of substitution. On the other hand, each individual consumer will only consider his or her own marginal rate of substitution. Thus, criteria air pollution is not a private good, rather a local public good at each location.

### 3.7.3 Electricity Generation

The optimal solution for each generation unit in the social planner's problems considering global and criteria pollution have an important difference. This difference determines whether, given that a central planner sets transmission grid dependent variables, profit maximizing generation units are able to achieve the socially optimal solution in a competitive market.

First, consider the social planner's problem when considering a global pollutant. Equation (3.32) outlines the optimal decision of how each generator should allocate the single resource to the production of electricity for consumption and for electric reliability. Equation (3.33) outlines the optimal choice for investment in global pollutant emission reductions. Though both of these equations are complicated expressions that rely on a central planner setting the optimal values for the public goods, $\alpha^*$ and $\beta^*$, they both are pair-wise matched for each generation unit. Therefore, if a central planner set the optimal values for variables that are dependent on the electric grid, $\mu_i^*$ and $\tau_i^*$, each individual generation unit would be able to achieve the socially optimal solution in a competitive market when considering a global air pollutant.

Consider on the other hand equations (3.49) and (3.50) from the social planner's problem when considering a criteria pollutant. Both of these equations contain summations over the optimal decisions of all other generation units in the model. Therefore, even if a central planner set the optimal values for variables that are dependent on the electric grid, each individual generator would still need to compensate for the optimal choices of all other generation units. These cross-terms make the socially optimal solution in a competitive market unlikely when considering a criteria air pollutant.

CHAPTER 4

# AN ECONOMIC AND ENGINEERING NUMERICAL SIMULATION ANALYSIS OF THE IMPACT OF CARBON DIOXIDE, SULFUR DIOXIDE, AND NITROGEN OXIDE REGULATION ON EMISSIONS AND COSTS IN THE ELECTRIC POWER SECTOR

## 4.1 Overview of Numerical Simulations

Numerical simulations of a highly simplified electricity network and airshed for Northeastern North America are exercised under varying combinations of variables allowing for meaningful research in two primary areas. The first area is understanding the policy impacts of environmental regulation, such as the RGGI, when faced with various constraints on the electric grid, such as a required reserve margin. The second area is to study varying methodological practices for modeling the electric grid by comparing AC and DC simulation results as well as examine line constraints.

## 4.2 Simulation Model Variables

Eleven different variables, each discussed in detail in the following sections, are adjusted to create each individual simulated scenario. Some of the variables are binary, while others have multiple options. The variables considered in this modeling are:

1. AC or DC model (2 options),
2. transmission line constraints (2 options),
3. seasonal availability (2 options),

4. drought (2 options),
5. required reserve margin (2 options),
6. seasonal variation (16 options),
7. price of $CO_2$ allowances (8 options),
8. price of $SO_2$ allowances (4 options),
9. price of $NO_x$ allowances (4 options),
10. the applicability of emission costs by geographic location (2 options), and
11. the applicability of emission costs by generation unit size (2 options).

Variables 1. through 3. are used to study the various methodological practices for modeling the electric grid, while variables 4. through 11. are used to understand the policy impacts of environmental regulation. A total of $2^7 * 4^2 * 8 * 16 = 262,144$ scenarios are simulated.[1]

### 4.2.1 AC and DC modeling

A common simplified method of modeling a non-linear AC system is to model it as if it were a linear DC system. General Electric's MAPS™ and PowerWorld Corporation's Simulator® are two software packages that use this modeling technique. DC systems remove voltage constraints and simplify stability constraints by imposing tighter flow constraints, known as "proxy limits," on transmission lines. These linear simplifications and proxy limits are designed to approximate the characteristics of the system under a specific pattern of operation. The more a system departs from that pattern of operation, the less accurate the results are by using these "proxy limits."

[1]Because the cases of applying a $0/tonne $CO_2$ emission cost to different geographically located and sized generation units is redundant, there are only 245,760 unique scenarios.

The reason to focus on this issue is that electric power systems are predominantly AC. Furthermore, the characteristics of an electric power network can strongly influence the effects of environmental policies that are applied to the power sector. The flows in such a network do not follow the shortest or most under-utilized route from where power is generated to where it is consumed. Rather, electricity flows follow laws of physics known as Kirchoff's Laws. The resulting constraints and flow equations affect which set of generation units satisfies electricity demand at the lowest cost in each moment. If emerging environmental regulations cause the electric system to operate under conditions substantially different than at present, then these constraints and flow equations also play a major role in determining the effects of a $CO_2$ emission regulation on emissions, cost, prices, profits, fuel use, and leakage.

So, for example, more stringent emission regulations are likely to result in less use of coal-burning generation units and more use of gas-burning generation units. Coal-burning and gas-burning generation units have different geographic locations, so more stringent environmental regulations may drastically alter the pattern of operation of the power system. In addition to dispatch changes inside the regulated region, leakage might occur across regulated and unregulated program boundaries. Leakage refers to the increased emissions from generators outside of a regulated region as a result of the increased marginal operating cost for generators inside a regulated region. This is of particular concern because leakage could potentially partially, or completely, offset the emission reductions from inside the regulated area with increased emissions from outside the regulated area.

Several studies of the economic and environmental effects of $CO_2$ regulation have been conducted to examine the issue of leakage. First, ICF International was hired by the RGGI participating states to use their Integrated Planning Model® (IPM®) to examine the impacts of implementing the RGGI. The IPM® is a national model that includes very detailed data on every generator in the United States as well as emission rates for various pollutants, including $CO_2$. However, it assumes that transmission is unconstrained within regions (New York, for example, has five regions) and constrained by aggregate flow limits between adjacent regions [10]. Though easier to solve with this simplifying assumption, the model does not even represent simplified DC flows.

Similarly, the Haiku model employed by Resources for the Future uses constraints between regions and it models generation using hundreds of characteristic "typical" generators including typical emission characteristics, but does not incorporate widely varying locational specific characteristics [16].

Though the two models differ in how they treat fuel prices, investment, retirement of generators, etc., both studies suggest that leakage occurs but is not so great as to negate the intended $CO_2$ emission reductions by the RGGI [3].

Because every model is a simplification of reality, this research sets out to determine whether or not, and which, simplifications are acceptable. Detailed network modeling is quite difficult and may not be important enough to justify the effort required. One of the goals of this simulation is to test the hypothesis that it is important to model the network with the added realism of AC constraints and flow equations.

### 4.2.2 Transmission Line Constraints

In order to understand the importance of the transmission grid in the model (in comparison to IPM® and Haiku modeling), simulations are run both with and without the enforcement of transmission line capacity constraints.

### 4.2.3 Seasonal Availability

A seasonal availability constraint on generators, which in reality is usually self-imposed because of the costs of starting-up and shutting-down some types of large thermal units, may be relevant for modeling purposes. In the basic optimal power flow (OPF) problem formulation, all generation units are assumed to be available to generate power between each unit's minimum and maximum generating capability, i.e. each generator must be dispatched to generate at least its minimum generating capacity in the optimal solution. This minimum generation imposition for each generator is unrealistic because the actual dispatch of the electric grid never requires all generators to produce simultaneously at or above their minimum. Rather, generators bid into an auction the price at which they are willing to generate electricity and the dispatcher chooses the generators that will meet demand at the lowest cost to operate the electric grid. Therefore, this constraint is relaxed in the seasonal availability constrained dispatch scenarios by shutting down eligible units for an entire season.

Because gas- and oil-fired generation units have very short startup times, they are assumed to have a generating capacity ranging from zero at its minimum to the specific unit's maximum generating capability. Therefore, gas- and oil-fired generation units are not considered in the seasonal availability algorithm.

On the other hand, coal-fired generation units have a very long startup time and are therefore the only generators considered for shut down via the seasonal availability algorithm.[2] The candidate list for shutdown is built by ranking each coal-fired generation unit by its time-weighted mean profits over the entire season. The coal-fired generation unit with the least profits over the entire season is shutdown sequentially and each subse-

[2]Nuclear-powered generation units also have a very long startup time, but because they have a marginal cost of electricity generation close to zero, they are not considered in the seasonal availability algorithm.

quent seasonal scenario is run with that generator unavailable. The process of removing the least profitable coal-fired generation unit continues until either the time-weighted mean objective function (i.e. the total cost of operating the electric system) increases, at least one of the seasonal scenarios results in an infeasible solution, or the candidate list is exhausted.

### 4.2.4 Drought

One type of event that could cause a change in generator availability expectations is a drought, which reduces the amount of hydropower available for dispatch. Hydropower is one of the two largest sources of electricity generation that produces virtually zero air emissions (the other being nuclear) and a drought could cause a significant shift in the optimal dispatching and emissions in a situation with high emissions prices.

A drought scenario is modeled by reducing hydropower capacity to be 80 percent of its maximum generating capacity under normal conditions. This percentage is chosen based on the past 40 years of data (ending in 1999) that recorded four "severe" or "extreme" droughts in the Northeastern United States. Each drought lasted between one to five years, resulting in a reduction of rainfall of at least approximately 20 percent of normal (the largest was a 50 percent reduction from normal from 1984–1985) [12].

### 4.2.5 Operating Reserve Margin

In the true dispatch of the electric grid, a reserve margin of available generation in excess of actual demand is mandated to ensure electric reliability. The operating reserve margin is calculated by considering the loss of the largest generator operating on the system, which translates to about two to three percent, depending on the system. When a reserve margin is enforced in a scenario, each RTO maintains its own reserve margin, which is set to be three percent of the summer peak load for all seasonal scenarios.

### 4.2.6 Seasonal Variation

#### Electric Demand

The electric demand modeled in the simulations is based on 16 typical hour types that represent one calendar year. For each of the four seasons: fall (October–November), winter (December–February), spring (March–April), and summer (May–September), the total electric demand is further split into four bins: peak, high, medium, and low.

In each season, the hours of 2007 total system demand (i.e. the sum all RTO's demand) is ranked. The top five percent of the hours are the peak bin, the next 25 percent of the hours is the high bin, the next 40 percent of the hours is the medium bin, and the low bin is the lowest 30 percent of the hours. To create a single value for each bin in each RTO, the demand in each RTO is the mean of the demand in that RTO in the corresponding time bin. The number of hours per year that each of these 16 different demand levels occur is outlined in Table 4.1.

Table 4.1 also presents the amount of electricity demanded in each region and hour type, as a proportion of the summer peak electric demand as provided in Allen, Lang, and Ilić [1].[3] Demand for electricity is highest during the hour that represents the highest-load hours of the summer and is lowest during the hour that represents the lowest-load hours of the fall. Electric demand is assumed to be perfectly inelastic be-

[3]The Allen, Lang, and Ilić model does not have any electricity demanded in the Quebec RTO, so its proportion is set to zero.

cause few electricity consumers currently face real-time electricity prices. Each hour type uses the average electric demand in each region during the corresponding hours based on 2007 hourly loads in each ISO.

Table 4.1: Electric demand as a ratio of summer peak electric demand

| Demand type | | Hours/ Year | PJM | NYISO | ISO-NE | IESO | Quebec | Maritimes |
|---|---|---|---|---|---|---|---|---|
| Fall | Peak | 73 | 0.67 | 0.68 | 0.69 | 0.74 | 0.00 | 0.90 |
| | High | 366 | 0.59 | 0.63 | 0.64 | 0.70 | 0.00 | 0.90 |
| | Medium | 586 | 0.52 | 0.56 | 0.57 | 0.64 | 0.00 | 0.86 |
| | Low | 439 | 0.42 | 0.45 | 0.43 | 0.53 | 0.00 | 0.74 |
| Winter | Peak | 108 | 0.72 | 0.73 | 0.76 | 0.85 | 0.00 | 1.15 |
| | High | 540 | 0.65 | 0.68 | 0.70 | 0.79 | 0.00 | 1.08 |
| | Medium | 864 | 0.58 | 0.61 | 0.62 | 0.71 | 0.00 | 1.01 |
| | Low | 648 | 0.48 | 0.50 | 0.49 | 0.60 | 0.00 | 0.91 |
| Spring | Peak | 73 | 0.67 | 0.67 | 0.72 | 0.80 | 0.00 | 1.09 |
| | High | 366 | 0.57 | 0.62 | 0.63 | 0.72 | 0.00 | 0.97 |
| | Medium | 585 | 0.52 | 0.56 | 0.57 | 0.65 | 0.00 | 0.91 |
| | Low | 439 | 0.43 | 0.46 | 0.45 | 0.55 | 0.00 | 0.84 |
| Summer | Peak | 184 | 0.87 | 0.87 | 0.87 | 0.87 | 0.00 | 0.87 |
| | High | 918 | 0.72 | 0.75 | 0.72 | 0.75 | 0.00 | 0.84 |
| | Medium | 1469 | 0.57 | 0.62 | 0.59 | 0.65 | 0.00 | 0.79 |
| | Low | 1102 | 0.44 | 0.48 | 0.45 | 0.53 | 0.00 | 0.69 |

### Availability of Generation Units

Generation units are sometimes not available for operation because of maintenance or repair. Rather than simulate discrete outages, maximum and minimum real power capability of each generation unit is scaled using an average availability rate. Availability is highest in the summer and winter seasons because that is the most profitable time of year to produce electricity. The spring and fall are relatively low demand seasons with low prices making them the best time to do maintenance.

For fossil fuel generation units, this availability adjustment is made by first multiplying the real and reactive power generation capacity[4] of all fossil fueled units by 0.9613, which is the proportion of the time they were not having unplanned outages in 2006 according to the NERC [14]. That result is then multiplied by an availability modifier specific to the hour type, as shown in Table 4.2. The fossil fuel adjustment factors differ from one in proportion to the amount by which the load during the respective hour type deviates from the load during the summer peak hour type.

Table 4.2: Generator capability scaling as a ratio of summer peak availability

| Demand type | | Hours/ Year | Coal | Oil | Gas | Hydro | Nuclear | Wind | Refuse |
|---|---|---|---|---|---|---|---|---|---|
| Fall | Peak | 73 | 0.93 | 0.93 | 0.93 | 0.97 | 0.73 | 1.00 | 1.00 |
| | High | 366 | 0.90 | 0.90 | 0.90 | 0.96 | 0.73 | 1.00 | 1.00 |
| | Medium | 586 | 0.87 | 0.87 | 0.87 | 0.95 | 0.73 | 1.00 | 1.00 |
| | Low | 439 | 0.83 | 0.83 | 0.83 | 0.93 | 0.73 | 1.00 | 1.00 |
| Winter | Peak | 108 | 0.96 | 0.96 | 0.96 | 0.98 | 0.84 | 1.00 | 1.00 |
| | High | 540 | 0.93 | 0.93 | 0.93 | 0.97 | 0.84 | 1.00 | 1.00 |
| | Medium | 864 | 0.90 | 0.90 | 0.90 | 0.96 | 0.84 | 1.00 | 1.00 |
| | Low | 648 | 0.85 | 0.85 | 0.85 | 0.94 | 0.84 | 1.00 | 1.00 |
| Spring | Peak | 73 | 0.93 | 0.93 | 0.93 | 0.98 | 0.75 | 1.00 | 1.00 |
| | High | 366 | 0.90 | 0.90 | 0.90 | 0.96 | 0.75 | 1.00 | 1.00 |
| | Medium | 585 | 0.87 | 0.87 | 0.87 | 0.95 | 0.75 | 1.00 | 1.00 |
| | Low | 439 | 0.83 | 0.83 | 0.83 | 0.93 | 0.75 | 1.00 | 1.00 |
| Summer | Peak | 184 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | High | 918 | 0.94 | 0.94 | 0.94 | 0.98 | 1.00 | 1.00 | 1.00 |
| | Medium | 1469 | 0.89 | 0.89 | 0.89 | 0.95 | 1.00 | 1.00 | 1.00 |
| | Low | 1102 | 0.83 | 0.83 | 0.83 | 0.93 | 1.00 | 1.00 | 1.00 |

The economics of using non-fossil fuel generation units (those relying on hydro, nuclear, wind, or refuse) are different from the economics of dispatching fossil fuel generation units. For nuclear, refuse, wood, and run-of-river hydropower generation units, the marginal cost of operation is typically close to zero. The non-fossil fuel generation

[4]The quantity of real power, usually in units of megawatts, a generation unit is capable of producing is commonly referred to as that generator's capacity. In fact though, all generation units have both real and reactive generation limits. The generation unit's "capability curve" plots the tradeoff between the unit's ability to generate real and reactive power.

units are modeled as having a marginal cost of zero,[5] but their maximum capacities are adjusted according to the hour type, as shown in Table 4.2.

For the nuclear units, these maximum capacity adjustments represent outages for refueling and other maintenance, which are most commonly scheduled in the fall and spring. For the hydro units, these adjustments represent the output decisions that result from water availability, environmental constraints on river flow, and intertemporal optimization of the use of available water. For wind and refuse, each of which constitutes only a miniscule proportion of total generation capacity, it is assumed that output does not vary by hour type, as shown in Table 4.2.

Allen, Lang, and Ilić report the approximate output from each non-fossil generator type at each bus in Northeast North America during the summer peak hour that they model, ignoring types that provide less than a few percent of the output at the bus. This output is taken as the maximum output in any hour type from that generation type at that bus, since the summer peak hour is the hour with greatest total demand.[6]

For hydro, the adjustment to hourly demand in Table 4.2 makes the total capacity factor (output divided by capacity) for the year equal to that reported by NERC in [14]. The hydro adjustment factors deviate from one in proportion to the amount by which load during the respective hour type deviates from load during the summer peak hour type.

For nuclear, the adjustment to hourly demand in Table 4.2 makes the total capacity

[5] A result of having a marginal cost of zero is that the unit generates at its maximum available capacity all, or almost all, of the time.

[6] For the hydro units taken together, this output is approximately 63 percent of the output that the units can produce when they all have an abundance of water. Sometimes, they do produce more than this amount of power, but much of the variation in water availability does not correlate with this model's hour types. Average hydropower output per month is close to being constant. Even in the spring, when snow is melting, Northeastern North America hydropower output is only about five percent higher than output in other seasons. This model does not represent this seasonal difference, but its effect on the results would be small.

factor for the year equal to the weighted equivalent availability factor[7] of 0.8899 reported by NERC in [14]. The nuclear adjustment factors are the same for all hour types of a season because nuclear generators generally have constant output when they operate. The nuclear adjustment factors deviate from one in proportion to the amount by which load during the respective hour type deviates from load during the summer peak hour type.

### 4.2.7 Emissions Prices

Various $CO_2$, $SO_2$, and $NO_x$ prices are considered in the simulations. These prices are chosen in order to cover a wide range of pricing (i.e. policy) scenarios — from very low to very high — to simulate both where prices have been recently and where they could go in the future. Furthermore, the wide range of prices considered allows the plotting of smoother curves when analyzing the impacts of price changes for each pollutant.

Table 4.3 outlines the eight prices used for $CO_2$. In particular, a $CO_2$ price of $3.51 is used because that is the auction clearing price from the March 2009 RGGI auction for 2009 allocation year $CO_2$ allowances.[8] The highest price chosen, $250 per metric tonne, is selected because at that price the dispatch of generators will certainly change and because it is an extremely high price relative to current experience, but is a level that might be reached in the future.

Table 4.3: Emission prices for $CO_2$ ($/metric tonne)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $CO_2$ | 0 | 3.51 | 10 | 25 | 50 | 100 | 175 | 250 |

[7]Roughly speaking, an "availability factor" indicates the proportion of the time a unit is not out of operation for maintenance or repair.

[8]At the time of running the simulations, this was the most recent RGGI auction price.

Table 4.4 outlines the four prices used for each of $SO_2$ and $NO_x$. A non-zero price of $SO_2$ and $NO_x$ is required because environmental standards are already in place for these pollutants, while this is not the case for $CO_2$. Furthermore, the emission rates of the generation units assume a non-zero price of $SO_2$ and $NO_x$.

Table 4.4: Emission prices for $SO_2$ and $NO_x$ ($/metric tonne)

| | | | | |
|---|---|---|---|---|
| $SO_2$ | 200 | 700 | 1,200 | 1,700 |
| $NO_x$ | 500 | 2,000 | 3,500 | 5,000 |

### 4.2.8 Applicability of Emission Costs

**By Geographic Location**

One of the main worries for all regional environmental programs is leakage. As generators inside the regulated area are forced to pay for $CO_2$ permits, the prices at which they can offer to profitably sell power rises compared to the prices at which generators outside of the regulated region can offer to profitably sell power. This may cause emissions outside of the regulated area to increase, partially (if not completely) offsetting the emission reductions in the regulated area, as cheaper, more polluting, power is imported from the non-regulated area to the regulated area.

Therefore, in an effort to understand the impacts of leakage, $CO_2$ emission costs are applied in two different ways in the simulation model:

1. to all generation units both in the United States and Canada, and
2. only to RGGI area generation units.

In both of these cases, $SO_2$ and $NO_x$ emission costs are applied to every generation unit in the simulation model.[9]

The geographic representation of the RGGI is approximate. One of the buses in the Allen, Lang, and Ilić model is enormous, and includes parts of states participating in the RGGI as well as parts of states not participating in the RGGI. The RGGI states included in this bus are all of Delaware and parts of New Jersey and Maryland. This bus is counted as being entirely outside of the RGGI area in order to maintain transmission constraints between RGGI and non-RGGI parts of the system.

**By Generation Unit Size**

As currently implemented, the RGGI exempts generation units with a nameplate capacity of less than 25 megawatts (MW). Therefore, simulations are run both enforcing and not enforcing this size limitation to evaluate the impact of such exemptions of relatively small generation units.

## 4.3 Simulation Data

These numerical simulations use the 2007 electric power system because complete data are readily available, allowing a representation of what is essentially the current system to be constructed. Investment in new generation and transmission capacity is a slow process, so it is worthwhile to examine what the existing possibilities are for $CO_2$ reduction in response to an emission tax or cap and trade program.

[9] Canada has its own $SO_2$ and $NO_x$ regulations, though it works closely with the United States because about half of the acid rain in eastern Canada comes from the United States. For simplicity, it is assumed that all generators, both in the United States and Canada, face the same $SO_2$ and $NO_x$ prices [7].

The underlying data used in these simulations are compiled from multiple sources and in some case are adjusted as described in the following sections.

### 4.3.1 Buses and Transmission Lines

The buses and transmission lines of the physical network used in these simulations are shown in Figure 4.1 [1]. The network includes buses and transmission lines from New York, New England, New Jersey, Delaware, Washington, D.C., and parts of Pennsylvania, Maryland, Ontario, Quebec, and the Maritime Provinces. Allen, Lang, and Ilić developed this network representation as a simplified version of the Northeastern North America power grid, which has thousands of buses and transmission lines. Their simplified representation aggregates the Northeastern North America grid into 36 buses and 121 transmission lines.

The simplified network approximates thermal, voltage, and reactive power constraints of the real system and "…some of the major intra- and inter-area congestion patterns are preserved…" [1]. Consequently, using a simplified representation of the AC network, with dozens instead of thousands of buses and transmission lines, is necessary because it allows the operation of the system to be solved. Given that no completed study of $CO_2$ regulation includes an AC network, it is at least reasonable to examine the issues raised by $CO_2$ regulation using an available, if simplified, AC network model.

Furthermore, the optimization problem associated with determining the operation of an AC network has more constraints, is non-linear, and is complex compared to DC system. It is this tradeoff between the complexity of an AC model to the speed of calculation of a DC model that will be explored in terms of its effect on emission patterns and system operating cost.

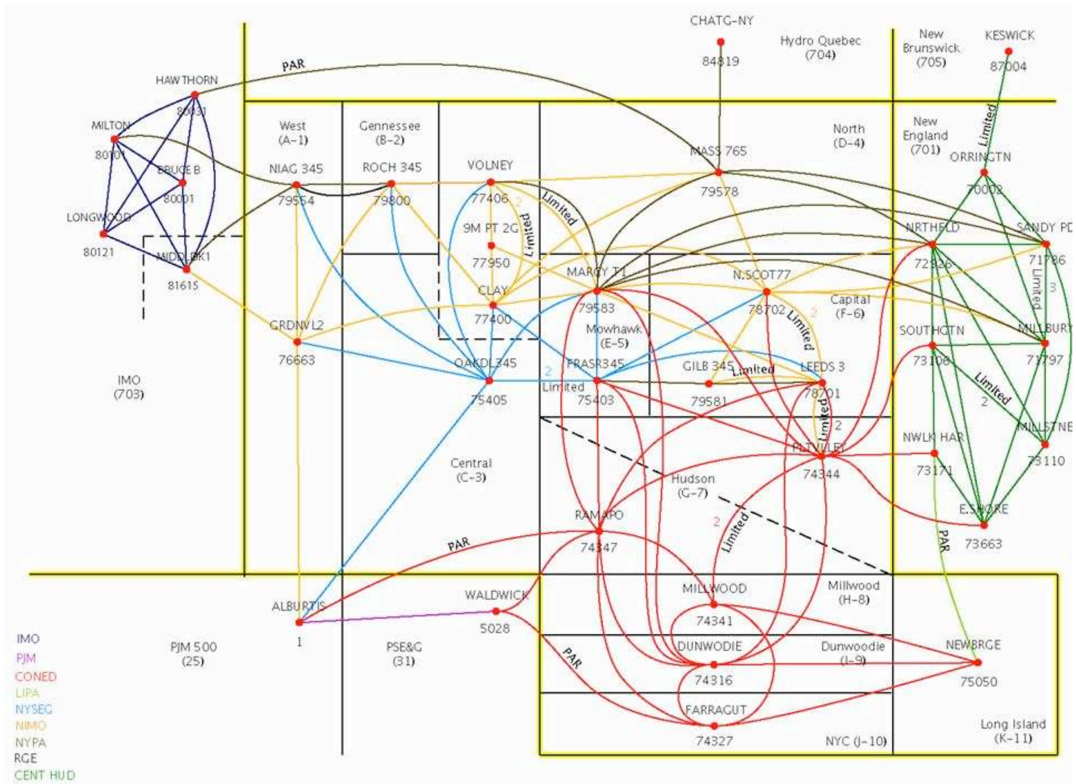


Figure 4.1: Physical network used in the simulation model

### 4.3.2 Generation Units

The generator data at each bus are a combination of data from Energy Visuals, Inc., Allen, Lang, and Ilić, and the EPA [20]. The data on generation units purchased from Energy Visuals, Inc. came from the 2006 reliability planning process of the Multiregional Modeling Working Group, the group responsible for examining the adequacy of the electric power system in the Eastern United States and Canada under the auspices of the NERC. The data consists of the generator units projected to be operational in the summer of 2008. There are approximately 2,000 such units in the region modeled. For each unit, its name, minimum and maximum real and reactive generating capability, fuel type, fuel use per megawatt-hour (MWh) of output, fuel price in 2007, longitude, and latitude is known.

### Real Power Capacity

The total amount of fossil-fueled real power capacity of each generator is calculated using data from Allen, Lang, and Ilić. At each of their 36 buses, they report total real and reactive generation capacity (in the second-to-last, fifth, and sixth columns of the generation block of their appendix), total real and reactive generation in the summer peak load hour (in the third and fourth columns of the generation block of their appendix), and approximate percentage of that real-power generation coming from each fuel type (coal, gas, oil, nuclear, hydro, refuse, and wind). At buses with more than zero percent of their real power generation from fossil fuels (coal, gas, and oil), fossil-fueled real power capacity is calculated as the total real power generation capacity minus generation from non-fossil sources.[10]

### Reactive Power Capacity

The total amount of reactive power capacity at each bus, which is important for voltage stability, is calculated by combining two parts. The first part is a constant reactive power injection that represents the amount of reactive power that the transmission system produces or absorbs at each bus. In this reduced model, many of these constant injections are negative and have large magnitudes, as a result of the model reduction.

The second part of the reactive power capacity is the reactive power capabilities of the generation units. Each generator has a range of reactive outputs it can produce, with a maximum that is typically positive and a minimum that is typically negative. The capabilities of the fossil-fueled generators are scaled so that the total maximum and

[10]This produces estimated fossil-fueled generation capacity of 93,772 MW. If instead fossil-fueled real-power capacity is calculated as total real-power generation capacity multiplied by the percent of generation coming from fossil fuels, the total is 92,515 MW.

minimum reactive capacity at each bus, including the fixed injection and the reactive capabilities at the non-fossil-fueled units, is ten percent farther from the fixed reactive power injection than the reactive power capacity totals in Allen, Lang, and Ilić. The total reactive power ranges are made wider than in Allen, Lang, and Ilić's model in order to represent relatively inexpensive opportunities for providing reactive power by other means that are not otherwise represented in this model, such as the installation of capacitors and inductors.

It is assumed that a generation unit can provide reactive power up to its maximum limit or down to its minimum limit without cost if that unit is running. The only generation units turned off in the optimization are coal-fired generators, as part of their seasonal availability economic calculation. Therefore, a need for reactive power can contribute to keeping a coal-fired generation unit turned on and available within a particular season.

**Emission Rates**

From the fuel type, fuel use per MWh, and carbon content of different fuel types [6] the $CO_2$ emission rate per MWh of each generation unit can be calculated. $SO_2$ and $NO_x$ emissions are calculated using EPA reports of $SO_2$ and $NO_x$ emissions and generation output. These reports contain information for most fossil-fueled generation units with capacities over 25 MW. The units in the EPA data are matched with units in the Energy Visuals, Inc. data based on name or owner name, fuel, and generation capacity. Latitude and longitude are used to verify the match. For units not included in the EPA data, the emissions rates in Table 4.5, which are the average emissions rates of the units that appear in both the EPA and Energy Visuals, Inc. data, are assigned.

Table 4.5: Assumed emission rates when unknown (tonne/MWh)

| Fuel | $SO_2$ rate | $NO_x$ rate |
|---|---|---|
| Coal | 0.006202 | 0.000824 |
| Diesel Oil | 0.000133 | 0.000927 |
| Pipeline Natural Gas | 0 | 0.000136 |
| Residual Oil | 0.000632 | 0.000504 |

**Assignment of Generation Units to Buses**

The assignment of some of the generation units by Allen, Lang, and Ilić to each of their 36 buses is known. The other generation units are assigned by geographic proximity and then scaled by their real power capabilities separately at each bus so that the real power capacity total at each bus matched the total from Allen, Lang, and Ilić.

## 4.4 Optimization Formulation Representing Generator Dispatch

The electricity system simulation software[11] is written in the MATLAB® programming language[12] utilizing the MATPOWER software package,[13] a full AC and DC optimization framework developed at Cornell University, to solve the OPF problem. Like a RTO, MATPOWER solves the OPF problem by minimizing the cost of operating the electric power system subject to the demands and availability of electricity at each node, the transmission capability of each line in the system, and the voltage and stability requirements.

The standard formulation of MATPOWER's AC OPF problem solves for the endogenous variable $x$, for vectors of voltage angles $\Theta$, voltage magnitudes $V_m$, real power

[11] See Appendix B for technical computation information and source code.
[12] See http://www.mathworks.com/products/matlab/ for more information.
[13] See http://www.pserc.cornell.edu/matpower/ for more information.

injections $P_g$, and reactive power injections $Q_g$ [28].[14]

$$x = \begin{bmatrix} \Theta \\ V_m \\ P_g \\ Q_g \end{bmatrix} \tag{4.1}$$

The standard MATPOWER formulation can be extended to include user-defined costs $f_u$ and endogenous variables $z$. For the purposes of these simulations, additional costs are imposed in the objective function to include the cost of the pollutants in the model, $CO_2$, $SO_2$, and $NO_x$.

Therefore, the generalized formulation of the OPF problem takes the following form.

$$\min_{x,z} \quad f(x) + f_u(x,z)$$

$$\ni \quad g(x) = 0 \tag{4.2}$$

$$h(x) \leq 0 \tag{4.3}$$

$$x_{\min} \leq x \leq x_{\max}$$

$$l \leq A \begin{bmatrix} x \\ z \end{bmatrix} \leq u$$

$$z_{\min} \leq z \leq z_{\max} \tag{4.4}$$

Using the theoretical model in Chapter 3 as an example, $x$ in equation (4.1) would be defined as the combined vector of $x_i$ and $\theta_i$. A user defined endogenous variable $z$ would include $z_i$ (in addition to other variables). Constraint (3.6) is an example of constraint (4.2). An example of an inequality constraint outlined in constraint (4.3) is constraint (3.8). Finally, constraint (3.9) provides and example of upper and lower bounded constraints on a variable, as described in constraint (4.4).

[14]The DC OPF problem only solves for $\Theta$ and $P_g$, not $V_m$ or $Q_g$.

It is assumed that in solving the OPF that the generators exist in a competitive market. The numerical simulations (and the theoretical model) do not attempt to analyze the potential for or impacts of exercising market power either in the electricity markets, cap and trade auctions for environmental allowances, or interactions between the two. Therefore, each generator is assumed to offer its entire range of real generation capacity at its (constant in these simulations) marginal cost.

## 4.5 Simulation Results

The results of the numerical simulations can be broken down into two categories. The first category examines environmental policy while the second examines methodological questions.

### 4.5.1 Policy Implications

This section looks at the policy implications of the RGGI predicted by the numerical simulations.

#### Leakage

Leakage is a concern in any regional program and the numerical simulations predict that leakage is an important problem facing the RGGI.

Figure 4.2 depicts the total $CO_2$ emissions, $CO_2$ emissions inside the RGGI area, and $CO_2$ emissions outside the RGGI area. At a RGGI price of \$3.51 per tonne, the

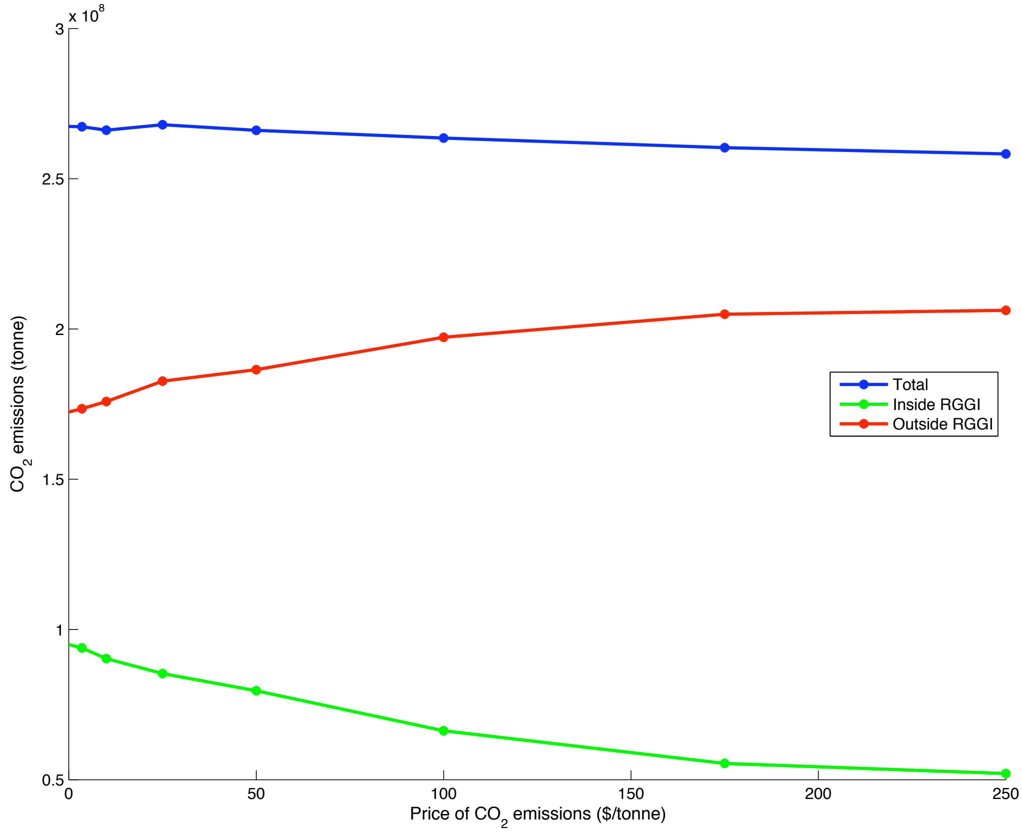


Figure 4.2: Leakage in the RGGI

model[15] predicts a reduction of about 1.15 million tonnes of $CO_2$ inside the RGGI area and an increase of 1.06 million tonnes outside the RGGI area, for a net reduction of 90,000 thousand tonnes of $CO_2$. Even at a very high $CO_2$ price of $250/tonne, the 45 percent reduction of $CO_2$ emissions inside the RGGI area only garner a net reduction of three percent total emissions in the entire model.

Comparing the net impacts of applying $CO_2$ costs to only some of the generators in the model, as is the case in the RGGI, with the case of applying $CO_2$ costs to all generators in the model, the clear difference is shown in Figure 4.3. With a very high $CO_2$ price of $250 tonne, the net $CO_2$ reduction from the RGGI is only a few percent.

[15] Seasonal availability, AC, emission costs to all generators greater than 25 MW in size, no drought, no reserve margin, $SO_2$ =$700/tonne, and $NO_x$ =2,000/tonne.

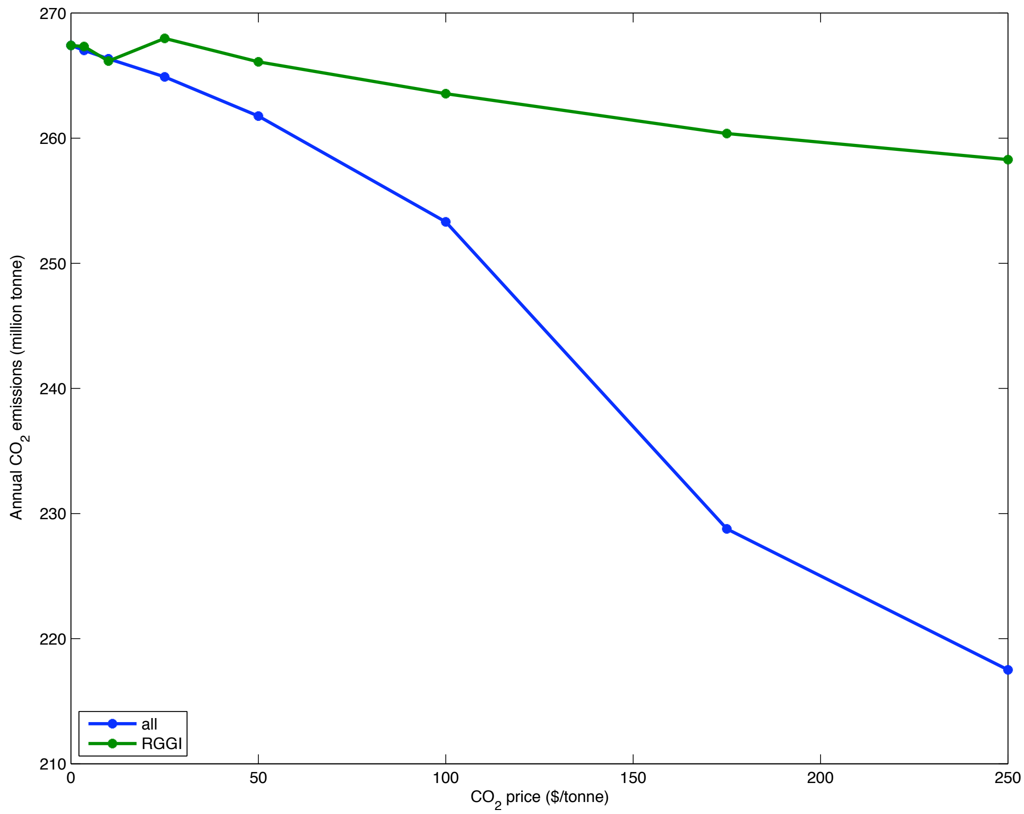


Figure 4.3: $CO_2$ emissions in the RGGI and with all generators facing $CO_2$ costs

On the other hand, when $CO_2$ costs are applied to all generators, an almost 20 percent reduction in $CO_2$ emissions occurs at a price of $250 per tonne.

Thus, the creation of a small regional $CO_2$ program, such as the RGGI, can have a limited net impact compared to a program that encompasses a much larger area. While gross emissions in the regulated area will decrease, the increased importation of relatively cheap, high-emitting generation from outside the program boundary can offset the reductions created by the regional program.

**Cost to Consumers**

The locational-based marginal price (LMP) at each bus provides an indication of how the RGGI will impact electricity prices for consumers. Figure 4.4 shows how various $CO_2$ prices change the time- and load-weighted mean LMP at each bus per year,[16] separated by buses inside and outside the RGGI area.

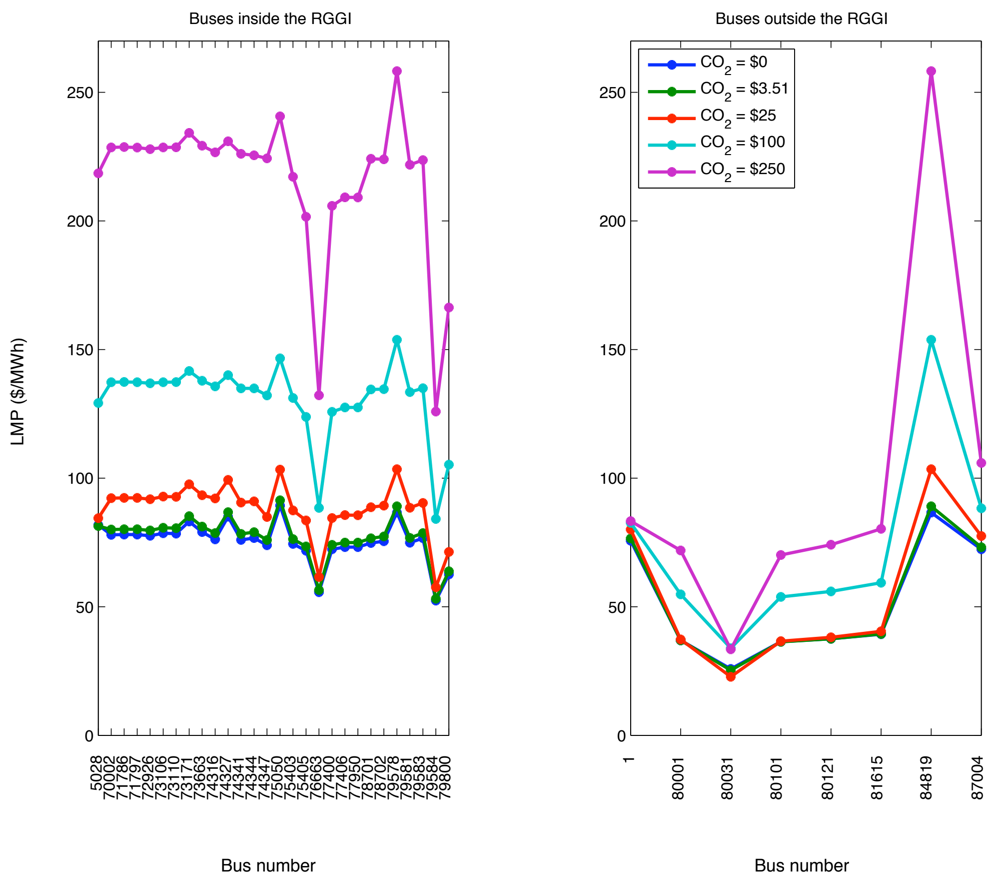


Figure 4.4: The LMP at each bus, both inside and outside the RGGI

At low $CO_2$ prices, for example the last RGGI auction price of $3.51 per tonne, the impact on LMP both inside and outside the RGGI area is quite small. Then, as expected,

[16]Seasonal availability, AC, emission costs to all generators greater than 25 MW in size, no drought, no reserve margin, $SO_2$ =$700/tonne, and $NO_x$ =2,000/tonne.

the LMP at buses inside the RGGI area are more drastically impacted by the imposition of increasingly higher $CO_2$ prices.

Of note inside the RGGI area are buses 76663 and 79584 which are located in northwestern New York State. Both of these buses are primarily serviced by large hydropower facilities (Niagara Falls). At a $CO_2$ price of \$250 per tonne, consumers at these buses are paying electricity prices similar to those paid by others in the RGGI area when the $CO_2$ price was only \$100 per tonne. This occurs because the large amount of non-$CO_2$ emitting hydropower servicing these consumers does not have to pay for costly $CO_2$ allowances. Nevertheless, the LMP at these buses is not constant because the hydropower generators cannot completely fulfill the demand for electricity at these buses and higher cost sources of electricity that use $CO_2$ allowances must be used.

A more aggregated analysis of the cost to consumers is presented in Table 4.6. This table shows, for all $CO_2$ prices, how the mean LMP both inside and outside the RGGI area changes when $CO_2$ costs are applied to all generators and those inside the RGGI area only.[17] From every consumer's perspective, it is cheaper to have the $CO_2$ costs applied only to the RGGI area generators, not applied to all generators in the system. This is especially true for the consumers living outside the RGGI area. The reason for this result is that when $CO_2$ costs are only applied to the RGGI area generators, there is an ability to import cheap power from the non-RGGI area, keeping RGGI area prices lower than if this opportunity was not there. But, when the $CO_2$ costs are applied to all generators, this opportunity disappears and all generators in the system face higher marginal costs of production, so all consumers face higher prices. Note that the exportation of cheap electricity from the non-RGGI area to the RGGI area does come at a price to consumers in the non-RGGI area. The price of electricity outside the RGGI area does

[17]Seasonal availability, AC, line constraints, no drought, no operating reserve margin, $SO_2$ =\$700/tonne, and $NO_x$ =2,000/tonne.

not stay constant. The increased supply of electricity from the non-RGGI area causes its price to increase even though no environmental regulation is imposed on its generators.

Table 4.6: Time- and load-weighted mean LMP ($/MWh)

| $CO_2$ price ($/MWh) | Inside the RGGI all | Inside the RGGI RGGI | Outside the RGGI all | Outside the RGGI RGGI |
|---|---|---|---|---|
| 0 | 70.95 | 70.95 | 63.50 | 63.50 |
| 3.51 | 73.39 | 72.64 | 66.19 | 64.12 |
| 10 | 77.80 | 76.20 | 71.08 | 65.13 |
| 25 | 87.81 | 84.01 | 81.76 | 67.02 |
| 50 | 104.11 | 97.77 | 99.45 | 70.02 |
| 100 | 139.67 | 124.93 | 136.47 | 73.54 |
| 175 | 191.76 | 162.07 | 193.68 | 75.28 |
| 250 | 244.20 | 199.03 | 251.67 | 76.74 |

Thus, regardless of whether the $CO_2$ price is imposed on all generators or only on those in a particular region, the price of electricity will increase for all consumers. Though all consumers will face an increase in their electricity rates, the magnitude of the change is dependent on which generators the $CO_2$ costs are applied. In the case that $CO_2$ costs are applied to all generators, the increase in electricity rates is roughly identical for all consumers. If $CO_2$ costs are applied to only generators in a small, regulated region, those consumers living inside the regulated area will face approximately the same rate increases as when the costs are applied to all generators, while consumers outside the regulated area will face only modest increases in their electricity rates.

### Industry Profit and Fuel Composition

Goulder [8] predicted that a $CO_2$ tax of $25 would reduce profits of the electric power industry by 7.4 percent in 2002. In contrast, Burtraw, Palmer, and Kahn [2] predicted that the RGGI would increase profits for generators by $0.9 billion in 2025. In Burtraw, Palmer, and Kahn's model, the effects are concentrated in the Northeast United States, while Goulder models the nationwide effects of a national American policy. In addition, Goulder uses a general equilibrium model that allows for the installation and removal of industrial plants and equipment. Either of these differences might possibly explain the difference in the signs of their estimated industry profit impacts.

Figure 4.5 shows this model's predictions of the effects on the short-run, aggregate profits of the modeled generators when $CO_2$ emission prices are imposed both on all generators and only RGGI area generators. Note that the added profits are the greatest for the least polluting generators, which can lead to a very different result in the long-run. In particular, as less polluting generators are built, LMPs and therefore profits will be reduced in the long-run. Nevertheless, the short-run distortion in profits is an argument in favor of having the government capture the $CO_2$ allowance fees rather than the generation units.

It is assumed that the generators must pay for all emissions at the specified emission price, and the short-run profits shown are net of these payments. These numerical simulations predict that industry profits increase with the implementation of the RGGI, and this effect increases with the stringency of the policy. This result suggests that, at least in Northeastern North America, the industry as a whole will gain profit as a result of the RGGI regulations, without receiving any emission permits for free or any rebate of emission taxes.

Of course, not all generation units are the same. Though total industry profits will increase, the profits of generators using different fuel types will vary. Figure 4.6 shows the profits of fossil-fired generation units[18] with different levels of $CO_2$ prices. Each bar stacks the profits of coal, oil, and natural gas-fired generation units. For each $CO_2$ price,

[18]The profits of non-fossil-fired generation units are not shown because their profits will always be strictly increasing with $CO_2$ price.

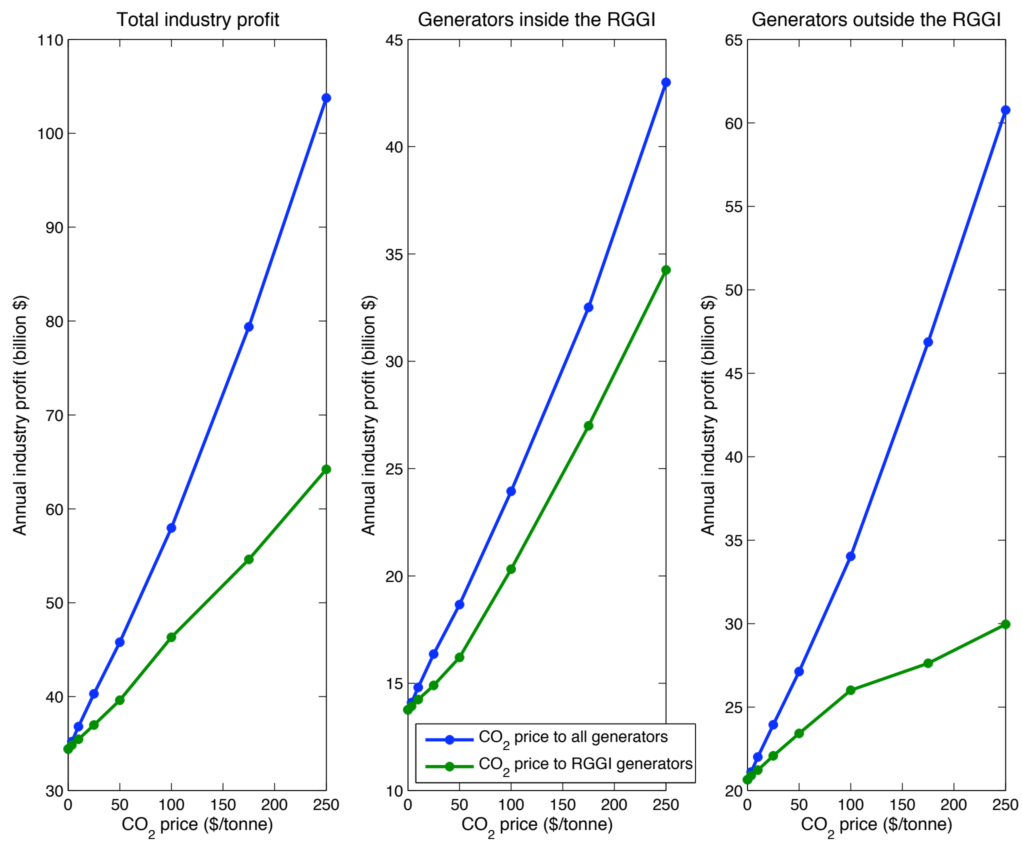


Figure 4.5: Total industry profits

the bar on the left denotes the profits when a $CO_2$ price is imposed on all generators in the model, while the bar on the right only imposes a $CO_2$ price on the generators inside the RGGI area.

When the $CO_2$ prices are imposed on only generators inside the RGGI area, coal profits from outside the RGGI area continue to increase. In this case, the gain in profits earned outside the RGGI area offset the dramatic decrease in profits from inside the RGGI area, thus providing a net an increase in total profits for coal-fired generation as a group.

On the other hand, when $CO_2$ prices are imposed on all generators in the model, the profits of all coal-fired generation fall while natural gas profits increase. Only at about

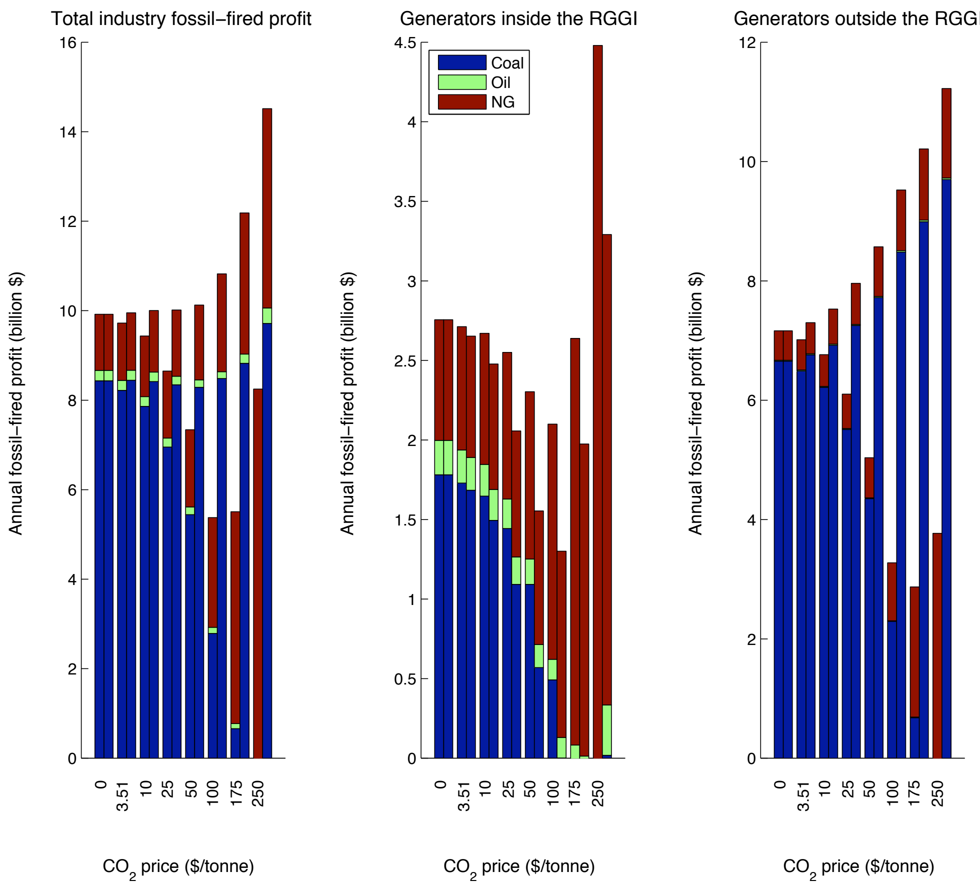


Figure 4.6: Fossil-fired generation profits

\$100/tonne of $CO_2$ does the loss in profit for coal-fired generation become offset by the increase in natural gas-fired generation profit. Hence, the profits fall at first, and then begin to rise once the $CO_2$ price is large enough.

Figure 4.7 demonstrates that the amount of generation by existing fossil-fired generation follows a similar direction as these same units' profits. When $CO_2$ costs are applied to generators in the RGGI area only, imports of electricity from outside the RGGI area increase while the number of MWh generated inside the RGGI area decrease. The imported generation is serviced by increased generation of both natural gas- and coal-fired generation. On the other hand, when $CO_2$ costs are applied to all generators in the model, coal-fired generation decreases everywhere and natural gas-fired generation

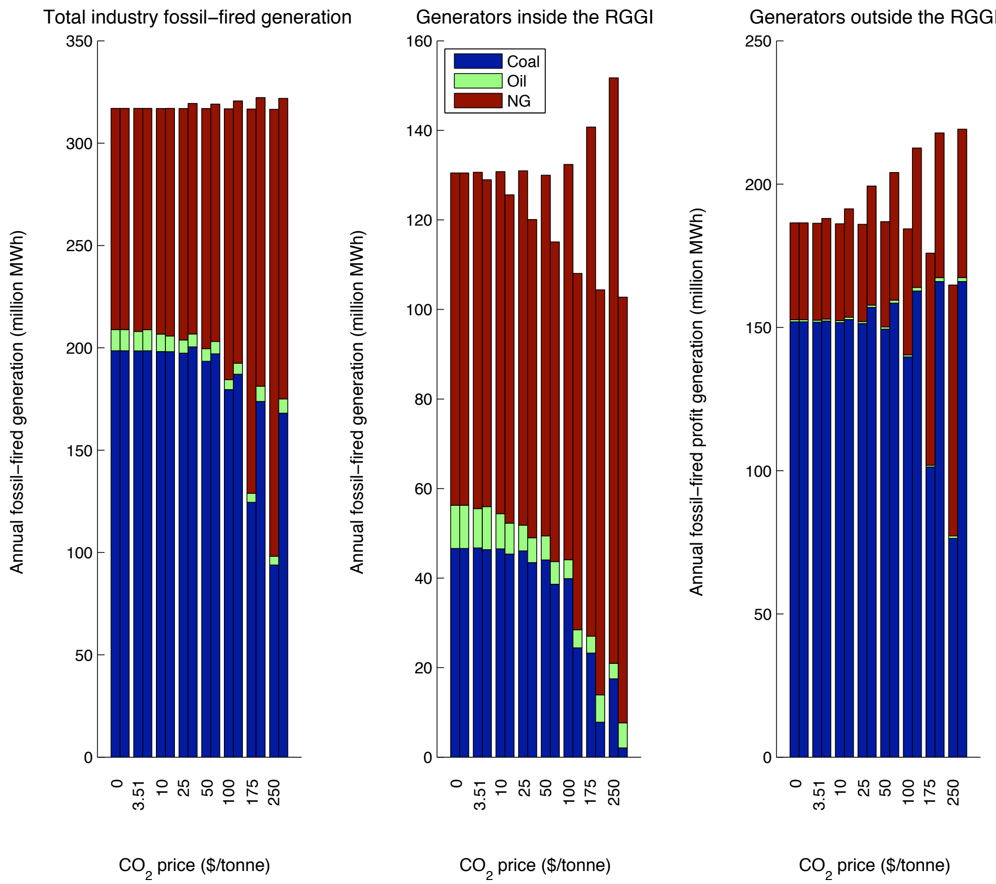


Figure 4.7: Fossil-fired generation

increases.

Thus, the long-run incentive for building new generation facilities depends on the expected $CO_2$ regulation. If the expectation is that a uniform policy will be applied to all generators, then non-emitting generation types, such as nuclear and wind, have a clear incentive to be built. On the other hand, if $CO_2$ policy will remain fragmented to specific regions, coal- and oil-fired generation are still profitable as long as they are constructed outside the regulated region(s).

**Emission Price Volatility — Drought**

A cap and trade program is susceptible to price volatility in response to changes in expected allowance supply or demand. One type of event that could cause such a change is a drought, which reduces the amount of hydropower, one of the two largest power types that are associated with virtually zero $CO_2$ emissions.

Figure 4.8 shows the effect of a drought that reduces hydropower production by 20 percent.[19] In the later years of the RGGI, annual emission reductions of two and a half

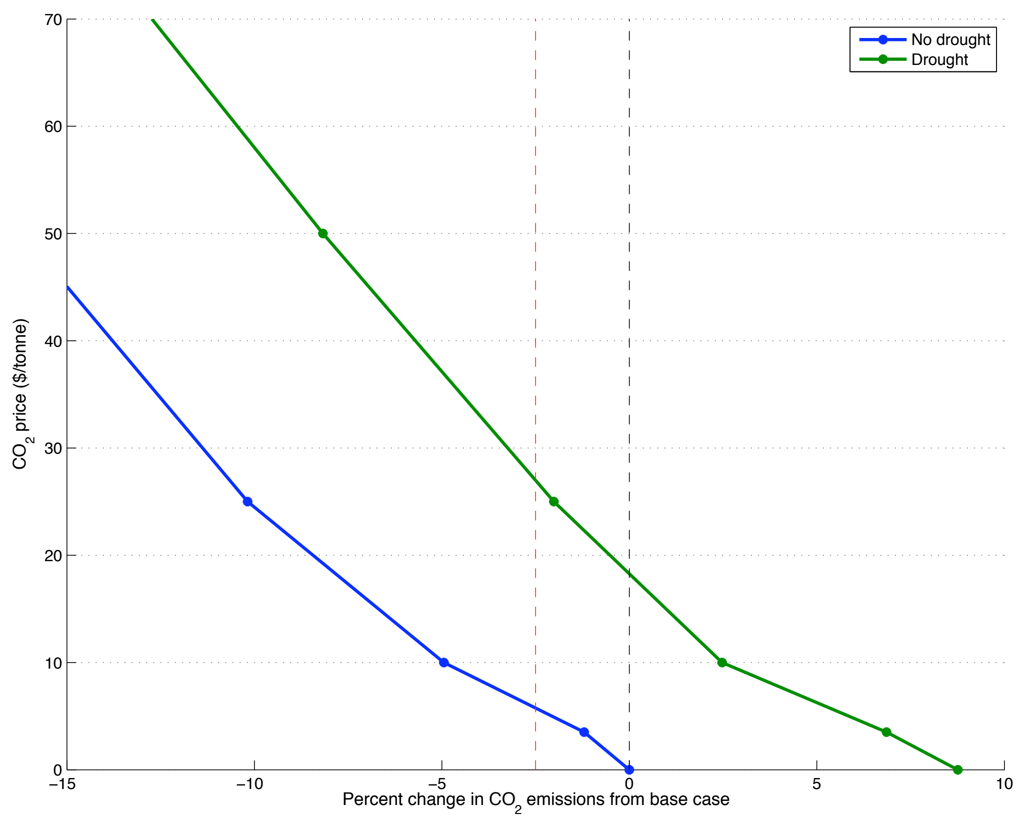


Figure 4.8: The impact of a drought on annual $CO_2$ emissions

percent are scheduled. Without a drought, this annual reduction could be achieved with

[19]Seasonal availability, AC, emission costs to all generators greater than 25 MW in size, no operating reserve margin, $SO_2$ =$700/tonne, and $NO_x$ =2,000/tonne.

a $CO_2$ price less than \$10 per tonne. In the case of a drought though, a $CO_2$ price of almost \$30 would be needed to achieve that same two and a half percent reduction.

Thus, an unexpected change in allowance supply or demand can cause a dramatic increase in the price of $CO_2$ allowances needed to meet a targeted emission reduction.

### Operating Reserve Margin

An operating reserve margin is implemented in a RTO in order to maintain a specified level of electric reliability. Table 4.7 shows the percentage change in total system cost and $CO_2$ emissions between not implementing an operating reserve margin and implementing an operating reserve margin of three percent in each RTO.

Table 4.7: Percent change of system cost and $CO_2$ emissions from a system without, to a system with, an operating reserve

| | System cost | | $CO_2$ emissions | |
|---|---|---|---|---|
| $CO_2$ price | all $CO_2$ cost | RGGI $CO_2$ cost | all $CO_2$ cost | RGGI $CO_2$ cost |
| \$0 | 0.01% | 0.01% | -0.01% | -0.01% |
| \$3.51 | 0.01% | 0.01% | -0.01% | -0.01% |
| \$10 | 0.01% | 0.01% | -0.01% | 0.01% |
| \$25 | 0.01% | 0.02% | -0.01% | -0.01% |
| \$50 | 0.01% | 0.04% | 0.01% | 0.01% |
| \$100 | 0.01% | 0.17% | 0.01% | 0.11% |
| \$175 | 0.02% | 0.43% | 0.12% | 0.20% |
| \$250 | 0.12% | 0.42% | 0.43% | -0.01% |

Thus, it is clear from these results that the modeled operating reserve margin has almost no impact on the dispatch of the system. Regardless of whether the $CO_2$ cost is applied to all generators, or just generators in the RGGI area, the results described in Table 4.7 yield a less than a half a percent change in either the system operating cost or $CO_2$ emissions. This result could be because of the coarse nature of the model.

With a finer grain, locational reliability might be impacted by the imposition of a $CO_2$ allowance price.

### $SO_2$ and $NO_x$ Emissions

Figure 4.9 shows the demand curves for $SO_2$ and $NO_x$ emission permits at $CO_2$ prices of \$0 and \$100. The emission rates for $SO_2$ and $NO_x$ for each generation unit are assumed to be constant. These demand curves are from an extremely short-run perspective. For example, in a matter of hours, days, or weeks, generators can change their $SO_2$ output rate by switching to coal with a different sulfur content. Therefore, over a period that allows for such a fuel change, the curves would be more elastic.

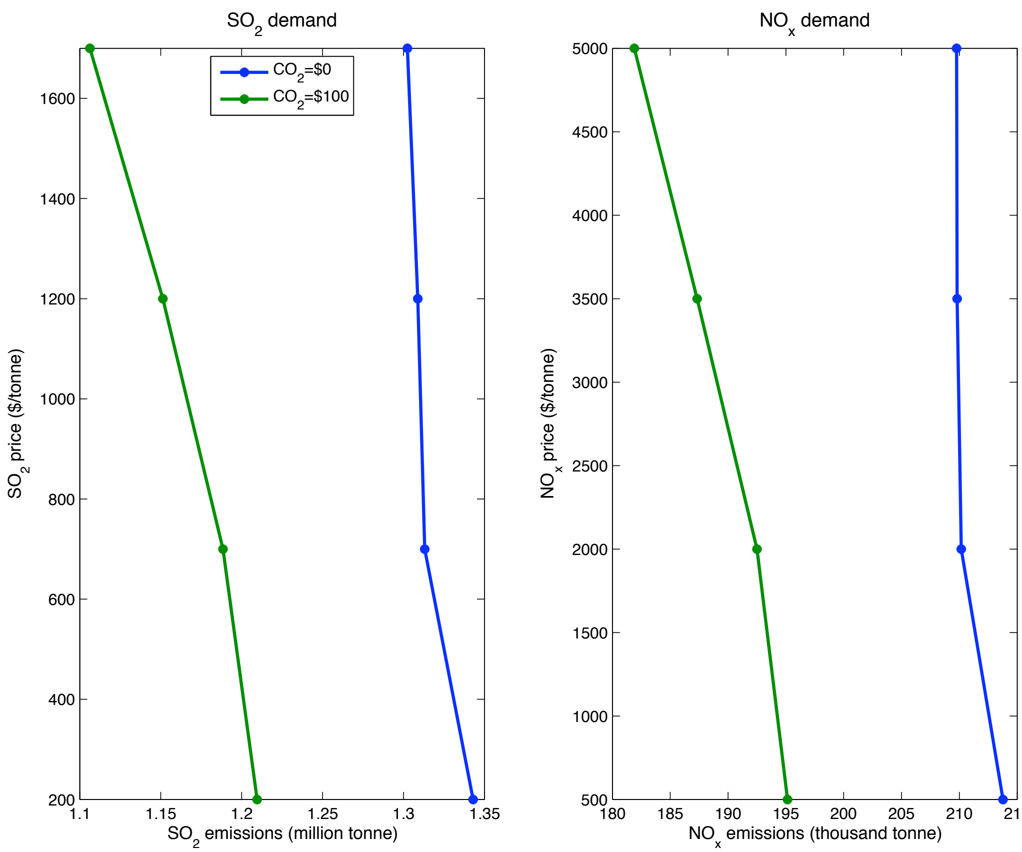


Figure 4.9: The impact of $CO_2$ price on $SO_2$ and $NO_x$ emissions

The numerical simulations show that by creating a regulatory policy, such as the RGGI, that would impose a $CO_2$ price on generators, the amount of $SO_2$ and $NO_x$ emissions would decrease. For example, if the $SO_2$ permit price were \$700 per tonne with no $CO_2$ price, imposing a $CO_2$ price of \$100 per tonne would reduce the quantity of $SO_2$ emission permits by about 10 percent. The price of $CO_2$ similarly interacts with $NO_x$ permit demand. Keeping the price of $NO_x$ permits at \$2,000 while increasing the $CO_2$ price from \$0 to \$100 would reduce the quantity of $NO_x$ permit demanded by nine percent. This results because the same generation units that produce the highest level of $CO_2$ emissions, i.e. coal-fired generation, also produce the highest level of $SO_2$ and $NO_x$. So, as the cost to generate electricity for $CO_2$ increases, coal-fired generation is decreased, reducing emissions of all three pollutants.

Thus, it is clear that the creation of a regulatory policy dealing with $CO_2$ has an important impact on $SO_2$ and $NO_x$ emissions. Assuming that the regulation of $SO_2$ and $NO_x$ is done through a cap and trade program (as is currently the case in the United States) and the caps for each pollutant remained constant, the decrease in demand of $SO_2$ and $NO_x$ permits would drive the market price of these pollutants down.

Because $SO_2$ and $NO_x$ are criteria pollutants whose impacts are most dramatic close to where they are emitted, it is interesting to consider the amount of these pollutants that are created in high population areas. New York City and Boston are the two largest cities that can be most closely identified in this model network.[20] Figure 4.10 shows how $SO_2$ and $NO_x$ emissions change in these two cities with various $CO_2$ prices.

Of particular interest is that in New York City, $SO_2$ and $NO_x$ emissions decrease with $CO_2$ price at first, but then begin to increase between \$50 and \$100 per tonne. Figure 4.11, which shows the generation by fuel type for various $CO_2$ prices, reveals the

[20]Buses 74327 and 71797 are used to represent New York City and Boston, respectively.

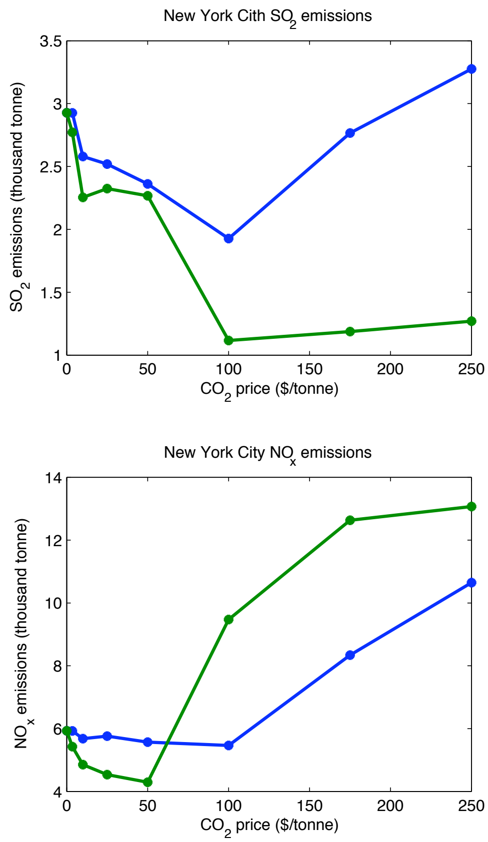


Figure 4.10: $SO_2$ and $NO_x$ emissions in New York City and Boston

reason this happens. For each $CO_2$ price, the bar on the left denotes the generation mix when $CO_2$ prices are applied to all generators in the model, while the bar on the right is the case when $CO_2$ prices are applied only to generators in the RGGI area.

In New York City, total fossil-fired generation decreases as $CO_2$ prices rise, but at low $CO_2$ prices. As the $CO_2$ price continues to increase though, the predominant trend is for oil-fired generation to be removed and natural gas-fired generation to be added. The net $SO_2$ and $NO_x$ emissions increase because the emissions from the natural gas-fired generators more than offset the decrease in emissions by removing oil-fired generation. In general, natural gas-fired generation has relatively low $SO_2$ emissions compared to its $NO_x$ emissions. This explains why the $SO_2$ emissions only modestly increase due

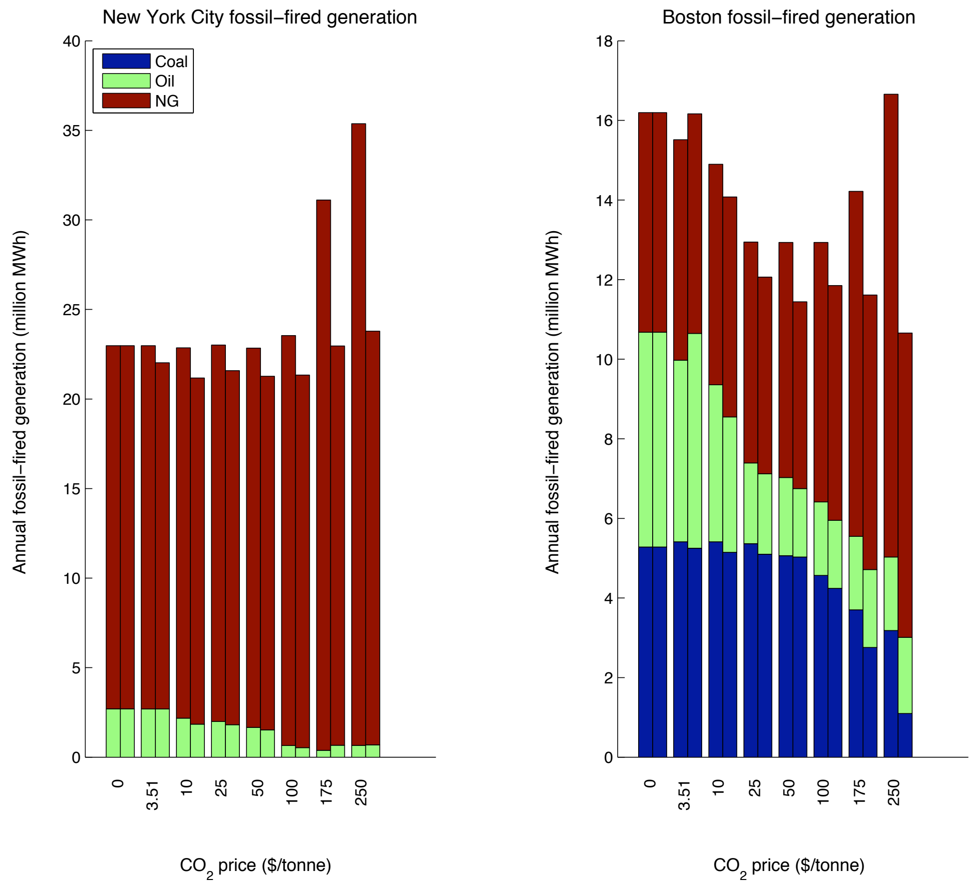


Figure 4.11: Fossil-fired generation in New York City and Boston

to the (very large, in the case of $CO_2$ costs being applied to all generators) addition of natural gas-fired generation and the removal of a small amount of oil-fired generation. Due to natural gas-fired generation's larger emissions of $NO_x$, the increase in emissions is more dramatic.

In Boston, $SO_2$ and $NO_x$ emissions monotonically decrease because, especially compared to New York City, there is a large amount of coal- and oil-fired generation that can be removed as $SO_2$ and $NO_x$ emissions prices increase. The increase in emissions as the amount of electricity produced by natural gas-fired generators increases does not exceed the amount of $SO_2$ and $NO_x$ emission reductions caused by removing coal- and oil-fired generation.

Thus, the locational impacts of $SO_2$ and $NO_x$ emissions, especially in high population metropolitan areas such as New York City and Boston, should be taken into consideration when creating an environmental program. This is even true for the creation of $CO_2$ programs, as there are related cross-effects from the emissions of $CO_2$, $SO_2$, and $NO_x$.

### 4.5.2 Methodological Selection

The methodological questions explored in these numerical simulations are the considerations of transmission line constraints, the use of AC or DC models, and the use of a seasonal availability algorithm.

#### Transmission Constraints and AC and DC Modeling

Consider the impact of enforcing transmission line constraints by looking at each individual transmission line under AC, DC, $CO_2$ cost applied to all generators, and $CO_2$ cost applied to the RGGI area generators only.[21] In particular, Table 4.8 presents the flow over the transmission lines connecting the RGGI area with the non-RGGI area, as a percentage above or below each line's maximum capacity.

It is more important to consider the sign of the percentages (a positive number indicates the flow was over the line maximum and a negative number indicates the flow was below the line maximum), not the magnitude, as these three lines are not the only lines connecting the RGGI area with the other RTO areas. Rather, these are the only lines that have constraining line limits that connect the RGGI area with the other RTO

[21] Seasonal availability, emission costs to all generators by size, no drought, no reserve margin, $SO_2$ =\$700/tonne, and $NO_x$ =2,000/tonne.

areas so electricity can cross RTO boundaries in many other ways beyond these three transmission lines.

Table 4.8: Flow over inter-RGGI area RTO transmission lines, as a percentage above (positive number) or below (negative number) the line maximum

| Bus | | Line max | $CO_2$ price | AC | | DC | |
|---|---|---|---|---|---|---|---|
| From | To | (MW) | ($/MWh) | all | RGGI | all | RGGI |
| 1 PJM | 74347 NYISO | 1000 | 0 | -41% | -41% | -82% | -82% |
| | | | 3.51 | -40% | -33% | -81% | -62% |
| | | | 10 | -40% | -24% | -80% | -36% |
| | | | 25 | -41% | 2% | -77% | -1% |
| | | | 50 | -47% | 29% | -81% | 55% |
| | | | 100 | -67% | 55% | -108% | 160% |
| | | | 175 | -99% | 66% | -200% | 238% |
| | | | 250 | -122% | 68% | -249% | 270% |
| 70002 ISO-NE | 87004 Maritimes | 730 | 0 | -156% | -156% | -180% | -180% |
| | | | 3.51 | -156% | -161% | -179% | -192% |
| | | | 10 | -156% | -172% | -179% | -200% |
| | | | 25 | -156% | -189% | -174% | -208% |
| | | | 50 | -152% | -211% | -171% | -217% |
| | | | 100 | -146% | -234% | -156% | -232% |
| | | | 175 | -101% | -241% | -130% | -236% |
| | | | 250 | -56% | -243% | -103% | -237% |
| 79578 IESO | 80031 ISO-NE | 600 | 0 | -210% | -210% | -359% | -359% |
| | | | 3.51 | -210% | -213% | -360% | -370% |
| | | | 10 | -209% | -217% | -361% | -377% |
| | | | 25 | -208% | -223% | -357% | -384% |
| | | | 50 | -206% | -230% | -355% | -391% |
| | | | 100 | -171% | -237% | -346% | -395% |
| | | | 175 | -131% | -233% | -281% | -377% |
| | | | 250 | -121% | -233% | -240% | -369% |

Only one of the lines, the line from bus 1 to 74347 connecting northeastern Pennsylvania in the PJM control area to Rockland County, New York in the NYISO control area, ever exceeds its line limit. Furthermore, the flows only exceed the limit for high $CO_2$ prices when the cost of $CO_2$ is applied to generators in the RGGI area only.

Also consider the transmission lines that have constraining line limits inside the

RGGI area. Table 4.9 indicates whether the line flow exceeds the maximum for at least one $CO_2$ price.

Table 4.9: Whether line flow exceeds the maximum for at least one $CO_2$ price

| Bus | | Line max | AC | | DC | |
|---|---|---|---|---|---|---|
| From | To | (MW) | all | RGGI | all | RGGI |
| 5028 | 74347 | 1261 | No | No | No | No |
| 5028 | 74327 | 1000 | No | Yes | No | Yes |
| 71786 | 71797 | 1434 | No | No | No | No |
| 71786 | 71797 | 1313 | No | No | No | No |
| 73106 | 73110 | 1255 | No | No | No | No |
| 73171 | 75050 | 301 | No | No | No | No |
| 74316 | 75050 | 690 | No | No | No | Yes |
| 74316 | 74327 | 2800 | Yes | Yes | Yes | Yes |
| 74341 | 74344 | 1720 | No | No | No | No |
| 74344 | 78701 | 1331 | No | No | No | No |
| 74344 | 78701 | 1331 | No | No | No | No |
| 75403 | 75405 | 1255 | No | No | No | No |
| 75403 | 79581 | 1494 | No | No | No | No |
| 77400 | 77406 | 1032 | No | No | No | No |
| 77406 | 79583 | 1434 | No | No | No | No |
| 78701 | 78702 | 1331 | No | No | No | No |
| 78701 | 79581 | 1428 | No | No | No | No |
| 79584 | 79800 | 1301 | No | Yes | Yes | Yes |

Only four of the 18 intra-RGGI area transmission lines ever exceed their maximum line limits. They are:

- the line from bus 5028 to 74327 connecting New Jersey to New York City,
- the line from bus 74316 to 75050 connecting Westchester to Long Island,
- the line from bus 74316 to 74327 connecting Westchester to New York City, and
- the line from bus 79584 to 79800 connecting Niagara Falls to Rochester.

The main result of considering flows over the transmission lines is that due to the high demand for electricity, and the limited pathways for electricity to reach consumers, all of the congested lines except one are in the greater New York City metropolitan area. The only congested line in this reduced model of the electricity network that is not near the New York City area is a transmission line connecting Niagara Falls, where low-cost hydropower is produced, to a high-demand area in Rochester. Furthermore, the transmission constraints are most important when the cost of $CO_2$ is applied to generators in the RGGI area only.

Now consider the differences between AC and DC modeling. Figure 4.12 shows both $CO_2$ emissions and the cost of operating the system as a function of $CO_2$ price, predicted using the four modeling methods when the $CO_2$ emission cost is applied to all generators in the model.[22] Each plotted point is a time-weighted mean of the sixteen representative hours that are modeled. This figure shows that in most instances, these aggregate results over the entire region can be quite similar across all of these modeling methods (though $CO_2$ emissions do vary by model).

As an example, an increasing $CO_2$ price tends to cause a shift from coal-fired generation units to gas-fired generation units, which tend to be located closer to customers. Therefore, if the $CO_2$ price is imposed throughout the entire network, the change in the operation of the power system that results from the $CO_2$ price may not substantially exacerbate transmission constraints.

In contrast, Figure 4.13 shows an example highlighting the impact the transmission system that is selected can have when $CO_2$ regulations are applied to only the RGGI area. This figure illustrates the predicted effects of the RGGI on $CO_2$ emissions both inside and outside the regulated region. For a $CO_2$ price of \$10/tonne, the AC model with constrained transmission predicts the highest amount of $CO_2$ in the RGGI area. The AC

[22] Seasonal availability, emission costs to all generators by size, no drought, no reserve margin, $SO_2$ =\$700/tonne, and $NO_x$ =2,000/tonne.

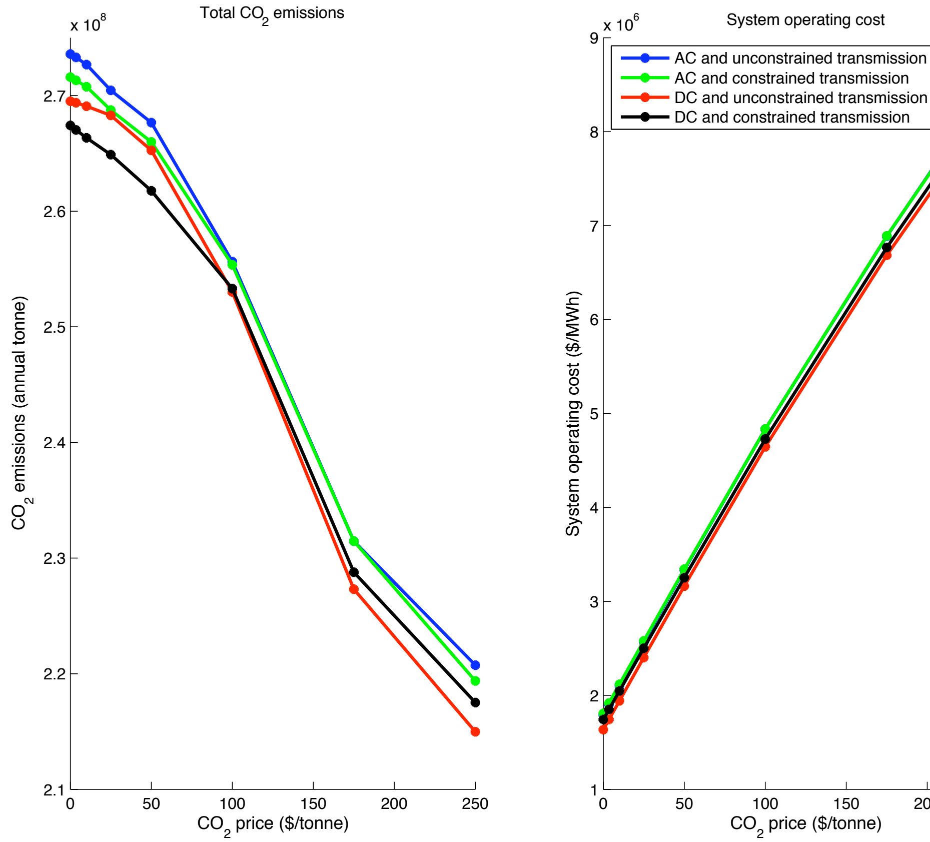


Figure 4.12: Various modeling methods with $CO_2$ emission costs to all generators

model with unconstrained transmission and DC model with constrained transmission both predict about three percent less than the AC model with constrained transmission. The biggest difference is seen in the DC model with unconstrained transmission, which predicts about 20 percent fewer emissions in the RGGI area than the AC model with constrained transmission. All of the differences between each of these predictions grow as the $CO_2$ price increases.

These differences occur because of the restrictions imposed on the OPF problem by each model. The AC model has more dispatch restrictions, such as voltage constraints, than the DC model. Similarly, constrained transmission lines restrict the flow of electricity over the grid. The numerical simulations show that the most restrictive model,

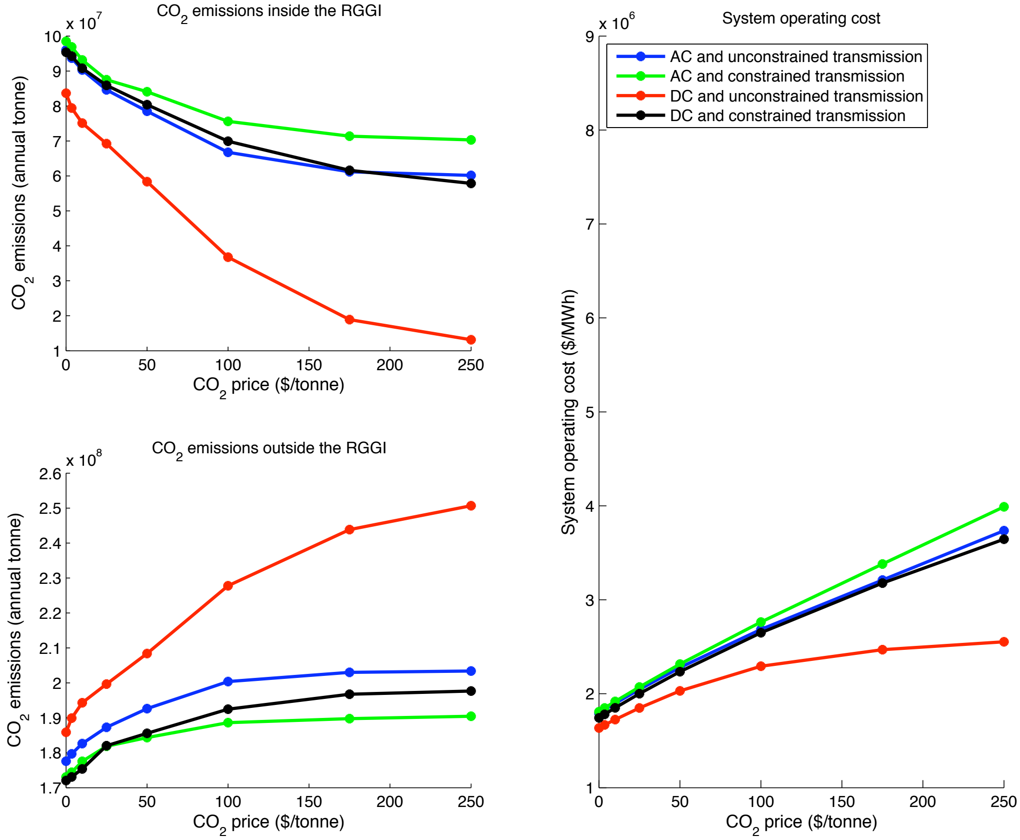


Figure 4.13: Various modeling methods with $CO_2$ emission costs to RGGI area generators

AC with constrained transmission, is the most expensive to operate and produces the most $CO_2$ emissions. On the other side, the least restrictive model, DC with unconstrained transmission lines, estimates the lowest operating costs and forecasts the least $CO_2$ emissions. Interestingly, enforcing only one of these constraints at a time yields very similar results.

In general, the differences between AC and DC models both with and without transmission constraints are most poignant when the cost of $CO_2$ emissions are not applied to all generators in the model and instead are focused on particular locations, like the RGGI area. In this case, the disparity between each model grows with the price per tonne of $CO_2$.

Thus, when attempting to estimate the effects of policies that are regionally specific, like the RGGI, Figure 4.13 illustrates the importance of depicting the electricity network accurately (AC with line constraints) in order to estimate locational differences.

### Seasonal Availability

A seasonal availability constraint should be imposed on coal-fired generation units in this model to reflect actual operations realistically. The results of the numerical simulations show that the seasonal availability algorithm plays an important role in shutting down coal-fired generation units when the costs of dispatching coal-fired generation becomes too expensive.

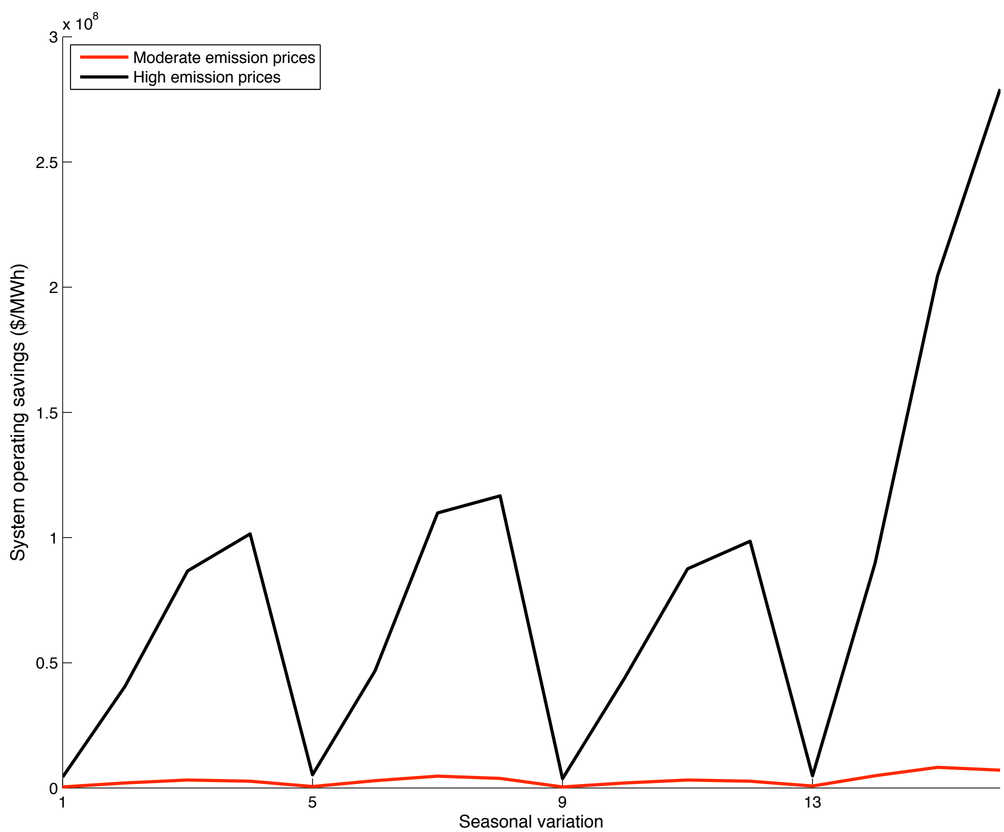


Figure 4.14: Seasonal availability savings in each season

To demonstrate the impact of the seasonal availability algorithm, consider two emission price scenarios,[23] one with moderate emission prices[24] and another with high emission prices.[25]

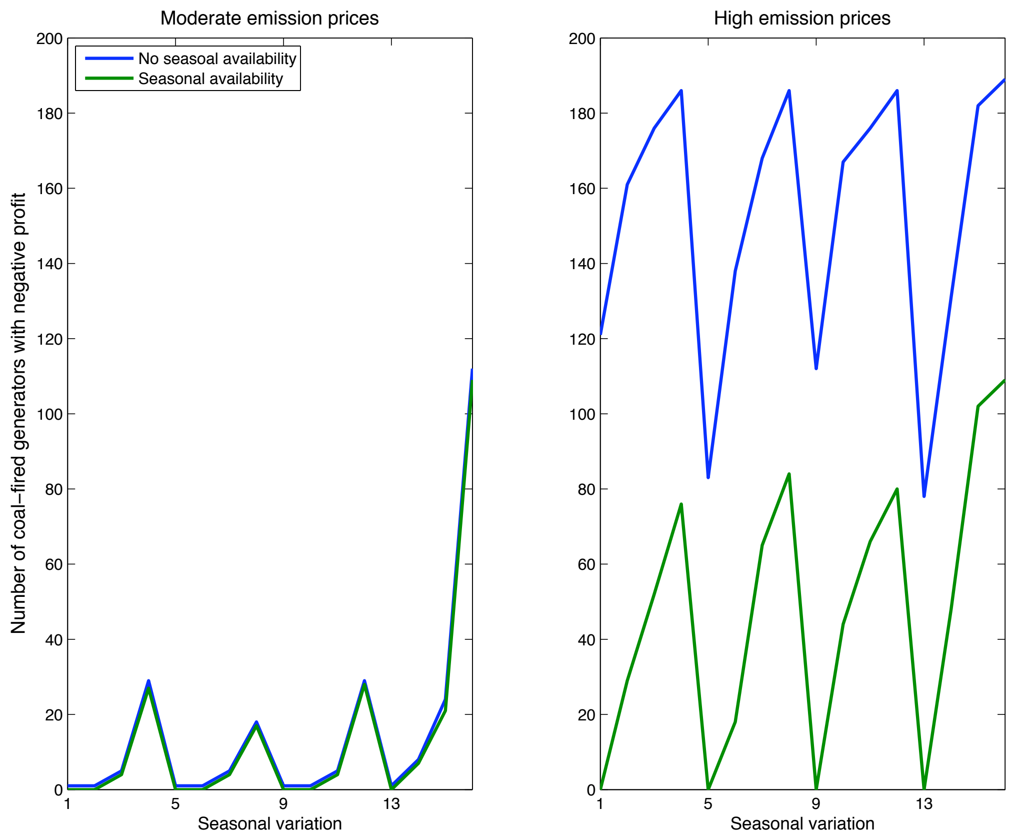


Figure 4.15: Number of coal-fired generators with negative profit in each season

Figure 4.14 shows the difference between the amount of savings, in terms of total system operating cost, created by running the seasonal availability algorithm. The difference is significant when the emission prices are high. In this example, the savings in operating costs that are predicted by running the seasonal availability algorithm is about \$50 million per year when the emission prices are moderate and \$1.4 billion per year

[23] AC, line constraints, emission costs to all generators by geography, emission costs to all generators by size, no drought, no reserve margin.

[24] $CO_2$ = \$10/tonne, $SO_2$ =\$700/tonne, and $NO_x$ =2,000/tonne.

[25] $CO_2$ = \$250/tonne, $SO_2$ =\$1700/tonne, and $NO_x$ =5,000/tonne.

when the emission prices are high.

The vast difference in savings results from coal-fired generators that are not profitable when operated at low generation levels are being shutdown. Figure 4.15 shows the difference between the number of coal-fired generators with negative profits at moderate and high emission prices. In most cases, at least 100 generators with negative profit are shutdown by the seasonal availability algorithm.

Thus, these simulations illustrate the importance of including a generator shutdown mechanism in any model of the electric system operation that is intended to estimate the operating, reliability, and cost consequences of environmental policies.

CHAPTER 5

# CONCLUSIONS AND FUTURE WORK

The theoretical model described in Chapter 3 explores the interactions of electric reliability and environmental regulation by comparing the social welfare maximizing solution to the competitive market solution. The main result is that after assuming a central planner has set variables surrounding the transmission grid, complicating interdependencies in markets for criteria pollutants make achieving the socially optimal solution unlikely. Markets for global pollutants can more easily achieve the socially optimal solution due to the lack of these interdependencies. This result highlights the importance of a "smart-grid" that disseminates price information to buyers and sellers in real-time to reduce the cost of supplying reliable electricity to consumers.

The numerical simulations described in Chapter 4 represent a highly simplified model of Northeastern North America. Yet, the complications of a full non-linear AC electricity dispatch are introduced and the simulations yield the following results when considering the RGGI environmental policy. Leakage seems to be an important issue for the RGGI, as the modeled results show that most of the reduction in emissions inside the RGGI area are countered by an increase in emissions outside the RGGI area. Furthermore, the cost of electricity to consumers inside the RGGI area will marginally increase at the current RGGI allowance price. At much higher $CO_2$ prices than present, customer electricity prices are estimated to increase in both the RGGI and non-RGGI areas, but by much more within the RGGI area. Unfortunately, due to leakage, these higher electricity prices in the RGGI area do not result in much net $CO_2$ reductions. Only a uniform, region-wide $CO_2$ regulation can achieve large reductions in $CO_2$ emissions.

The industry as a whole will see an increase in profits as a result of $CO_2$ regulations, though the increases are not uniform across all types of generation and also depend heavily on which generation units face the emission costs. Also, a drought that reduces the amount of hydropower available for dispatch could lead to a significantly higher $CO_2$ allowance price in the RGGI. With regards to the operating reserve margin, this modeling shows that it has little short-run impact on total system operating cost or $CO_2$ emissions when different reserve margins are applied uniformly over all generators.

Finally, the imposition of a $CO_2$ price on generation units will significantly impact the demand for $SO_2$ and $NO_x$ allowances under a cap and trade program. Furthermore, the consequences of a particular environmental initiative are not monotonic. As an example, the total generation of $SO_2$ and $NO_x$ in large metropolitan centers, such as New York City or Boston, can either increase or decrease with increasing $CO_2$ prices depending on the level of $CO_2$ price imposed. This varying result occurs because the emission savings by reducing the generation from high $SO_2$ and $NO_x$ emitting generation at low $CO_2$ prices is eventually overcome by the much larger increase in natural gas-fired generation, with relatively lower $SO_2$ and $NO_x$ emissions, at high $CO_2$ prices.

From the perspective of the methodology used to simulate electric power grids, the seasonal availability algorithm plays an important role in reducing the cost of operating the system when considering high emission prices. AC and DC modeling, done with and without transmission constraints, are most important when there is a regional disparity between the application of emission costs.

While these results are useful, it is important to understand that these numerical simulations are based on a spatial simplification of the actual RGGI area and the Northeastern North America electric power grid. Many provisions implemented under the RGGI are not considered in these simulations. For instance, neither the ability to satisfy some of the emission reduction requirements by purchasing offsets nor multiple-year control periods are modeled. Because this is not a general equilibrium model, neither demand response nor individual RGGI participating states' use of RGGI auction revenues to fund programs that help energy customers to improve their energy efficiency, an important, low-cost source of emission reductions, [4] are considered. Finally, the ideal physical model of the electric grid would combine both thermal and voltage limits that fully match the real system. Additionally, many more lines and buses would be included.

Nevertheless, this research contributes to the economics and power systems literature by providing insights towards setting optimal environmental and electric reliability standards, predictions of current environmental policies, and understanding of the methodological differences in power system modeling and therefore the extent of uncertainty about estimated outcomes.

In future research, the theoretical model could be expanded to compare the socially optimal and market solutions when electric reliability, global pollution, and criteria pollution are all included in the same model. Also, the model could explore the socially optimal solutions when the environmental and electric reliability agencies play a sequential and/or simultaneous game. This will provide a better understanding of how, in practice, environmental and electric reliability regulations are often set. Finally, instead of having the entire system regulated by a single environmental agency and a single electric reliability agency, the system could be split to examine the optimal outcomes when the regulatory oversight of the environmental and electric reliability agencies do not perfectly intersect.

In the numerical simulations, added detail would increase the accuracy of the predicted results. For instance, building a dynamic general equilibrium model that allows fossil fuel prices to fluctuate, electricity demand response to changing prices, and investment in new generation (not just the removal as currently implemented with the seasonal availability algorithm). The physical grid could also become more detailed or even expanded to include the entire Eastern interconnection.

Contingencies other than drought could be considered as well. For example, transmission line contingencies could be modeled. Similarly, allowing the removal of a large nuclear generator, as proposed in New York State, would provide a different type of contingency to consider in the face of environmental regulation.

Furthermore, investigations into mathematically identifying portions of the transmission grid that are "environmentally weak" could be conducted. This would be done in an effort to relate transmission patterns to environmental issues by studying where the transmission grid is most highly impacted by changes in environmental regulation.

Finally, when considering the impacts of criteria pollutants such as $SO_2$ and $NO_x$, a detailed transport model could be built into the numerical simulations. This feature would provide a more accurate understanding of how emissions from each generator affect populations across entire regions, not just at the bus from which the criteria emissions were emitted.

APPENDIX A

**CHAPTER 3 MATHEMATICS**

# A.1 Electric Reliability

## A.1.1 Social Planner

$$\max_{\substack{x_i, y_i, \beta, \\ g_i, r_i, z_i^g, z_i^r, \theta_i}} \quad W(u_1(x_1, y_1, \beta), \ldots, u_I(x_I, y_I, \beta))$$

$$\ni \quad g_i = R_i(z_i^g), \ \forall\, i$$

$$r_i = R_i(z_i^r), \ \forall\, i$$

$$x_i - g_i = \sum_{j=1}^{I} B_{ij}\theta_j, \ \forall\, i$$

$$r_i = \beta g_i, \ \forall\, i$$

$$\sum_{j=1}^{I} y_j + \sum_{j=1}^{I} z_j^g + \sum_{j=1}^{I} z_j^r \leq G$$

$$P_i^{min} \leq g_i + r_i \leq P_i^{max}, \ \forall\, i$$

$$\sum_{j=1}^{I} C_{lj}\theta_j \leq |M_l|, \ \forall\, l$$

$$\theta_1 = 0$$

Re-arranging and substituting in equations yields:

$$\max_{\substack{x_i, y_i, \beta \\ z_i^g, z_i^r, \theta_i}} \quad W(u_1(x_1, y_1, \beta), \ldots, u_I(x_I, y_I, \beta))$$

$$\ni \quad 0 = \sum_{j=1}^{I} B_{ij}\theta_j - x_i + R_i(z_i^g), \ \forall\, i$$

$$0 = R_i(z_i^r) - \beta R_i(z_i^g), \ \forall\, i$$

$$0 \leq G - \sum_{j=1}^{I} y_j - \sum_{j=1}^{I} z_j^g - \sum_{j=1}^{I} z_j^r$$

$$0 \leq R_i(z_i^g) + R_i(z_i^r) - P_i^{min}, \ \forall\, i$$

$$0 \leq P_i^{max} - R_i(z_i^g) - R_i(z_i^r), \ \forall\, i$$

$$0 \leq M_l + \sum_{j=1}^{I} C_{lj}\theta_j, \ \forall\, l$$

$$0 \leq M_l - \sum_{j=1}^{I} C_{lj}\theta_j, \ \forall\, l$$

$$0 = \theta_1$$

The Lagrangian for this maximization problem is:

$$
\begin{aligned}
\mathcal{L} = {} & W(u_1(x_1, y_1, \beta), \ldots, u_I(x_I, y_I, \beta)) \\
& + \sum_{i=1}^{I} \lambda_i \left[ \sum_{j=1}^{I} B_{ij}\theta_j - x_i + R_i(z_i^g) \right] \\
& + \sum_{i=1}^{I} \kappa_i \left[ R_i(z_i^r) - \beta R_i(z_i^g) \right] \\
& + \rho \left[ G - \sum_{j=1}^{I} y_j - \sum_{j=1}^{I} z_j^g - \sum_{j=1}^{I} z_j^r \right] \\
& + \sum_{i=1}^{I} \mu_i [R_i(z_i^g) + R_i(z_i^r) - P_i^{min}] \\
& + \sum_{i=1}^{I} \tau_i [P_i^{max} - R_i(z_i^g) - R_i(z_i^r)] \\
& + \sum_{l=1}^{L} \delta_l \left[ M_l + \sum_{j=1}^{I} C_{lj}\theta_j \right] \\
& + \sum_{l=1}^{L} \sigma_l \left[ M_l - \sum_{j=1}^{I} C_{lj}\theta_j \right] \\
& + \xi\theta_1
\end{aligned}
$$

In order for endogenous variables $x_i^*$, $y_i^*$, $\beta^*$, $z_i^{g*}$, $z_i^{r*}$, and $\theta_i^*$ to be optimal, the following first order conditions must be satisfied:

$$
\begin{aligned}
x_i &: \left(\frac{\partial W(\cdot)}{\partial u_i(\cdot)}\right)\left(\frac{\partial u_i(\cdot)}{\partial x_i}\right) - \lambda_i^* = 0, \ \forall\, i \\
y_i &: \left(\frac{\partial W(\cdot)}{\partial u_i(\cdot)}\right)\left(\frac{\partial u_i(\cdot)}{\partial y_i}\right) - \rho^* = 0, \ \forall\, i \\
\beta &: \sum_{j=1}^{I} \left(\frac{\partial W(\cdot)}{\partial u_j(\cdot)}\right)\left(\frac{\partial u_j(\cdot)}{\partial \beta}\right) - \sum_{j=1}^{I} \kappa_j^* R_j(z_j^{g*}) = 0 \\
z_i^g &: \lambda_i^* R_i'(z_i^{g*}) - \kappa_i^* \beta^* R_i(z_i^{g*}) - \rho^* + \mu_i^* R_i'(z_i^{g*}) - \tau_i^* R_i'(z_i^{g*}) = 0, \ \forall\, i \\
z_i^r &: \kappa_i^* R_i'(z_i^{r*}) - \rho^* + \mu_i^* R_i'(z_i^{g*}) - \tau_i^* R_i'(z_i^{g*}) = 0, \ \forall\, i \\
\theta_i &: \sum_{j=1}^{I} \lambda_j^* B_{ji} - \sum_{l=1}^{L} \delta_l^* C_{li} + \sum_{l=1}^{L} \sigma_l^* C_{li} = 0, \ \forall\, i
\end{aligned}
$$

Furthermore, the following first order conditions for Lagrange multipliers $\lambda_i^*, \kappa_i^*, \rho^*$, $\mu_i^*, \tau_i^*, \delta_l^*, \sigma_l^*$, and $\xi^*$ must be satisfied at the optimal solution:

$$\lambda_i : \lambda_i^* \left[ \sum_{j=1}^{I} B_{ij}\theta_j^* - x_i^* + \beta^* R_i(z_i^*) \right] = 0,\ \lambda_i^* \geq 0,\ \forall\, i$$

$$\kappa_i : \kappa_i^* \left[ R_i(z_i^{r*}) - \beta R_i(z_i^{g*}) \right],\ \kappa_i^* \geq 0,\ \forall\, i$$

$$\rho : \rho^* \left[ G - \sum_{j=1}^{I} y_j^* - \sum_{j=1}^{I} z_j^{g*} - \sum_{j=1}^{I} z_j^{r*} \right] = 0,\ \rho^* \geq 0$$

$$\mu_i : \mu_i^* [R_i(z_i^{g*}) + R_i(z_i^{r*}) - P_i^{min}] = 0,\ \mu_i^* \geq 0,\ \forall\, i$$

$$\tau_i : \tau_i^* [P_i^{max} - R_i(z_i^{g*}) - R_i(z_i^{r*})] = 0,\ \tau_i^* \geq 0,\ \forall\, i$$

$$\delta_l : \delta_l^* \left[ M_l + \sum_{i=1}^{I} C_{lj}\theta_j^* \right] = 0,\ \delta_l^* \geq 0,\ \forall\, i$$

$$\sigma_l : \sigma_l^* \left[ M_l - \sum_{i=1}^{I} C_{lj}\theta_j^* \right] = 0,\ \sigma_l^* \geq 0,\ \forall\, i$$

$$\xi : \xi^* \theta_1 =,\ \xi^* \geq 0$$

### A.1.2 Individual Consumer

Each individual consumer at location $i$ has allocation of the resource $\bar{y}_i$ so that each consumer's allocated wealth, $m_i$ is equal to $\rho\bar{y}_i$. Consumer $i$ solves the following utility maximization problem.

$$\max_{x_i, y_i, \beta} \quad u_i(x_i, y_i, \beta)$$

$$\ni \quad \lambda_i x_i + \rho y_i + \kappa_i \beta \leq m_i$$

The Lagrangian for this maximization problem is:

$$\mathcal{L} = u_i(x_i, y_i, \beta) + \nu(m_i - \lambda_i x_i - \rho y_i - \kappa_i \beta)$$

In order for endogenous variables $x_i^*$, $y_i^*$, and $\beta^*$ to be optimal, the following first order conditions must be satisfied:

$$
\begin{aligned}
x_i &: \frac{\partial u_i(\cdot)}{\partial x_i} - \nu^* \lambda_i = 0 \\
y_i &: \frac{\partial u_i(\cdot)}{\partial y_i} - \nu^* \rho = 0 \\
\beta &: \frac{\partial u_i(\cdot)}{\partial \beta} - \nu^* \kappa_i = 0
\end{aligned}
$$

Furthermore, the following first order conditions for Lagrange multiplier $\nu^*$ must be satisfied at the optimal solution:

$$\nu : \nu^*(m_i - \lambda_i x_i^* - \rho y_i^* - \kappa_i \beta^*) = 0,\ \nu^* \geq 0$$

## A.2 Global Pollutant and Electric Reliability

### A.2.1 Social Planner

$$\max_{\substack{x_i, y_i, \alpha, \beta, \\ g_i, r_i, z_i^g, z_i^r, w_i^\alpha, \theta_i}} \quad W(u_1(x_1, y_1, \alpha, \beta), \ldots, u_I(x_I, y_I, \alpha, \beta))$$

$$\ni \quad g_i = R_i(z_i^g),\ \forall\, i$$

$$r_i = R_i(z_i^r),\ \forall\, i$$

$$e_i^\alpha = E_i^\alpha(g_i, r_i, w_i^\alpha),\ \forall\, i$$

$$\alpha = Q^\alpha(e_1^\alpha, \ldots, e_I^\alpha)$$

$$x_i - g_i = \sum_{j=1}^{I} B_{ij}\theta_j,\ \forall\, i$$

$$r_i = \beta g_i,\ \forall\, i$$

$$\sum_{j=1}^{I} w_j^\alpha + \sum_{j=1}^{I} y_j + \sum_{j=1}^{I} z_j^g + \sum_{j=1}^{I} z_j^r \leq G$$

$$P_i^{min} \leq g_i + r_i \leq P_i^{max},\ \forall\, i$$

$$\sum_{j=1}^{I} C_{lj}\theta_j \leq |M_l|,\ \forall\, l$$

$$\theta_1 = 0$$

Re-arranging and substituting in equations yields:

$$
\begin{aligned}
\max_{\substack{x_i, y_i, \alpha, \beta \\ z_i^g, z_i^r, w_i^\alpha, \theta_i}} \quad & W(u_1(x_1, y_1, \alpha, \beta), \ldots, u_I(x_I, y_I, \alpha, \beta)) \\
\ni \quad & 0 = A(z_1^g, z_1^r, w_1^\alpha, \ldots, z_I^g, z_I^r, w_I^\alpha) - \alpha \\
& 0 = \sum_{j=1}^{I} B_{ij}\theta_j - x_i + R_i(z_i^g), \ \forall\, i \\
& 0 = R_i(z_i^r) - \beta R_i(z_i^g), \ \forall\, i \\
& 0 \leq G - \sum_{j=1}^{I} w_j^\alpha - \sum_{j=1}^{I} y_j - \sum_{j=1}^{I} z_j^g - \sum_{j=1}^{I} z_j^r \\
& 0 \leq R_i(z_i^g) + R_i(z_i^r) - P_i^{min}, \ \forall\, i \\
& 0 \leq P_i^{max} - R_i(z_i^g) - R_i(z_i^r), \ \forall\, i \\
& 0 \leq M_l + \sum_{j=1}^{I} C_{lj}\theta_j, \ \forall\, l \\
& 0 \leq M_l - \sum_{j=1}^{I} C_{lj}\theta_j, \ \forall\, l \\
& 0 = \theta_1
\end{aligned}
$$

The Lagrangian for this maximization problem is:

$$
\begin{aligned}
\mathcal{L} = {} & W(u_1(x_1, y_1, \alpha, \beta), \ldots, u_I(x_I, y_I, \alpha, \beta)) \\
& + \psi \left[ A(z_1^g, z_1^r, w_1^\alpha, \ldots, z_I^g, z_I^r, w_I^\alpha) - \alpha \right] \\
& + \sum_{i=1}^{I} \lambda_i \left[ \sum_{j=1}^{I} B_{ij}\theta_j - x_i + R_i(z_i^g) \right] \\
& + \sum_{i=1}^{I} \kappa_i \left[ R_i(z_i^r) - \beta R_i(z_i^g) \right] \\
& + \rho \left[ G - \sum_{i=1}^{I} w_i^\alpha - \sum_{i=1}^{I} y_i - \sum_{j=1}^{I} z_j^g - \sum_{j=1}^{I} z_j^r \right] \\
& + \sum_{i=1}^{I} \mu_i [R_i(z_i^g) + R_i(z_i^r) - P_i^{min}] \\
& + \sum_{i=1}^{I} \tau_i [P_i^{max} - R_i(z_i^g) - R_i(z_i^r)] \\
& + \sum_{l=1}^{L} \delta_l \left[ M_l + \sum_{j=1}^{I} C_{lj}\theta_j \right] \\
& + \sum_{l=1}^{L} \sigma_l \left[ M_l - \sum_{j=1}^{I} C_{lj}\theta_j \right] \\
& + \xi\theta_1
\end{aligned}
$$

In order for endogenous variables $x_i^*$, $y_i^*$, $\alpha^*$, $\beta^*$, $z_i^{g*}$, $z_i^{r*}$, $w_i^{\alpha*}$, and $\theta_i^*$ to be optimal, the following first order conditions must be satisfied:

$$
\begin{aligned}
x_i &: \left(\frac{\partial W(\cdot)}{\partial u_i(\cdot)}\right)\left(\frac{\partial u_i(\cdot)}{\partial x_i}\right) - \lambda_i^* = 0, \ \forall\, i \\
y_i &: \left(\frac{\partial W(\cdot)}{\partial u_i(\cdot)}\right)\left(\frac{\partial u_i(\cdot)}{\partial y_i}\right) - \rho^* = 0, \ \forall\, i \\
\alpha &: \sum_{j=1}^{I}\left(\frac{\partial W(\cdot)}{\partial u_j(\cdot)}\right)\left(\frac{\partial u_j(\cdot)}{\partial \alpha}\right) - \psi^* = 0 \\
\beta &: \sum_{j=1}^{I}\left(\frac{\partial W(\cdot)}{\partial u_i(\cdot)}\right)\left(\frac{\partial u_i(\cdot)}{\partial \beta}\right) - \sum_{j=1}^{I}\kappa_j^* R_j(z_j^{g*}) = 0 \\
z_i^g &: \psi^*\frac{\partial A(\cdot)}{\partial z_i^g} + \lambda_i^* R_i'(z_i^{g*}) - \kappa_i^* \beta R_i'(z_i^{g*}) - \rho^* + \mu_i^* R_i'(z_i^{g*}) - \tau_i^* R_i'(z_i^{g*}) = 0, \ \forall\, i \\
z_i^r &: \psi^*\frac{\partial A(\cdot)}{\partial z_i^r} + \kappa_i^* R_i'(z_i^{r*}) - \rho^* + \mu_i^* R_i'(z_i^{r*}) - \tau_i^* R_i'(z_i^{r*}) = 0, \ \forall\, i \\
w_i^\alpha &: \psi^*\frac{\partial A(\cdot)}{\partial w_i^\alpha} - \rho^* = 0, \ \forall\, i \\
\theta_i &: \sum_{j=1}^{I}\lambda_j^* B_{ji} - \sum_{l=1}^{L}\delta_l^* C_{li} + \sum_{l=1}^{L}\sigma_l^* C_{li} = 0, \ \forall\, i
\end{aligned}
$$

Furthermore, the following first order conditions for Lagrange multipliers $\psi^*$, $\lambda_i^*$, $\kappa_i^*$,

$\rho^*$, $\mu_i^*$, $\tau_i^*$, $\delta_l^*$, $\sigma_l^*$, and $\xi^*$ must be satisfied at the optimal solution:

$$\psi^* : \psi^* \left[ A(z_1^{g*}, z_1^{r*}, w_1^{\alpha*}, \ldots, z_I^{g*}, z_I^{r*}, w_I^{\alpha*}) - \alpha^* \right] = 0, \; \psi^* \geq 0$$

$$\lambda_i : \lambda_i^* \left[ \sum_{j=1}^{I} B_{ij}\theta_j^* - x_i^* + R_i(z_i^{g*}) \right] = 0, \; \lambda_i^* \geq 0, \; \forall \, i$$

$$\kappa_i : \kappa_i^* \left[ R_i(z_i^{r*}) - \beta R_i(z_i^{g*}) \right] = 0, \; \kappa_i^* \geq 0, \; \forall \, i$$

$$\rho : \rho^* \left[ G - \sum_{i=1}^{I} w_i^{\alpha*} - \sum_{i=1}^{I} y_i^* - - \sum_{j=1}^{I} z_j^{g*} - \sum_{j=1}^{I} z_j^{r*} \right] = 0, \; \rho^* \geq 0$$

$$\mu_i : \mu_i^* [R_i(z_i^{g*}) + R_i(z_i^{r*}) - P_i^{min}] = 0, \; \mu_i^* \geq 0, \; \forall \, i$$

$$\tau_i : \tau_i^* [P_i^{max} - R_i(z_i^{g*}) - R_i(z_i^{r*})] = 0, \; \tau_i^* \geq 0, \; \forall \, i$$

$$\delta_l : \delta_l^* \left[ M_l + \sum_{i=1}^{I} C_{lj}\theta_j^* \right] = 0, \; \delta_l^* \geq 0, \; \forall \, i$$

$$\sigma_l : \sigma_l^* \left[ M_l - \sum_{i=1}^{I} C_{lj}\theta_j^* \right] = 0, \; \sigma_l^* \geq 0, \; \forall \, i$$

$$\xi : \xi^* \theta_1 =, \; \xi^* \geq 0$$

### A.2.2 Individual Consumer

Each individual consumer at location $i$ has allocation of the resource $\bar{y}_i$ so that each consumer's allocated wealth, $m_i$ is equal to $\rho \bar{y}_i$. Consumer $i$ solves the following utility maximization problem:

$$\max_{x_i, y_i, \alpha, \beta} \quad u_i(x_i, y_i, \alpha, \beta)$$

$$\ni \quad \lambda_i x_i + \rho y_i + \psi \alpha + \kappa_i \beta \leq m_i$$

The Lagrangian for this maximization problem is:

$$\mathcal{L} = u_i(x_i, y_i, \alpha, \beta) + \nu(m_i - \lambda_i x_i - \rho y_i - \psi \alpha - \kappa_i \beta)$$

In order for endogenous variables $x_i^*$, $y_i^*$, $\alpha^*$, and $\beta^*$ to be optimal, the following first order conditions must be satisfied:

$$
\begin{aligned}
x_i &: \frac{\partial u_i(\cdot)}{\partial x_i} - \nu^* \lambda_i = 0 \\
y_i &: \frac{\partial u_i(\cdot)}{\partial y_i} - \nu^* \rho = 0 \\
\alpha &: \frac{\partial u_i(\cdot)}{\partial \alpha} - \nu^* \psi = 0 \\
\beta &: \frac{\partial u_i(\cdot)}{\partial \beta} - \nu^* \kappa_i = 0
\end{aligned}
$$

Furthermore, the following first order conditions for Lagrange multiplier $\nu^*$ must be satisfied at the optimal solution:

$$\nu : \nu^*(m_i - \lambda_i x_i^* - \rho y_i^* - \psi \alpha^* - \kappa_i \beta^*) = 0,\ \nu^* \geq 0$$

## A.3 Criteria Pollutant and Electric Reliability

### A.3.1 Social Planner

$$
\begin{aligned}
\max_{\substack{x_i, y_i, \gamma_i, \beta,\\ g_i, r_i, z_i^g, z_i^r, w_i^\gamma, \theta_i}} \quad & W(u_1(x_1, y_1, \gamma_1, \beta), \ldots, u_I(x_I, y_I, \gamma_I, \beta)) \\
\ni \quad & g_i = R_i(z_i^g), \ \forall\, i \\
& r_i = R_i(z_i^r), \ \forall\, i \\
& e_i^\gamma = E_i^\gamma(g_i, r_i, w_i^\gamma), \ \forall\, i \\
& \gamma_i = Q_i^\gamma(e_1^\gamma, \ldots, e_I^\gamma), \ \forall\, i \\
& x_i - g_i = \sum_{j=1}^{I} B_{ij}\theta_j, \ \forall\, i \\
& r_i = \beta g_i, \ \forall\, i \\
& \sum_{j=1}^{I} w_j^\gamma + \sum_{j=1}^{I} y_j + \sum_{j=1}^{I} z_j^g + \sum_{j=1}^{I} z_j^r \le G \\
& P_i^{min} \le g_i + r_i \le P_i^{max}, \ \forall\, i \\
& \sum_{j=1}^{I} C_{lj}\theta_j \le |M_l|, \ \forall\, l \\
& \theta_1 = 0
\end{aligned}
$$

Re-arranging and substituting in equations yields:

$$
\begin{aligned}
\max_{\substack{x_i, y_i, \gamma_i, \beta \\ z_i^g, z_i^r, w_i^\gamma, \theta_i}} \quad & W(u_1(x_1, y_1, \gamma_1, \beta), \ldots, u_I(x_I, y_I, \gamma_I, \beta)) \\
\ni \quad & 0 = \Gamma_i(z_1^g, z_1^r, w_1^\gamma, \ldots, z_I^g, z_I^r, w_I^\gamma) - \gamma_i, \ \forall\, i \\
& 0 = \sum_{j=1}^{I} B_{ij}\theta_j - x_i + R_i(z_i^g), \ \forall\, i \\
& 0 = R_i(z_i^r) - \beta R_i(z_i^g), \ \forall\, i \\
& 0 \leq G - \sum_{j=1}^{I} w_j^\gamma - \sum_{j=1}^{I} y_j - \sum_{j=1}^{I} z_j^g - \sum_{j=1}^{I} z_j^r \\
& 0 \leq R_i(z_i^g) + R_i(z_i^r) - P_i^{min}, \ \forall\, i \\
& 0 \leq P_i^{max} - R_i(z_i^g) - R_i(z_i^r), \ \forall\, i \\
& 0 \leq M_l + \sum_{j=1}^{I} C_{lj}\theta_j, \ \forall\, l \\
& 0 \leq M_l - \sum_{j=1}^{I} C_{lj}\theta_j, \ \forall\, l \\
& 0 = \theta_1
\end{aligned}
$$

The Lagrangian for this maximization problem is:

$$\begin{aligned}
\mathcal{L} = & W(u_1(x_1, y_1, \gamma_1, \beta), \ldots, u_I(x_I, y_I, \gamma_I, \beta)) \\
& + \sum_{i=1}^{I} \phi_i \left[\Gamma_i(z_1^g, z_1^r, w_1^\gamma, \ldots, z_I^g, z_I^r, w_I^\gamma) - \gamma_i\right] \\
& + \sum_{i=1}^{I} \lambda_i \left[\sum_{j=1}^{I} B_{ij}\theta_j - x_i + R_i(z_i^g)\right] \\
& + \sum_{i=1}^{I} \kappa_i \left[R_i(z_i^r) - \beta R_i(z_i^g)\right] \\
& + \rho \left[G - \sum_{i=1}^{I} w_i^\gamma - \sum_{i=1}^{I} y_i - \sum_{j=1}^{I} z_j^g - \sum_{j=1}^{I} z_j^r\right] \\
& + \sum_{i=1}^{I} \mu_i [R_i(z_i^g) + R_i(z_i^r) - P_i^{min}] \\
& + \sum_{i=1}^{I} \tau_i [P_i^{max} - R_i(z_i^g) - R_i(z_i^r)] \\
& + \sum_{l=1}^{L} \delta_l \left[M_l + \sum_{j=1}^{I} C_{lj}\theta_j\right] \\
& + \sum_{l=1}^{L} \sigma_l \left[M_l - \sum_{j=1}^{I} C_{lj}\theta_j\right] \\
& + \xi\theta_1
\end{aligned}$$

In order for endogenous variables $x_i^*$, $y_i^*$, $\gamma_i^*$, $\beta^*$, $z_i^{g*}$, $z_i^{r*}$, $w_i^{\gamma*}$, and $\theta_i^*$ to be optimal, the following first order conditions must be satisfied:

$$
\begin{aligned}
x_i &: \left(\frac{\partial W(\cdot)}{\partial u_i(\cdot)}\right)\left(\frac{\partial u_i(\cdot)}{\partial x_i}\right) - \lambda_i^* = 0, \ \forall\, i \\
y_i &: \left(\frac{\partial W(\cdot)}{\partial u_i(\cdot)}\right)\left(\frac{\partial u_i(\cdot)}{\partial y_i}\right) - \rho^* = 0, \ \forall\, i \\
\gamma_i &: \left(\frac{\partial W(\cdot)}{\partial u_i(\cdot)}\right)\left(\frac{\partial u_i(\cdot)}{\partial \gamma_i}\right) - \phi_i^* = 0, \ \forall\, i \\
\beta &: \sum_{j=1}^{I}\left(\frac{\partial W(\cdot)}{\partial u_i(\cdot)}\right)\left(\frac{\partial u_i(\cdot)}{\partial \beta}\right) - \sum_{j=1}^{I} \kappa_j^* R_j(z_j^{g*}) = 0 \\
z_i^g &: \sum_{j=1}^{I} \phi_j^* \frac{\partial \Gamma_j(\cdot)}{\partial z_i^g} + \lambda_i^* R_i'(z_i^{g*}) - \kappa_i^* \beta R_i'(z_i^{g*}) - \rho^* + \mu_i^* R_i'(z_i^{g*}) - \tau_i^* R_i'(z_i^{g*}) = 0, \ \forall\, i \\
z_i^r &: \sum_{j=1}^{I} \phi_j^* \frac{\partial \Gamma_j(\cdot)}{\partial z_i^r} + \kappa_i^* R_i'(z_i^{r*}) - \rho^* + \mu_i^* R_i'(z_i^{r*}) - \tau_i^* R_i'(z_i^{r*}) = 0, \ \forall\, i \\
w_i^\gamma &: \sum_{j=1}^{I} \phi_j^* \frac{\partial \Gamma_j(\cdot)}{\partial w_i^\gamma} - \rho^* = 0, \ \forall\, i \\
\theta_i &: \sum_{j=1}^{I} \lambda_j^* B_{ji} - \sum_{l=1}^{L} \delta_l^* C_{li} + \sum_{l=1}^{L} \sigma_l^* C_{li} = 0, \ \forall\, i
\end{aligned}
$$

Furthermore, the following first order conditions for Lagrange multipliers $\phi_i^*$, $\lambda_i^*$, $\kappa_i^*$,

$\rho^*$, $\mu_i^*$, $\tau_i^*$, $\delta_l^*$, $\sigma_l^*$, and $\xi^*$ must be satisfied at the optimal solution:

$$\phi_i : \phi_i^* \left[\Gamma_i(z_1^{g*}, z_1^{r*}, w_1^{\gamma*}, \ldots, z_I^{g*}, z_I^{r*}, w_I^{\gamma*}) - \gamma_i^*\right] = 0,\ \phi_i^* \geq 0,\ \forall\, i$$

$$\lambda_i : \lambda_i^* \left[\sum_{j=1}^{I} B_{ij}\theta_j^* - x_i^* + R_i(z_i^{g*})\right] = 0,\ \lambda_i^* \geq 0,\ \forall\, i$$

$$\kappa_i : \kappa_i^* \left[R_i(z_i^{r*}) - \beta R_i(z_i^{g*})\right] = 0,\ \kappa_i^* \geq 0,\ \forall\, i$$

$$\rho : \rho^* \left[G - \sum_{i=1}^{I} w_i^{\gamma*} - \sum_{i=1}^{I} y_i^* - \sum_{j=1}^{I} z_j^{g*} - \sum_{j=1}^{I} z_j^{r*}\right] = 0,\ \rho^* \geq 0$$

$$\mu_i : \mu_i^*[R_i(z_i^{g*}) + R_i(z_i^{r*}) - P_i^{min}] = 0,\ \mu_i^* \geq 0,\ \forall\, i$$

$$\tau_i : \tau_i^*[P_i^{max} - R_i(z_i^{g*}) - R_i(z_i^{r*})] = 0,\ \tau_i^* \geq 0,\ \forall\, i$$

$$\delta_l : \delta_l^* \left[M_l + \sum_{i=1}^{I} C_{lj}\theta_j^*\right] = 0,\ \delta_l^* \geq 0,\ \forall\, i$$

$$\sigma_l : \sigma_l^* \left[M_l - \sum_{i=1}^{I} C_{lj}\theta_j^*\right] = 0,\ \sigma_l^* \geq 0,\ \forall\, i$$

$$\xi : \xi^*\theta_1 =,\ \xi^* \geq 0$$

### A.3.2 Individual Consumer

Each individual consumer at location $i$ has allocation of the resource $\bar{y}_i$ so that each consumer's allocated wealth, $m_i$ is equal to $\rho\bar{y}_i$. Consumer $i$ solves the following utility maximization problem:

$$\max_{x_i, y_i, \gamma_i, \beta} \quad u_i(x_i, y_i, \gamma_i, \beta)$$
$$\ni \quad \lambda_i x_i + \rho y_i + \phi_i \gamma_i + \kappa_i \beta \leq m_i$$

The Lagrangian for this maximization problem is:

$$\mathcal{L} = u_i(x_i, y_i, \gamma_i, \beta) + \nu(m_i - \lambda_i x_i - \rho y_i - \phi_i \gamma_i - \kappa_i \beta)$$

In order for endogenous variables $x_i^*$, $y_i^*$, $\gamma_i^*$, and $\beta^*$ to be optimal, the following first order conditions must be satisfied:

$$x_i : \frac{\partial u_i(\cdot)}{\partial x_i} - \nu^* \lambda_i = 0$$
$$y_i : \frac{\partial u_i(\cdot)}{\partial y_i} - \nu^* \rho = 0$$
$$\gamma_i : \frac{\partial u_i(\cdot)}{\partial \gamma_i} - \nu^* \phi_i = 0$$
$$\beta : \frac{\partial u_i(\cdot)}{\partial \beta} - \nu^* \kappa_i = 0$$

Furthermore, the following first order conditions for Lagrange multiplier $\nu^*$ must be satisfied at the optimal solution:

$$\nu : \nu^*(m_i - \lambda_i x_i^* - \rho y_i^* - \phi_i \gamma_i^* - \kappa_i \beta^*) = 0,\ \nu^* \geq 0$$

APPENDIX B

# TECHNICAL COMPUTATION INFORMATION

## B.1 Computer details

The numerical simulations were run in parallel on 26 Gateway Model E-2600S computers, each with a 3.40 GHz Intel Pentium D Processor and 896 MB of RAM. The machines were running Microsoft Windows® XP Professional, Version 2002, Service Pack 2 with MATLAB® version 7.4.0.287 (R2007a) and MATPOWER development version “matpower-dev-2009-05-27.”

## B.2 Simulation code

Due to the terms and conditions signed with Energy Visuals, Inc. the specific generator data used to conduct the numerical simulations cannot be published or distributed. Nevertheless, numerous MATLAB® functions and scripts were written in order to run the numerical simulations that are not related to the specific Energy Visuals, Inc. data and can be shared. Because the distributable software is thousands of lines of code, it is not reproduced here. Contact the author to receive an electronic version of the code.

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