Presents

Power Generation for the 21st Century

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Power Generation In Texas

A number of primary energy sources such as coal, uranium, natural gas, biomass, sun, water, or wind, can be used to generate electricity, which is then consumed by domestic, commercial, and industrial customers. Using different processes, energy within these fuel sources (atomic, chemical, kinetic, or radiant energy) is converted into electrical energy, which powers many different aspects of society, including lighting homes and businesses and running industrial machinery and processes. As shown in Figure 1, electricity consumption for residential purposes – lighting and heating homes, as well as powering appliances – is 37% of the total electricity use in the U.S. and 33% in Texas. Although electricity powers some transportation, the amount used is negligible for both the U.S. and Texas. Since Texas is home to many energy-intensive refining, chemical, and manufacturing facilities, industrial electricity use is higher than in the country as a whole.

Texas generates and consumes more electricity than any other state in the United States. In 2006, power plants in Texas generated more than 400 terawatt-hours (billion kWh) of electricity, with 49% from natural gas as a fuel source as shown in Figure 2. Figure 2 also shows the percentages of electricity generation for the U.S. The discrepancies in total electricity between Figure 1 and Figure 2 are due to energy losses during distribution. The Texas fuel mix differs from that of the U.S. with two major primary energy sources: coal and natural gas. Though coal produces nearly half of the electricity generated nationwide, it accounts for 37% of electricity generated in Texas. Nearly half of the electricity generated in Texas is from natural gas, compared to the national average of 20%.

Figure 1. U.S. (left) and Texas (right) electricity consumption, in percent, by sector for 2006. Texas uses a larger percentage of electricity for industrial purposes than does the U.S. as a whole. [EIA 2006, EIA 2008]
While nearly half of the electricity generated nationwide is from coal, nearly half of the electricity generated in Texas is from natural gas. Here, renewable includes traditional hydropower, solar, and wind power. [EIA 2006, EIA 2008]

With this fuel mix and consumption, Texas emits more carbon dioxide and nitrogen oxides resulting from the generation of electricity than any other state, releasing 257 million metric tons and 260 thousand metric tons respectively during 2006. At the same time, Texas emissions rates per quantity of electricity generated (e.g. lbs CO2/kWh) are below the average in the United States because of the extensive use of natural gas (and increasingly wind). [EIA 2006]

This mix of sources for electricity generation changes gradually as new power plants and new power generation technologies come on-line. For example, the renewable source in Figure 2 from 2006 includes wind power, along with other sources like hydropower and solar power. In 2008, Texas wind turbines generated over 12 terawatt-hours (TWh) of electricity – more than the total renewable generation in 2006. [EIA 2009] Texas has been increasing its use of renewable electricity generation technologies including wind and solar power. In 1999, a renewable portfolio standard was established for the state requiring 2,000 MW of new installed renewable capacity by 2009. Since 1999, due largely to the rapidly growing wind power industry in Texas, the renewable portfolio standard has been amended. Most recently in August of 2005, Senate Bill 20 was passed to require 5,000 MW of newly installed renewable capacity by 2015. That bill also includes a target of installing 500 MW of non-wind renewable capacity within the 5,000 MW. Further, this bill established a long-term goal of 10,000 MW of new installed renewable energy capacity by 2025. [SECO 2008] As of early 2009, Texas has 7,907 MW of installed wind capacity. [CPA 2008] The current legislative session is considering additional action related to fostering growth in renewable energy, including subsidies, mandates for non-wind and non-hydro renewable energy, and novel financing mechanisms for homeowners who wish to install distributed solar units.
While pursuing goals for reducing emissions and increasing renewable energy it would be useful for policymakers, regulators, and planners to understand the economic and environmental tradeoffs of the available options. The Texas Interactive Power Simulator (described below) was designed to calculate the economic costs and environmental impacts of different electricity generation mixes, allowing for more educated choices to be made.

**Baseload, Intermediate Load, and Peak Load**

The demand for power typically varies significantly throughout the day (see Figure 3). The minimum power needed during a 24-hour period (typically at night) is referred to as the baseload; the power needed for nominal daytime activities is intermediate load; and the power needed during a few hours each day with the highest demand represents the peak load. In addition to diurnal variations, electrical load has seasonal variations, as shown in Figure 4. The total demand for power can vary as much as a factor of three between the highest peak load in the summer to the lowest baseload in the spring or winter. The highest peak load day in 2006 was the highest ERCOT has ever experienced.

These variations are met in Texas with a variety of fuels, as shown in Figure 5, which displays the total electricity demand and generation by plant type in ERCOT on August 23, 2005, the day when peak demand was its greatest in 2005. Coal and nuclear-based facilities supplied most of the base load generation. Natural gas provided the remaining base load generation and is utilized as necessary to meet any demand variations throughout the day. Other sources such as wind, hydroelectric, and direct current (DC) connections to other grids constituted substantially smaller portions of generation and are often mismatched with peak load. Consequently, wind energy, for example, often cuts into natural gas for baseload power generation. These usage patterns are typical of each plant type throughout the year.

With expected growth in overall peak load and electricity consumption, planners must understand what fuels and technologies might be available to meet demand.
Figure 3. Demand varies throughout the day: baseload represents the minimum power needed (typically at night), intermediate load meets increased demand for daytime activities, and peak load represents a few hours in the day when load is at its maximum.

Figure 4. Load varies during the day (as seen above, in Figure 3), and during the year, as shown here. The total demand for power can vary as much as a factor of three between the highest peak load in the summer to the lowest baseload in the spring or winter. The peak load day in 2006 was the highest ERCOT has ever experienced. [ERCOT 2006]
Figure 5. ERCOT electricity demand (load) on the highest peak demand day of 2008 (August 4) is met primarily by coal, natural gas, and nuclear-based facilities. [ERCOT 2009]

Understanding Environmental and Economic Tradeoffs

All the fuel choices for power in Texas have different economic or environmental tradeoffs. However, because some of these tradeoffs are not always obvious, there is a need for analytical tools that demonstrate some simple lessons about them.

The Texas Interactive Power Simulator was designed at the University of Texas at Austin to communicate key lessons concerning the tradeoffs of electricity generation methods in Texas. [Lott 2009] The key target audiences for this project include college students, high school students, state legislators and their staff, as well as the general public. The Texas Interactive Power Simulator accomplishes the project goals by allowing the user to manipulate the electricity generation mix in the state of Texas and immediately view the economic and environmental impacts of these changes. It is designed to allow for easy communication of the tradeoffs of different electricity generation technologies. It is currently being used in two courses at the University of Texas at Austin aimed at teaching the basics of energy technology and energy policy to those with little or no background in the field.
The Texas Interactive Power Simulator allows the user to change the amount of electricity that is generated using each of six types of fuels (coal, natural gas, nuclear, wind, hydro, solar). The simulator describes the current electricity generation landscape across the state of Texas. Changes can be made to the existing landscape, and these changes are used to calculate economic costs and environmental impacts.

Economic impacts are measured in terms of three categories: cost of new capacity, cost of fuel, and cost of operation and maintenance of the plant facility. Cost of new capacity includes the capital investment required to build any new power plants required by the generation mix the user specifies (“Your Mix”). Cost of fuel and cost of operation and maintenance (O&M) are calculated on a cost per megawatt-hour generated basis. Costs used in the simulator are selected as a representative value from within a range of published costs for all technologies that utilize the indicated fuel type.

Environmental impacts that result from power plant operations are characterized in three categories: air emissions, water consumption, and land required for the power plant footprint. Air emissions and water consumption are calculated on a per megawatt-hour basis similar to the cost calculations previously described. Values are calculated for a weighted average megawatt-hour of generated electricity and are displayed using the graphs shown in Figure 7. These environmental impact values are non-lifecycle, including only the environmental impacts at the point of generation. Lifecycle values are not used because of the very small magnitude of the environmental impacts not associated with generation. The variability of environmental impacts, when measured for the entire lifecycle, make it inappropriate to use in TIPS, given the generalizations used for each fuel type. Water consumption does not refer to the total amount of water withdrawn and used for power plant cooling (pass-through water use), but specifically refers to the amount of water that is consumed during this process.

The Texas Interactive Power Simulator’s user interface is designed to allow for the effective communication of key lessons to the user in a self-teaching environment. The initial portal into the website is displayed in Figure 6 and provides background information and collects statistical data about the user.
Figure 6: The welcome page for the Texas Interactive Power Simulator collects basic user information (zip code and organization).

After the welcome page, the user is directed to the main interface page for TIPS. TIPS calculates the output values based on user inputs (“Your Mix”). The changes are displayed in green throughout the webpage with the exception of total new capacity cost displayed in red. Values for the “Current Mix” are fixed and displayed in blue to provide users with an easy way to compare the differences between their customized “Your Mix” and the “Current Mix”. The simulator’s interface design is displayed in Figure 7. As the user changes values for percent of total electricity generation, TIPS displays the altered impacts in real time.
Figure 7: The main page for the Texas Interactive Power Simulator gives the user an opportunity to change the fuel mix for power generation in Texas and subsequently calculates some top-level economic and environmental impacts of those changes.

For a fuller explanation of the Texas Interactive Power Simulator and examples of how it can be used to analyze different power generation scenarios, please see the conference paper included in this primer.
References


ANALYZING TRADEOFFS IN ELECTRICITY CHOICES USING THE TEXAS INTERACTIVE POWER SIMULATOR (TIPS)

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ABSTRACT

The Texas Interactive Power Simulator (TIPS) is an interactive analytical tool developed at the University of Texas at Austin for quantitatively comparing the first-order economic and environmental tradeoffs of different electricity production methods in Texas. The tool is designed for analysis of different power choices and is presented in an online format for use by students, the general public, and government decision-makers. The core electricity industry data are Texas-specific, but the flexibility of the framework, when combined with user supplied content, extends its applicability to the United States and world electricity markets.

TIPS provides a method for assessing the tradeoffs of electricity generation technologies in terms of economic costs and environmental impacts. Economic costs include major factors such as the cost of capacity, fuel, operation and maintenance (O&M), as well as the costs of conservation programs and environmental impact mitigation technology. Environmental impacts include market externalities such as the environmental impacts on air, land, and water, and are normalized per kWh generated (for example, pounds of CO₂ or NOₓ, acres of land, or gallons of cooling water consumed per kWh of generated electricity). Environmental impacts can further be associated with a cost, which is included in the overall levelized cost of electricity. Users can supply their own data for interactive experimentation, though peer-reviewed data are provided as default values.

TIPS’ outputs include text, graphs, and pictograms showing the electricity output and environmental impact of the user’s selections, which allow the user to interpret the overall impact for different fuel mixes. Source data are incorporated from government sources and peer reviewed technical literature. The TIPS interactive interface allows the user to analyze a desired electricity mix according to the percentage breakdown of electricity production for each generation technology. The user input determines the overall direct and indirect costs of a unit of electricity according to the particular cost parameters associated with each generation technology. This manuscript discusses the methodology used in TIPS calculation and shares the results of using TIPS to analyze the cost and environmental impacts for a variety of illustrative and possible generation scenarios in Texas, including the following: high carbon prices, nuclear renaissance, and continuing wind market growth.

INTRODUCTION

The Texas Interactive Power Simulator was designed to serve as a tool that can be used for analyzing tradeoffs of electricity generation methods, specifically in the state of Texas. In addition, the tool is designed for communicating energy concepts to policy makers and the public in general.
There are many publicly available tools that compare electricity generation technologies. However, while they excel in one or two design criteria, they are generally limited in scope or transparency. Many major oil & gas companies have their own online tools, available for consumer use via their corporate website. Each has a slightly differing apparent goal. For instance, BP’s online tools focus primarily on consumer’s personal energy use and carbon footprint (1). Chevron’s “Energy Generator” focuses on how to save energy through small changes in your lifestyle (2). Research institutions have also designed energy generation analysis tools that are available online. One such example is HOMER, a micropower optimization model developed by the National Renewable Energy Laboratory is designed to optimize off-grid and grid-connected renewable systems through multivariable system analysis (3). Its design is thorough, offering many types of renewable technologies for use in your system design. However, its focus is on small-scale off-grid renewable systems making it inapplicable for people to learn about large grid-scale scenarios. The Renewable Energy Costs and Benefits for Society (RECaBS) tool allows for more technologies than HOMER, including coal with carbon capture, coal combined heat and power systems, and waste incineration (4). However, its design does not incorporate other technologies that are prevalent today including natural gas and nuclear power generation technologies. Additionally, it is again difficult to access the backend calculations used in each of these tools.

The analysis desired by the authors requires a tool that is both transparent and has the flexibility to incorporate the typical desired generation technologies. The analysis also requires a tool that is Texas-specific, utilizing Texas state data as inputs wherever possible. As no available tool currently exists that meets these requirements, the Texas Interactive Power Simulator was created.

BACKGROUND

Texas generates and consumes more electricity than any other state in the United States. In 2006, power plants in Texas generated more than 400 terawatt-hours of electricity, with 49% from natural gas as a fuel source as shown in Figure 1. Texas emits more air emissions of carbon dioxide and nitrogen oxides resulting from the generation of electricity, emitting 257,552,000 metric tons and 260,000 metric tons respectively during 2006. At the same time, Texas emissions rates per quantity of electricity generated (e.g. lbs CO2/kWh) are below the average in the United States because of the extensive use of natural gas (5).

![Figure 1: The fuel mix for power generation in Texas in 2007 shows high use of natural gas as an electricity generation fuel source (5).](image)

Texas is and has been increasing its use of renewable electricity generation technologies including wind and solar power. In 1999, a renewable portfolio standard was established for the state requiring 2,000 MW of new installed renewable capacity by 2009. (6) Since 1999, due largely to the rapidly growing wind power industry in Texas, the renewable portfolio standard has been amended. Most recently in August of 2005, Senate Bill 20 was passed to require 5,000 MW of newly installed renewable capacity by 2015. That bill also includes a target of installing 500 MW of non-wind renewable capacity within the 5,000 MW. Further, this bill established a long term goal of 10,000 MW of new installed renewable energy capacity by 2025. (7) As of early 2009, Texas has 7,907 MW of installed wind capacity. (8)

While striving to reach these renewable energy and other emissions and energy goals, and to inform policymakers, environmental regulators, and planners, as they consider additional modifications to the generation mix, it would be useful to understand the tradeoffs of the available options. All existing fuels and technologies have tradeoffs, whether environmental or economic; they key is to understand and balance these tradeoffs with each region’s priorities. The Texas Interactive Power Simulator analyzes the economic costs and environmental impacts of electricity generation mixes, allowing for more educated choices to be made.
TIPS OVERVIEW

The Texas Interactive Power Simulator is designed using LabVIEW software to allow the user to virtually change the electricity generation mix in the state of Texas in terms of the percentage of total generation from each generation source. Total generation is determined using electricity demand inputs as described in subsequent sections. The user may specify generation technologies (e.g. Pressurized Water Reactor, wind turbine, etc) that they wish to incorporate, or may choose from a more general set of categories which refer to the specific fuel source (e.g. coal, nuclear). In the latter case, TIPS utilizes representative average values for economic costs and environmental impacts based on the current Texas electricity generation mix. This manuscript will discuss specific analyses using fuel category changes as opposed to specific technology changes.

User inputs result in differences between the economic costs and environmental impacts of the current electricity mix and the user specified mix. These differences are compared both numerically and graphically to increase the user’s ease of understanding.

FUEL AND TECHNOLOGY OPTIONS

The Texas Interactive Power Simulator allows the user to select technologies from the following classifications of fuels and technologies:

1. Coal
   a. Pulverized Coal – Supercritical (PCS)
   b. Integrated Gasification Combined Cycle (IGCC)
2. Natural Gas
   a. Natural Gas Combined Cycle (NGCC)
   b. Natural Gas Steam Turbine (NGST)
   c. Natural Gas Gas Turbine (NGGT)
3. Nuclear
   a. Pressurized Water Reactor (PWR)
   b. Boiling Water Reactor (BWR)
4. Wind
5. Hydroelectric
6. Solar
   a. Photovoltaic – thin film
   b. Photovoltaic – traditional panels
   c. Concentrating Solar Power

TIPS allows the user to specify the general category of fuel (e.g. coal) or the specific technology (e.g. IGCC) that they would like to select to generate the chosen percentage of total generation. If they select the category of fuel without specifying the technology, representative values are used based on the current breakdown in Texas.

ELECTRICITY DEMAND

The Texas Interactive Power Simulator may operate in either a time independent or a time dependent mode. The former allows for instantaneous changes in the generation mix. This time independence eliminates the incorporation of concepts such as construction timelines, the time value of money (discount rate), and construction interest rates in all calculations.

The time dependant mode uses an analysis period of twenty-one years, to the year 2030. In this mode the user’s inputted generation mix is incorporated to determine the generation mix in the year 2030. That is, the Texas Interactive Power Simulator ensures that the user specified generation mix is achieved no later than 2030. New power plant construction is completed such that the user defined generation mix is achieved as rapidly as possible within the twenty-one year timeframe, given construction timeline constraints. Appropriate discount rates and construction loan interest rates are incorporated into applicable equations per user inputs or using default values of 5% and 10%, respectively. Additionally, demand changes over time are incorporated in this time dependent mode. The user is required to enter one of the following combinations of options: the annual electricity demand (in megawatt-hours or MWh) growth rate or a combination of the population growth rate and per capita energy demand for the analysis period. This mode is utilized in all analysis and discussion provided in this manuscript. While analysis in time independent mode also provides useful insight, it is not incorporated into this paper for the sake of clarity and brevity.

Electricity generation from the current year to 2030 is calculated based on user inputs. It should be understood that the term electricity generation refers specifically to the amount of electricity required during the year by the end use customer in addition to the amount of electricity lost during transmission and distribution of this electricity.

The user may enter either the demand growth rate (%/year) or the population growth rate (%/year) and a corresponding per capita electricity demand value. Should the user chose the first option, the electricity generation over time is calculated using Equation 1, electricity generation (EGt) versus time for an inputted
annual growth rate (AGR, %/year):

\[ EG_t = E_G_0 \times (1 + \frac{AGR}{100})^t \]

Eq. 1

EG\(_0\) refers to the electricity generation at time (t) equal to 0, which is the case in 2009. The electricity generation in the year 2030 is represented as \( EG_{21} \) (21 indicating the number of years after 2009). Alternatively, the electricity demand may be calculated using the annual population growth rate (%/year) and per capita electricity demand (MWh/person \( \cdot \) year) which is assumed to equal the electricity generation rate when multiplied by the population size. In this case, the electricity generation requirement is calculated using Equation 2, electricity generation versus time for an inputted annual population growth rate (APGR) and per capita electricity demand (PCED).

\[ EG_t = Total Population \times PCED \times (1 + \frac{APGR}{100})^t \]

Eq. 2

Per capita electricity demand is assumed to be constant, but will change over time in future versions due to the potential value of this degree of freedom. As with electricity generation (EG) requirements, per capita electricity demand refers to the amount of electricity generation required by each person, taking into account losses during the transmission and distribution of this electricity. Default values for the previously discussed inputs are not provided to the user at this time.

**ECONOMIC COSTS**

Economic costs are measured in terms of two categories: cost of new capacity and levelized cost of electricity (LCOE). New capacity cost (NCC) includes the capital investment required to build any new power plants required by the generation mix the user specifies as shown below in Equation 3 using the capacity factor (CF, expressed as a percent) for each technology. If this value is negative, then the new capacity cost is zero. When positive, the new capacity required is multiplied by the capacity cost (CC) as shown in Equations 3 and 4 below, which calculate new capacity cost for a technology or fuel category (j).

\[ NCC_j = [TC – EC] \times CC \]

Eq. 3

New Capacity Cost (NCC) is summed for all technologies (or fuels) to determine the total new capacity cost (TNCC). In TIPS calculations, the existing capacity values shown below in Table 1 are used for fuel categories.

<table>
<thead>
<tr>
<th>Existing Capacity (MW)</th>
<th>Coal</th>
<th>Natural Gas</th>
<th>Nuclear</th>
<th>Wind</th>
<th>Hydro</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>21,381</td>
<td>71,737</td>
<td>5,138</td>
<td>8,100</td>
<td>674</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Existing Capacity for Fuel Sources (5) (9)

Levelized cost of electricity (LCOE) incorporates multiple economic parameters to effectively compare each generation technology or fuel category. These parameters include:

- O&M: annual cost of plant operation and maintenance ($/MWh)
- Fuel: annual cost of fuel ($/MWh)
- Externalities: annual cost of environmental externalities ($/MWh)
- CC: capacity costs ($/MW)
- IDC: interest during construction
- PV: present value
- \( C_{total} \): annual cost (O&M, fuel, environmental impacts cost) for total generation from source
- \( N_{constr} \): number of years the plant is under construction
- \( N_{years} \): economic life of power plant
- \( r \): construction loan interest rate (%)
- IC: initial installed cost ($)
- i: market discount rate (%)

The user inherently chooses the MWh/year for each technology by firstly dictating the total MWh/year by specifying a demand growth rate and secondly choosing the percentage of electricity from each fuel/technology category. There is no feedback mechanism for modifying the user’s inputs based on the resulting LCOE values calculated. Rather, the LCOE is strictly calculated using the user’s input values for the generation mix. Levelized cost of electricity is calculated using Equation
5, Equation 6, and Equation 7 below. Costs and impacts are non-lifecycle costs, selected as a representative value from within a range of published costs for all included technologies. All monetary values are expressed in 2009 dollars. Interest rates are determined as previously discussed.

\[
\text{LCOE} = \frac{CC + IDC(r, N_{connstr}, IC) + PV(i, N_{yrs} \times (O&M + \text{fuel + externalities}))}{PV(i, N_{yrs}, C_{total}) \times (\text{MWh/yr})}
\]

Eq. 5

\[
PV(i, N_{yrs}, C_{total}) = \frac{C_{total}}{i/100} \left[1 - \frac{1}{(1 + i/100)^{N_{yrs}}}\right]
\]

Eq. 6

\[
IDC(r, N_{connstr}, IC) \approx IC \times (r/100) \times N_{connstr}
\]

Eq. 7

Note that equation 7 is an approximate value because this equation does not take into account for compounding.

ENVIRONMENTAL IMPACTS

Environmental impacts from power plant operations are characterized in two categories: air emissions and water consumption. Air emissions include carbon dioxide (CO₂), sulfur dioxide (SO₂), and Nitrogen Oxides (NOₓ) emitted during plant operation. Water consumption does not refer to the total amount of water used for power plant cooling (pass-through water use), but specifically refers to the amount of water that is consumed during this process (consumptive water use).

Air emissions and water consumption are calculated on a per megawatt-hour basis. Values are calculated for a generation-mix-weighted average megawatt-hour of generated electricity. As with economic costs, environmental impact values do not account for the full power plant life cycle. For instance, we do not attempt to quantify the full externality of dealing with spent nuclear fuel or the air emissions released during power plant construction. Research showing the impacts of the manufacturing and construction phases of electricity generation equipment, for example life cycle greenhouse gas emissions, shows that those with no direct emissions emit 1-2 orders of magnitude less. (10) Thus, while valuable for research and technology development, for the target audience of this initial version of TIPS, the lifecycle impacts from indirect energy and emissions are not currently of high value. Values for environmental impacts are determined using Equation 8, which calculates the average environmental impact (ei) to determine the average environmental impact per MWh.

\[
e_i = \sum_{f} (\% \text{Generation})_f \times \left(\frac{\text{amt. of pollutant or resource use}}{\text{MWh}}\right)
\]

Eq. 8

Note than values for this calculation are populated from Table 3 (below). Total emissions per year (EI) are found by multiplying the environmental impact (ei) by the total annual generation as shown below in Equation 9.

\[
EI = e_i \times E_{Gt}
\]

Eq. 9

THREE SCENARIOS WERE ANALYZED

Three scenarios were analyzed using the Texas Interactive power simulator. The generation mix for each scenario is shown below in Table 2.

<table>
<thead>
<tr>
<th>Carbon Price</th>
<th>Coal</th>
<th>Natural Gas</th>
<th>Nuclear</th>
<th>Wind</th>
<th>Hydro</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>36%</td>
<td>49%</td>
<td>10%</td>
<td>4%</td>
<td>1%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Nuclear Renaissance</td>
<td>16%</td>
<td>29%</td>
<td>50%</td>
<td>4%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>High Wind Growth</td>
<td>20%</td>
<td>49%</td>
<td>10%</td>
<td>4%</td>
<td>20%</td>
<td>1%</td>
</tr>
<tr>
<td>Current (2009*)</td>
<td>36%</td>
<td>49%</td>
<td>10%</td>
<td>4%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>144 TWh</td>
<td>197 TWh</td>
<td>40 TWh</td>
<td>16 TWh</td>
<td>4 TWh</td>
<td>TWh</td>
<td></td>
</tr>
</tbody>
</table>

*Values are approximate based on 2007 values until updated reports are published.

Carbon Price Scenario (carbon price) examined the effects of putting a price on carbon, a likely result of current energy policy proposals. For the purpose of this analysis, the generation mix was held constant with current day. The purpose of this scenario was to discover and illustrate the effect of a carbon price on the levelized cost of electricity for coal and natural gas electricity generation. Accordingly, no price was assigned to either sulfur dioxide or nitrogen oxides. An initial price of $50 per 2000 pounds ($55 per metric ton) of carbon dioxide was analyzed. This value was chosen to represent an aggressive carbon price scheme. The user’s generation mix inputs were not changed due to the carbon price, though it has significant impact on the LCOE for these two generation sources. In practice, this change in cost would undoubtedly affect the generation mix. However, TIPS design is targeted toward allowing the user to designate the generation mix, regardless of the economic and environmental impacts. Clean coal technology is not
Nuclear Renaissance Scenario examined a future nuclear renaissance. In this scenario, the percent of total generation from nuclear power rose to 50% of total generation. Additional generation from nuclear was assumed to displace coal and natural gas equally. Many factors are currently acting as drivers toward a nuclear renaissance in the United States, including concerns regarding climate change and the United States’ dependence on foreign fuels. This scenario analysis was conducted to understand the economic costs and environmental impacts of a transition from the current fossil fuel based Texas electricity generation mix.

High Wind Growth Scenario analyzed a trend of continued wind market growth in Texas between now and 2030. At the end of 2007, Texas had installed 4,296 MW of wind generation capacity, or approximately ¼ of the entire US wind generation capacity at 16,596 MW. Extensive projects, both on- and offshore are currently either in the planning stage or already under construction. With the extension of the production tax credit for wind energy in the Emergency Economic Stabilization Act of 2008 (11), the trend of continued wind capacity growth is likely to continue.

Table 3: The input data used in all scenario analyses discussed in this manuscript (14-22)

<table>
<thead>
<tr>
<th></th>
<th>Coal</th>
<th>Natural Gas</th>
<th>Nuclear</th>
<th>Wind</th>
<th>Hydro</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Capacity</td>
<td>1.5</td>
<td>0.9</td>
<td>5.0</td>
<td>2.5</td>
<td>1.7</td>
<td>5.0</td>
</tr>
<tr>
<td>(million$/MW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O&amp;M Cost* ($/MWh)</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>9.5</td>
</tr>
<tr>
<td>Fuel Cost ($/MWh)</td>
<td>15</td>
<td>80</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CO2 Emissions (lbs/MW)</td>
<td>2293</td>
<td>1146</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SO2 Emissions (lbs/MW)</td>
<td>6.8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NOx Emissions (lbs/MW)</td>
<td>5</td>
<td>0.03</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Water Consumption (gal/MWh)</td>
<td>426</td>
<td>223</td>
<td>600</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Land Use (acres/MW)</td>
<td>1.2</td>
<td>0.05</td>
<td>0.05</td>
<td>25</td>
<td>131</td>
<td>4.6</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>84</td>
<td>80</td>
<td>90</td>
<td>26</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>Construction Timeline (years)</td>
<td>8</td>
<td>8</td>
<td>15</td>
<td>2</td>
<td>n/a</td>
<td>2</td>
</tr>
<tr>
<td>Economic life (years)</td>
<td>30</td>
<td>30</td>
<td>40</td>
<td>15</td>
<td>n/a</td>
<td>20</td>
</tr>
</tbody>
</table>

*O&M is the operation and maintenance cost

All scenario analyses in this manuscript used the following parameters:

1. End user demand and resulting generation growth rate of 1% per year
2. 10% discount rate
3. 3% loan interest rate for construction loan

Additionally, the input data shown in Table 3 (above) were included for the economic cost and environmental impact calculations. The demand growth rate of 1% per year leads to a year 2030 annual demand of just greater than 494 TWh, given that current demand in Texas is approximately 401 TWh.

For Carbon Price Scenario, to achieve the indicated generation mix, $18 billion of new capacity cost was incurred over the 21 year time period. This new capacity cost resulted from the need for additional coal, nuclear, and wind power generation facilities to meet growing demand. The final cost LCOE of electricity generation, were as follows:
Table 4: LCOE with carbon tax rises sharply for carbon-intensive fuels

<table>
<thead>
<tr>
<th>LCOE without CO₂ Tax ($/MWh)</th>
<th>Coal</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCOE with CO₂ Tax of $55/ton ($/MWh)</td>
<td>77</td>
<td>114</td>
</tr>
</tbody>
</table>

| Difference in cost ($/MWh) | +57  | +29         |

Table 4 illustrates how dramatically a carbon tax affects the price electricity generated using carbon-intensive fuels. With a $55 per ton tax on carbon dioxide emissions, the cost gap between coal and natural gas generation drops over 40 percent from $65 per MWh to $37 per MWh. Coal, with its higher rate of carbon dioxide emissions during generation is affected more intensely than natural gas by a carbon tax policy. Because the generation mix itself has not changed in this analysis, the environmental impacts were identical per MWh in both the current and the future mix.

In Nuclear Renaissance Scenario the amount of generation from nuclear power was increased to 50% of total generation. To meet the generation mix requirements for this scenario, TIPS found that a capital investment of $118 billion would be required for new nuclear power plant construction. Nuclear power would have a resulting levelized cost of electricity (LCOE) of $86.

The increase in the percent of total generation that comes from nuclear power had a noticeable impact on the environmental impacts that were calculated using the Texas Interactive Power Simulator. These impacts are quantitatively displayed below in Table 5.

Table 5: Air emissions are reduced and water consumption is increased with higher nuclear power use

<table>
<thead>
<tr>
<th>Air Emissions (10⁹ lbs/year)</th>
<th>Water Consumption (10⁹ gal/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>SO₂</td>
</tr>
<tr>
<td>Current Generation mix</td>
<td>690</td>
</tr>
<tr>
<td>Nuclear Renaissance Scenario</td>
<td>350</td>
</tr>
<tr>
<td>% Change</td>
<td>-49%</td>
</tr>
</tbody>
</table>

Total annual air emissions were reduced by 49%, 55%, and 56% for carbon dioxide, sulfur dioxide, and nitrogen oxides respectively. Water consumption increased by 31% from $1.6 \times 10^{11}$ to $2.1 \times 10^{11}$ gallons consumed per year. This increase in water consumption leads to potential concerns for water constrained states.

In High Wind Growth Scenario, the increase in electricity generation from wind resulted in a new capacity cost of $71 billion and a LCOE for wind of $124 per MWh. While some of this capacity cost ($3 billion) was due to increasing nuclear capacity with the increasing electricity demand, the majority of this cost ($68 billion) was associated with the new wind generation capacity required to supply the more than 48 TWh that will be needed from wind generation in 2030 with a 1% per year demand growth rate. All construction is front-loaded (e.g. wind turbines are assumed to be installed as quickly as allowed given construction timeline constraints shown in Table 2). In this scenario, concerns regarding wind intermittency and its effects on system reliability are negated by an excess of natural gas generation capacity. No energy storage system is incorporated into this analysis.

Environmental impacts were also affected with this increase in wind power generation. Air emissions, again weighted per MWh of generated electricity decreased significantly with increasing wind power generation.

Table 6: Environmental impacts decrease as wind generation increases

<table>
<thead>
<tr>
<th>Air Emissions (10⁹ lbs/year)</th>
<th>Water Consumption (10⁹ gal/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>SO₂</td>
</tr>
<tr>
<td>Current Generation mix</td>
<td>690</td>
</tr>
<tr>
<td>High Wind Growth Scenario</td>
<td>504</td>
</tr>
<tr>
<td>% Change</td>
<td>-27%</td>
</tr>
</tbody>
</table>

SUMMARY & FUTURE WORK

The Texas Interactive Power Simulator was developed by the University of Texas at Austin in order to analyze the tradeoffs of electricity generation choices in the state of Texas. Inputs were used to determine the generation mix in the year 2030 and TIPS calculated the tradeoffs associated with three distinct scenarios.
Tradeoffs were calculated in two main categories: economic costs and environmental impacts. Economic costs included the cost of new capacity and the levelized cost of electricity (LCOE). Environmental impacts included:

1. Air emissions of carbon dioxide, sulfur dioxide, and nitrogen oxides (lbs/MWh)
2. Consumptive water use (gal/MWh)

All environmental impacts were calculated for a generation-mix-weighted megawatt-hour of generated electricity.

Three scenarios were analyzed using the TIPS interface: high carbon price, nuclear renaissance, and continued wind market growth. Each analysis revealed distinct tradeoffs between power generation technologies. The first scenario, introduction of a carbon tax showed that even with a relatively aggressive tax of $55/ton natural gas still maintained a higher LCOE than coal. The second scenario, nuclear renaissance resulted in a high capital cost and significant increase in water consumption. There was also a decrease in air emissions (lbs/year). The third scenario, continued wind market growth revealed a significant decrease in environmental impacts (air emissions and water consumption). To achieve the required increase in electricity generation from wind power there was also a high new capacity cost of $71 billion.

Other scenarios currently of interest include solar market growth and conservation scenarios. The solar market in Texas is virtually non-existent, with only 6.5 MW of currently installed solar, none of which is dispatchable grid-based power. With the Texas renewable portfolio standard non-wind renewable energy requirement, solar stands as a potential supplier to meet the 500 MW requirement under the Senate Bill 20 revised renewable portfolio standard. An analysis of the potential impacts of this type of scenario is of interest. Conservation efforts could also be included, offsetting increasing demand.

Future work will focus upon making TIPS integrated with policy-making processes by providing the ability to project impacts from proposed bills and legislation. Additional future work will incorporate the costs of electric grid ancillary services as well as other peak and base load considerations. The costs and environmental impacts will also be added for additional technologies such as storage systems (e.g. batteries, compressed air energy storage), demand response, and CO₂ capture systems on fossil power plants.

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