Spring 2020

Testing the Robustness of Electric Transmission Expansion Plans of an Independent System Operator

Joe Eilers

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Testing the Robustness of Electric Transmission Expansion Plans of an Independent System Operator

by

Joe Eilers

A Creative Component submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Electrical Engineering (Electric Power & Energy Systems Emphasis)

Program of Study Committee:
Dr. Ian Dobson, Major Professor

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation/thesis. The Graduate College will ensure this dissertation/thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2020

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The Midcontinent Independent System Operator (MISO) is responsible for the operation and planning of the electric transmission grid for 15 states in the middle section of the United States. Every year, MISO produces forward looking scenarios called Futures to help economically evaluate transmission additions. These Futures attempt to capture uncertainty in the energy industry with high confidence over a 20 year planning cycle. In order to test the robustness of these Futures, Integrated Resource Plans (IRPs) were collected and examined from the stakeholder utilities in MISO’s footprint. An IRP is an electric utility’s long-term plan for their resource needs to meet future electric demand. The generation additions in these plans were summed and compared against the Futures, which showed that the Futures were under projecting renewable generation. In order to measure the historical accuracy of IRPs, previously filed IRPs of stakeholder utilities were collected and examined to compare their projections of their 2019 capacity and energy mixes vs their actual 2019 capacity and energy mixes. The older IRPs were found to have on average under projected renewable generation and over projected coal generation.
CHAPTER 1. OVERVIEW

1.1 Introduction

The Midcontinent Independent System Operator (MISO) is a not-for-profit organization that delivers safe, cost-effective electric power across 15 USA states and the Canadian province of Manitoba. MISO is responsible for the regulation of the electricity markets as well as the operation and planning of the electric transmission grid over the next 20 years [1]. Its mission is to foster wholesale electric competition in the region, create greater system reliability, and establish coordinated, value-based regional planning. MISO achieves this by working with their stakeholders which include state representatives, transmission owners, generation owners, and utilities to solve system wide problems.

There is a large monetary value saved by these system wide solutions. By increasing footprint diversity for generation, MISO saves its members 2.2 – 2.7 billion dollars annually. These savings are ensured to continue by planning for system wide generation and transmission additions as a group. By creating a plan for future transmission additions, MISO can ensure with a certain level of confidence that economic benefits for members will continue.

Every year, MISO produces the MISO Transmission Expansion Plan (MTEP) which helps MISO and their stakeholders plan transmission additions. These additions are economically evaluated based on forward looking scenarios called Futures. These Futures attempt to capture uncertainty in the energy industry with high confidence across multiple planning cycles while building in flexibility to maintain accuracy. In more simple terms, the Futures are used to develop the most robust plan for an uncertain future.

One of the main components of these Futures is the renewable energy penetration projections. These projections are based on the energy served by fuel type in the MISO fleet, and are made using a linear program called Electric Generation Expansion Analysis System (EGEAS). EGEAS is
an electric generation expansion program. Programs like EGEAS are used by independent system operators and some larger utilities to forecast their future generation additions and retirements in the next 5, 10, or 20 years. By adding different inputs and constraints to EGEAS based on the Futures, energy provided by renewable generation sources can be modeled out 20 years.

1.2 MISO Generation Mix

Energy mix is one of the main ways MISO defines their existing fleet, and it is evolving. It affects both how much transmission is planned for and where said transmission is placed. This in turn affects MISO stakeholders, which in the end affects every single person living in the MISO footprint. Figure 1.2 MISO Fuel Mix Change shows MISO’s past energy mix in 2005, the energy mix in 2017, as well as the projected mix in 2033 for the four future scenarios of MTEP 2018. Some states in the MISO footprint also look to the future by creating legislative goals and initiatives for the electricity produced in their state. These initiatives affect MISO stakeholders and how they plan for their future. MISO utility members then create plans of their own in the form of Integrated Resource Plans.

Figure 1.1 MISO Fuel Mix Change [1]
An Integrated Resource Plan (IRP) is a road-map that companies use to plan out their generation and transmission additions, as well as their various goals for their future in the energy industry. A large part of many IRPs is the future renewable generation additions as well the goal renewable generation percentage after the planning cycle. This percentage along with planned retirements can help inform us as to how MISO’s overall fleet will change. These plans were compiled together to project what MISO’s future fuel mix would be if IPRs were used to plan generation additions. Because the Futures are currently independent of these IRPs, the generation mix projected using IRPs was then compared to the Future based EGEAS projections of percent generation coming from wind and solar. This report focuses on renewable generation percentages instead of capacity additions because many state and utility goals and/or projections are in terms of generation mixes.

After these projections were compared, previously filed IRPs from the last 15 years in the MISO footprint were gathered. In order to use the current IRP projections for comparison with a relatively high amount of confidence, we must also look at their historical accuracy. The IRP projected generation mix for 2019 was compared with the actual generation mix for each utility with a previously filed IRP.

As previously stated, the Futures are designed to bookend uncertainty in the energy industry including renewable growth. By comparing the IRP additions to the EGEAS projections, as well as understanding the historical accuracy of IRPs, we can see if the current Futures have properly book-ended renewable growth in the MISO footprint.
CHAPTER 2. BACKGROUND INFORMATION

2.1 History of IRPs

An IRP is an electric utility’s long-term plan for their resource needs to meet future electric demand. IRPs first originated out of the financial crises in the 70’s and 80’s in the US. These crises were partly caused from a combination of utilities choosing to invest in expensive and unnecessary power plants, as well as cost overruns from nuclear power plants. “One of the worst cases was the 820 MW Shoreham nuclear power plant, which in 1968 was projected by Long Island Lighting Co. in New York to cost 350 million dollars. When it was finally completed 20 years later, its final cost was 15 times the original estimate. The plant never went into commercial operation and was sold to the state for one dollar in 1989.” [3]. Many plants in the same area had total final costs ten times higher than the original final cost estimates. These cost overruns and over projected load forecasts led to bankruptcy filings for a large number of utilities, including New Hampshire Electric Coop, Public Service of New Hampshire, Vermont Electric Coop, Eastern Maine Electric Coop, and Eastern Utilities.

Modern integrated resource planning is, “a planning approach that has the potential to take a society-wide perspective and incorporate public participation in meaningful ways, and has a strong track record in creating plans that are low-cost, low risk, and with outcomes that minimize environmental and social impacts.” [3]. In more simple terms, modern resource planning with IRPs is a broad view of the energy landscape that provides a lower cost and lower risk path forward for utilities. Currently, 33 states require utilities to file IRPs with their state public utility commissions as shown in Figure 2.1. IRP requirements vary state to state, but generally IRPs address resource needs for a twenty year planning horizon, with updates made every two to three years. The IRP process generally consists of the following objectives:

- Establish scope and objectives
• Survey energy use patterns and develop demand forecasts

• Develop load growth forecasts

• Investigate supply-side generation options

• Investigate demand-side management measures

• Prepare and evaluate supply plans

• Prepare and evaluate demand-side management plans

• Integrate supply-side and demand-side plans into a candidate plan

• Selection of a preferred plan

![Diagram of Utilities Required to File an IRP with their PUC](image)

Figure 2.1 States Requiring an IRP [2]

During and after implementation of an IRP, it is common for steps to be taken to monitor, evaluate, and update future IRPs to keep in line with changes to industry trends and technological advances. [3]
2.2 IRPs in MISO Footprint

There are currently 10 states in the MISO footprint that require utilities to file IRPs. These filing requirements are different for each state; however, generation additions are included in each report. Other states have different filing requirements for utilities as well as regulatory bodies. For example, the state of Iowa has the Iowa Utilities Board to ensure reasonable pricing and safe utility services for all Iowans. Regulatory bodies like these work with MISO and collect information on future plans for the utilities and generation owners that they oversee. These company future plans reported through the state as well as publicly announced plans for capacity additions are also collected by MISO. MISO has used these company IRPs as well as publicly announced plans by companies without IRPs for various reasons but has yet to aggregate them to represent a footprint wide projection.
CHAPTER 3. METHODS AND PROCEDURES

3.1 System of Notation

A system of notation was established to more concisely describe the evaluation process. This system describes actual amounts such as capacity or energy values using lowercase letters \((c, e)\), percentages of capacity and or energy using uppercase letters \((C, E)\), and projected values using a prime notation \(('')\).

\[
e_w = \text{Energy served by wind (GWh)}
\]
\[
e_s = \text{Energy served by solar (GWh)}
\]
\[
e_t = \text{Total annual energy produced in MISO footprint (GWh)}
\]
\[
E_w = \text{Percent of energy served by wind}
\]
\[
E_s = \text{Percent of energy served by solar}
\]
\[
E'_w = \text{Projected percent of energy served by wind}
\]
\[
E'_s = \text{Projected percent of energy served by solar}
\]
\[
c_w = \text{Current wind capacity (MW)}
\]
\[
c_s = \text{Current solar capacity (MW)}
\]
\[
P_w = \text{Planned IRP additions to wind capacity (MW)}
\]
\[
P_s = \text{Planned IRP additions to solar capacity (MW)}
\]
\[
\Delta c_w = \text{Wind capacity added (MW)}
\]
\[
\Delta c_s = \text{Solar capacity added (MW)}
\]
\[
c'_w = \text{Projected wind capacity (MW)}
\]
\[
c'_s = \text{Projected solar capacity (MW)}
\]
\[
C_w = \text{Current percent wind capacity}
\]
\[
C_s = \text{Current percent solar capacity}
\]
\[
C'_w = \text{Projected percent wind capacity}
\]
\[ C'_s = \text{Projected percent solar capacity} \]
\[ C'_t = \text{Projected total capacity (MW)} \]
\[ F_i = \text{Actual 2019 generation % of fuel source } i \]
\[ F'_i = \text{Projected generation % of fuel source } i \]

### 3.2 Process for Futures Evaluation using IRPs

In the past, MISO has collected IRPs, but has not aggregated them on a footprint wide level due to the fact that not all of the footprint is represented in IRPs. By creating a process to aggregate the most recently filed IRPs along with utility company announced plans, we can get an approximate footprint level view of generation additions over the planning cycle. We can compare this aggregate “IRP Future” to the MTEP Futures, to see if the Futures are properly robust enough to bookend the aggregate “IRP Future.”

1. First, previous EGEAS projections of wind and solar growth in the MISO footprint were analyzed, and the percent energy served from wind and solar was calculated from 2018 to 2030.

\[ E_w = \frac{c_w}{e_t} \]
\[ E_s = \frac{c_s}{e_t} \]

2. Second, IRP planned generation additions for wind and solar up to 2030 were compiled from utility stakeholders in the MISO footprint. These IRP generation additions were then added to announced plans of wind and solar additions for companies without IRPs. These projected new additions were then added to the current wind and solar in MISO for an aggregate MISO footprint projected solar and wind capacity at 2030.

\[ \Delta c_w = \sum P_w \]
\[ \Delta c_s = \sum P_s \]
\[ c'_w = \Delta c_w + c_w \]
\[ c'_s = \Delta c_s + c_s \]

3. The projected solar and wind capacity was then converted into percent of total MISO capacity. The current generation capacity of 175,528 MW was assumed to grow at a rate of 0.75% per year based on historical data.

\[ C'_w = \frac{c'_w}{175,528 \times (1 + 0.0075)^{11}} \]
\[ C'_s = \frac{c'_s}{175,528 \times (1 + 0.0075)^{11}} \]

4. The projected percent wind and solar capacity was then converted into projected percent wind and solar energy served. This was done by using the proportion of percent wind capacity vs. percent energy served by wind historically in MISO. However, since there was no significant historical precedent for the percent energy served by solar in MISO, the capacity factor of solar was considered. Since the capacity factor of solar is about half the capacity factor of wind, the proportion used to convert capacity to energy for wind was halved and used to convert capacity to energy for solar.

\[ E'_w = \left( \frac{E_w}{C'_w} \right) \times C'_t \]
\[ E'_s = \left( \frac{E_s}{C'_s} \right) \times C'_t \]

3.2.1 Illustrative Example of a Proper Futures Bookend

The projected percent energy served by wind and solar was then compared to the EGEAS projections to see if the renewable growth was properly captured with a large confidence. An example is shown in Figure 3.1, which shows the MTEP09 Future with the lowest projected wind growth, the MTEP09 Future with the highest projected wind growth, and an illustrative example of an artificial “IRP Future” projected wind growth not based on actual IRP data. The goal of the
Futures process is to provide proper bookends for growth scenarios as shown in Figure 3.1. Proper bookends would not only capture the “IRP Future,” but also the uncertainty of the “IRP Future,” also shown in Figure 3.1, with a relatively high amount of confidence. To help us calculate this “IRP Future” uncertainty, we need to look at the historical accuracy of previous IRPs.

![MTEP09 vs. Artificial IRP Wind](image)

Figure 3.1 Artificial IRP Projections vs MTEP Futures Projections

### 3.3 Process for Calculating the Historical Accuracy of IRPs

In order to have a higher level of confidence in the most up-to-date filed IRPs, the historical accuracy of previously filed IRPs must be measured. By compiling all of the IRPs in the MISO footprint of the last 15 years, we can compare their projections of their 2019 generation mix vs their actual 2019 generation mix. The deviation of each IRPs projected generation mix vs actual
generation mix will help us quantify the accuracy of IRPs as well as let us study the evolution of the long term projections for each utility.

1. First, previously filed IRPs were gathered from MISO’s utility stakeholders.

2. Second, the projected electric energy and capacity mix of 2019 was gathered from each collected IRP. The categories for energy and capacity mix fuel sources differed in each IRP, therefore all projected mixes were compiled under the following five fuel categories: Coal, Natural Gas, Nuclear, Renewables (Wind and Solar), and Other.

3. Next, the deviation from the projected electric energy and capacity mix compared to the actual mix was calculated for each IRP. This was done by taking the projections of the percentage generation mixes for 2019 for the five fuel categories, and finding the deviation from the actual generation mix using the Euclidean distance formula in five dimensional space.

\[
% \text{ Deviation} = \sqrt{\frac{1}{5} \sum_{i=1}^{5} (F_i - F_i')^2}
\]

4. Finally, the average deviations, average of the absolute values of the deviations, and standard deviation of the deviations by fuel type were calculated for each IRP.

3.3.1 Graphical Example of Calculating the Historical Accuracy of IRPs

For this study, the projections of the percentages of the five fuel categories of coal, natural gas, nuclear, renewables, and other were each defined as a dimension. The percent deviation from the actual mix was then calculated using the distance formula in five dimensional space. This graphic helps to visualize this percent deviation from an example fuel mix in three dimensional space.
1. There are uncertainties in these EGEAS projections based on the assumptions used in the creation of the Futures. These uncertainties will be discussed in chapter 5.

2. The IRP generation additions are not certain, and are only planned for by the utilities. They could build more or less renewable generation. However, since these IRPs are often shared with company shareholders, there are legal implications for not following the published plans. Secondly, not all utilities in the MISO footprint have published IRPs. However, many utilities have announced plans for capacity additions in their future. For the utilities with no IRPs, announced company plans for renewable additions were used instead. Finally, not all IRPs and announcements were planned out exactly to 2030. Some IRPs total capacity additions
goals were set before 2030, and some were set after 2030. For IRP projections ending before 2030, a similar growth of generation was assumed to continue proportionally to 2030. For IRP projections ending after 2030, a linear growth was assumed per year towards the total renewable capacity addition resulting in a proportional amount of the goal capacity being added.

3. The growth rate of the total generation capacity was assumed based on historical data. This rate could be more or less depending on multiple influences including: energy efficiency gains, peak load carrying capability changes of new energy resources, as well as higher system wide electrification.

4. The capacity factor assumption was based on historical data, and could change in the future if wind and solar curtailment became more common, or if the capacity factor of wind or solar increases due to technological advancements.
CHAPTER 4. RESULTS AND DISCUSSION

4.1 Results

4.1.1 Futures Evaluation using IRPs

As described in the last section, by aggregating the IRPs and company announced plans we can create an “IRP Future.” By comparing the percent of generation from renewables projected in the Futures compared to the IRPs we can test the robustness of the Futures. We first start with the comparison of the projections of the percent of energy served by wind. This is shown in Figure 4.1.

![MTEP Wind Projections vs. IRP Wind Projections](image)

Figure 4.1  MTEP Wind Projections vs. IRP Wind Projections

Next, we look at the same comparison of the projections, but this time of the percent of energy served by solar. This is shown in Figure 4.2.
Figure 4.2 MTEP Solar Projections vs. IRP Solar Projections

Figure 4.1 shows the MTEP wind high and low projections through 2030. Figure 4.2 shows the same, but with solar projections. They both compare these projections to the IRP projections for wind and solar respectively. For both the wind and solar projection comparisons, the IRP projections were higher or comparable to the highest projections of the Futures for each of the last four years.

4.1.2 Historical Accuracy of IRPs

In order to use the current IRP projections for comparison with a relatively high amount of confidence, we must also look at their historical accuracy. By comparing the projected mix of 2019 with the actual mix for each utility with a filed IRP, we can start to gain an understanding of the historical accuracy of previously filed IRPs.

First, we start with the deviations of the projected energy mix of 2019 vs the actual energy mix organized by utility and by year. Some utilities were more accurate in their projections than
others. In general, with the exception of a few outliers, the closer to 2019 of the filed IRP, the more accurate the projection.

Figure 4.3 Deviation from Energy Projection by Utility

Figure 4.4 Deviation from Energy Projection by Year
Next, we look at the deviations of the projected capacity mix of 2019 vs the actual capacity mix organized by utility and by year. This followed a similar pattern as the energy mix graphics with an even stronger pattern of accuracy of IRPs filed closer to 2019.

Figure 4.5  Deviation from Capacity Projection by Utility

Figure 4.6  Deviation from Capacity Projection by Year
Now we look at the average deviations of energy by fuel type. In order to create robust Futures that properly “bookend” generation change, we must look at how accurate IRPs have been by each type of generation. Figure 4.7 shows coal being on average over projected, with natural gas and renewables under projected for energy mix percentages.

Figure 4.7  Average Energy Deviation by Fuel Type

Figure 4.8  Average Absolute Value of Energy Deviations by Fuel Type
Next, let’s look at the average deviations of capacity by fuel type. Capacity mix follows a similar pattern as energy mix with Figure 4.9 showing coal over projected and renewables under projected.

Figure 4.9  Average Capacity Deviation by Fuel Type

Figure 4.10  Average Absolute Value of Capacity Deviations by Fuel Type
Finally, let’s look at the distributions as well as the standard deviations of the energy and capacity IRP deviations by fuel type. Energy projections had a similar or lower standard deviation for all fuel categories than capacity projections. Energy projection standard deviations were similar for coal, natural gas, and renewables. However, capacity projection standard deviations were higher for coal and natural gas than the other fuel types. The deviations for both energy and capacity show a roughly normal form for both distributions.

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Energy Deviation Standard Deviation</th>
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<tbody>
<tr>
<td>Coal</td>
<td>5.8%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>6.3%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.9%</td>
</tr>
<tr>
<td>Renewable</td>
<td>5.9%</td>
</tr>
<tr>
<td>Other</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Table 4.1 Standard Deviations of Energy Deviations by Fuel Type

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Capacity Deviation Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>7.5%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>7.8%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.7%</td>
</tr>
<tr>
<td>Renewable</td>
<td>5.2%</td>
</tr>
<tr>
<td>Other</td>
<td>4.0%</td>
</tr>
</tbody>
</table>

Table 4.2 Standard Deviations of Capacity Deviations by Fuel Type

![Distribution of Energy Deviations](image)

Figure 4.11 Distribution of Fuel Type Deviations for Energy
4.2 Discussion

4.2.1 Futures Evaluation using IRPs

The data from section 4.1.1 show MTEP16-MTEP19 high and low wind and solar projections. For wind, when the MTEP projections are compared to the compiled IRPs, the MTEP projections consistently underproject the IRP projections. For solar, the MTEP high projections slightly out-project the IRP projection.

Both of these show a failure of the Futures of the previous four MTEPs to provide proper bookends for wind and solar growth. Improper book-ending across multiple planning cycles presents a challenge to the robustness of Futures, and suggests that the next set of Futures must have a higher bookend when it comes to renewable growth. The question is, how high does this upper bookend of renewable penetration for these Futures need to be? This question can be answered by applying what we know about the historical accuracy of IRPs.
4.2.2 Historical Accuracy of IRPs

The data from section 4.1.1 show that IRPs are not perfect, and their projections of future generation mixes are often wrong to varying degrees. The deviation of projections for some utilities were less than for others. This is due, in part, to some utilities projecting very little change from their existing fleet. However, some utilities projected a large amount of change to their renewable capacity and therefore were relatively accurate in their projections. The most telling part of this data is the deviation by fuel type. The average deviations of energy and capacity show that coal is often over projected, while natural gas and renewables are often under projected. When we look at the absolute value of each deviation it shows that coal and natural gas have the highest deviation in projections. This is supported by looking at the standard deviation by fuel type. It further supports that coal and natural gas had the most inaccuracy in their projections, followed by renewables. Nuclear was the most accurate and certain.

The combination of this data suggests that historically, coal capacity is over projected in IRPs by 4.0% with a standard deviation of 7.5%, natural gas capacity is under projected in IRPs by 0.3% with a standard deviation of 7.8%, and renewable capacity is under projected in IRPs by 2.7% with a standard deviation of 5.2%.

4.3 Summary

In simple terms, the Futures are used to develop the most robust plan for an uncertain future. One of the main components of these robust Futures are the renewable energy penetration projections. These projections should properly bookend renewable generation growth over the twenty year planning period. The results of the process outlined in this report show that the Futures are under projecting renewable penetration percentage, as the Future with the highest renewable penetration projection was not a true bookend. Furthermore, the IRP projections of generation mixes were also shown to under project renewable generation and over project coal generation. This suggests that the IRP projections used to challenge the robustness of the Futures are conservative for future renewable growth.
In order for the next planning cycle to able to create a robust set of Futures, the renewable penetration percentage must be increased to properly bookend the calculated “IRP Future” as well as its uncertainty. Due to the approximate normality of the energy deviations data, as shown in Figure 4.11, we can use the standard deviations of the fuel type deviations to provide a confidence interval and capture the uncertainty in the “IRP Future” renewable projections. Two standard deviations of the IRP projection deviations for the energy served by renewables plus the average deviation of renewable projections is approximately 14%. The current Futures’ low bookend already captures this uncertainty. However, increasing the next Futures top bookend by 14% would account for the historical under projection of renewables, as well as provide a 95% confidence level for the low end and high end Futures to bookend both the “IRP Future” as well as the uncertainty of the “IRP Future” projections. This would result in a suggested upper-bookend for renewables to be approximately 49% at the end of the 20 year planning cycle. This suggestion mirrors closely the development of the MTEP21 Futures as the upper end renewable penetration percentage has been publicly announced in MISO stakeholder meetings to be approximately 50%.
CHAPTER 5. FUTURE WORK

5.1 Electric Generation Expansion System Characterization

5.1.1 Introduction

As previously mentioned, electric generation expansion programs are used by independent system operators and some larger utilities to forecast their future generation for the next 5, 10, or 20 years. MISO has used a program called EGEAS for the last ten planning cycles to project electric generation additions and retirements for a twenty year planning period. These projections were based on a number of inputs and constraints. It is desirable from a planning perspective to understand the relationship between the inputs and the outputs, no matter what program or system is used. Finding the sensitivities between the inputs and outputs is crucial for understanding the inputs that have the highest sensitivity as well as the outputs that have the highest uncertainty.

The outputs of interest are the generation additions which are uncertain due to our inputs and assumptions being uncertain. By following a process that can define the uncertainty of these generation addition outputs of the “black boxes” that are these programs, we can create a useful tool for any organization in the energy industry that utilizes them for planning. This process for defining output uncertainty would follow a process similar to that in Zhang and Dobson [4]. Although this work is not carried out, this report sketches out a brief overview of an approach for determining input-output sensitivities and output uncertainties for electric generation expansion programs.

5.1.2 Input and Output Relationships

Every electric generation expansion program has inputs and outputs. These inputs and outputs are related in different ways depending on the constraints used as well as the program itself. As described before, many of these programs are “black boxes” and do not analytically or
directly describe the exact effects one input has to the outputs. These input/output relationships are key to understanding the uncertainties of the outputs due to the uncertainties in the inputs.

5.1.3 Linearizing the input-output relationship

Since the input-output relationship is nonlinear, we need to consider the sensitivities to small changes and linearize the input/output relationships around an operating point. The linearization is a Jacobian matrix describing the change in each output per change in each input. Once the inputs have been modeled with some randomness, and a linearised model of the “black box” is empirically derived, we can use the Central Limit Theorem to help us understand the uncertainties of the outputs.

5.1.4 Central Limit Theorem

The central limit theorem (CLT) can be used to characterize the probability distributions of the outputs. The CLT establishes that when a sufficient number of independent random variables are added, their properly normalized sum tends toward a normal distribution, also known as a bell curve, even if the original variables themselves are not normally distributed [5]. In other words, the CLT says that if there are many random inputs that contribute linearly to the outputs, then those outputs will be approximately normally distributed. The standard deviation of the normal distribution can be computed from the linear relationship and the standard deviations of the inputs. Therefore, linearization together with the CLT can quantitatively describe the uncertainty of each type of generation addition projected in an electric generation expansion system.

5.1.5 Process for Calculating Input Sensitivities and Output Uncertainties

We outline a method for characterizing electric generation expansion program output uncertainties. This method can be used for any electric generation expansion program used in planning processes.
1. Identify the inputs into the program and their base case values. There should be at least a
dozen uncertain inputs; the method works better for many inputs.

2. Characterize the input uncertainties, ensuring that the inputs are independent or a linear
function of independent uncertainties. The standard deviation of each uncertain input should
be estimated.

3. Linearize the relationship of the inputs to the outputs around their base case values using a
Jacobian matrix. This can be done by running the software by changing each input in turn
by a small amount and observing the changes in the outputs.

4. The central limit theorem can ensure that the outputs are normally distributed to a useful
accuracy. The standard deviations of the normal distributions of the outputs can now be
calculated from the Jacobian and the standard deviations of the inputs using the theory of
linear combinations of random inputs.

5. The outcome of the calculation is the standard deviation of the outputs that result from the
uncertainties of the inputs. Since the outputs are normally distributed, confidence intervals
can easily be found.

These results can be used to quantitatively describe the uncertainty of each projection based
on the sensitivity of the inputs. In other words, depending on the variance of the inputs, there
will be a resulting uncertainty of the outputs. The inputs could be ranked by their sensitivities
to determine which ones are the most important and influential. By quantitatively describing the
uncertainty of each projection, we can further test the robustness of each set of Futures by seeing
if they capture this uncertainty by properly book ending projections.

5.2 Updating Future IRPs

During each new Futures development cycle, new IRPs would be filed with their respective
states. If the process outlined in this paper were to be used in determining the robustness of new
Futures, the newly filed IRPs would have to be examined and used to update the aggregate IRP projections. A similar process would have to be done for measuring the historical accuracy of IRPs. As more IRPs are filed, the sample size increases for measuring the accuracy of IRPs, and would allow us to say with higher confidence how accurate IRP projections are for generation expansion.
CHAPTER 6. CONCLUSION

Futures are a key part of planning our future energy grid. However, there are complexities in Futures modeling with a constantly evolving generation fleet. This report began with the question of whether the Futures renewable penetration levels were robust enough. The results have shown that the MTEP19 Futures were not high enough on renewable penetration levels based on MISO stakeholder utility IRPs. The data presented in this paper suggests that during the next Futures development cycle, the new Futures cohort should raise their renewable penetration percentage by approximately 14%. In order to continue to create robust Futures, this paper suggests that the Futures development process be changed to incorporate the following improvements:

1. Tracking previous Futures’ performance

2. Investigating stakeholder IRPs for planned additions and retirements

3. Incorporating aggregated stakeholder IRPs as a possible “reference” or “baseline” to test the bookends of the Futures

4. Updating the historical accuracy of previously filed IRPs to develop a quantitative level of confidence in both the accuracy of IRPs as well as the bookends of the Futures.

This process could be standardized each year as a way to see if the Futures are “book-ending” uncertainty by being properly robust.
Bibliography


APPENDIX A. ADDITIONAL MATERIAL

Alphabetically ordered list of Utilities in MISO footprint who’s IRPs were studied.

• Allete (Minnesota Power)
• Ameren
• Cleco
• Consumers
• DTE Energy
• Duke Indiana
• Entergy
• Great River Energy
• Indianapolis Power & Light
• Northern Indiana Public Service Company
• Vectren
• XCEL