Power System Reliability in the Midwest for High Wind and Solar Levels

Final Project Report

May19-24
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Revised: April 28, 2019

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List of Definitions

Balancing Authority (BA): Combination of buses.

Capacity Credit: Ratio of average energy production during peak net load conditions over the installed capacity reported as a percentage or a number between 0 and 1.

Capacity Factor: Ratio of actual energy production in a year divided over the total energy production in a year Reported as a percentage or a number between 0 and 1.

DG: Distributed generation.

DPV: Distributed photovoltaic.

Eastern Interconnect: One of the 3 major grid interconnections in the United States. It borders the Western Interconnection on the border of Nebraska and Colorado and stretches North-South from Mexico to the Upper Canada.

Expected Load Carrying Capability (ELCC): The largest amount of load that the grid could produce if all generators were turned up to highest performance.

Federal Energy Regulatory Commission (FERC): United States Federal Agency that regulates the interstate transmission of natural gas, oil, and electricity.

GUI: Graphical User Interface

Loss of Load Expectation (LOLE): A NERC requirement that states that any location cannot expect to have a loss of load (under-generation) that is greater than one event in 10 years.

Midcontinent Independent System Operator (MISO): Sponsor of this research project. MISO is the system operator that operates within 14 states. Figure 5 shows a map of the MISO region [2].

North American Electric Reliability Corporation (NERC): A nonprofit corporation with the goal of reliability throughout the North American power grid.

Net Load: The difference between the gross load and renewable generation.

PLEXOS: Modeling software that is used by system operators to predict how the grid will be affected by proposed changes.

Python: A computer programming language that will be used to automate part of this project.

Renewable Energy: Energy produced by renewables sources such as wind and solar.

Renewable Integration Impact Assessment (RIIA): A study performed by MISO to look into how renewable energy, based on several projections, will impact the power grid in different ways. [3].

Renewable Energy Penetration: Amount of renewable energy that is on the grid or the area. This is given in a percentage form. Thus, 10% renewable penetration indicates that 10% of the generation produced are from renewable energy.

UPV: Utility scale solar photovoltaic.

PASA: Projected Assessment of System Adequacy

0. Executive Summary

This document outlines the operations of a study to determine the effects of increased renewable wind and solar generation on the midwestern power grid. A system to strategically place new generation was derived using public NREL data, from which three PLEXOS models were created. These models were then tested at increasing amounts of wind and solar generation to derive average amounts of additional load that could be added to the grid while maintaining compliance with NERC standards.

1. Requirements Specification

a) Functional Requirements:

There were several functional requirements that the senior design team needed to follow for this study. The two main requirements of the study were the construction of a 50 percent wind and 50 percent solar model as well as a 75 percent wind and 25 percent solar model. Each of these models were to be evaluated at different renewable energy penetration levels in order to compare their performance to a model without any renewable generation.

In order to perform analysis on the models, the team needed to have functioning PASA simulations which allowed the team to run the models and specify different outputs for the system. The output of most interest for this study was the Loss of Load Expectation, or LOLE, which is what was used to compare the reliability of each model to the comparison model with zero installed renewable energy. Once this data was retrieved and validated, there were several graphs that were required to be made in order to evaluate the results.

Another functional requirement separate from the model building and evaluation was the automation of finding the LOLE and ELCC for the different models.

b) Non-Functional Requirements:

Non-functional requirements for this project included some technical aspects to the PLEXOS models as well as given reports and structuring of data. The team desired to have two virtual machines running on campus that would allow for any group member to be able to login and continue work without needing to be directly on campus or requiring a specific PC.

Documentation, such as the team's siting report and excel files used for creating the PLEXOS model, also needed to be well structured and comprehensible so it could be successfully passed on to MISO for potential further study.

Lastly, the team was prepared to hold a presentation at MISO headquarters in Eagan, Minnesota to demonstrate what this project has accomplished in terms of research as well as writing a NAPS paper for IEEE detailing the study.

2. System Design and Development

a) Design Plan

This project must answer questions that will highlight where and what problems might arise in the future due to added renewable generation and what the future of the grid will look like. The design of the study had to be planned around the LOLE, which sets the criteria of having "one event in ten years", or in other words, only losing load one day in ten years due to a shortage of generation. There is no way of knowing for sure what the future of the grid will look like, but using current grid data along with analysis in PLEXOS, an adequate prediction can be made. To do this, the team needed to run through a series of steps to try and design a reasonable prediction for the future. These steps included: integration of historic load profiles, development of siting criteria, and creation of generation profiles. These steps led the team to develop two models: 50 percent wind and 50 percent solar, 75 percent wind and 25 percent solar. Additionally, the team will be evaluating a model with zero renewables, called a comparison model. The team can compare the load capabilities of their models to the zero-renewable model using a metric called ELCC.

i. Load Profiles

The load profiles used in this study come from historical load data collected from the MISO grid at every hour of the year. Because every year varies in load, the load profiles for 2007 through 2012 were taken and scaled to 2017 peak load values. Now, there are effectively six different years of load for 2017 simulations to be run on.

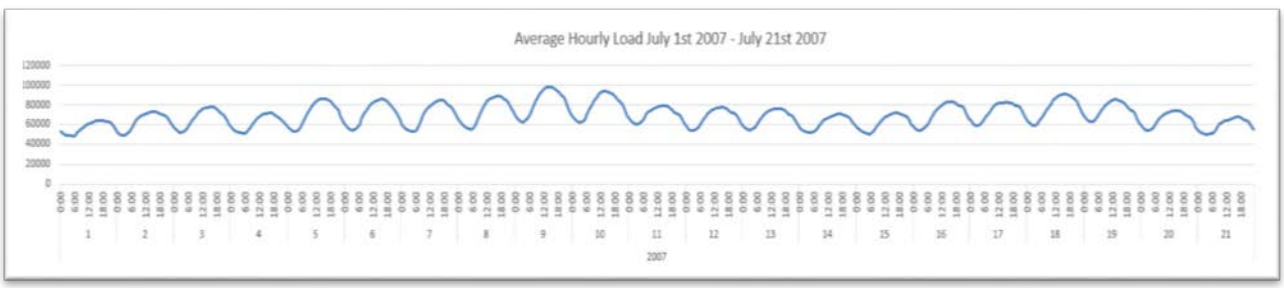

Figure 1: Average Hourly

ii. Siting

In order to evaluate the MISO system with more renewables integrated, extensive research was done to determine desirable sites for new wind and solar energy to be built. Several different criteria can affect the likelihood that a generator will be built in a specific location. For all four technologies in this study, wind, fixed solar, tracking solar, and rooftop solar, an equation was derived to determine the worthiness for each site at different levels of renewable penetrations. Important criteria that were considered include: capacity factor, population density, capacity value, the current interconnection queue, which will be referred to as the queue, and state or utility policies.

All statistics were scaled to be between 0 and 1 depending on how large of a factor they played in the determination of siting that renewable technology. This was done by using each criterion's max value as "1" and scaling the rest based off that max. From there, the team determined what statistics were the most important. All statistics were weighted according to their importance. As an example, if only one statistic out of those listed above was applicable, then that data would be weighted 100%, if the statistic was not applicable at all, then it would be weighted 0%. The following statistics at the following levels of importance for the four different technologies is the final "grading criteria" this study follows.

10% Chart	**Wind 10%**	**Tracking 10%**	**Fixed 10%**	**Rooftop 10%**
Capacity Factor	65	65	65	25
Pop. Density	15	15	15	35
Queue	10	10	10	0
Incentives	10	10	10	0
Capacity Credit	0	0	0	0
Average Income	0	0	0	40
30% Chart	**Wind 30%**	**Tracking 30%**	**Fixed 30%**	**Rooftop 30%**
Capacity Factor	65	65	65	30
Pop. Density	15	15	15	35
Queue	10	10	10	0
Incentives	10	10	10	0
Capacity Credit	0	0	0	0
Average Income	0	0	0	35
50% Chart	**Wind 50%**	**Tracking 50%**	**Fixed 50%**	**Rooftop 50%**
Capacity Factor	50	50	50	35
Pop. Density	10	10	10	35
Queue	10	10	10	0
Incentives	10	10	10	0
Capacity Credit	20	20	20	0
Average Income	0	0	0	30
100% Chart	**Wind 100%**	**Tracking 100%**	**Fixed 100%**	**Rooftop 100%**
Capacity Factor	40	40	40	40
Pop. Density	10	10	10	35
Queue	10	10	10	0
Incentives	10	10	10	0
Capacity Credit	30	30	30	0
Average Income	0	0	0	25

Table 1: Siting

iii. The Siting Equation

These six measured metrics get inserted into a developed equation in Excel which is described below. The different weight given on each of the metrics is a representation of how important that metric will be in predicting the future of where new renewable generation will be built.

As an example, the equation for wind at 30 percent penetration would look like the following:

0.65*(Capacity factor of bus) + 0.15*(Inverse Population Density Rank) + 0.1*(Queue Rank) + 0.1*(Incentives Rank) + 0*(Capacity Credit at Bus) + 0*(Average Income Rank) **= Number between 0 and 1**

With the changing weight of each of the metrics, it is possible to accurately assign a comparable number to each bus for each different technology.

iv. Generation Profiles

After the completion of siting, the team was able to begin work on creating a hypothetical generation profile based on the siting criteria. Generation profiles are needed by PLEXOS to know the amount of power produced by the four different renewable technologies at every hour. To create a profile for each technology, the sited installed generation for each bus was multiplied by that bus's hourly capacity factor. Because transmission constraints were ignored, all the generation for each technology was aggregated at each hour and then linked into PLEXOS as one generator with an hourly generation profile. This serves two major purposes: it simplifies the model which makes it easier to adjust various attributes by hand and it reduces the time taken by PLEXOS to run simulations. While more complex PLEXOS models have been known to take multiple hours to simulate, this model can be simulated in about 20 to 30 minutes.

v. The Comparison Model

The above siting criteria describes how renewable generation will be sited for different penetration levels, however for the purposes of this study, the team must also evaluate the MISO system as it is with zero renewable energy. The team calls this model the comparison model because they compare the developed models with sited renewable energy to this zero-renewable model in order to get a better idea of how reliable the system is as more renewable energy is integrated. This comparison is what the ELCC refers to. The ELCC describes the difference in fixed load of the comparison model versus the sited models while maintaining the 0.1 LOLE as required by NERC.

b) Design Objectives, Constraints, and Trade-offs

The objective of this project was to perform an accurate study of the MISO grid using only publicly available data and an aggregated model of the grid. The study aimed to look at the LOLE and ELCC of the grid at different penetration levels, with two different mixes of wind and solar. One mix composed of a 50 percent wind and 50 percent solar split for all new generation, and the other with 75 percent wind and 25 percent solar. The reason for both models is that MISO and the design teams were curious which model would perform more reliably.

The largest trade off for this project was the time constraint. While more in-depth models may be more accurate, the simulation time for them can last for several days. The model the team developed and tested gave an accurate enough prediction, while taking under an hour to run for each simulation.

Additionally, there are several different ways to evaluate the results of this model as well as several different things the team could have included to get a better picture of this future grid, i.e. include transmission, however this could be an entirely different study in itself and would not have been possible in the time allotted for this senior design project.

c) Design Block Diagram

To provide a visualization of how the models are designed, the team has developed the flowchart below. The siting equation was developed from the six criteria described in section 2(a) and the NREL data consists of capacity factors of various renewable generation types throughout the year. The use of these two factors allowed the team to develop the siting criteria, how much generation will be required at each penetration level, as well as the generation profiles, how the sited generation will react under peak net load conditions. All of this information is compiled into different Excel .csv files, along with a .csv file for the load profiles, and loaded into PLEXOS. Now, the design is at a point where it can begin to be implemented and tested inside PLEXOS.

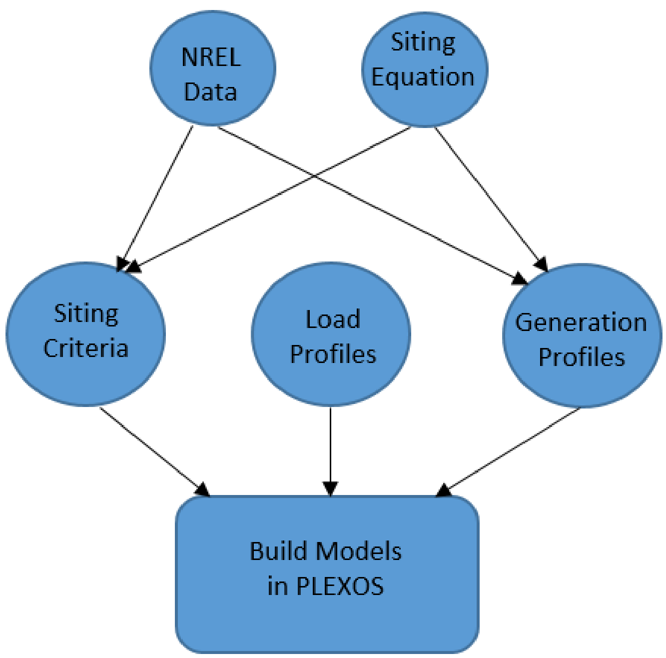

Figure 2: Design Block

d) Description of Modules, Constraints, and Interfaces

As previously stated, this project has the constraint of being a simplified model with no transmission analysis for the sake of allowing MISO to run quick reliability analysis for potential futures of their power grid. The data for these models is also restricted to PLEXOS and Microsoft Excel, which works well in tandem with PLEXOS. Recreating, editing, or continuing any operation of this project would therefore require knowledge of both systems as well as the significance of all data used.

3. Implementation

a) Implementation Diagram

Building on the understanding of the design of the PLEXOS models, the diagram below gives a brief overview of what the team did with these models once they were built inside of PLEXOS. First, the team's goal was to achieve the required 0.1 LOLE for all years in each of the models. This step was used to help the team verify if their models were built correctly as well as evaluate the performance of the models.

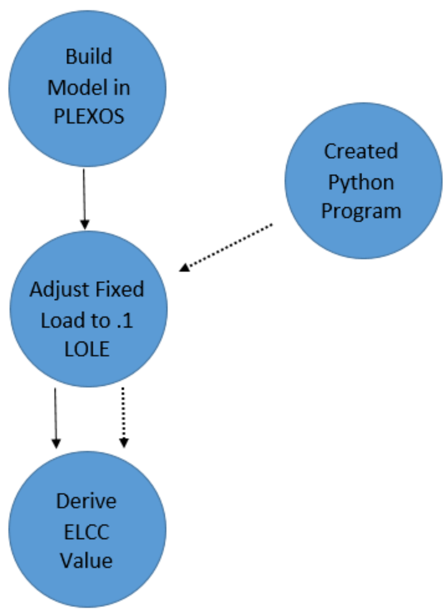

Figure 3: Implementation

b) Rationale for Software

Two main software programs were used for completing this project, Microsoft Excel and PLEXOS. PLEXOS is a power grid simulation software that can run predictions on how the grid will act hourly, taking both economic and physical variables into account. In the team's study all nodes were aggregated into one node. The team used PLEXOS to calculate the LOLE of the system with the given load conditions. This in turn allowed for the calculation of the ELCC to follow.

While it is possible to enter data directly into PLEXOS using the GUI provided by the software, uploading the data in specifically formatted excel files proved to be a much faster method. Additionally, excel allowed the team to quickly analyze and manipulate large amounts of data, which was necessary as we could be looking at generation data from multiple sources for every hour in a year. The ability to accurately filter out, aggregate, and overall manipulate the data proved to be a valuable asset for the team.

c) PLEXOS Automation

In parallel with our PLEXOS work, the team developed a python script to assist in finding the LOLE. This python script eliminates the need for the team to work through the PLEXOS GUI manually after each iteration. Instead, the script handles the fixed load manipulation to reach the 0.1 LOLE that is sought after. It does this through communicating with the PLEXOS API.

The script was developed during the process of the team finding these LOLE values by hand. As the script matured, it was used to double check fixed load values gotten manually by team members. After the script was getting the same results as those gotten by hand, the focus was then pushed onto optimizing the logic inside the script. This involved using a logarithmic equation to adjust the fixed load based upon iterations given from the team. This cut down the iterations needed for the script to hit our target, saving computer processing time and allowing the team to check results faster.

d) Applicable Standards and Best Practices

1. ***EEE 1094-1991: IEEE Recommended Practice for the Electrical Design and Operation of Windfarm Generating Stations. [7]***

   To create the grid, the team has to create imaginary wind farm sites that were likely to be set up in the future, according to different variables at different locations. This standard provides recommended practices for the creation sound, economic design setups for interconnecting multiple wind farms. While siting generating plants for the grid, the team may have to refer to this document in order to ensure that the proposed design matches the criteria presented by this standard.

2. ***IEEE 493-1997: IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems [8]***

   A large part of the project MISO has commissioned the team to do has to do with finding the reliability of a proposed system, up to a certain economically feasible point. This engineering standards provides data “cost vs reliability” studies that the team can refer to when making decisions that would affect the reliability of the grid, and decide if the cost of it is preferable.

3. ***IEEE 141-1993 -IEEE Recommended Practice for Electric Power Distribution for Industrial Plants [9]***

   One end goal of the project is to find older, less efficient power plants that will be un-needed after enough new renewable generation comes onto the grid and retire these plants. The team would need to refer to this document, as it provides information on how these plants are set up, and could provide insight on what effect the retirement of a major source could have on the grid.

4. ***NERC Standard BAL-502-RF-03 [10]***

   NERC has many standards on energy balancing and resource adequacy. Standard BAL-502-RF-03 [4] is one we are particularly interested in adhering to. This is because it talks about a planning reserve margin for LOLE. The standard we will adhere to is comparable to a one day in ten-year LOLE expectation.

5. ***IEEE 762–2006 -Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity [111]***

   For reporting generating unit outages. This standard provides a methodology for the interpretation of electric generating unit performance data.

4. Testing, Validation, and Evaluation

a) Test Plan

The testing for this project was done manually for the majority of tasks. All inputs were graphed to look for patterns and anomalies, if present. By charting the inputs, data could be checked for missing or incorrect points that would be missed by a visual check. Generation profiles, siting, and load profiles were all graphed in Excel to check for accuracy.

b) Model Testing

Model testing was conducted using a simple guess and check approach in order to determine correct fixed load amounts to derive a 0.1 LOLE value for all years of each penetration level for both models. An example would be starting the fixed load for the 30 percent penetration level of the 50/50 model to be 20000 MW. After a simulation, it could be found that the LOLE values range around 0.3 for all scaled years 2007-2012, signifying that the grid is considerably more unreliable than desired by NERC standards, and the fixed load for all six years would then need to be reduced in order to achieve the 0.1 LOLE. This process was made slightly more efficient with the team understanding that the curve for determining the LOLE was logarithmic in nature and the amount of fixed load to be increased or decreased got larger with increasing or decreasing penetration levels.

c) System Integration Testing

Below is a graphic of how the design team is doing their testing within PLEXOS in order to get the final results. Since the first goal was to get each model to a 0.1 LOLE value for all years, in order to achieve this the fixed load property in PLEXOS needed adjusted until that 0.1 value was hit. The fixed load property gives an idea of how much extra load the system can handle while maintaining that 0.1, or one day in ten years, LOLE value. This was an iterative process that could be done by hand or through the developed Python automation.

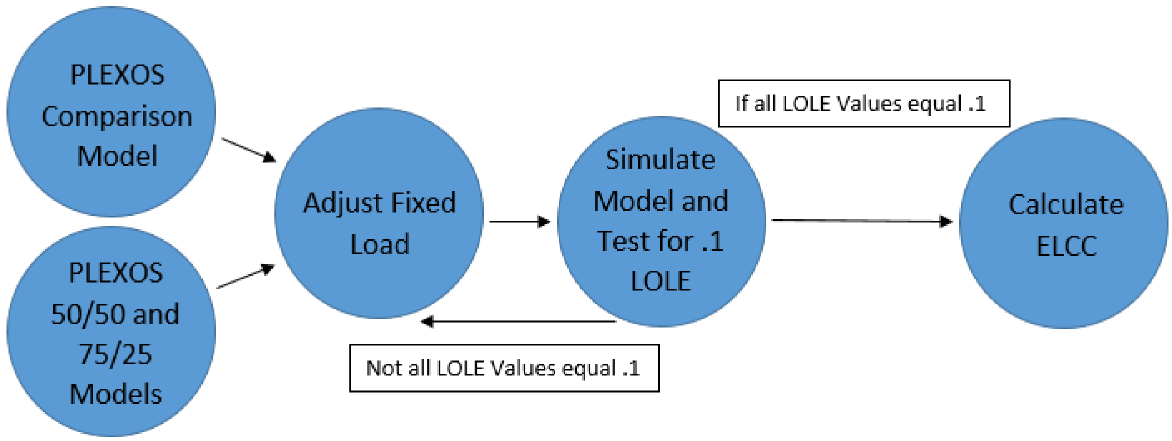

Figure 4: System Testing

d) Validation and Verification

Throughout the simulation phase of the project, it was possible to use some logical deductions and industry experience from MISO in order to determine correctness of what the team was finding from the PLEXOS models. An example of this check was when the design team did their first values for LOLE and ELCC and the MISO team pointed out that the generators were acting like perfect units. From this information, the team was able to recognize that the wind and solar generation installed in the model had been running at 100% efficiency and that additional metrics for capacity factor were not being properly read by the model. Similar deductions, like ensuring max generation never exceed max installed capacity were also ways to ensure realism of the model.

i. Evaluation of Results

As previously stated, the purpose of this project was to determine the effects of high renewable energy penetration on the MISO power grid. As such, the team was highly interested in viewing the LOLE and subsequent ELCC values of both the 50/50 and 75/25 models at 10%, 30%, 50%, and 100% renewable penetration.

All six studied years had to have a specific fixed load to reach a 0.1 LOLE. This is due to the weather for each iteration being different. The difference between these fixed load values and the fixed load of the comparison model is the ELCC value. An average was then taken across all six years to derive an average ELCC for that penetration level of that model.

It would be expected that the amount of fixed load the models could handle would increase with the further addition of renewable generation. Additionally, the ELCC decreased as higher penetration levels were achieved for both models. The team was also able to see the difference in ELCC between the two models and recognize that the 75/25 model consistently has a higher ELCC at most penetration levels compared to the 50/50 model. At 100 percent penetration, the 75/25 model outperforms the 50/50 model in all years. This means that overall the 75/25 model is more reliable than the 50/50 model, which the team believes is due to the fact that wind has approximately twice the capacity factor of solar.

Below is the graphical representation of these results.

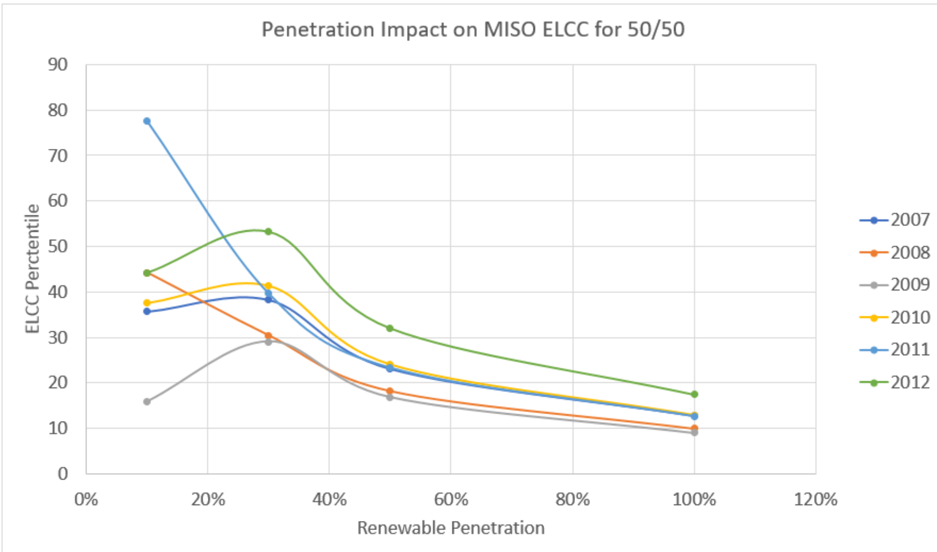

Figure 5: Penetration Impact on MISO for 50/50

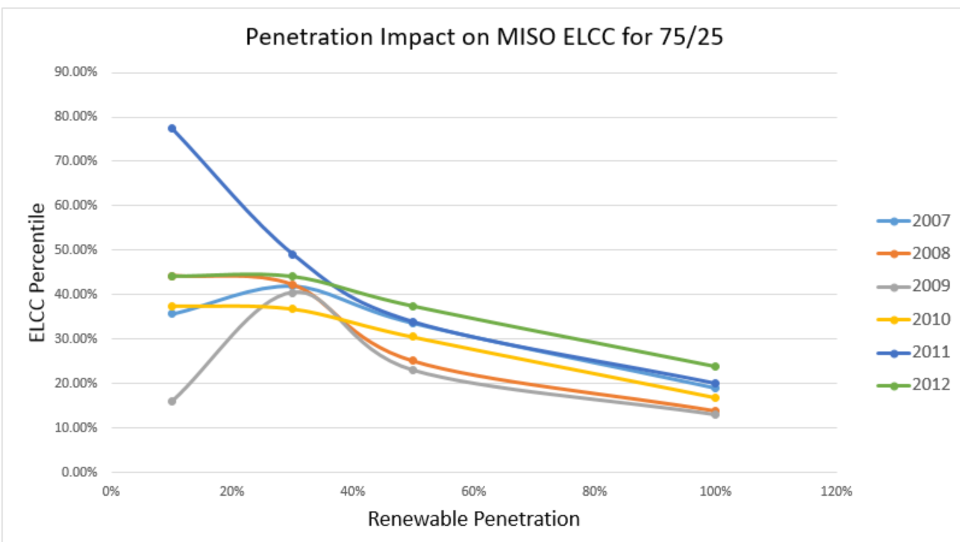

Figure 6: Penetration Impact on MISO for 75/25

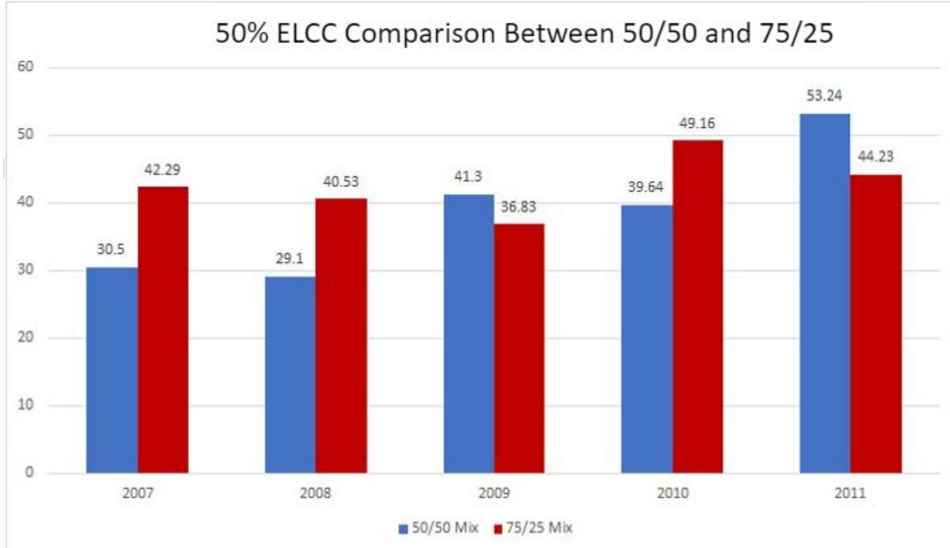

Figure 7: 50% ELCC Comparison Between 50/50 and 75/25

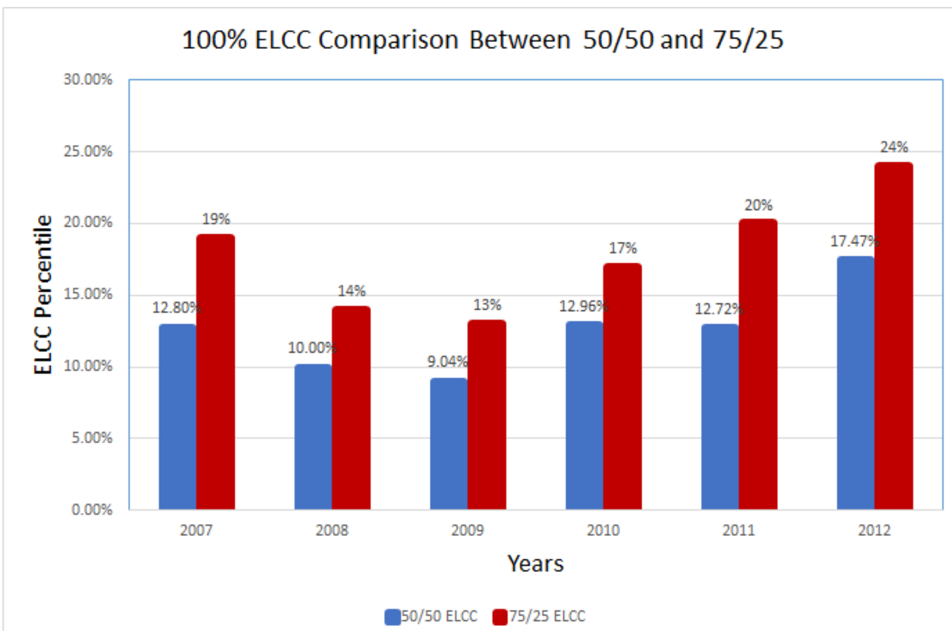

Figure 8: 100% ELCC Comparison Between 50/50 and 75/25

5. Project and Risk Management

a) Task Decomposition ~ Roles and Responsibilities

In order to best accomplish the milestones set for this project, the team adopted a format where individuals would focus on some special delegated tasks; roles such as team communicator, team scribe, lead programmer, and so on. However, it was also stressed that each team member would contribute towards major milestones such as creating the siting criteria, building the PLEXOS models, and assisting with simulations. This choice in task management made it so that progress towards the major milestones could be made even when the full team was unable to assemble or when one or two members had more time outside of scheduled group meetings. This also ensured that the knowledge of the major points of this project were explored and solidified for each team member and no one fell behind in terms of understanding or usefulness.

b) Project Schedule

Originally, this project began with the intention of being extremely optimistic in terms of development for the fall semester of 2018. This would allow ample time to review results, draw comparisons and eventually report on all data gathered from this study. This meant that in addition to researching and deriving the siting criteria used for placing generation, the team also sought to begin modeling the grid in PLEXOS and run simulations by the end of the fall semester.

However, it took more time than the team originally thought to secure PLEXOS licenses from Energy Exemplar. Due to this, PLEXOS modeling and simulations had to be pushed back into the spring semester. This essentially split the yearlong timeframe for this project into two phases between the two semesters. Phase one was entirely focused on researching proper ways to develop the siting criteria that would be used in Phase two. Phase two would then focus entirely on PLEXOS modeling, running the needed simulations in order to calculate LOLE and ELCC values, and then finalizing results and conclusions from these simulations and values.

Senior Design Gantt Chart

* = an automatically calculated cell

TASK NAME	START DATE	END DATE	START ON DAY*	DURATION* (WORK DAYS)
Phase 1	8/27/2018	12/5/2018		
Meet MISO Staff + Learn Important Terms	8/27/2018	9/3/2018	0	7
Calculate Capacity Factor & Credit	9/3/2018	9/17/2018	7	14
Generate Heat Maps	9/17/2018	9/24/2018	21	7
Recalculate and Regenerate Heat Maps (Due to bad data)	9/24/2018	10/1/2018	28	7
Create Siting Criteria	10/1/2018	10/21/2018	35	20
Siting Criteria Calculations	10/21/2018	11/5/2018	55	15
List Busses in Order of Desirability	11/5/2018	11/12/2018	70	7
Grouped Busses for Penetration Models + Calculated Averages	11/12/2018	11/26/2018	77	14
Phase 1 Report & Presentation + Run MT Model	11/26/2018	12/5/2018	91	9
Phase 2	1/14/2019	5/1/2019		
Create Excel Sheet for 50/50 Model	1/14/2019	2/1/2019	140	18
Create Excel Sheet for 75/25 Model	1/21/2019	2/8/2019	147	18
Create PLEXOS 50/50 Model	2/11/2019	3/1/2019	168	18
Create PLEXOS 75/25 Model	2/18/2019	3/8/2019	175	18
Simulate PLEXOS Models	3/15/2019	4/12/2019	200	28
Derive ELLC Values and Data Plots	3/25/2019	4/12/2019	210	18
Compile Results and Conclusions	4/15/2019	4/26/2019	231	11
MISO Presentation	4/21/2019	4/22/2019	237	1
Python Automation Code	2/25/2019	4/26/2019	182	60
Final Documentation + Presentation	4/26/2019	5/1/2019	242	5

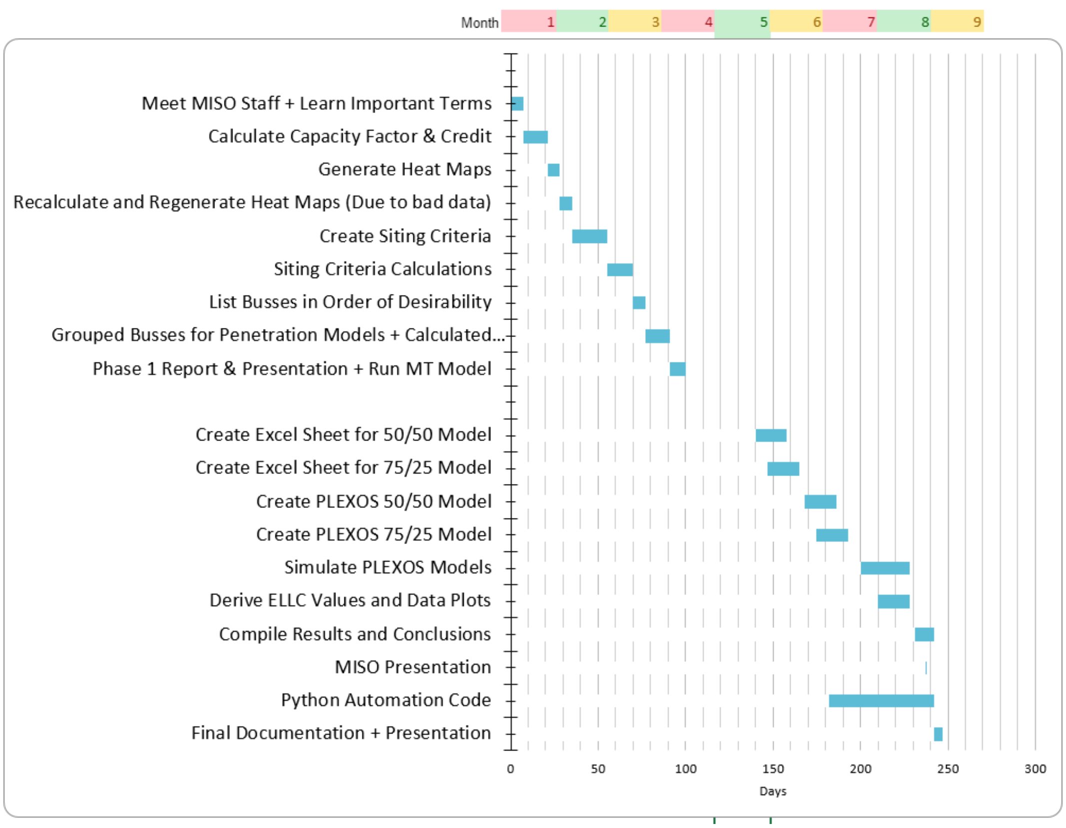

Figure 9: Project Schedule

c) Risks and Mitigation

In order to mitigate errors and concerns with time, the team continued to hold weekly meetings with MISO as well as being in consistent email communication throughout each work week. This helped to prevent the team from making considerable errors, as questions were answered relatively quickly and mistakes were usually quickly spotted by MISO during meetings. All data and the PLEXOS models were shared between the team members and MISO contacts via CyBox to allow for quick reviews throughout the project's lifespan. In the case that a mistake was spotted, the team was usually able to review and rectify the issue without any significant loss in time.

d) Lessons Learned

Over the course of this project the team has learned many things, both in regards to the industry value of the project's content as well as how to better approach project management.

The team learned very quickly the benefit of being able to divide up work in accordance to individual strengths. This made accomplishing deadlines more feasible as the team was able to have sub-projects being worked concurrently. For example, the team had a large time window where two to three individuals were working on building the PLEXOS models while others were developing the automation script or running simulations.

In terms of industry knowledge, the team now has a better understanding of what major companies like MISO and other utility aligned entities consider when discussing renewable energy and the reliability of the power grid.

6. Conclusions

a) Closing Remarks

As more renewables are integrated into the grid, the ELCC decreases per generator added. This shows us the greater the renewable penetration of renewable energy, the less beneficial each MW of renewable is to maintain the 0.1 LOLE as required by NERC.

It can be interpreted from the higher ELCC values in the 75/25 model that it can reliably handle more load than the 50/50 model. This makes sense because wind generation is generally more reliable and has a higher capacity factor than solar.

This project has given MISO, and thus other power distributers around the Midwest, the knowledge of how solar and wind energy will decrease in capacity credit as the amount renewable penetration increases. The effects of this are important to include in studies of the future as the Eastern Interconnection grows in renewable energy usage. Understanding increasing renewable penetration levels on capacity credit gives one further insight on making the grid as low cost as possible.

b) Future Uses

The goal of the policy studies team is to make multiple predictions for possible futures so that proper infrastructure planning can start years in advance. By experimenting with and planning our model, we have shown that it is possible for policy studies work to be done without having to be bound by company classified information. Additionally, this project showed that using a more simplified model of the grid still nets a plausible study. This means that work can be outsourced to universities to run their own research and studies on the grid.

By allowing this outsourcing of work, more possible futures can be studied and predicted for, allowing for a better understanding of the kind of infrastructure that will have to be built in the future. Better planning from the outsourcing of some of their work will help mitigate future costs for building and planning later down the road.

7. References

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