PROBABILISITIC BULK RESOURCE PLANNING WITH VARIABLE NON-DISPATCHABLE RESOURCE PENETRATION

A Dissertation
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Electrical and Computer Engineering in the
School of Electrical and Computer Engineering

Georgia Institute of Technology
December, 2018

PROBABILISITIC BULK RESOURCE PLANNING WITH VARIABLE NON-DISPATCHABLE RESOURCE PENETRATION

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ACKNOWLEDGEMENTS

I would like to thank Harvey Scribner and Jay Caspary for their assitance with the collection of generator and load data values that constitute the basis for this thesis and their patience in obtaining the data.

I would also like to extend my thanks towards Professor Sakis Meliopoulos, my thesis advisor, for offering guidance, help, and assistance in understanding the assessment methodlogy.

Finally, I with to thank my family for their support and encouragement during the preparation of this thesis.

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LIST OF SYMBOLS AND ABBREVIATIONS

GW	Gigawatt
MW	Megawatt
EPA	Environmental Protection Agency
NERC	North American Electric Reliability Corporation
FACTS	Flexible Alternating Current Transmission System
DOE	Department of Energy
NARUC	National Association of Regulatory Utility Commissioners
EISPC	Eastern Interconnection Stats' Planning Collaborative
ERCOT	Electric Reliability Council of Texas
LOLE	Loss of Load Expectation
ERO	Electric Reliability Organization
PAC	Planning Advisory Committee
ISO-NE	Independent System Operator – New England
FOR	Forced Outage Rate
DFO	Diesel Fuel Oil
LOLP	Loss of Load Probability
EUE	Expected Unserved Energy
PMU	Phasor Measurement Unit
SCADA	Supervisory Control and Data Acquisition
NREL	National Renewable Energy Laboratory
SPP	Southwest Power Pool
TVA	Tennessee Valley Authority
WASP	Wien Automatic System Planning Package

ABB	ASEA Brown Boveri
PROMOD	Production Module (a Southern Company probabilistic production simulation program)
LMP	Locational Marginal Pricing

SUMMARY

Transmission planning with respect to resource adequacy has largely been a deterministic process that fixes the hour of study to a predetermined point. With the rise of non-dispatchable generation, namely photovoltaic solar and wind turbine plants, these set hours may not be an accurate assessment of the reliability of the transmission system. This thesis aims to provide a methodology a Transmission Planner may utilize in order to probabilistically calculate reliability metrics for processes that were originally done deterministically.

A test system consisting of dispatchable and non-dispatchable generation serving load on a perfect transmission system is utilized to calculate the LOLP, EUE, and LOLE through a production costing methodology and varying penetration levels of the non-dispatchable resources. Four different scenarios were chosen to illustrate the relationship between the increase of penetration for these non-dispatchable resources and the decrease of the LOLP, EUE, and LOLE. Choosing the worst-case scenario, the author then attempts to determine the equivalent generating capacity increases to capture the reliability improvement of a dispatchable resource.

CHAPTER 1. INTRODUCTION

This chapter covers the Motivation, objectives, and summary of background studies conducted for the betterment of Transmission Planning and System Reliability.

1.1 Motivation and Objective

As the dependence on dispatchable resources is diminishing, the dependence on non-dispatchable resources must increase to serve the same energy demand. In the case of the current state of the Transmission grid, there are a few large resources installed; however, there are plans for an aggregate installment of over 100 GW capacity for just solar based resources by 2021 [1]. These staggering installations will increase the penetration of renewable and non-dispatchable resources significantly. As these numbers increase, Transmission Planners must be able to fully understand their impacts on serving their current and future load.

The rise of these renewable resources has also been coupled with political and environmental urges to change the current paradigm for energy generation. The Clean Energy Plan and the more recent Affordable Clean Energy Rule by the EPA demonstrate a large attention to power plant emissions and urge towards reduction of these emissions [2]. These plans focus on reduction of emissions, but even the change towards other, less emissions laden fuel sources carry other issues. These issues culminate in a larger risk depending on fuel supply issues as the fuel storage transfers from an on-site, readily stored material towards a network of pipelines and control systems [2].

Due to the reasons posed above, a need rises for Transmission Planners to study their respective areas in a probabilistic sense. This thesis outlines the probabilistic methodologies, a study procedure, and a ranking procedure for Transmission Planners to utilize in various renewable resource penetration levels and determine the most effective solution to improve the reliability of their transmission system according to relevant NERC standards.

1.2 Background

Transmission Planners are tasked by NERC to ensure the long-term reliability of the Bulk Electric System. Factors such as line overloads and steady-state voltage stability are primarily covered by deterministic methods such as positive sequence loadflow software; factors such as transient stability are covered by dynamic simulation software that also run deterministic methods to arrive at their conclusions. Industry has also focused on system adequacy, or a measure of how reliable the current resource procurements are at balancing to their obligated load. These measures previously took a determined maximum system load and the total generation assumed to be available to meet that load to find the relationship from maximum load to generation. This reserve margin should be high enough to be able to ride through a large enough contingency as dictated by the NERC standards. The assumptions this method uses are that the probability of all lines being available, all generators being available, and all FACTS devices being available is one, or that all can be dispatched up to and including their maximum values. In addition, the load value used is 50/50 or 90/10 load value. This means that the probability that the maximum load used doesn’t exceed this value is 50% or 90%, respectively. Historically, a high enough reserve margin was assumed to be ample to cover the unknowns in the system and the edge cases not normally seen by the determined worst-case scenario.

With the rapid increase of variable energy resources and increasing computation power available to Transmission Planners, these deterministic methods are not adequate in capturing the spectrum of scenarios that affect reliability of the modern power systems. Concerning resources such as solar, wind, and more recently natural gas, the fuel source may not always be available for the generator to extract the energy and resulting in a generator Forced Outage. In the case of renewable resources, the generation facility enters this state of operation more frequently than conventional generation types. As such, it is prudent to determine exactly how reliable the renewable resources are for providing a source of generation. To tackle this problem, two different approaches were historically considered. Industry attempted to model the solar generation by adding assumptions on the amount of generation expected out of the facilities and place that amount into the resource adequacy formulas to determine if there was enough generation available to meet the growing load in their long-term reliability assessments. Factors would vary widely across each region as environment variables dramatically changed based on the area the transmission planner was studying. This approach used deterministic methods to attempt to quantify and solve the growing problem described. The deterministic model is one approach to solve the problem, and it does so by taking the issue and trying to have it conform to the historical structure. In contrast, the probabilistic method analyzes the entire spectrum of possibilities of generation resources and uses that information to probabilistically characterize generation and ability to serve loads.

Whenever a deficiency has been found in interconnecting these variable resources, a transmission planner will look to acquire more generation to solve these deficiencies. In the deterministic viewpoint, the variable generation sources already have an impairment as their reserve margin is fixed based upon the hour the peak load was determined to be at. These factors are usually very low, even in regions where the resource in question is in abundance (i.e. solar irradiation in the desert climates of California). For each MVA of installed capacity, a dispatchable resource with a very low forced outage rate will most likely outperform a variable resource knowing that the variable resource has a much lower capacity factor. The probabilistic methodology in this case is more technology agnostic. It utilizes historical data to formulate the probability of availability a certain amount of generation is available from a generation plant. In probabilistic methods, other factors can impact each generators probability of availability in any given study. When finding solutions to an inadequacy found in a probability study, a transmission planner is more likely to optimize the current configuration of the transmission system or look to factors other than acquiring more dispatchable generation to solve the inadequacy.

1.2.1 Previous Studies

The DOE funded a study under the American Recovery and Reinvestment Act of 2009 in conjunction with the NARUC/ EISPC to investigate the planning risks associated with transmission planning. In contrast, the probabilistic method analyzes the entire spectrum of possibilities of generation resources and uses that information to probabilistically characterize generation and ability to serve loads. They assessed each uncertainty through a risk that was calculated as

$$Risk = Probability * Consequence \tag{1.0}$$

Where the Consequence term is a MW impact of the loss and the Probability term is probability of such a loss occurring. These risks were used as a method for determining the impact in each case study [3].

In that same study, there was an overview of the probabilistic concepts and software tools employed in each of the studies. These were identified as related to the current software tools available as well as the tools developed for that study. Each tool allowed for the study group to perform different types of analysis on each of the case studies in order to identify sets of contingencies and the probability of a specific state occurring in the power system. The study went into detail on both the resource planning and transmission planning aspects of the system, delving into contingency analysis and enumeration based on the probabilistic methodologies. In each case, however, a variety of load shapes based on historical patterns of Variable Generation and Load were utilized as the source for calculation of the reliability metrics [3].

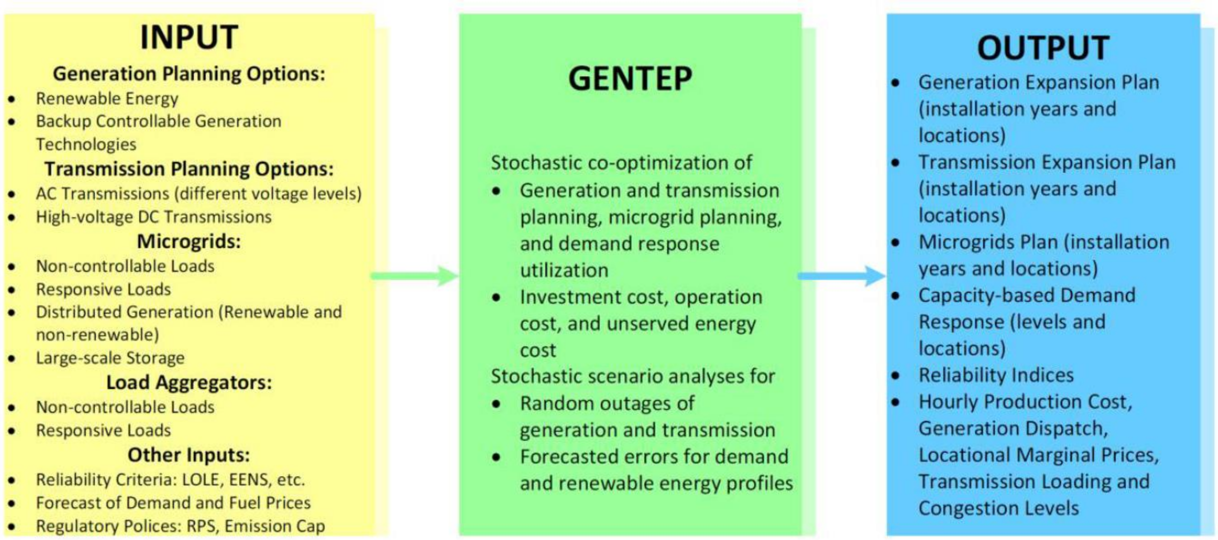

Figure 1.0 – Stochastic Based Generation and Transmission Expansion and Optimization Process [3]

After processing each of the study cases, the study group ended the report with a strong recommendation that further research should be done “to further limit the scenarios that must be considered to adequately capture the risk distributions with precision” [3]. The group also demonstrated that the benefits the probabilistic methodologies had were best served in conjunction with the current deterministic planning processes that currently are practiced in industry. It is pertinent to note that the recommendation to limit the scenarios to capture the risk distributions is not the same as making assumptions about it as would be seen in a deterministic approach.

In addition to the report on probabilistic methods described above, a few NERC led efforts and industry stakeholder groups have added to the discussion on the benefits of stochastic approaches to transmission planning in relation to topics at the time. Similar conditions in this thesis were also explored by varying renewable penetration [4]. The study team utilized an aggregate load formulation to demonstrate the reliability impacts of the renewable penetration, but only did so utilizing the measured MW provided by the electrical utility balancing the load and generation on their system [4]. In addition, the scope of their study was limited to peak values in a day and did not include off-peak scenarios to determine the impact of the renewable generation. This thesis will utilize a similar methodology to produce reliability indices but will include all study hours and weather data sources to produce the expected generation from the wind and solar facilities. Overall, their conclusions focused on examining the amount of generation acquisition required to serve the net load and using the stochastic methodologies in determining the aggregate loading. These results largely support and indicate parts of the planning process are probabilistic by their nature [4].

Another study completed under NERC staff is an analysis of the ERCOT Interconnection in determining the capacity factor of interconnected solar and wind resources. They utilize a time series analysis to determine the direct impact of solar and wind on an aggregate loading and determined that at varying penetration levels, the capacity factor of each resource can change with respect to the penetration level [5]. Solar generation demonstrates a high dependence to the penetration levels after hitting a critical point that coincides with the peak load and the maximum solar generation for that day [5]. These conclusions can best be understood by their capacity factor by penetration level graph reproduced in Figure 1.1.

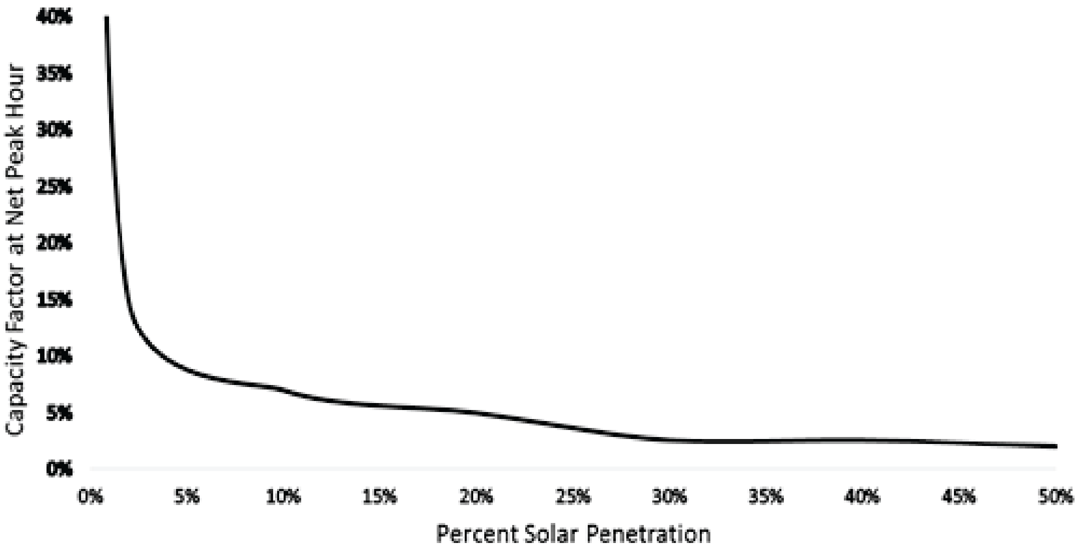

Figure 1.1 – Capacity factor by solar penetration level [5]

In the end, however, the capacity factor approach to determine the reliability metrics utilizes the probabilistic methods only in supporting the deterministic functions already instituted. The conclusions due to the capacity factor portion thus do not readily equate to a fully probabilistic study in resource planning. Other recommendations from that paper points to equating the industry practice of a Loss of Load Expectation of 0.1 day/year to other metrics such as the Loss of Load Probability and a possible function of LOLE that equates to reachable, but enforceable targets. As the ERO for North America, NERC does tend to have a bias in finding an enforceable methodology that will reach targets; however, in this study the group demonstrated that current industry practices and targets can be found through probabilistic methods. In the end, the NERC led efforts culminated in strides towards a full look into probabilistic approaches for resource adequacy under transmission constraints, i.e. transmission planning. This thesis will address the approaches for resource adequacy under idealized transmission.

1.2.2 Current Efforts by Industry

In ISO-NE, a few engineers have identified some of the risks and have taken some of the methodologies and study reports from the DOE funded study to capture specific risks in their system footprint. ISO-NE have a few reports in the PAC meeting databases that describe some of their assumptions and the impact of those assumptions into the probabilistic assessments they have done. M. Perben overviewed how utilizing different unavailable generation distributions under different system conditions impacts the discretization of reasonable test conditions [6]. In that same report, Perben also identified how the load duration curve is to not favor any one seasonal and/or hourly load condition [6]. That is, taking daily peak values for a year de-emphasizes the impact of hours near the peak conditions as well as impacts in a system where the peaks are not as pronounced from the base load. In an earlier PAC meeting, the same author used the previous DOE study as a basis for comparing the tool capabilities and limitations of the probabilistic studies [7]. As such, the author identified that the current tools are not developed in a way to meet or provide support for current NERC standards in addition to not capturing assumptions surrounding the loading values utilized in the base cases [7]. However, the author did note that the current trend is to capture these base case uncertainties and utilize other data sources to help assuage those base case assumptions [7]. This thesis will utilize other data sources to reduce the impact of the loading assumptions as that author described.

Another engineer presented ISO-NE’s efforts in the probabilistic modeling presented two reports at the same PAC committee at different times. The engineer took the ideas in the DOE report and applied them to describe a most probable generation condition for a set of generators [8]. ISO-NE took the initiative to demonstrate how this most probable condition of MW outages in their generation fleet can impact specific configurations in a transmission system [8]. Overall, the impact of this methodology can be seen in the computation power required to find the most probable generation dispatch as the increasing number of generators creates a vast array of system configuration conditions. This same idea is demonstrated in the DOE study; however, the ISO-NE efforts were focusing on identifying the assumptions made on those conditions and found that for a good assessment, a Transmission Planner would require the resource unavailability, load characteristics, disturbance resource availability, and any co-dependencies on these data sets [8]. In the other report, the ISO-NE compared their deterministic approach with some probabilistic methods they were considering [9]. In this, however, the engineer described a method much like in the other report that identified the most probable consideration of load and generation as opposed to only generation [8, 9]. Overall, these methods and efforts allowed for industry to look at issues in producing some curves and ideas at looking into the LOLP of their systems; however, the methodologies described resemble a probabilistic confirmation of deterministic methods. As in [8] where the report demonstrates how ISO-NE utilizes a capacity factor when determining the impacts of intermittent resources to align their contributions to the study hour with measured values. These methods are not entirely probability focused methods and are ways to begin incorporating the methods in industry especially concerning the transmission portion of power system planning. In contrast, a resource planner may not have the same benefit with these methods as they are still attempting to focus on a single system configuration for a normal and stressed scenario.

CHAPTER 2. STUDY METHODOLOGY

This chapter covers the probabilistic methods utilized in the study as well as the case wide assumptions for each scenario. In addition, some discussion over how other variables can impact a Transmission Planner's viewpoint into the probabilistic study is addressed. Results from these methods on the study cases in this section are found in Chapter 3.

2.1 Probabilistic Modeling Case Setup

A Transmission Planner starts primarily with a set of models in their interconnection that provide the deterministic values utilized in their steady state and transient studies. Each of these studies has a vetted process that identifies all the relevant parameters for the simulation and identifies how the cases are to be setup to determine the study's goal. A probabilistic case is no exception to that rule. Some of the data parameters for a probabilistic study can be directly taken from these studies and utilized in the probability models; however, some parameters require values to be calculated based on historical generation data.

2.1.1 Base Case Setup and Scenarios

In this thesis, the base case starts with 575 MW of conventional generation broken up into five different generating units. The load values here start at 510 MW and the Solar and Wind penetration levels are near 58 MW. This base case represents a low penetration of non-dispatchable resources whose capacity may not be indicative of the power injection at any given time. The base case and further scenarios can be found in Table 2.0.

Table 2.0 – Scenario Generation and Load Comparison

Scenario Number	Dispatchable Generation [MW]	Non-Dispatchable Generation [MW]	Load [MW]
1	580	58	510
2	580	120	535
3	580	175	565
4	580	230	595

Each study scenario will be increasing the load and non-dispatchable generation in such a way that increases the penetration of the non-dispatchable sources. Table 2.1 shows the increase in generation between cases, the capacity factor for that case, and the case description for what the case is to model. For a Transmission Planner, these scenarios are a familiar formulation as they are expected to test strained conditions in their deterministic simulations. This formulation is akin to that process.

Table 2.1 – Scenario Description, Capacity Factor, and Non-dispatchable Resource Penetration

Scenario Number	Description	Non-dispatchable Resource Penetration [%]	Capacity Factor
1	Base Case	9.090	0.25098
2	Doubling of Non-Dispatchable Base Case Resources	17.143	0.308411
3	High Non-Dispatchable Penetration	23.179	0.336283
4	Very High Non-Dispatchable Penetration	28.395	0.361345

In higher number scenarios, the conventional, dispatchable generation remains the same throughout the scenario number. The generators that comprise the 580 MW of generation are described in Table 2.2, which describes the generator’s fuel type and FOR. These values were not altered for any of the scenarios.

Table 2.2 – Dispatchable Generation Fuel Type, Capacity, and FOR

Generator Number	Fuel Type	Capacity [MW]	FOR
1	Steam Turbine – Coal	200	0.016446623
2	Combustion Turbine – DFO	135	0.027206477
3	Combustion Turbine – DFO	135	0.027206477
4	Combustion Turbine – Natural Gas	55	0.012378225
5	Combustion Turbine – Natural Gas	55	0.012378225

However, the non-dispatchable generation is distributed pseudo-randomly between two different geographic locations and two different sources (i.e. Wind and Solar) through normal distributions. Table 2.3 demonstrates how the capacity is distributed across the two locations.

Table 2.3 – Distribution of Solar and Wind Resources per Scenario

Scenario Number	Solar Facility 1 Capacity [MW]	Solar Facility 2 Capacity [MW]	Wind Facility 1 Capacity [MW]	Wind Facility 2 Capacity [MW]
1	15	13	15	15
2	17.236	28.98	32.99	40.8
3	37.912	33.539	52.56	50.99
4	63.13	46.093	61.693	59.141

2.1.2 Study Assumptions

In this study, the normal deterministic assumptions that pertain to aligning the non-dispatchable resources through to the determined peak hour for the adequacy study. In addition, the above NERC study that demonstrated the variable capacity factor study for the renewable resource plants assumptions will also not be used. Instead of determining a capacity factor before determining the impact of a non-dispatchable resource, two other assumptions are made.

First, it is assumed that there is no correlation between the solar irradiance and the wind speed for the sampled locations. With this assumption in place, it follows then that there exists no covariance in the expected value of the active power for different non-dispatchable resource types. This allows for the direct usage of wind speed and solar irradiation measured at or near the facility's location to determine the expected active power output.

Secondly, the transmission system is assumed to be perfect. That is, any active power generated at the terminals of the conventional generator, photovoltaic cell, or wind turbine can be delivered to the terminals of the load. This essentially condenses the problem into a single bus with all load and generation connected to it. It also allows for an aggregate load to be used in the load duration curve formulation as in Equation 2.0. The aggregate load is defined as the load that the dispatchable units must supply.

$$\text{Aggregate Load[t]} = \begin{cases} \text{load[t]} - \text{PV[t]} - W[t] & if\ load[t] \geq PV[t] + W[t] \\ 0 & otherwise \end{cases} \tag{2.0}$$

While the last two assumptions dealt with producing the load duration curve in the study, the last two assumptions deal with the conditional failure rate of the conventional generation units. In the early stages of a unit's interconnection, the failure rate is higher than in the middle of its life. In addition, even the most liberal of maintenance plans will only extend this middle portion of the unit's lifetime before the maintenance outages themselves are the cause for a higher FOR. This is described by the conditional failure rate that looks like Figure 2.2. It is assumed that in this study, all previously interconnected units are in the middle of their lifetimes and have a constant failure rate. For the units in the generation queue, the failure rate is also assumed to be constant, but at a higher rate. These two assumptions allow for the Transmission Planner to determine the greatest impact a resource can have in their long-term assessments for the addition of the generation unit. As the failure rate drops with age, the new unit will only better represent an ability to service the aggregated load, thus the solved reliability metrics will inherently be a "worst case" result when ranking the resources. Concerning already interconnected units, the Transmission Planner may also wish to test a higher failure rate for some of the older units as a sensitivity to these studies; however, this thesis will not consider end of life conditions.

2.2 Study Process and Other Variable Considerations

This study process could entail the usage of a Monte Carlo simulation as indicated in [10] to calculate the LOLP of a system. The simulation would follow a process like Figure 2.0 by setting the Pc of the system to zero and iterating until the simulation accounts for all the randomly produced set of generation states. This process, however, does not allow for readily computed values for the EUE in addition to the LOLP and a different method discussed in [10] is utilized.

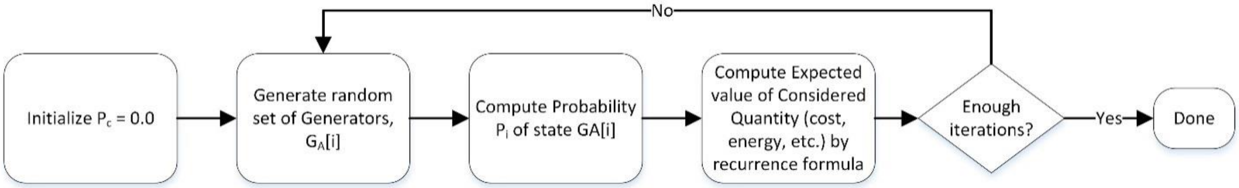

Figure 2.0 – Monte Carlo Logic Chart [10]

In the second process outlined in [10], a Transmission Planner views both the generation and the load variables as random in order to calculate the LOLP and EUE. They first start with measuring and defining the load duration curve shape, which is defined as the inverted cumulative probability function of the residual load. Figure 2.1 demonstrates a sample load duration curve that a Transmission Planner might see. This curve represents the probability that a given demand has of existing on the system.

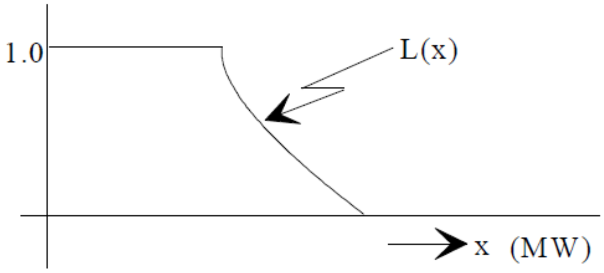

Figure 2.1 – Load Duration Curve [10]

After calculating the Inverted Cumulative Probability function of the system load by sampling the system load for a given period T and building the Load Duration curve from the collected data. With the rise of PMUs and the pervasive nature of the SCADA system, these load values can be easy to collect. If the Transmission Planner is unable to visualize that section of the system by monitoring the load data, a sampling of the generation data assuming no losses could be a starting point to build their expected load duration curve. Once the load duration curve is built, the focus turns towards the conventional generation fleet. Take for instance a single generator with capacity C1 and a probability, p1 that such generator is available to produce. The probability that the loading of the unit is below a certain demand, y is given by Equation 2.1:

$$\Pr[C(y)] = 1 - \Pr[\bar{C}(y)] = \begin{cases} 1\ if\ y < 0 \\ 1 - p_1 * L(y)\ if\ 0 \le y < C_1 \\ 0\ if\ C_1 \le y \end{cases} \tag{2.1}$$

This for each unit, the expected amount of energy, A, provided for a given demand level, y, is demonstrated in Equation 2.2 and the residual demand, R, remaining after accounting for this generation unit can be described as in Equation 2.3.

$$\mathrm{A} = \mathrm{E[Ty]} = \mathrm{T} * \mathrm{E[y]} = \mathrm{T} * \int_0^{C_1} y * p(y)dy \tag{2.2}$$

$$\text{where } p(y) = \frac{d}{dy}\Pr[C(y)]$$

$$R = L - A \tag{2.3}$$

Thus, after construction of the Load Duration Curve, the only other data required to compute the residual of the load is the capacity of each unit, and the probability that unit will be available. The probability of availability is given by Equations 2.4 to 2.5 and assume that the repair and failure rate of the generation unit are constant at μ and γ, respectively. The probability of unavailability is also referred to as the FOR of the generator.

$$P_1 = \ p = \frac{\mu}{\mu+\gamma} \tag{2.4}$$

$$P_0 = \ q = \frac{\gamma}{\mu+\gamma} \tag{2.5}$$

where q is the probability of unavailability and p is the probability of availability

The conditional unavailability of the unit is determined by a function of how long the generator has been in operation and represents the failure rate of the unit as in Equation 2.5. If the generator is assumed to have a constant failure rate, the assumption translates to being in the middle portion of the conditional failure rate curve in Figure 2.2. If the Transmission Planner desires to understand the impact of a new generator, can assume the generator to be operating in the maturity period of the conditional unavailability curve. If such a generator has a low slope in the maturity period, it is also fair to assume that an Average FOR calculated in the break-in region can be utilized.

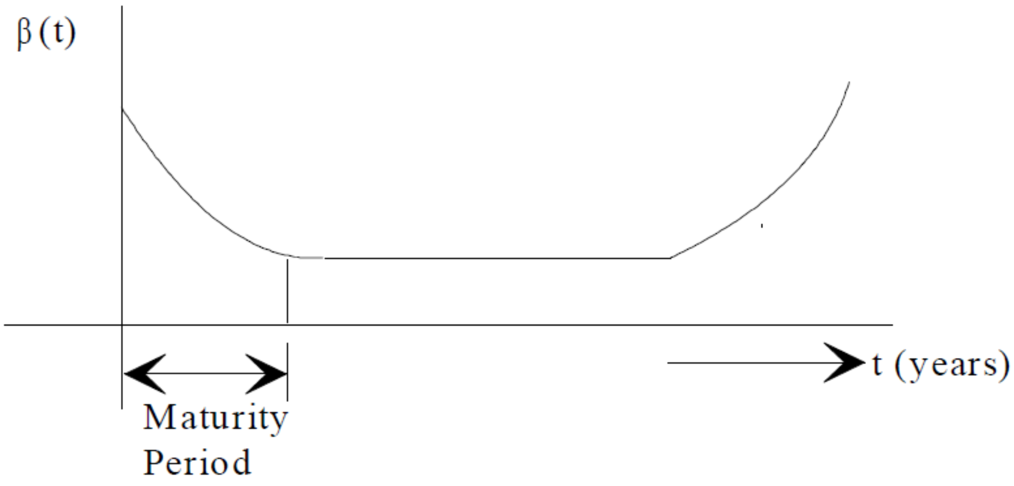

Figure 2.2 – Conditional Unavailability of a Conventional Generator [10]

The overall process and iterative logic can be found in Figure 2.3. The logic flow chart can be implemented in many different software platforms and a few academic and industry developed tools are available that use this process, or the Monte Carlo simulation briefly discussed. This thesis will use the logic in Figure 2.3 to calculate the LOLP and EUE reliability metrics.

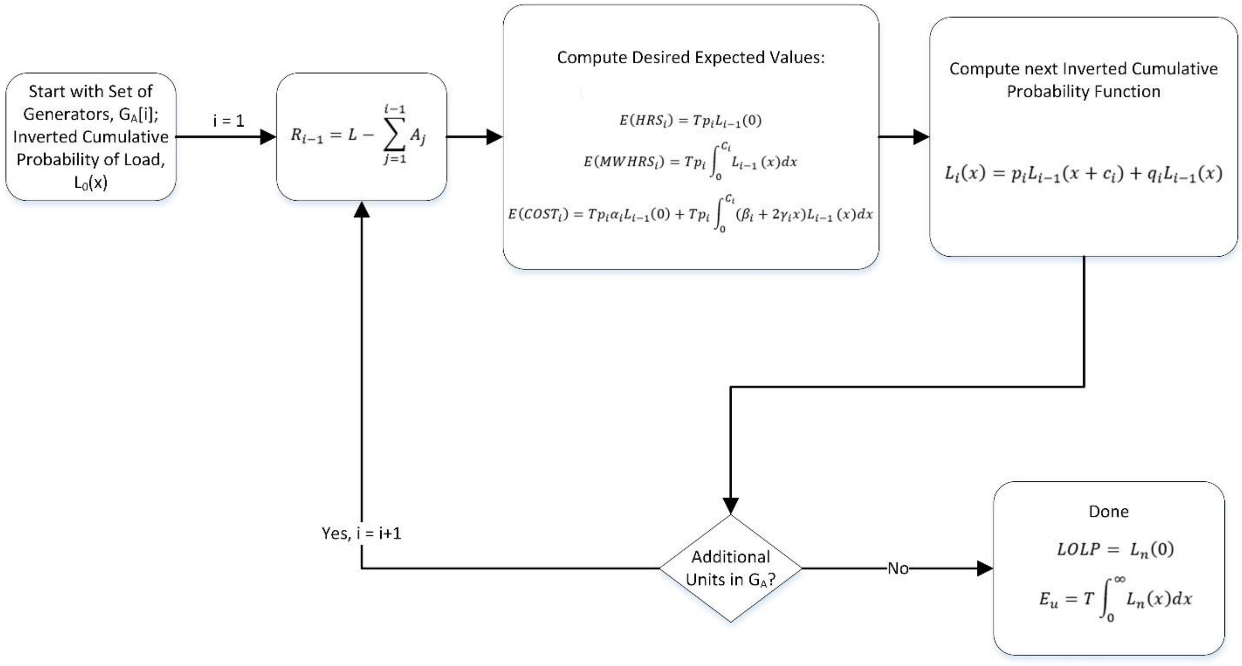

Figure 2.3 – Flow Diagram for the Probabilistic Scenario [10]

In the above figure, the αi, βi, and γi are the cost coefficients for unit i, the ci variable is the expected output of unit i, and the Eu in the flow diagram is the computed EUE for the system described by the Load Duration curve and the set of generator capacities and FORs. It is worthwhile to note that the E_u variable can also be computed utilizing the Residual Load, R, variable; however, the integrand can be reduced to that seen in the flowchart. After going through the process for all generators and their capacities, the end Ln graph may be positive if the set of generators can meet the demand and may be zero or positive if the generators can meet the demand. Thus, in order to improve the LOLP and EUE, a strategic process for eliminating the Residuals by acquiring specific generation profiles is anticipated.

2.3 Data Requirements and Tools

As mentioned above, the data requirements for the probabilistic study are much more intensive than that required for a deterministic process. For conventional units, a FOR is associated with a generation capacity block and for non-dispatchable resources, their aggregate output is required to be related to an annual quantity nearby the interconnection point. For currently interconnected non-dispatchable sources, their impact can be measured; however, for a Transmission Planner, many of the resources in consideration are not currently interconnected and must use a different data source for their impact on resource adequacy. These data sources usually are in the form of weather readings and other measurable quantities that impact the MW output of the plants.

2.3.1 Generation and Load Data

For this thesis, the non-dispatchable generation uses two different sample locations in the National Solar Radiation Database from NREL to provide the total incident global irradiation and average wind speed for every hour. The data sets from this database can also include peak conditions and other data measurements made public for many of the geographic locations in the United States, where the load data source was acquired. These locations were chosen at random within the geographic boundary of the load data; however, for an interconnection site whose geographic location is well known and understood, this process proves easy to get a direct relationship between the output of each solar facility to the rest of the system.

After acquiring the data sets for the solar irradiation and wind speed, the next step is to relate the measurement to the electrical power output of that facility. For solar irradiation, an assumption was made that the facility's MW can be represented as a plant that contains no losses from the photovoltaic cell and the interconnection point. To overcome the realized losses for photovoltaic generation, more surface area would be required. Hence, each photovoltaic solar plant can be represented as a smaller surface area with no losses. After calculating the surface area for the solar facilities, the Transmission Planner can directly multiply as in Equation number 2.6.

$$MW_{PV}[t] = Equivalent\ Surface\ Area * Irradiation[t] \tag{2.6}$$

Where Irradiation[t] is the set of time sampled global solar irradiation

For wind turbines, the equivalent power is harder to compute. Each wind turbine manufacturer has a wind speed curve that will dictate how much active power is capable of being produced at each wind speed. Using this curve, a Transmission Planner can directly compute the available active power from the wind plant; however, most of these curves are confidential in nature and the Transmission Planner may not have access to this data depending upon their region. These curves can be easily approximated through a cut-in, maximum power, and cut-out wind speed as represented in Figure 2.4. The cut-in speed being the point at which active power can be continually maintained up and until the cut-off speed. Above the maximum power speed, no extra active power can be produced. If the testing is an available option for that turbine type, the Transmission Planner need only test between the cut-in and maximum power wind speeds to get a good approximation. Otherwise, a linear approximation between the cut-in speed and the maximum wind speed provides a good approximation.

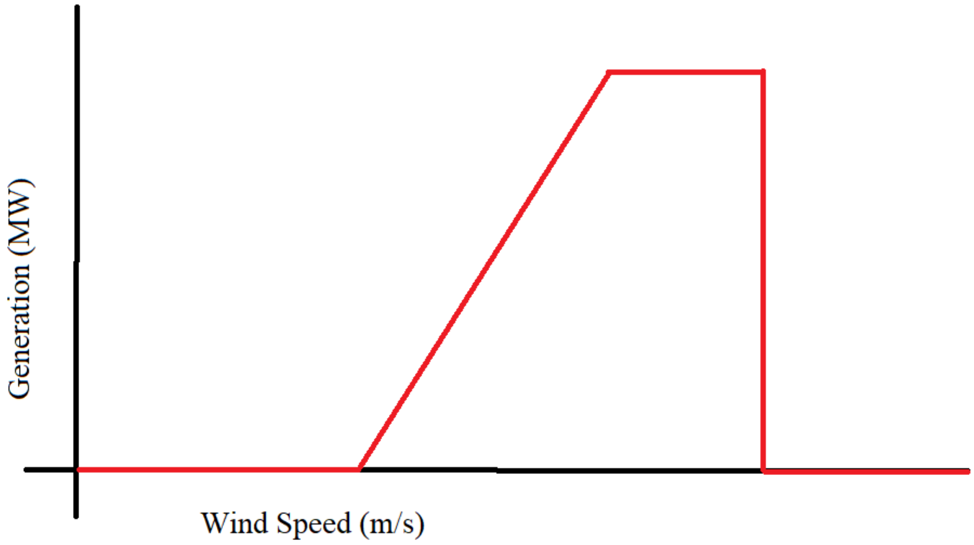

Figure 2.4 – Approximate Wind Speed Capability Curve

No matter the method by which the Transmission Planner gets this data, the wind speed samples at the turbine height are related to turbine output through that curve. As the study assumption of perfect transmission holds, this active power can directly be used in the study.

Southwest Power Pool provided time sampled load data in the same hourly resolution of the National Solar Radiation Database. The total number of hours provided was 13,843, which set the number of samples required from the NREL database. The load data was scaled from the raw levels to allow the control over the capacity factor; however, the Transmission Planner need not scale measured values for their region of the system. In addition, conventional generator FORs were provided by SPP generators. These FORs were averaged for each fuel type and used to represent the generators in the test system based on its fuel type.

2.3.2 Study Tool Requirements

Multiple different tools exist for the probabilistic production costing and Monte Carlo methods described above. The primary function for each of those tools are the core probability module, with additional functions to help manage the massive amounts of data utilized to calculate and derive the values associated with the outage statistics and other generator parameters. One model is the WASP and WASP type programs that were developed by TVA to deal with the economic impacts of nuclear generation [11]. Some WASP models are open source; however, some of the more detailed and developed modules are confidential programs and require licensure to run. Additionally, an ABB sold module, PROMOD, that originally does LMP and other economic functions has some probabilistic production costing functions associated with the package if the Transmission Planner would prefer to utilize a well-vetted and supported software platform [12]. Each of these software packages may have different functions and more development or simplifications of the production costing model, much like how some of the assumptions for this thesis were presented; however, each software platform demonstrates a shift from deterministic methods in resource and transmission planning towards a probabilistic method.

CHAPTER 3. RESULTS

This chapter covers the results utilizing the probabilistic methodologies on the test system described in Chapter 2. Each of the scenarios are analyzed to determine the worst scenario for reliability and a few possible plants to interconnect different fuel types into the test system. The primary variables determining the reliability are also presented and quantified.

3.1 Demonstration of Worsening Reliability

As the load values increase with each scenario, the capacity factors for each of the scenarios are also increasing. If the increase in generation was conventional units, this generally would equate to a betterment of reliability. In Table 3.0, the total Load, Generation, capacity factor, and non-dispatchable resource penetration are presented and a positive trend between the capacity factor and load is obvious. Other studies have determined that non-dispatchable resources do not have a stable capacity factor and deterministic studies have provided methods for an equivalent capacity factor for these resources, which will reduce the overall capacity factor in the scenario. The rest of this section outlines the primary variables affecting reliability and the trends in the data.

Table 3.0 – Scenario Pertinent Characteristics

Scenario Number	Load [MW]	Generation [MW]	Capacity Factor	Non-Dispatchable Resource Penetration [%]
1	510	638	0.25098	9.090
2	535	700	0.308411	17.143
3	565	755	0.336283	23.179
4	595	810	0.361345	28.395

3.1.1 Main operators

In the four cases, the LOLP, EUE, and LOLE reliability metrics are summarized in Table 3.1 and the LOLE is benchmarked against a current industry target value of one day in 10 years performance metric in Figure 3.1. LOLE is calculated by the ratio between the EUE and total energy generated. It is worth to note that while SPP data was utilized to determine the parameters of these scenarios, the capacity margin and many other parameters were constrained to not reflect current SPP reliability metrics. In no way is this thesis intended to determine SPP reliability, but to utilize current values associated with the FOR of current industry available fuel sources and extrapolate with current trends.

Table 3.1 – LOLP, EUE, and LOLE for Each Study Scenario

Scenario Number	LOLP	EUE [MW]	LOLE
1	0.00267	1,430.74	0.000360035
2	0.00227	1,196.21	0.000306964
3	0.00496	2,897.94	0.000677362
4	0.00523	3,102.18	0.000719319

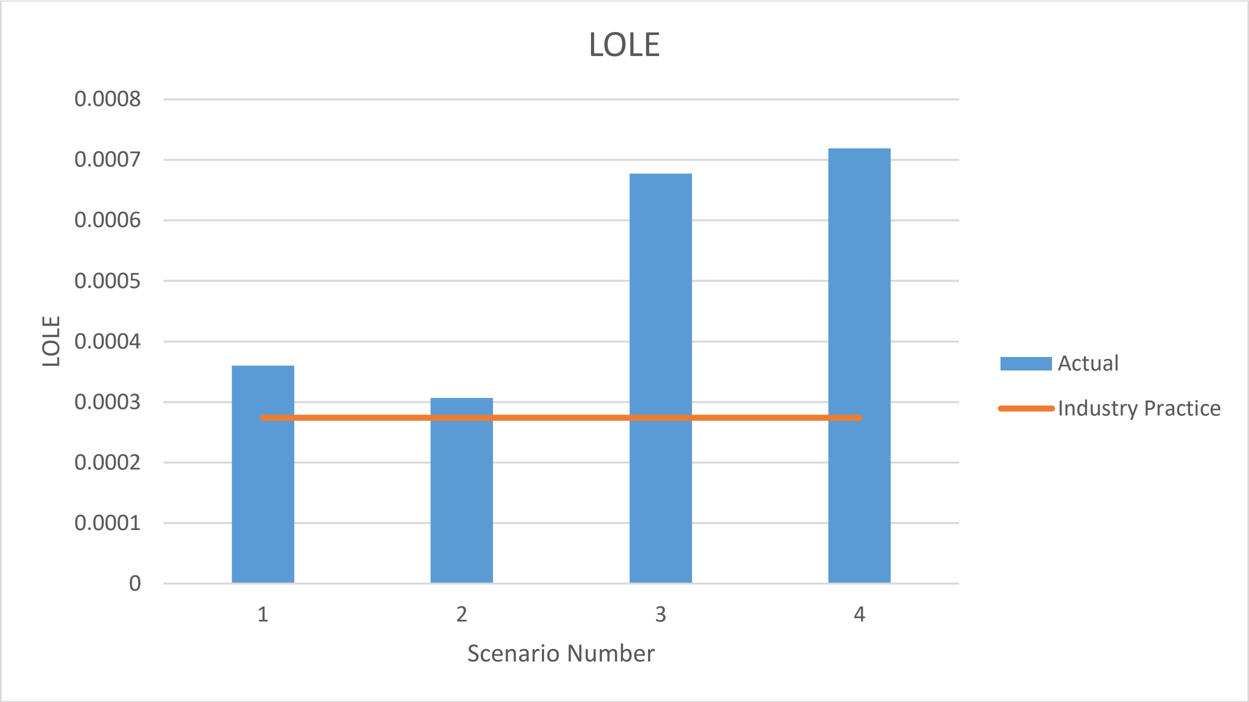

Figure 3.1 – LOLE values per scenario with Benchmarking line

The current industry practice for determining LOLE is a “1 day in 10 years” metric and was utilized to adjust the scenarios such that Scenario 1 is close to this line. As seen in the figure, the LOLP decreases between the first and second scenarios, and from there continues to increase as the non-dispatchable resource penetration level also increases. This is primarily due to a time series analysis of the load data SPP’s system presents. The load data here peaks in the middle of the day and has valleys towards the early morning and late evening portions of the day. A time series plot of a generic day for the load data with a solar output curve is in Figure 3.2.

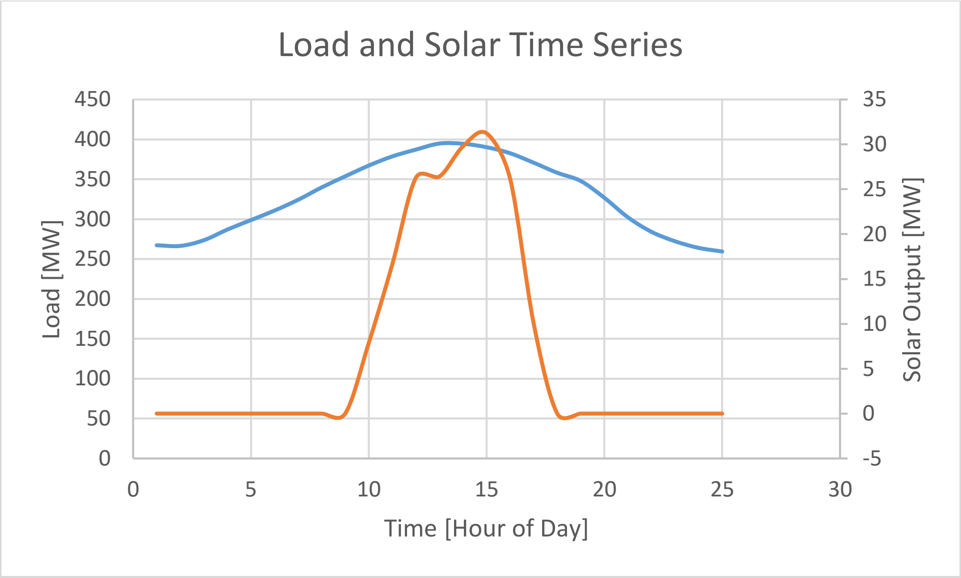

Figure 3.2 – Time Series Load and Solar Data for 24 Hours

Thus, solar generation has a significant impact towards the load duration curve as it has a high likelihood of reducing the peak of the load duration curve and will impact the EUE and thus significantly reducing the LOLE. However, the LOLP may remain high as the LOLP factors are largely impacted by having redundancy in the system. In these scenarios, no additional facility is considered for interconnection, so a larger capacity for any generator in the set will only slightly impact the LOLP.

3.1.2 Correlation to Increasing Non-Dispatchable Resource Penetration

As demonstrated in Table 3.2, the overall reliability metrics have worsened with respect to the penetration levels of the non-dispatchable resources. This demonstrates that with the growing rise of non-dispatchable resources, benefits are to be had; however, as the penetration grows to higher rates the resource mix must reflect the load profiles as well.

Table 3.2 – Non-Dispatchable Resource Penetration versus Reliability Metrics

Scenario Number	Non-dispatchable Resource Penetration [%]	LOLP	EUE [MW]	LOLE
1	9.090	0.00267	1,430.74	0.000360035
2	17.143	0.00227	1,196.21	0.000306964
3	23.179	0.00496	2,897.94	0.000677362
4	28.395	0.00523	3,102.18	0.000719319

As this increase continues, it can be expected to have a much greater LOLP and EUE; however, as the LOLP is also dependent on the size of the available generation set, the capacity of such generators will most greatly affect the EUE of the system, as demonstrated in the above table.

3.2 Interconnection Study on Worst Case Impacts

In a generic interconnection queue, the first interconnection request will be studied as solid prior to the study of an interconnection request. As economic incentives increase for grid connected non-dispatchable resources, these projects will be seen at higher rates in these queues. Transmission Planners then have a unique opportunity to change the generic queue structure into a priority queue whose priority can be related by the benefit of the interconnection. For this thesis, four different fuel types of the same 50 MW will be studied and their relative impact on the very high non-dispatchable resources case, Scenario 4, will be tallied. It is assumed that any of these interconnection requests will be close to the same geographic point and will be further away from the other Wind and Solar generation facilities to have different wind speeds and irradiances from the other facilities.

3.2.1 Interconnection of 50 MW Wind Plant

In the interconnection of a new 50 MW wind plant, a separate location as described above was utilized for the same wind speed parameters as the other plant. Based on an examination of the data, the average wind speeds of the generator location are roughly similar to that of the other two generation facilities, equaling roughly 3.5 m/s wind speed for all the data entries. After running the Probabilistic Production Costing methodology described in Chapter 2, the EUE, LOLP, and LOLE changed according to the values in Table 3.3. Of the changes, the most significant was to the EUE from the base of Scenario 4; however, the percentage change isn't largely more significant than the reduction of the LOLP.

Table 3.3 – Evaluation of 50 MW Wind Plant added to Scenario 4

LOLP	Change [%]	EUE	Change [%]	LOLE	Change [%]
0.00490	-6.31	2901.00	-6.49	0.000681588	-5.25

3.2.2 Interconnection of 50 MW Solar Plant

When running the simulations for the solar plant, the same facility location as determined in Section 3.2.1 is utilized for the solar irradiation. The solar plant studied for interconnection will output 50 MW at nearly 1000 watts per square meter of photovoltaic cells. The peak solar irradiation at the interconnection site studied is 999 watts per square meter. As the losses from a non-ideal solar cell's imperfections can be compensated for via supplemental photovoltaic strings and other plant specific technology, it is assumed that the output of the plant is dependent solely on the solar irradiance. The impact of the solar plant is depicted in Table 3.4, in which the LOLP, EUE, and LOLE is compared to the results from Scenario 4.

Table 3.4 – Evaluation of 50 MW Solar Plant added to Scenario 4

LOLP	Change [%]	EUE	Change [%]	LOLE	Change [%]
0.00416	-20.46	2408.29	-22.37	0.000575301	-20.02

3.2.3 Interconnection of 50 MW Combustion Turbine – Gas Plant

In order to determine a baseline for reliability improvement, two conventional generation plants were tested in addition to the above non dispatchable resources. The combustion turbine fired by natural gas uses the same FOR rate as the gas fired generation in Table 2.3. The LOLP, EUE, and LOLE are tabulated in Table 3.5 and compare the results to the results of Scenario 4. Here, the EUE and LOLE are reduced by nearly four percent more than the LOLP.

Table 3.5 – Evaluation of 50 MW Gas Plant added to Scenario 4

LOLP	Change [%]	EUE	Change [%]	LOLE	Change [%]
0.00176	-66.31	937.56	-69.78	0.000217237	-69.80

3.2.4 Interconnection of 50 MW Combustion Turbine – DFO Plant

In similar fashion, a 50 MW combustion turbine fueled by diesel fuel oil was interconnected to demonstrate how a higher FOR can impact the reliability metrics. Thus, the increase in the FOR demonstrates a lesser improvement of the reliability metrics as indicated in Table 3.6. That table holds the LOLP, EUE, and LOLE reliability indices for the DFO combustion turbine plant. Again, as with the gas plant, the LOLP improvements were behind the EUE and LOLE improvements by about 3.5 percent.

Table 3.6 – Evaluation of 50 MW DFO Plant added to Scenario 4

LOLP	Change [%]	EUE	Change [%]	LOLE	Change [%]
0.00181	-65.39	968.81	-68.77	0.000225071	-68.71

3.3 Methods for Equating Reliability

As a Transmission Planner, these interconnection studies are valuable to indicate how a specific fuel type can impact the long-term reliability of the system. As such, the best choice in the studied interconnections would be the natural gas fired 50 MW combustion cycle plant for its impacts on the reliability indices. However, since a Transmission Planner does not normally have control over the size of the plant, in order to evaluate an equivalent impact of a size variant plant, a few adjustments can be made by the Planner when looking to resource adequacy.

3.3.1 Determining Baseline Reliability - General Parameters

A baseline for a study is required in order to determine the equivalent size of other fuel sources in a generation queue or for determining incentivization for other fuel sources. Here, the 50 MW natural gas plant serves as the highest impact to these reliability indices and therefore will be the values utilized to match the improvements to one of the reliability indices. As the above section demonstrates, each of the reliabilities are not impacted as the same as the other indices for all fuel types. For some, there are a near direct correlation is between the EUE and LOLE, but there exists a difference in the rate of improvement for each of the indices as there is about a two to four percent difference in the LOLP and the other two indices. In this process, a fixed test conventional generation unit can be used to determine the impact a facility of that size has on the current state of the BES. Afterwards, the Planner can find a capacity of other fuel sources through a procedure outlined in Chapter 2 that varies the interconnected capacity until the improvements to the current system are equal. This can be coined as the Equivalent Generation Capacity, which is not akin to an equivalent Capacity Factor used in the deterministic process but attempts to allow a direct comparison between the non-dispatchable and dispatchable resources. Using this definition, the Equivalent Generation Capacity required for the above studied resources to have the same impact as the natural gas plant are found in Table 3.7. The target reliability metric in that table is equivalencing the EUE. It is prudent to note that based on the previous Chapter 3 tables, the Solar and Wind capacity numbers may dramatically change between equating LOLP and EUE as the improvements on those reliability metrics have lower variance in comparison to the dispatchable resources. For the table listed below, the study stopped once the resource demonstrated a slower convergence rate to the desired reliability metric. That is, once the reliability metrics demonstrated a lower impact, the simulation halted increasing generation for the resource, this impact is described in higher detail below.

Table 3.7 – Equivalent Generation Capacity to a 50 MW Natural Gas Plant

Natural Gas Capacity	Diesel Fuel Oil Capacity	Solar Capacity	Wind Capacity
50 MW	56 MW	>250 MW	>450 MW

3.3.2 Factors that Equate to Baseline

In the baseline, it is good to note that the reliability improvement for a specified generator capacity interconnection can be impacted by the surrounding shape of the load profile primarily, and the impact of the break in portion of the conditional failure rate. Dealing with the latter first, the assumption that the conditional failure rate is constant will not hold for a newly interconnected generation facility as the generation plant will have a higher FOR during its break in period. Thus, the construction procedures and other mechanical and environmental factors can greatly impact this baseline. These impacts are heightened during the baseline process and are accounted for in raising the FOR during this specific instance according to the conditional failure rate. The way the load profile impacts the baseline is simply that the non-dispatchable resources have different correlations with the peak generation and the peak load. In the system studied for this thesis, the load profile had peaks coincident with the solar generation; however, in areas where the peak load may be shifted to a "shoulder" condition, the reliability impact of a photovoltaic generation facility may not have as great of an impact as demonstrated in this study. In addition, the Wind and Solar resources have such a high equivalent generation capacity in comparison to the DFO plant due to the limitation on how “effective” an additional MW of interconnected wind or solar generation has on the system’s load graph. In the case of solar resources, this is clearly demonstrated when the peak of solar generation matches the current loading of the system. After that point, the effectiveness of an additional MW of interconnected capacity does not have the same impact as the previous additional capacity. Compounding this effect is the very low FOR numbers for the generators, with a higher average FOR, these equivalent numbers can be reduced simply because impact of the dispatchable generators will be lesser to the reliability metrics. This is a good indication that these parameters are system specific and should not be studied as a lumped system. Each separate area will have different non-electrotechnical phenomena that impact the FOR of dispatchable units as well as the MW output of the non-dispatchable units.

CHAPTER 4. CONCLUSIONS AND RANKING PROCESS OVERVIEW

This chapter overviews the ranking of the interconnection processes done in Chapter 3, demonstrates the possible impacts this study may have, and indicates where future efforts can be considered. It is worthwhile to note that these types of studies are recently getting more interest at the high voltage transmission level.

4.1 Interconnection Ranking and Performance

Based on the results in Chapter 3, percentage change from the fourth Scenario's reliability metrics against the ranking for this test system is held in Table 4.0. The best solution for the increase in the LOLE for this test system was the natural gas combustion turbine plant; however, this is likely due to the low FOR factors indicated in Chapter 3. Overall, this ranking demonstrates that in a high non-dispatchable environment, the most effective way at reducing the LOLP, EUE, and LOLE is to acquire low FOR, dispatchable generation facilities to service the load.

Table 4.0 – Interconnection Ranking on Percentage change from Scenario 4

Fuel Type	LOLP [%]	EUE [%]	LOLE [%]	Ranking
Gas	-66.31	-69.78	-69.80	1
DFO	-65.39	-68.77	-68.71	2
Wind	-6.31	-6.49	-5.25	4
Solar	-20.46	-22.37	-20.02	3

4.1.1 Considerations on Specific Study

In this study, the system was modeled to have a specific capacity factor and that the development of the non-dispatchable resources were the only growing factors to meet the growing load. Depending on load growth and other initiatives, the numbers here will reflect the lower load levels and greater energy efficiencies. In addition, this study is indicative of a desire to compare a capacity factor towards the increasing LOLP, EUE, and LOLE metrics and demonstrate possible improvements to the metrics in a high penetration of non-dispatchable resources environment. These solutions here are not a call to build more generation facilities, but to demonstrate a way that a Transmission Planner can utilize probabilistic methodologies when evaluating the impact of interconnected facilities.

4.1.2 Extrapolations on Other Systems

In the equivalencing portion of this thesis, the gas generator was utilized to find the Equivalent Generation Capacity of other fuel sources; however, a Transmission Planner may be limited in acquiring new capacities and might desire to match a similar dispatchable resource to the non-dispatchable resource. In any case, the Transmission Planner can utilize these methodologies to demonstrate equivalence and/or decrementing reliability metrics in their system. Depending on the environmental variables or other fuel supply variables, this framework can be adjusted accordingly. This framework is best suited for problems that can be simplified down to a single bus scenario, so if there are highly congested transmission elements that have a high failure rate, these results may be more optimistic than desired. Besides the one exemption, this framework can readily apply to local region of generation or to the larger high voltage transmission system.

4.2 Preliminary Methodology for Continual Study

Based on the framework's portability to other systems, it is best understood to have a methodology going forward for a transmission planner. The framework steps are demonstrated in Figure 4.0 and depict how a Transmission Planner may generate and solve a set of scenarios to evaluate the impact a generation facility has on the reliability of the system. This is a preliminary methodology and can be refined and improved upon with efforts depicted below.

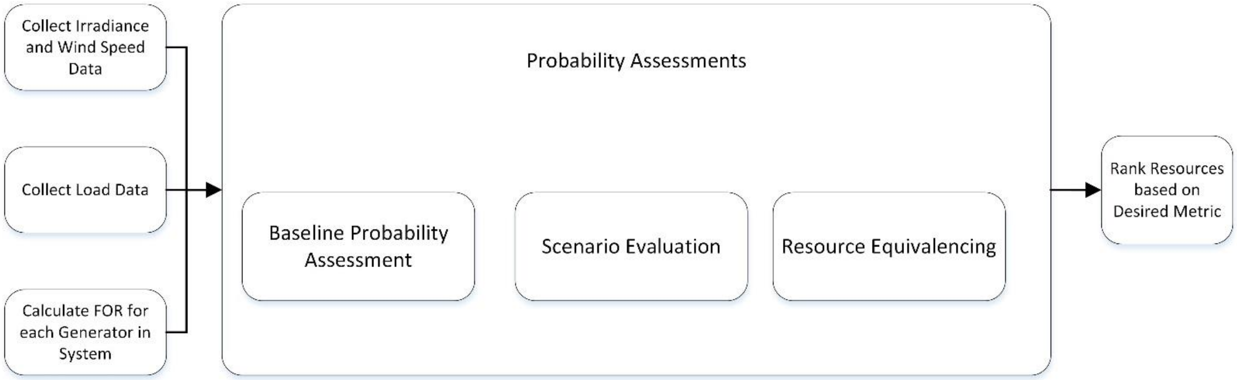

Figure 4.0 – Methodology for Future Studies Following Thesis Framework

4.3 Further Study

For future study efforts, a look into the study assumption on the wind speed and solar irradiation being independent of each other when determining the output of the non-dispatchable resources should be evaluated. This assumption in the study allows a Transmission Planner to utilize wind speed and solar irradiation directly; however, the correlation between wind and solar output should be determined to fully separate them. It is presumed that this correlation will be dependent upon the geographic features prominent in the system and may be a positive or negative correlation. If more time could be spent on this test system, a dive into the solar irradiation and wind speed data can determine a correlation and adjust the models accordingly. This could readily be utilized in either the Monte Carlo or Production Costing methodologies to possibly correct some of the calculations utilized in the programs. In addition, further fuel sources such as tidal and other non-dispatchable resources can be considered and their corresponding data source that links the MW production to the environmental conditions. Even a study into the impacts of highly regulated dispatchable fuel sources such as nuclear energy could yield promising results as such units are normally maintained in such a way that the output of the plant has a very low FOR. The impacts of such high certainty can readily counterbalance the uncertainty of the non-dispatchable resources. It is speculated that efforts by the groups identified in Chapter 1 may have an interest in identifying some of the above-mentioned items. Also, with the onset of energy storage devices, a non-dispatchable resource's ineffectiveness at certain times of the day may be offset and provide a greater impact to the overall reliability of the system, but future study is warranted on the impact, controllability, and implementation of this technology.

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