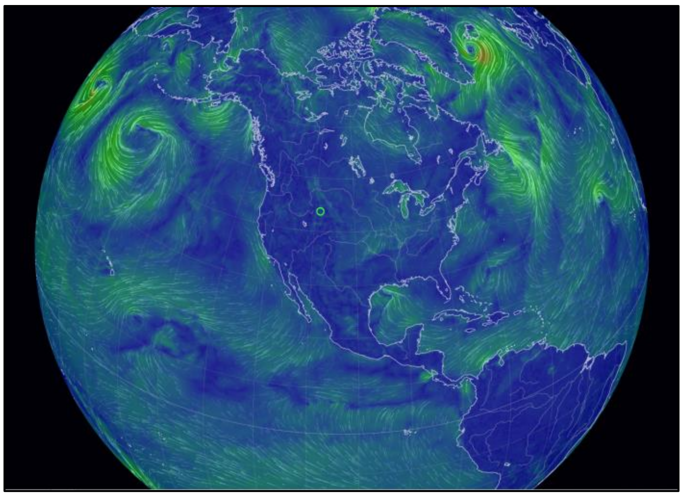

TURBINE CLUSTER SIMULATION

Group Project Final Report

Revision: A

Team 7

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Table of Contents

1 Executive Summary 7

2 Background 8

3 Problem Statement 10

3.1 Systems Engineering Lifecycle Phase 10

4 Data Collection 12

5 Conceptual Model 15

5.1 Representations 15

5.2 Key Parameters 15

5.2.1 Inputs 16

5.2.2 Outputs 17

5.2.3 Assumptions 17

6 Verification & Validation 19

6.1 Verification Plan 19

6.2 Validation Plan 19

6.3 Verification and Validation Execution 19

7 Simulation Implementation 22

7.1 Scope of the Simulation 22

7.2 Turbine Cluster Simulation 22

8 Simulation Model/Simulation Program 25

8.1 Code Operation (Sample) 28

8.2 Comment on Fidelity 30

9 Presentation 31

10 Experiments 32

10.1 Experiment 1: GE Wind 1.5 MW-77 33

10.2 Experiment 2: GE Wind 2.75 MW-120 33

10.3 Experiment 3: Vestas V100-1.8 34

10.4 Experiment 4: Vestas V136-3.45 34

10.5 Experiment 5: Siemens Gamesa G97-2 MW 34

10.6 Experiment 6: Siemens Gamesa G126-2.5 MW 34
11 Results and Conclusions 35
11.1 Results 35
11.2 Conclusion 39
12 Recommendations 41
12.1 Recommendation for the Proposed Wind Farm 41
12.2 Stretch Goals 41
13 Summary 42
14 Acknowledgements 43
15 References 44
16 Appendix A: Requirements Definition 46
17 Appendix B: Modeling & Simulation Timeline 47
18 Appendix C: Turbine Spacing Factor Calculations 48
19 Appendix D: Power Curves for Wind Turbine Models 50
19.1 Experiment 1: GE Wind 1.5 MW-77 50
19.2 Experiment 2: GE Wind 2.75 MW-120 50
19.3 Experiment 3: Vestas V100-1.8 51
19.4 Experiment 4: Vestas V136-3.45 51
19.5 Experiment 5: Siemens Gamesa G97-2 MW 52
19.6 Experiment 6: Siemens Gamesa G126-2.5 MW 52
20 Appendix E: MATLAB Code 53
20.1 Code Operation 59
20.1.1 Input GUI 59
20.1.2 Output Power Plot 59
20.1.3 Output Summary Message 60
21 Appendix F: Additional Background Work 61
22 Appendix G: Literature Review 62

List of Figures

Figure 1 Annual Average Wind Speeds in the US, Map 8
Figure 2 Annual Average Wind Speeds in Wyoming, Map 9
Figure 3 Systems Engineering Lifecycle Phase 11
Figure 4 Data Collection Initiative 13
Figure 5 Iteration 1: Conceptual Model for the M&S 15
Figure 6 Validation Results Plot, Energy Generation - Casper Wind Farm vs Simulation 21
Figure 7 Iteration 1: Mathematical Model of the Simulation 23
Figure 8 Simulation Computational Model 25
Figure 9 Simulation Computational Model, Land Use Calculation 27
Figure 10 Code Operation, Step 1) Start Program 28
Figure 11 Code Operation, Step 2) Input Turbine Model Information 28
Figure 12 Code Operation, Step 3) Simulation Computation 29
Figure 13 Code Operation, Step 4) Sample Output 29
Figure 14 Simulation Model Output Power Plot 30
Figure 15 U.S. Wind Turbine Market Share, 2014 [13] 33
Figure 16 Experimentation Results Plot, Minimum Number of Turbines 37
Figure 17 Experimentation Results Plot, Land Usage 38
Figure 18 Analysis by Number of Turbines 39
Figure 19 Analysis by Land Utilization 40
Figure 20 High-Level M&S Requirements Hierarchy 46
Figure 21 M&S Timeline 47
Figure 22 Turbine Spacing Factor Calculation, Part 1 48
Figure 23 Turbine Spacing Factor Calculation, Part 2 49
Figure 24 GE Wind 1.5 MW–77 Power Curve 50
Figure 25 GE Wind 2.75 MW-120 Power Curve 50
Figure 26 Vestas V100-1.8 Power Curve 51
Figure 27 Vestas V136-3.45 Power Curve 51
Figure 28 Siemens Gamesa G97-2 MW Power Curve 52
Figure 29 Siemens Gamesa G126-2.5 MW Power Curve 52
Figure 30 Input GUI 59
Figure 31 Sample Output Power Plot 59
Figure 32 Sample Output Summary Message 60
Figure 33 Background Notes 61
Figure 34 Literature Review 62

List of Tables

Table 1 Key Data Sources Breakdown 14
Table 2 Summary of Major Parameters for Model... 17
Table 3 Experimentation Results Summary, Minimum Number of Wind Turbines..................... 36
Table 4 Experimentation Results Summary, Land Usage 36
Table 5 High-Level M&S Requirements Definition 46

1 Executive Summary

Recently, there has been a desire in the United States to move the nation towards renewable energy. The state of Wyoming is currently predominantly powered by fossil fuels but has an immense potential to expand its wind energy capacity. This project has been adapted as a scenario in response to an article from the Sheridan Press. The article refers to the goal of Wyoming's electric power company, PacifiCorp, to create six new wind farms that could "add more than 1,600 MW of electricity generation capacity to Wyoming's grid" [1]. The goal of this project was to use modeling and simulation (M&S) to help PacifiCorp in the development of a wind farm. The M&S project team functioned as consultants in this hypothetical scenario.

The M&S team's goal in creating the Turbine Cluster Simulator was to provide valuable feedback to PacifiCorp during the planning phase of their project. The simulation was created in MATLAB from scratch and outputs the recommended quantity of wind turbines required to produce a targeted energy for a given land area. It considers wind, turbine, geographic and risk preference parameters. Since the general location has been selected during project planning by PacifiCorp, assumptions like fixed location, elevation, air attributes (temperature and density) were incorporated directly into the model. The model output contains useful insight that enables PacifiCorp to make a well-informed decision on turbine vendor selection.

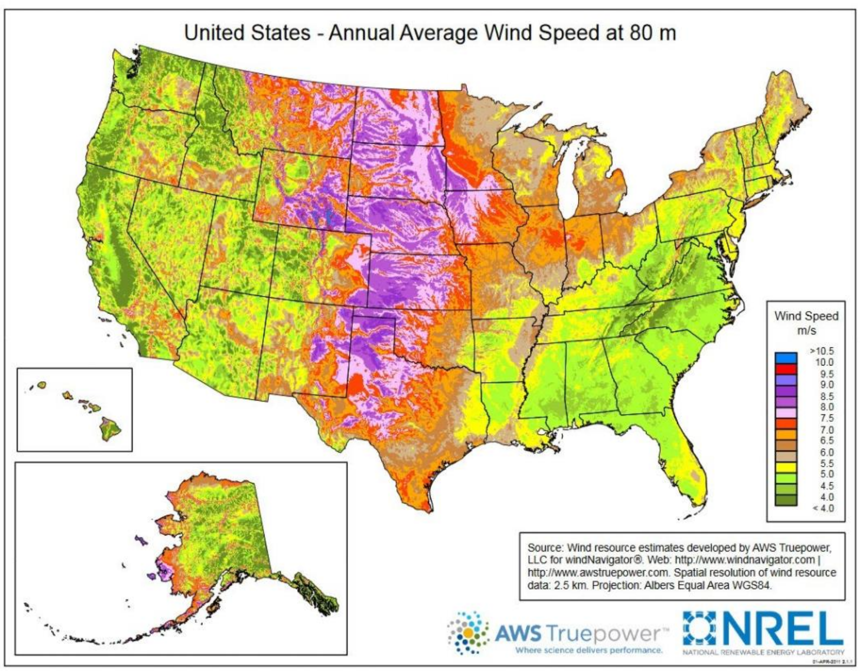
The verification and validation approach involves a direct mapping of the simulation requirements to the model, allowing for enhanced traceability. The output of the simulation model at various levels of turbine efficiency was compared to the annual energy generated at a known wind farm. Using an incremental and iterative approach with credible, real-world data, the M&S project team aimed to provide PacifiCorp with fair insight during the planning stage.

Six turbine models were evaluated across three distinct manufactures. A wind farm using the GE Wind 2.75 MW-120 maintained the lowest land utilization and the smallest number of turbines needed while meeting the targeted energy generation. This wind turbine model outperformed the competition during experimentation, and it was the clear option for PacifiCorp's proposed wind farm based on their problem statement.

2 Background

Recently, there has been a desire in the United States (US) to move the nation toward more renewable and emission free energy sources. In 2008, the US Department of Energy (DOE) evaluated the nation's energy portfolio diversity because of the growing concerns with "energy prices, supply uncertainties, and environmental impacts" [2]. To address those concerns, the US DOE modeled a scenario that would diversify the nation's energy portfolio such that 20% of the nation's electricity will be generated from wind energy. Pursuing this target would require the existing wind energy capacity to be increased from 11.6 gigawatts (GW), the total wind energy in 2006, to 305 GW. It is an ambitious growth that would require a dramatic change in the nation's electricity generation infrastructure. The US DOE estimates this scenario could be attainable by 2030 [2].

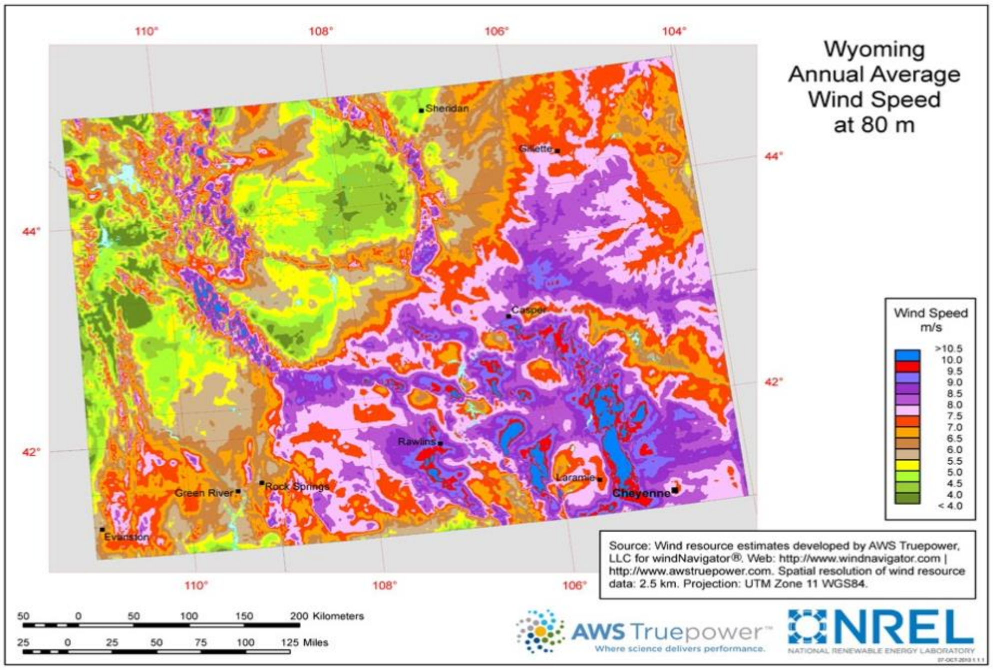
The potential to harness wind energy is greatest in the Midwest compared against other regions across the continental US. The annual average wind speeds exceed 7.5 meters per second (m/s) in the Midwest, as observed Figure 1. The color of the shading in the map illustrates the wind speeds. Green indicates lower average wind speeds while purple indicates higher average wind speeds, as shown in the legend.



[3]

Figure 1 Annual Average Wind Speeds in the US, Map

Moreover, Wyoming is an excellent candidate for wind energy generation as more than half of the state experiences wind speeds that exceed than 9.0 m/s. Figure 2 focuses on Wyoming and illustrates that much of the state is subject to high wind speeds.



[4]

Figure 2 Annual Average Wind Speeds in Wyoming, Map

Wyoming holds about 2% of U.S. proved crude oil reserves, and the state is the eighth-largest crude oil producer, accounting for just over 2% of the nation's total crude oil output. The state has five operating petroleum refineries that can process almost 169,000 barrels of crude oil per calendar day, providing one-fourth of the refining capacity in the Rocky Mountain region that includes Colorado, Montana, and Utah. Those refineries deliver most of their petroleum products to neighboring states [5]. A renewed focus on wind energy will allow the state of Wyoming to better manage its existing fossil fuel resources and invest more heavily in the manufacturing and distribution of downstream oil and gas products. Additionally, any divergence from the state’s reliance on oil and gas as a fuel source is going to help reduce the overall Green House Gas (GHG) emissions and pave the way to a “greener” tomorrow.

3 Problem Statement

The city of Casper, Wyoming has proposed the addition of six new wind farms that "could add more than 1,600 megawatts of electricity generation capacity to Wyoming's grid" [1]. The electrical utility company, PacifiCorp, has begun the process of designing these wind farms and required a M&S to help inform their design decisions.

PacifiCorp planned to establish a single wind farm at a time. If each wind farm has the same electricity generation capacity, then a single wind farm should maintain a 270 MW rating to meet the 1,600-megawatt (MW) goal.

For their first wind farm, PacifiCorp intended to use a plot of land with an area of 6 square miles. Their primary concern was to establish a 270 MW rated wind farm within the land size constraint. Land utilization was the focus rather than the cost of establishing and maintaining the single wind farm. PacifiCorp needed to determine which wind turbine model to procure, as well as the quantity required to meet the minimum energy generation requirement for the first of the six proposed wind farms in Casper.

Therefore, the problem that this M&S aimed to answer was:

What is the minimum number of wind turbines (of a particular model) required for a wind farm of 6 square miles to produce an energy output of at least 700 GWh over a year?

3.1 Systems Engineering Lifecycle Phase

This M&S project addresses the initial phase in the Systems Engineering project lifecycle – the Planning Phase (see Figure 3). PacifiCorp requested M&S services to help them select a suitable wind turbine model and determine the number of those turbines needed to produce the required energy (700 GWh) over a year within the constraint of available land size. As such, the project team aimed to support PacifiCorp by creating a model and conducting a simulation during the planning phase of the overall project (the establishment of the first of six new wind farms). The execution of this simulation exercise provided PacifiCorp with information needed to support their design decisions, especially as it relates to which turbine model and the quantities required.

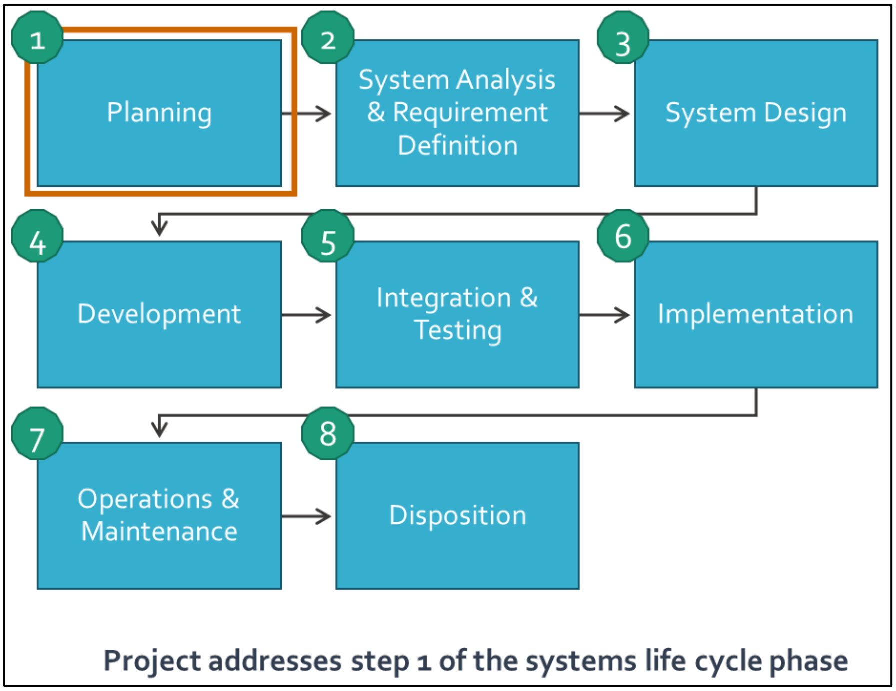


Figure 3 Systems Engineering Lifecycle Phase

4 Data Collection

The data used to drive this simulation was split into two broad categories: 1) Locational Data and 2) Technology Data. Locational Data included wind data and extreme weather data while Technology Data focused on the turbine data such as turbine technical specifications and spacing or separation. Turbine reliability data, energy storage & transmission data as well as financial data were not included in the data collection approach as this was not included in the scope of the simulation and would go beyond PacifiCorp's ask.

The team approached several Subject Matter Experts (SMEs) from GE Wind & Power, requesting their guidance on the data considerations for this endeavor. These sessions provided the team with insight into the necessary wind turbine information that needed to be incorporated for the model's fidelity.

The team made a conscious effort to utilize information hosted on US government websites, with a focus on the recency and relevancy of any potential data set. Publicly available tools like the US Wind Turbine Database [6] and Google Maps were used to measure the spacing between turbines. The result of this data collection effort is highlighted in Figure 4 illustrated below. The table below, Table 1, also outlines the data sources for the key data inputs.

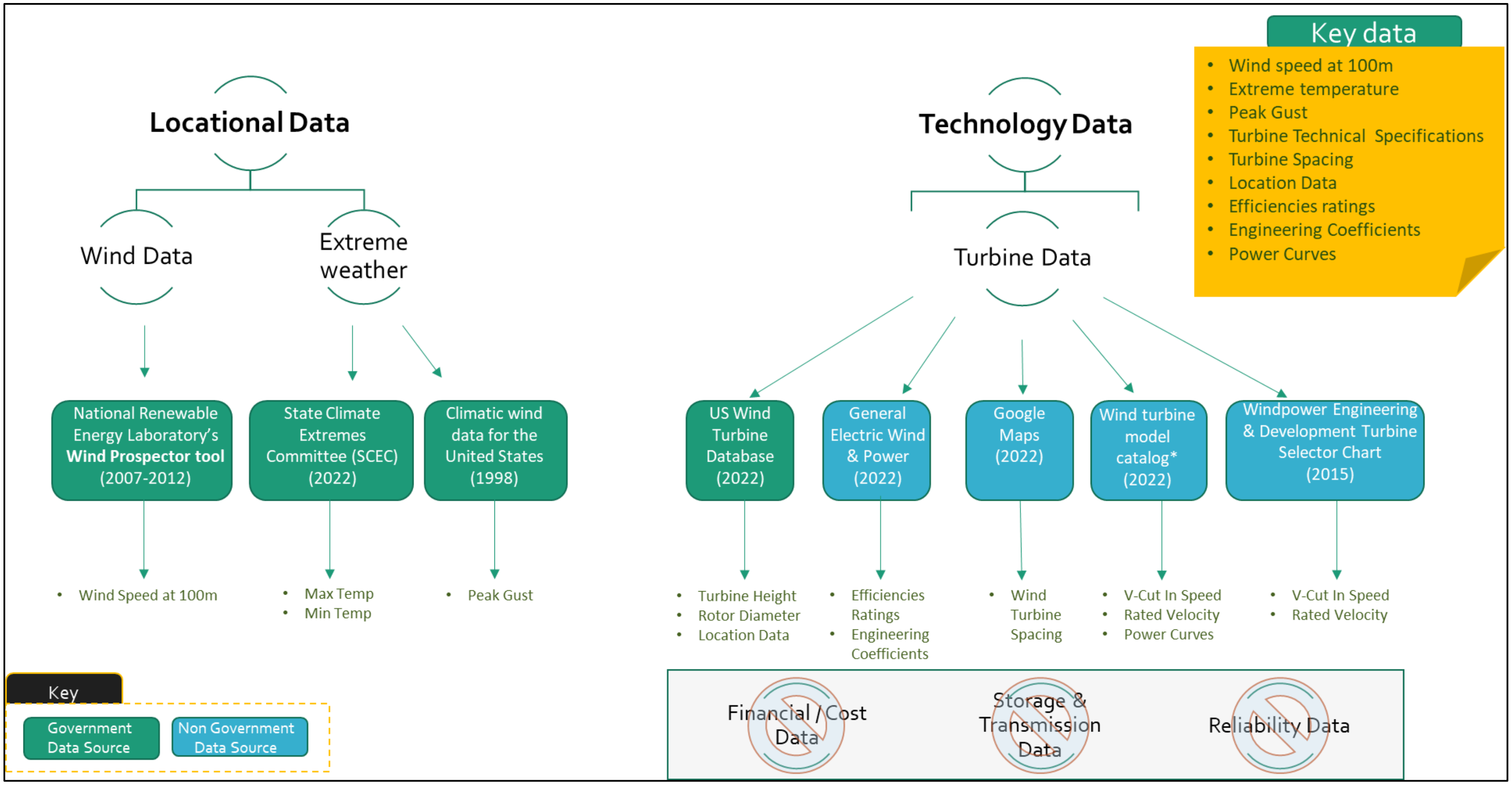


Figure 4 Data Collection Initiative

Table 1 Key Data Sources Breakdown

Resource	Key Data Provided
National Renewable Energy Laboratory's Wind Prospector Tool ***[7]***	• Wind Speed at 100m
State Climate Extremes Committee (SCEC) ***[8]***	• Max Temp • Min Temp
Climatic wind data for the United States ***[9]***	• Peak Gust
US Wind Turbine Database ***[6]***	• Turbine Height • Rotor Diameter • Location Data
General Electric Wind & Power	• Efficiencies Ratings • Engineering Coefficients
Google Maps	• Wind Turbine Spacing
Wind turbine model catalog ***[10]***	• V-Cut-In Speed • Rated Velocity • Power Curves
Windpower Engineering & Development Turbine Selector Chart ***[11]***	• V-Cut-In Speed • Rated Velocity

5 Conceptual Model

The goal of the M&S project was to develop a simulation model that can assist PacifiCorp in the selection of a wind turbine model for their proposed wind farm. The model provides feedback on the number of turbines the proposed wind farm needs to generate 700 GWh over the period of a year. The size of the proposed wind farm was constrained to a maximum area of six square miles as per PacifiCorp's requirements.

This section provides an overview of the conceptual model developed. It details the key parameters involved, scope of the simulation and major assumptions that were made during the initial stage of modelling. The M&S team adopted an iterative and incremental development approach and feedback from the proposal stage was reviewed and key considerations incorporated in the final model. The model was refined to constrain the problem further throughout the model's development.

5.1 Representations

Figure 5 provides an overview of the conceptual model developed by the M&S team for the Turbine Cluster Simulation. It includes the key input and output parameters detailed below.

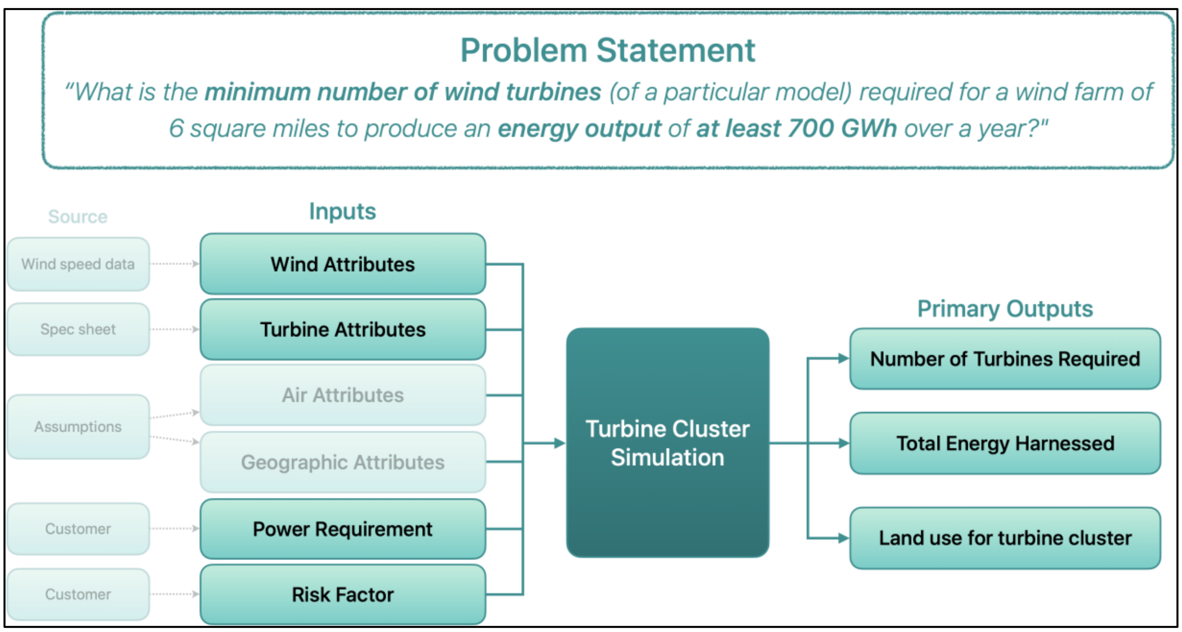


Figure 5 Iteration 1: Conceptual Model for the M&S

5.2 Key Parameters

The key parameters used for the Turbine Cluster Simulation include wind attributes, turbine attributes, air and geographic attributes, power requirements and a risk factor:

5.2.1 Inputs

- Wind Attributes: The M&S team obtained wind speed data, and this served as a key data input. The wind speed data directly impacts the energy generated by the proposed wind farm. The data was fed in from sources like the "National Renewable Energy Laboratory's Wind Prospector tool (2007-2012)" [7]. The extracted dataset provides the hourly wind speed for the city of Casper, Wyoming for the period 2007-2012. Using the granular wind speed information provided by this tool, the simulation is able to provide the number of turbines required to reach the target targeted energy output within the required land size constraint.
- Turbine Attributes: For a selected turbine model, the simulation can read in key parameters such as Rotor Diameter, Cut-in Velocity, Adjusted Rated Velocity and Efficiency. These variables are important as they feed into the wind power formula. This equation is the basis for calculating the generated energy from each turbine. The Cut-In Velocity, or $V_{cut\text{-}in}$, is the speed at which the turbine starts generating electricity from turning the turbine blades. The Adjusted Rated Velocity is the speed at which the motor will first produce its maximum power output.
- Air Attributes: The primary air attributes are temperature and density. These parameters are critical inputs for the power generation formula. Considering the complexity of the simulation, the M&S project team decided to retain constant values for these parameters during this phase of the M&S project.
- Geographic Attributes: PacifiCorp has allocated a location for this project and so geographic attributes that affect wind speed, like altitude and proximity to hills, etc. have been pre-determined.
- Power Requirement: This is considered an input into the model. A goal of the project was to meet a minimum power that can fulfill PacifiCorp's energy output requirement. Thus, this requirement enables the M&S team to treat power as a constant associated with targeted energy generation capacity.
- Risk Factor: This factor brings into consideration a risk tolerance to the energy production that can be utilized in the event that some of the turbines are undergoing scheduled maintenance or repair downtime.
- Additional factors like maintenance duration and its impact to the overall power generation, turbine separation distance, net installation space, etc. have also been included as design considerations. These considerations helped improve the fidelity of the model and makes for more a realistic output.

5.2.2 Outputs

- Number of Turbines: This represents the minimum number of wind turbines that are needed to produce the required energy.
- Total Energy Output: This is the net energy generated by the total number of wind turbines in the wind farm over the single year.
- Land Used by Turbine Cluster Simulation: This represents the land utilized by the proposed wind farm over the six square mile land plot.

This output of the simulation allows PacifiCorp to make a reasonable choice in the selection of a wind turbine model for their proposed wind farm.

5.2.3 Assumptions

Some of the key assumptions that are incorporated into the model are highlighted in Table 2 below.

Table 2 Summary of Major Parameters for Model

Key Inputs	Assumption List	
	Constants	Variables
Wind Attributes	Direction	Speed *(varied by time of year selected)*
Turbine Attributes	Down Time, Hub Height	Turbine *(Rotor Diameter, Cut-in Wind Speed, Efficiency, Rated Velocity)*
Air Attributes	Temperature, Density *(20°C @1 atm = 1.204kg/m^3)*	-
Geographic Attributes	Location, Elevation, Land Plot Size	-
Wind Farm Power Rating	270 MW	-

- To constrain the model reasonably, a number of parameters were assumed as constant in this simulation. This includes *wind direction*, *air temperature* and *density*, *location,* and *elevation.*
- Other turbine parameters like blade angle, blade design, material and weight considerations are be assumed to be of negligible impact to this simulation.

- Land plot size is fixed and was the primary constraint over cost.
- The topography of the location of the wind farm was considered a flat land. This is a crucial assumption since wind turbine selections are based on terrain, which impacts the wind (proximity to mountains, upwind or down-wind turbines, etc.) For the scope of this project, the design of the wind turbines was limited to horizontal-axis wind turbine (HAWT).
- Energy transmission, consumption and storage are not considered for the purposes of this simulation.
- The overall efficiency of a turbine was considered the same for all turbine models regardless of manufacturer.
- Turbine spacing or separation was defined by a separation factor applied across all turbine models regardless of manufacturer.
- The dataset of wind speed data provided hourly wind data and as such wind speed was assumed to be constant in an hour.

6 Verification & Validation

6.1 Verification Plan

The verification plan included two steps. The M&S team intended to examine whether they built the model right. First, the simulation was verified by ensuring that traceability exists between the requirements and the conceptual model. Secondly, the results of the M&S were verified against real-world data at a selected wind farm.

6.2 Validation Plan

The M&S team's plan for validation is also two-fold. Validation of the conceptual model was achieved by using the requirements that were defined. The simulation was validated by cross referencing it with the conceptual model and the initial requirements.

The model was built referencing an existing wind farm in Casper, WY whose specifications were already established. There is data available as it relates to the power the existing wind farm generated [12]. This data will be used to verify the results of the M&S. Given that the M&S team have considered some parameters (e.g. air density) constants, the results will not be exactly equal, but the goal was to make them as close as possible to the real world. This would support the validity of the model and adds to the reliability of results from experimentation.

6.3 Verification and Validation Execution

The verification and validation plan for our M&S project was be performed iteratively after each phase of the M&S project was completed. Verification and validation processes were conducted throughout the stages of the wind turbine M&S project lifecycle.

The verification and validation plan first began with the M&S team choosing an area of interest in power generation sector, from which a problem idea in renewable energy was derived. The team then developed the problem idea into a refined problem statement. It was pertinent that the team verify the chosen problem statement was realistic and logical. To achieve this, we sought the advice and expertise of Systems Engineering mentors. With their help, the M&S team established a problem statement that was clear and concise. After several iterations, the problem statement was refined such that it addressed the issue at hand without any signs of ambiguity.

A list of systems requirements (see Appendix A: Requirements Definition) was developed to create a framework for the logic of the model. These requirements were verified against the primary objective of the M&S project to ensure synchronization with the problem statement. The M&S team wanted to ensure that the requirements did not capture an out-of-scope item.

In the next phase of the verification and validation process, the team produced a conceptual model, which considers incoming wind speed data along with some turbine parameters as key input (independent) variables. Output (dependent) variables comprise of output energy (in GWh), the number of wind turbines needed for the energy output requirement, and the amount of land (square miles) needed for that suggested number of wind turbines. The documentation of the model was verified by continually vetting it against the system requirements to ensure there was a smooth flow from the latter to the former.

With a conceptual model established, the M&S team began to transform the conceptual model into a simulation model. The tool utilized was MATLAB software program. Verification of the code and its intended purpose was performed by checking to see whether the logic of the model was consistent with the documented behavior of the conceptual model.

To further validate the simulation model, information regarding the energy output for wind turbines at the Casper Wind Farm project was utilized [12]. It contains energy generation data for 2009 through 2012 and details the total energy output for 11 units of the GE 1.5MW-77 turbine models. A GIS locator was dropped in the Wind Prospector tool [7] on top of a point where there is currently a turbine as seen in U.S. Wind Turbine Database [6].

The assumption here is that for the sake of the simulation exercise, the 11 turbines were operating without any downtime. As such, the simulation model was set to compute energy output for 11 units based on the data profile for GE 1.5 MW-77, and the results compared to the real-world numbers. Based on the GE SME input, the efficiency of wind turbines ranges from 40% to 50%. Therefore, simulation runs were performed at 40%, 45%, and 50% efficiency ratings, as shown in Figure 6., so the best efficiency for experimentation could be identified.

With a simulation model in place, the experimentation phase was the next and final phase of the Verification and Validation cycle. The simulation results for different turbine models were captured on a graphical output window display for easy readability to the end user. The results were evaluated to understand whether the requirements of the problem statement had been addressed. This model validation step provided some assurance that the results of the simulation model achieved give a reasonable answer to the problem statement in its entirety.

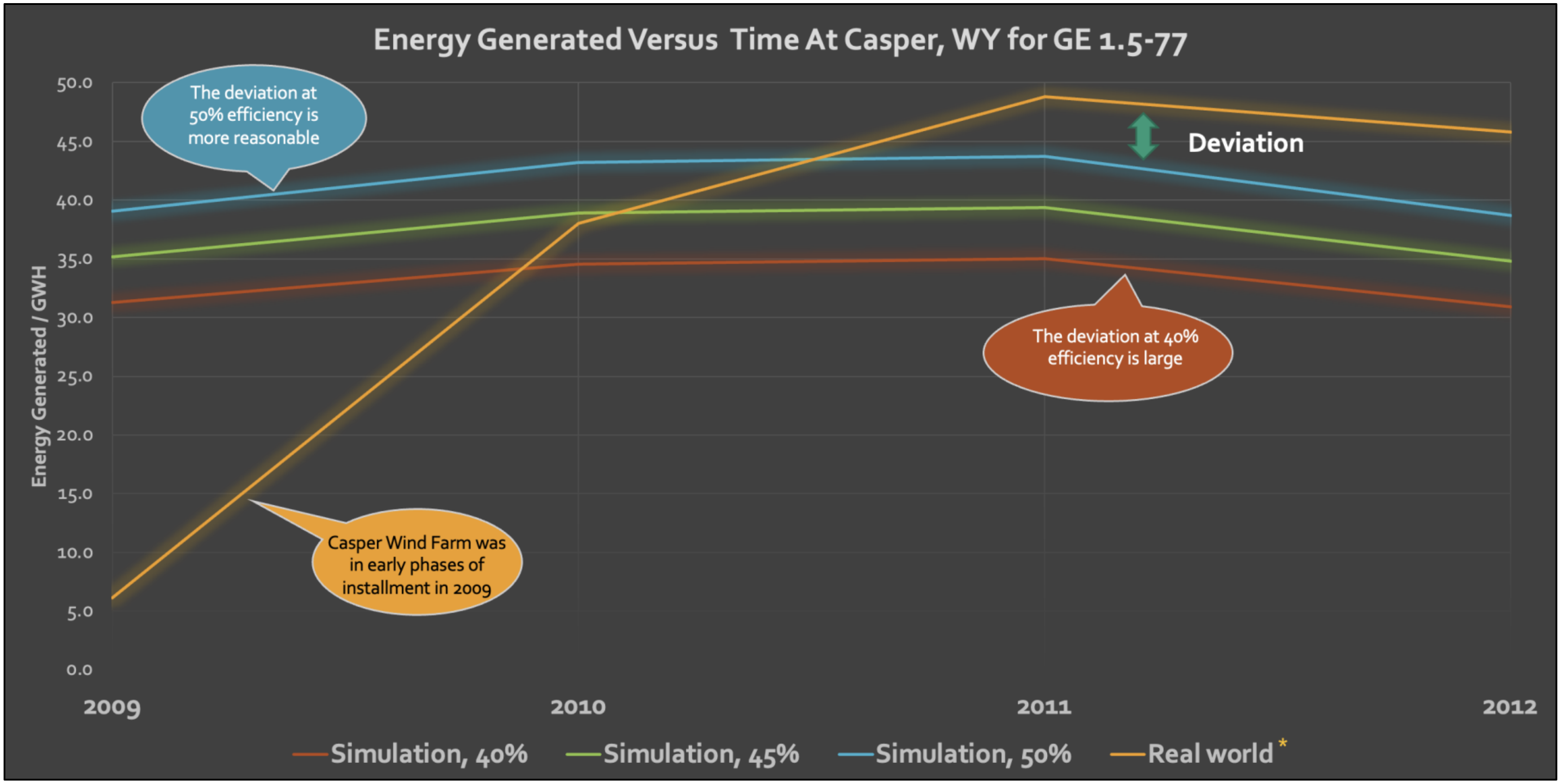


Figure 6 Validation Results Plot, Energy Generation - Casper Wind Farm vs Simulation

In Figure 6, the orange plot represents the real-world data from the Casper Wind Farm. The steep dip in 2009 and the lower value in 2010 is expected because the Casper Wind Farm began installation in 2009 and did not complete until mid-2010. Hence, these two points are considered outliers. The efficiency rating at 50% for the simulation model showed the least deviation relative to the real-world plot and thus, provides a reasonable estimation of the real-world system.

7 Simulation Implementation

The M&S team considered using several tools to build this model, ranging from Python to AnyLogic to MATLAB. None of the team members had pre-existing knowledge of the Java programming language and consequently decided against using AnyLogic. This was also because the application in this project also needed more of a computational model rather than a behavioral model for which AnyLogic would have been more suited. When choosing between Python and MATLAB, it was determined that there were more verified learning resources for MATLAB than Python, which is an open-source tool. As such MATLAB was selected to develop the computerized model.

The MATLAB model was made entirely from scratch and was customized so the M&S team could effectively answer the problem statement. The level of customization was one of the perks of creating the model with a programming language rather than an out of the box tool. This choice also aided in faster execution of experiments as the experiment results could also be configured to illustrate vital information at a glance. Another advantage of using MATLAB was the ability to use the GitHub online repository and version control. This tool allowed the team to work on different sections of the model in tandem without causing much friction during consolidation.

7.1 Scope of the Simulation

As stated previously, the key output from the simulation includes the number of turbines, total output energy and land utilization. This addresses the problem statement directly by suggesting the number of turbines needed for a specified turbine model within the land size constraint. This simulation considers data over a period of a year. The cost factor is not considered to be the focus of this simulation but rather, land utilization. The major design constraint for the model is Land Plot size (as defined by PacifiCorp in the problem statement).

7.2 Turbine Cluster Simulation

Figure 7 below captures a deeper look at the conceptual model previously discussed. The listed parameters and design constraints were incorporated into the model using the MATLAB code. A simulation development plan was first created with white-board discussions to understand the key parameters that fed into the simulation and its internal operation (computation). This was then fed into the mathematical model which is described below. Next, the computational model was created on MATLAB (which is described in more detail in the Simulation Implementation section of this report.

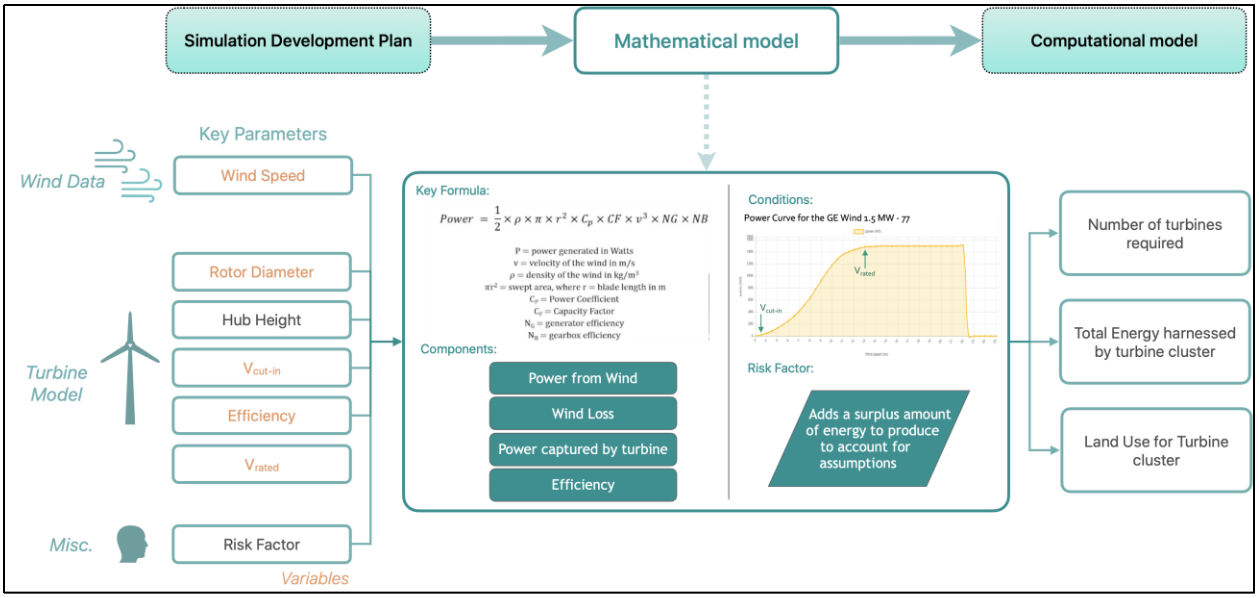


Figure 7 Iteration 1: Mathematical Model of the Simulation

The simulation leverages the wind power equation, from which the energy generated in a single year can be ascertained. The flow of the data analysis involves calculating the available power in the wind and then converting that into the actual power harnessed by the turbine. The simulation also incorporates Cut-in Velocity ($V_{cut\text{-}in}$) and Adjusted Rated Velocity (V_{rated}). Wind speeds below $V_{cut\text{-}in}$ will not allow the turbine to generate any energy. Both values were determined from the power curve for the respective turbine models [10].

The power of the wind is understood to be directly proportional to density, swept area (determined from the rotor diameter), and wind speed. Once net power is calculated, the energy generated in Gigawatt Hours (GWh) over a single year can be deduced. The output is used to determine the number of turbines needed to meet the target energy generation capacity set by PacifiCorp.

The efficiency for the respective wind turbine models was not provided in any technical specification documentation, as this value is largely dependent on the turbine and its surrounding environment. Consequently, the M&S team consulted with GE wind turbine SMEs to understand what factors go into the efficiency rating of a wind turbine. The SMEs highlighted the Betz' law which states that you can convert a maximum of 16/27 (or 59%) of the kinetic energy in the wind to mechanical energy using a wind turbine. Further to this, there are turbine efficiency losses associated with converting mechanical energy to electrical energy. The SMEs were able to provide an overall range for turbine efficiency of 40% to 50%. The M&S team used the validation approach to determine the most appropriate efficiency value. Since the three selected turbine manufactures produce products which are comparable, the M&S team chose to use the same overall efficiency factor across all turbines, irrespective of manufacturer, during simulation runs.

One of PacifiCorp's requirements is that the proposed wind farm should not exceed 6 square miles. An important consideration that the M&S team included was the separation between wind turbines. The M&S team accounted for this by incorporating a turbine spacing factor that could be applied across all turbine models regardless of manufacturer. Pre-existing windfarms were selected from the US Wind Turbine Database [6] based on the three selected turbine manufacturers. Two adjacent wind turbines were selected from randomly chosen wind farms. The average separation distance between adjacent turbines was measured using Google Maps. This procedure was reperformed for different Wind Turbines models across the three main turbine manufacturers. The average spacing for each wind turbine model was calculated and this average was used to create the turbine spacing factor. The spacing factor is the ratio of the average distance between two turbines (of the same model and manufacturer) divided by the rotor diameter of said turbine. An average of all spacing factors was collated, and the M&S team rounded this figure up to the nearest integer value. The spacing factor was determined to be three times the rotor diameter of any turbine selected. Refer to Appendix C: Turbine Spacing Factor Calculations for the calculations performed.

8 Simulation Model/Simulation Program

As described earlier, the platform used to simulate this model was MATLAB. The computational model that was generated based on the conceptual model and the mathematical model is further elaborated on in this section.

The figure below, Figure 8**,** is a flowchart showing the overall operation of the code. This logic flow was used to create a custom MATLAB code from scratch, which is available in Appendix E: MATLAB Code**.**

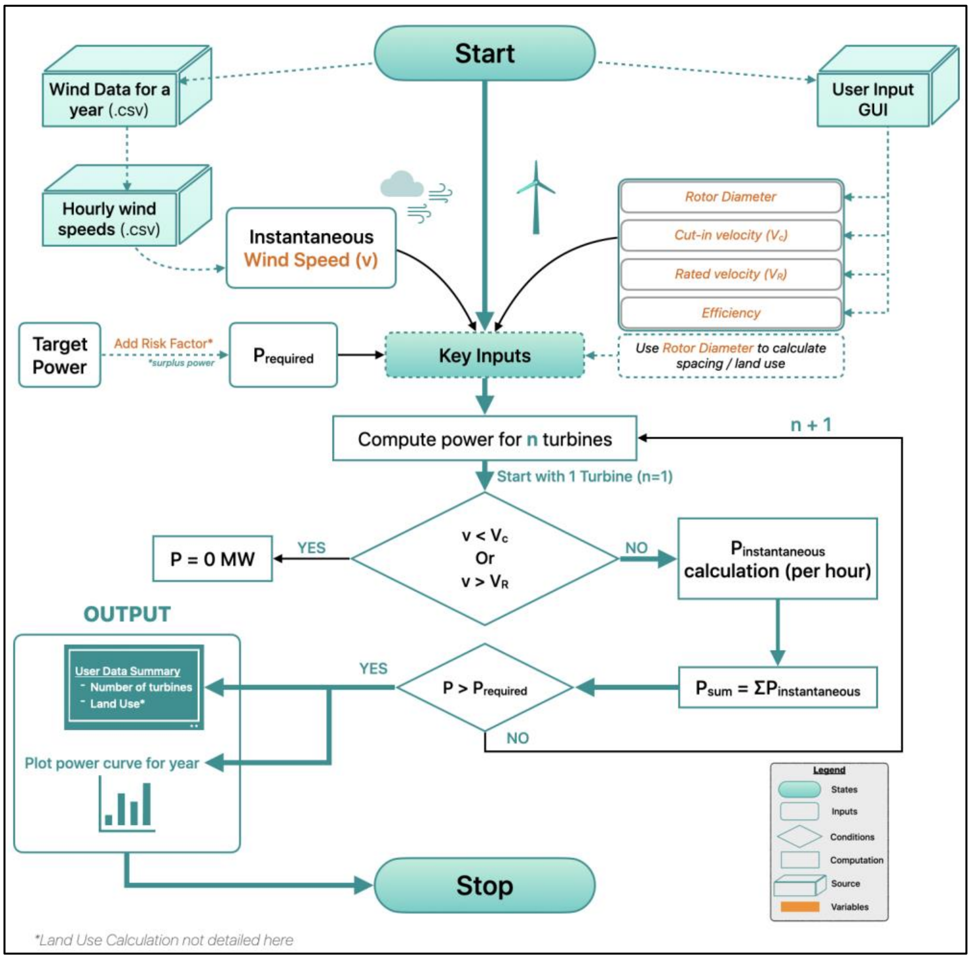


Figure 8 Simulation Computational Model

From the flowchart, note that the primary operation of the code is to gather the three major inputs before the computation process begins.

Input 1 – Wind Speed: Wind speed for this location was captured and discretized from government sources. The final file that is input into the model contains hourly wind speed information for an entire year. In this code, the file that is input is for the year 2012 but swapping the file input name in the code can enable testing with other years (2007-2012) for which the data was collected and sanitized for use in the simulation.

Input 2 – Power Required: The target energy output from the problem statement is the power required from the recommended wind farm computed within simulation. However, a factor 'risk factor' is added to the Power requirement to account for assumptions made and other variability that is not considered. This way, having the risk factor changes the 'target power' to a 'required power' value that is higher (which equates to a higher energy requirement for the simulation to attain). This in turn increases the recommended number of turbines to the customer (like a design 'safety factor').

Input 3 – Graphical User Interface: User enters turbine information into this Graphical User Interface (GUI) and this gets pulled into the simulation. The rotor diameter value is also critical to perform land use calculations and area coverage for the plot size. Land use for each turbine is measured as the space the turbine requires, in addition to the distance/spacing for each turbine (further detailed later in this section).

Once the key inputs are received the power calculation begins starting with 1 turbine. The simulation calculates the power using the formula for each hour using the input parameters (wind speed, turbine parameters and power). The computation is done for the entire year and at each hour the power value is stored into an array. Once the power computation is complete, the true power that is generated by this turbine is compared to the required power. If the required power is reached, the simulation exits and stores 1 as the number of turbines. Else, the simulation increases the number of turbines and now computes for 2 and so on, until the required power is reached.

Within the simulation, there are conditions that change the state of the wind turbines. There is a window in which the turbine produces power, and this is determined by the Cut-in Velocity (minimum speed needed to produce power) and the Adjusted Rated Velocity (speed at which the maximum power is generated). The simulation considers that for any wind speeds outside this range, there will not be any energy generation. That is, if the instantaneous wind speed data is less than Cut-in Velocity or greater than Adjusted Rated Velocity, the power calculation equals 0. This logic is embedded in the computational model for power calculation. The values are then converted to energy in alignment with the customer requirement.

The working of the land use calculations is excluded in this main process flow diagram, but Figure 9 below shows the flowchart used.

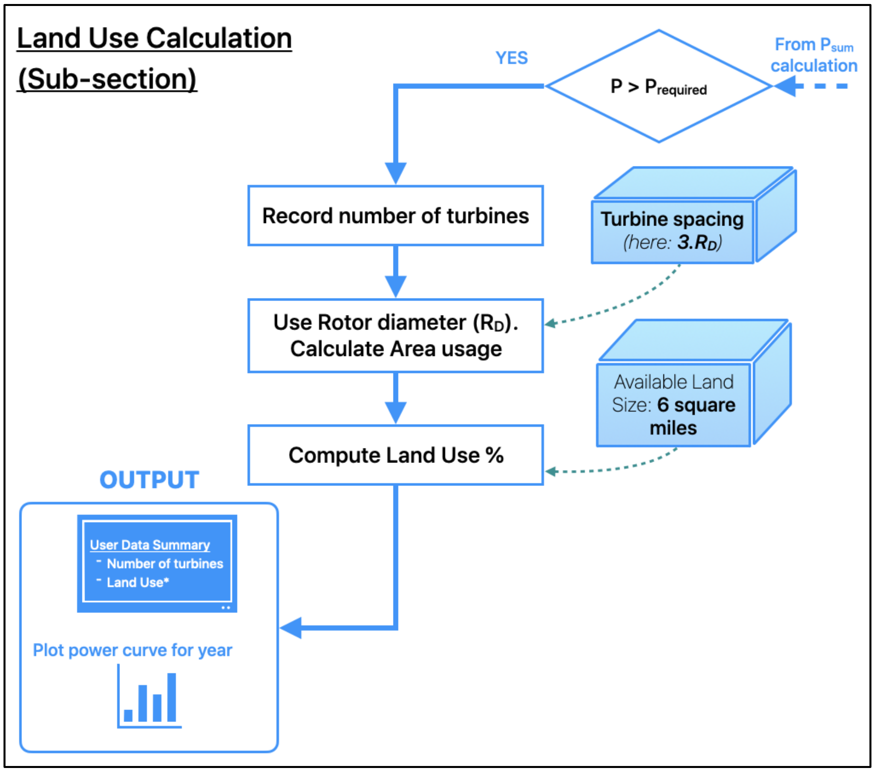


Figure 9 Simulation Computational Model, Land Use Calculation

As mentioned earlier, the land use for each turbine is measured as the space the turbine requires, in addition to the distance/spacing for each turbine. Once the number of turbines is determined from the power computation section of the simulation, the value is recorded, and the land use computation is completed. This is then compared to the overall plot size (6 square miles) to provide a percentage usage of the land to the user which is also displayed in the output window. The guidelines here for the percentage usage helps with laying out the turbines in the plot.

The operation of the code is highlighted in this section. On running the code, the user is presented with the GUI into which information is input. The simulation then runs to produce the final outputs, the primary one being the User Data Summary table as shown in Figure 13 and the plot that provides additional information on the spread of power in a year.

8.1 Code Operation (Sample)

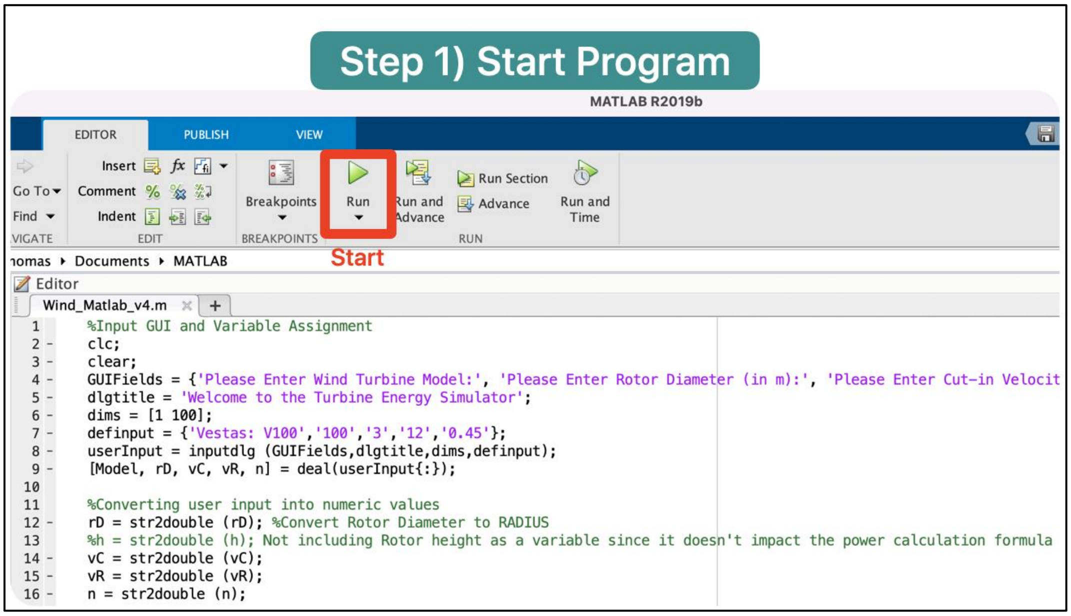


Figure 10 Code Operation, Step 1) Start Program

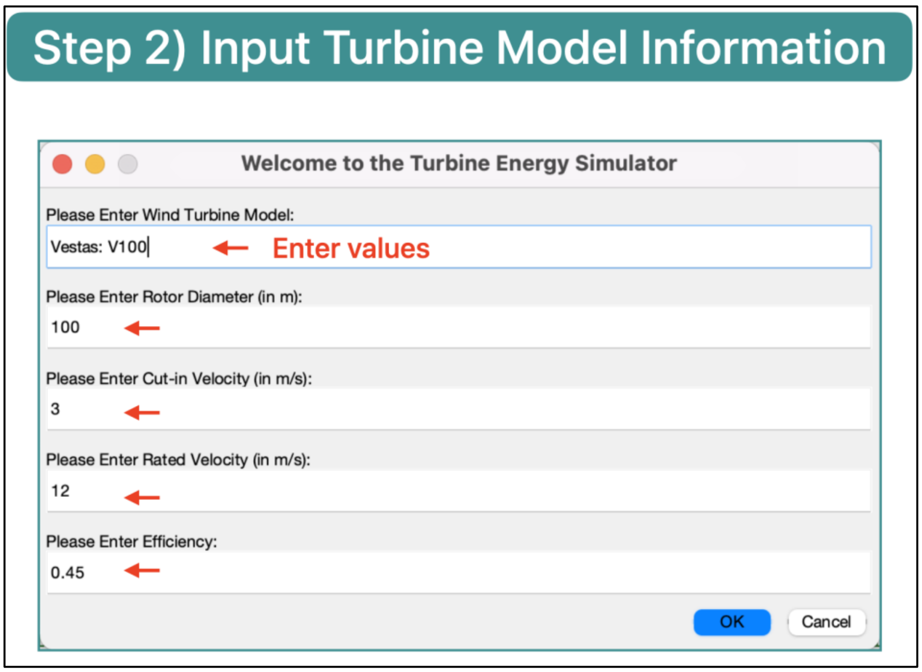


Figure 11 Code Operation, Step 2) Input Turbine Model Information

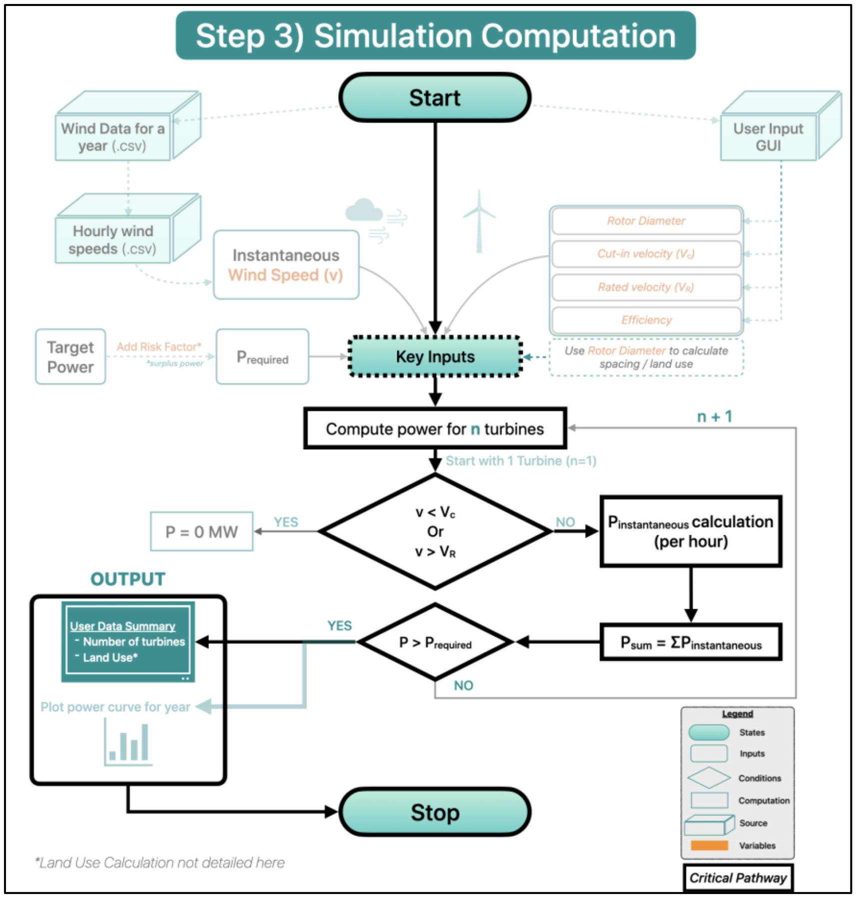


Figure 12 Code Operation, Step 3) Simulation Computation

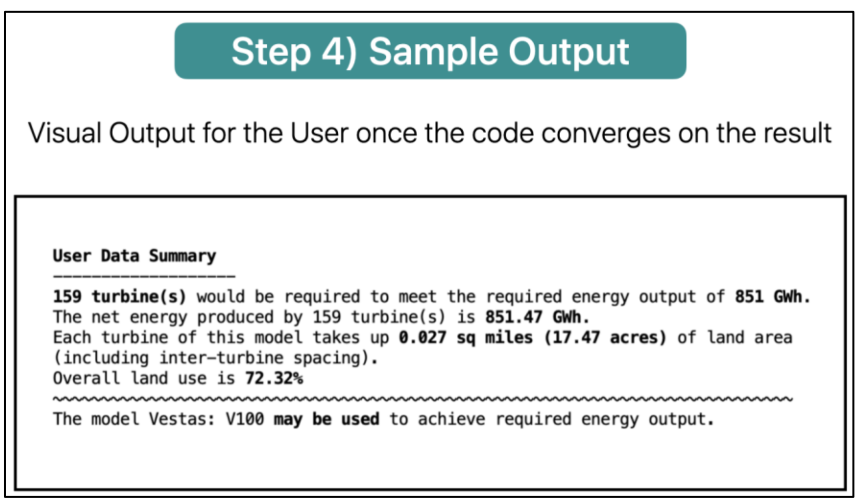


Figure 13 Code Operation, Step 4) Sample Output

Output Summary Message: Once the simulation is complete, the user data summary (see Figure 13) captures the results of the simulation that helps the user make an overall decision on the turbine model to be selected.

Output Power Plot: This plot, Figure 14, shows the power distribution for the entire duration (12 months). This wind data shows a more similar spread (on the plot, at this scale) however if there are significant wind speed variations (e.g., between summer and winter months), this power plot would show more of the spread or distribution from which the point-by-point power values may be inferred.

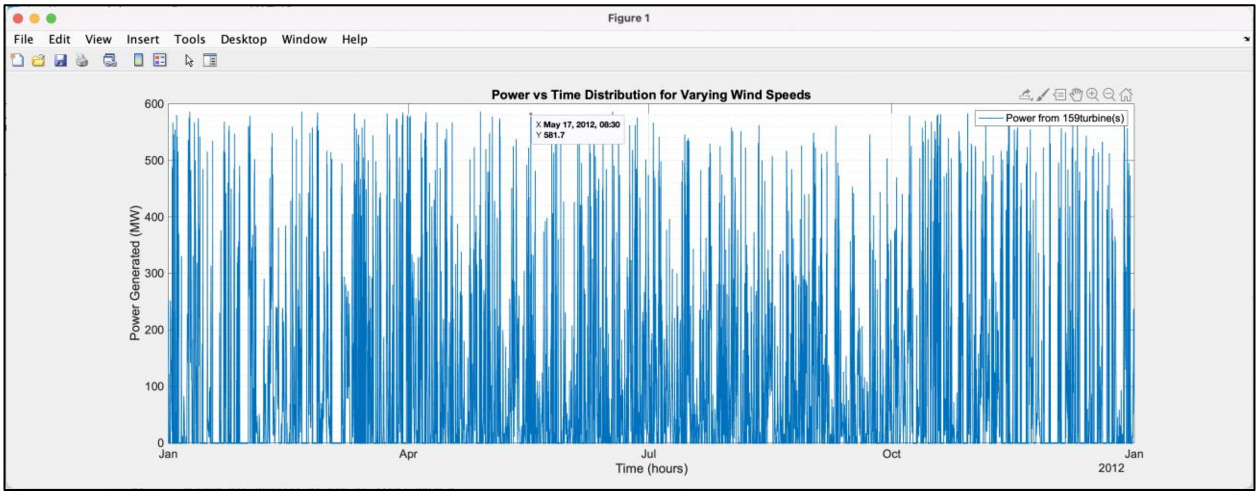


Figure 14 Simulation Model Output Power Plot

8.2 Comment on Fidelity

Energy production in real-life may vary due to several factors such as turbine spacing, terrain, wind directions, etc. These considerations do impact the simulation fidelity. Assuming constant wind direction, unchanging wind in an hour and turbine efficiencies as constants (as opposed to ranges) are some other domains that can be further developed to improve the fidelity of the model. The use of a risk factor also impacts the cost (with the larger number of turbines). Factors like downtime, maintenance period, etc. are also items that would be covered with this risk factor variable. Cost was out of scope of our simulation due to the limited access to the price point for the wind turbine but should be included to further the realism of the simulation for a real in-field application.

9 Presentation

The details of the operation of the code have been discussed in the previous section, Simulation Model/Simulation Program. The key presentation elements within the code are:

- A **graphical user interface (GUI)** to elicit user information on turbine parameters.
- Comma separated data files **(.csv files)** that were prepared based on code input means to provide hourly wind information.
- An **output (summary) window**: To summarize results in an easy-to-digest manner for the customer. This is provided in the Command Window of the MATLAB code.
- The **output plot** (supplemental) for capturing the spread of power in a year.

The goal of the simulation is to provide a recommendation to the user regarding the number of turbines needed to generate the required energy in the specified plot size. Since PacifiCorp is in their planning phase, the simulation generates a data summary that contains the necessary snapshots of information. This generated output provides information that addresses the problem statement and delivers on the PacifiCorp requirements.

One way the model could be expanded would be to include more visualization, graphically representing the layout of the wind turbines in the plot. In its current form, the system generates a visual readout with a direct answer to the problem statement. This output was easier to generate than a graphical layout, but a greater amount of simulation visualization would make the model more interactive. There are sections of the code (Appendix E: MATLAB Code) that have been commented out, that captured some additional plotting techniques that were removed in the final revision of this simulation.

10 Experiments

A series of six experiments were performed to analyze different turbine models using the model. The results of the analysis provide a comparison of the quantity of turbines that PacifiCorp needs to meet the targeted energy generation capacity outlined in the problem statement. For each experiment, six data points were generated by evaluating each wind turbine model against six different years of wind data. In this way, the energy output of the experiments was validated across more wind speed plots. Therefore, the recommendation that we offer PacifiCorp is further reinforced.

Each experiment evaluates the effectiveness of a specific wind turbine model in a 6 square mile plot of land by changing only a single variable in each experiment – the wind turbine model. While the user does enter multiple inputs in the GUI (see Figure 13), they are all turbine specific attributes of the selected wind turbine model being experimented. Thus, there is only one independent variable, which is turbine model type.

The criteria for selecting wind turbines for experimentation was two-fold. Firstly, the M&S team wanted to focus on the top three wind turbine manufacturers in the industry in the United States (see Figure 15) [13]. Because these wind turbines are more prevalent in the market, there is a greater availability for knowledgeable operators with technical experience for these turbine types as well as a greater availability of spare parts. Factors such as these would impact PacifiCorp's selection of turbine manufacturer. Moreover, because of the competitive nature of the wind turbine industry, much of the information needed for the simulation was not publicly available. To that end, the secondary selection criteria was availability of turbine data, specifically any associated power curves (see Appendix D: Power Curves for Wind Turbine Models) [10]. As mentioned previously, the power curves were used to gather both the $V_{\text{cut-in}}$ and Adjusted Rated Velocity for the respective models.

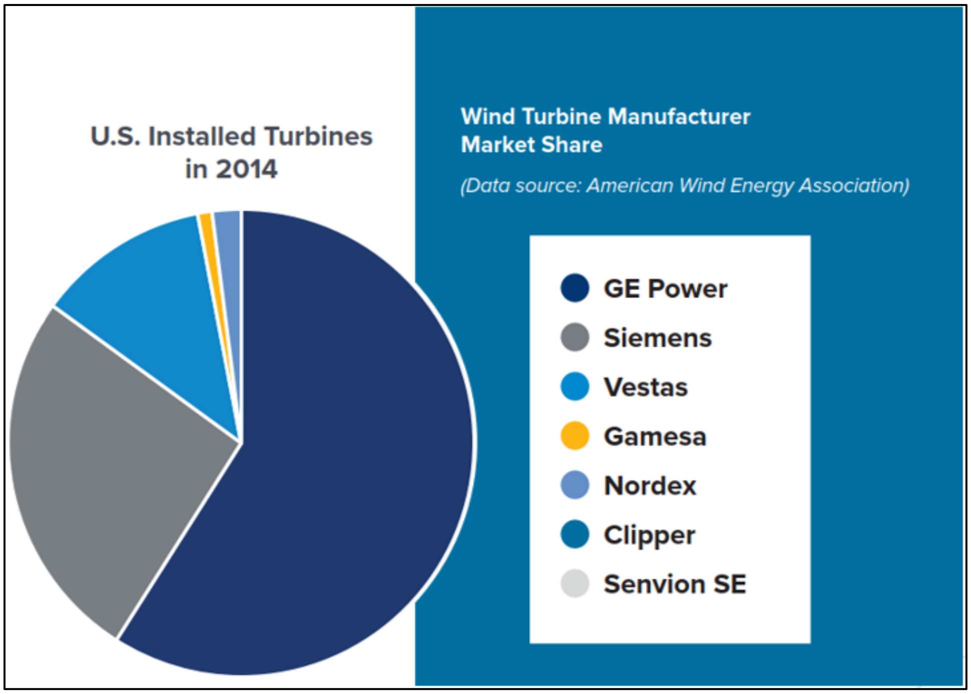


Figure 15 U.S. Wind Turbine Market Share, 2014 [13]

By changing just one variable, the wind turbine model, The M&S team can evaluate the energy output that is generated from multiple wind turbines of a single model. Thus, the M&S team can provide PacifiCorp with a recommendation of the best product available in the market for the area of Casper. In the subsections that follow, the wind turbine models that are being experimented with are described.

10.1 Experiment 1: GE Wind 1.5 MW-77

The GE Wind 1.5 MW-77 wind turbine model has the following turbine parameters:

- Rotor Diameter = 77.0 m
- Cut-In Velocity = 3.5 m/s
- Rated Velocity = 12.0 m/s

10.2 Experiment 2: GE Wind 2.75 MW-120

The GE Wind 2.75 MW-120 wind turbine model has the following turbine parameters:

- Rotor Diameter = 120.0 m
- Cut-In Velocity = 3.0 m/s
- Rated Velocity = 13.0 m/s

10.3 Experiment 3: Vestas V100-1.8

The Vestas V100-1.8 wind turbine model has the following turbine parameters:

- Rotor Diameter = 100.0 m
- Cut-In Velocity = 3.0 m/s
- Rated Velocity = 12.0 m/s

10.4 Experiment 4: Vestas V136-3.45

The Vestas V136-3.45 wind turbine model has the following turbine parameters:

- Rotor Diameter = 136.0 m
- Cut-In Velocity = 3.0 m/s
- Rated Velocity = 10.5 m/s

10.5 Experiment 5: Siemens Gamesa G97-2 MW

The Siemens Gamesa G97-2 MW wind turbine model has the following turbine parameters:

- Rotor Diameter = 97.0 m
- Cut-In Velocity = 3.0 m/s
- Rated Velocity = 11.0 m/s

10.6 Experiment 6: Siemens Gamesa G126-2.5 MW

The Siemens Gamesa G126-2.5 MW wind turbine model has the following turbine parameters:

- Rotor Diameter = 126.0 m
- Cut-In Velocity = 2.0 m/s
- Rated Velocity = 10.0 m/s

11 Results and Conclusions

11.1 Results

The results were provided in the “User Data Summary” (see Figure 11) in MATLAB’s Output Window. The User Data Summary identifies two pieces of information for each experiment: 1) the minimum number of wind turbines required to meet the energy output requirement (700 GWh) and 2) the land usage required for the minimum number of wind turbines. The results of all 6 experiments are summarized in and Table 4. The results are also shown in a two-dimensional plot in Figure 16 and Figure 17.

From Table 3 and Figure 16, we can make the following observations:

- The GE Wind 2.75 MW-120 model requires the least number of wind turbines during every year that was evaluated, resulting in an overall average of 73 wind turbines.

- The GE Wind 1.5 MW-77 model requires the greater number of wind turbines during every year that was evaluated, resulting in overall an average of 228 wind turbines. The difference of minimum number of turbines of GE models is expected because the GE Wind 1.5 MW-77 model is rated for less power and it would need to increase its quantity to make up for the smaller rating.

- The following models shown to best withstand the wind variations from year-to-year and maintained a relatively equal minimum number of turbines for the same energy output requirement: GE Wind 2.75 MW-120, Vestas V136, Siemens Gamesa G126-2.5 MW.

From Table 4 and Figure 17, we can make the following observations:

- The GE Wind 2.75 MW-120 model requires the least amount of land to accommodate the minimum number of wind turbines at approximately 3 square miles.
- The Vestas V136 model would require the entire plot of land that is available to accommodate the minimum number of wind turbines at just under 6 square miles. This option provides little room for scalability.
- The Siemens Gamesa G126-2.5 MW model would require more than the available 6 square miles to accommodate the minimum number of wind turbines at just under 7 square miles. Therefore, this would not be a viable option for PacifiCorp.

Table 3 Experimentation Results Summary, Minimum Number of Wind Turbines

Minimum Number of Wind Turbines						
Experiment No. & Wind Turbine Model	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
1. GE Wind 1.5 MW-77	231	217	240	217	215	243
2. GE Wind 2.75 MW-120	74	70	77	72	68	77
3. Vestas V100-1.8	137	128	142	129	127	144
4. Vestas V136-3.45	114	113	116	107	108	116
5. Siemens Gamesa G97-2 MW	192	185	194	179	177	198
6. Siemens Gamesa G126-2.5 MW	156	154	156	147	149	156

Table 4 Experimentation Results Summary, Land Usage

Land Usage for Minimum Number of Wind Turbines (sq. mi.)						
Experiment No. & Wind Turbine Model	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
1. GE Wind 1.5 MW-77	3.7	3.5	3.9	3.5	3.5	3.9
2. GE Wind 2.75 MW-120	2.9	2.8	3.0	2.8	2.7	3.0
3. Vestas V100-1.8	3.7	3.5	3.9	3.5	3.5	3.9
4. Vestas V136-3.45	5.8	5.7	5.9	5.4	5.5	5.9
5. Siemens Gamesa G97-2 MW	4.9	4.8	5.0	4.6	4.5	5.1
6. Siemens Gamesa G126-2.5 MW	6.8	6.7	6.8	6.4	6.5	6.8

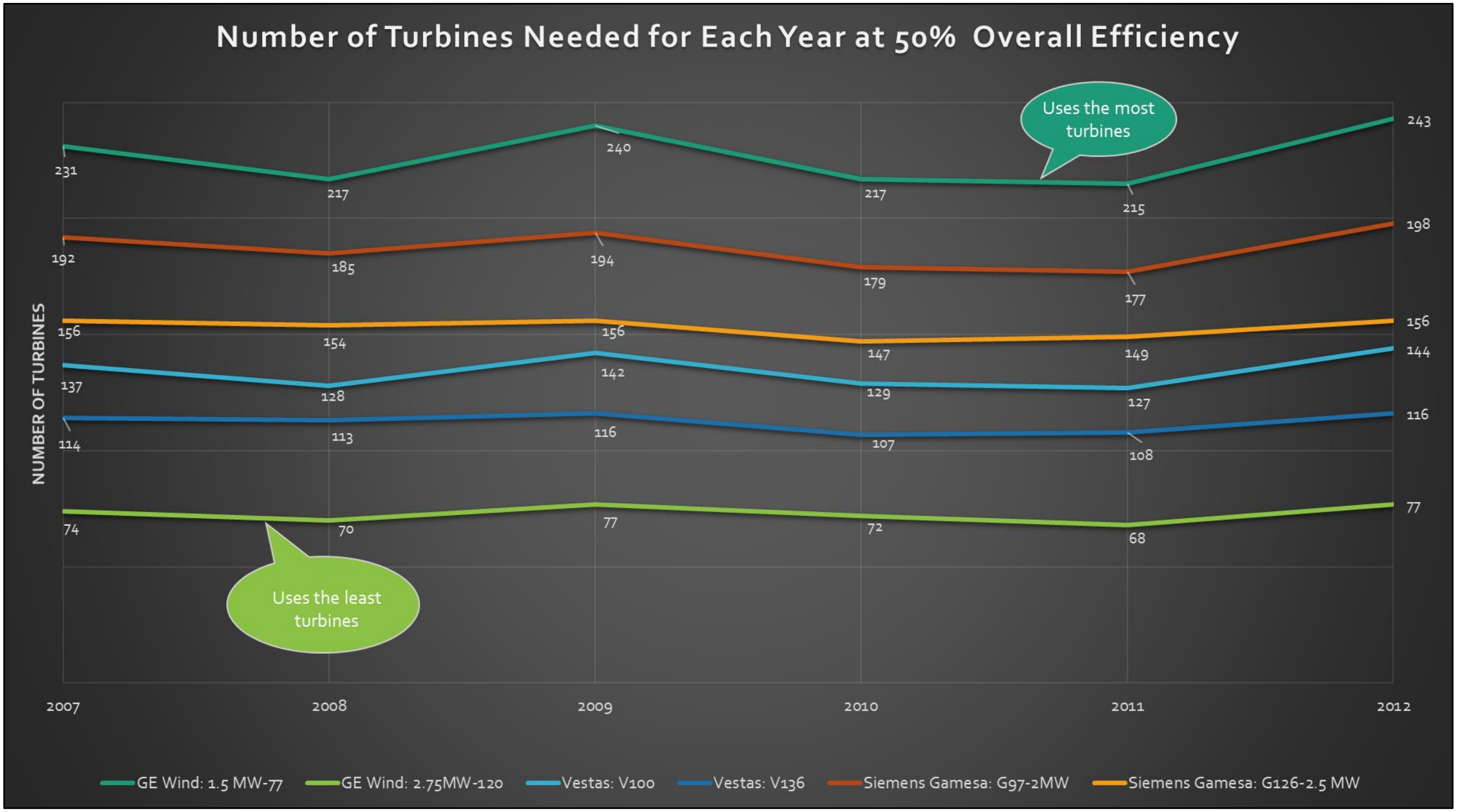


Figure 16 Experimentation Results Plot, Minimum Number of Turbines

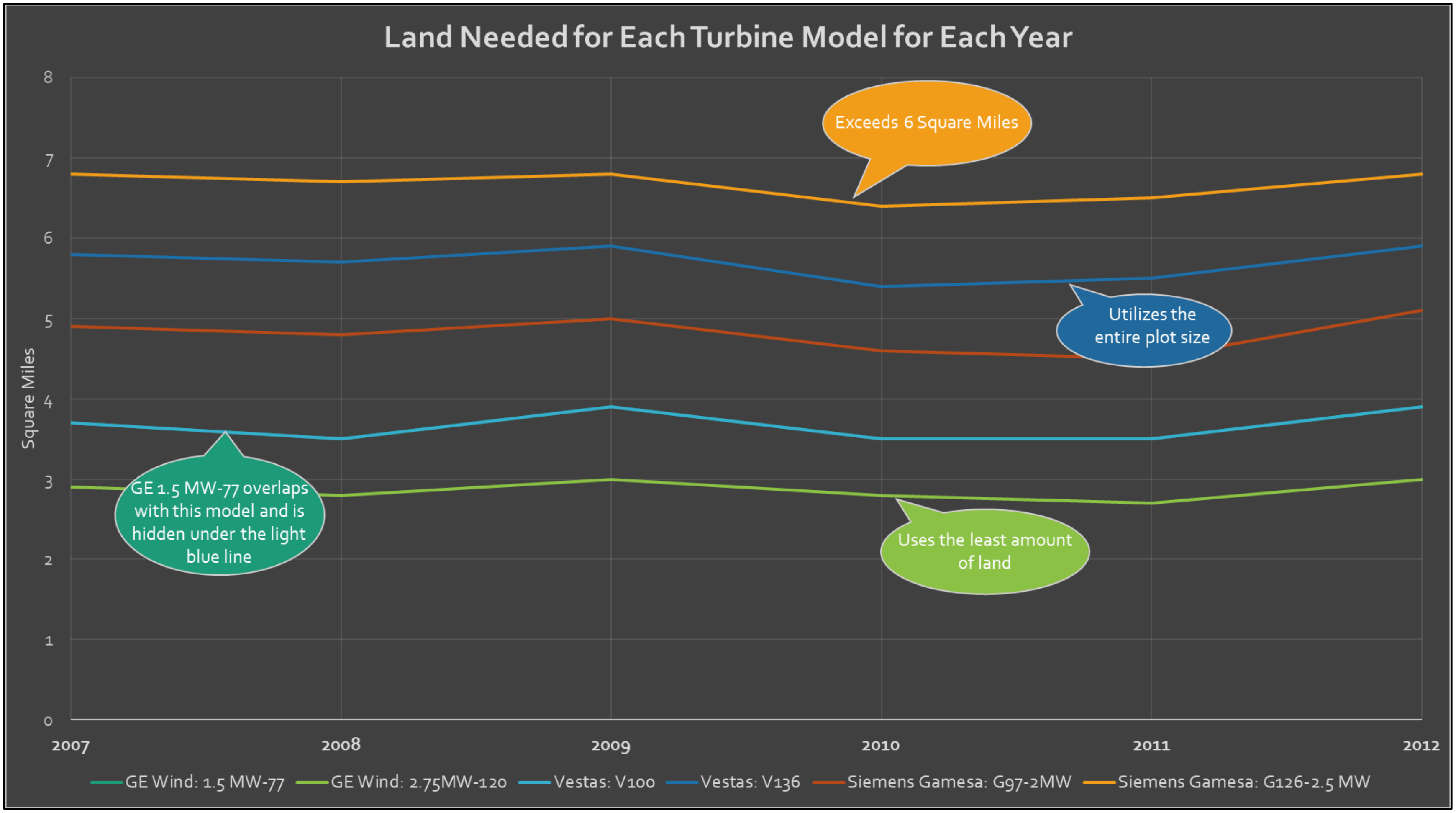


Figure 17 Experimentation Results Plot, Land Usage

11.2 Conclusion

As it relates to the minimum number of turbines, the experimentation identified the following models as the top three choices. That is, less units are needed to meet the energy output requirement of 700 GWh. This is also represented in Figure 18.

1. GE Wind 2.75 MW-120, which resulted in an average of approximately 73 wind turbines
2. Vestas V136, which resulted in an average of approximately 113 wind turbines
3. Vestas V100, which resulted in an average of approximately 135 wind turbines

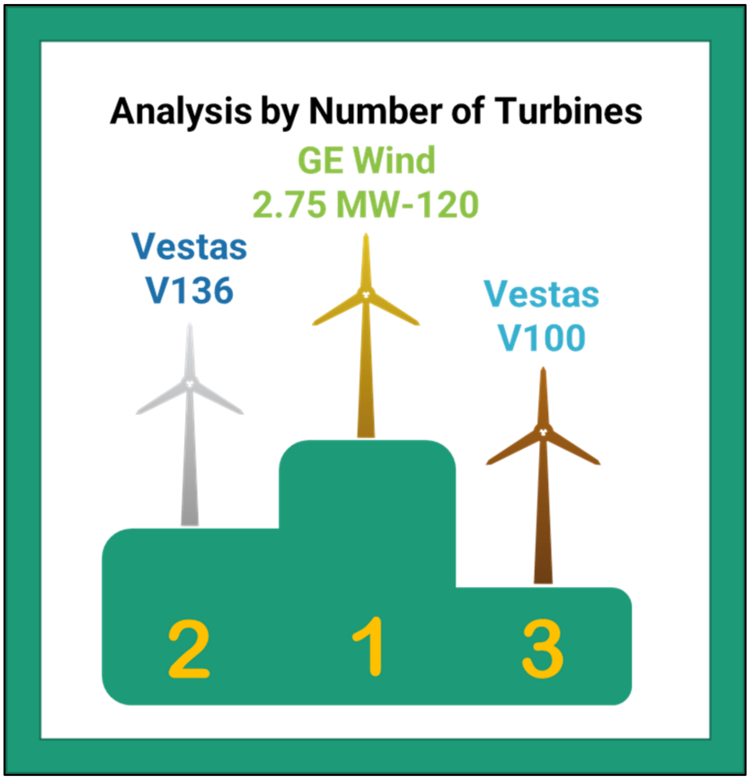


Figure 18 Analysis by Number of Turbines

Regarding the land utilization, the experimentation identified the following models as the top three choices. In other words, less land was needed to accommodate the minimum number of wind turbines needed to meet the energy output requirement of 700 GWh. This is also represented in Figure 19.

1. GE Wind 2.75 MW-120, which resulted in needing approximately 3 square miles of land
2. Vestas V100, which resulted in needing approximately 4 square miles of land
3. GE Wind 1.5 MW-77, which resulted in needing approximately 4 square miles of land

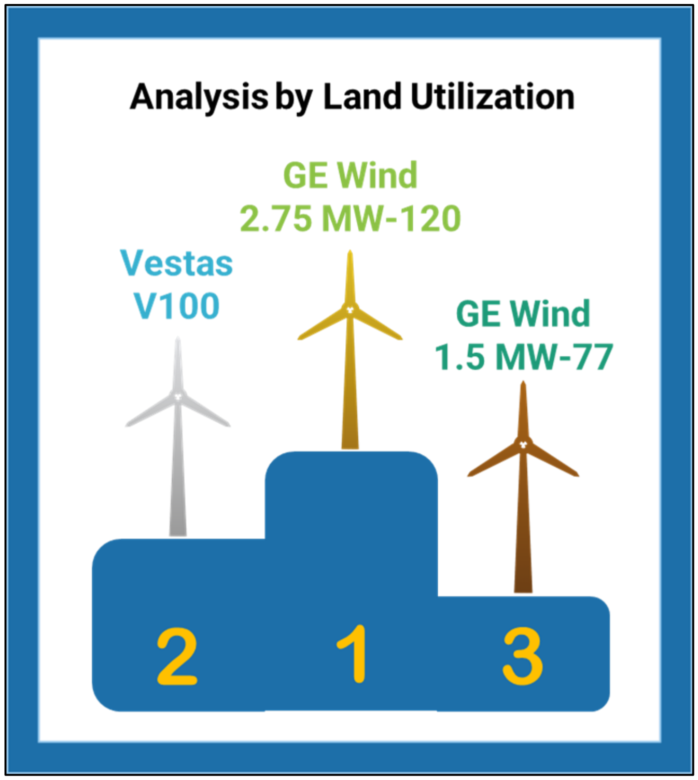


Figure 19 Analysis by Land Utilization

12 Recommendations

12.1 Recommendation for the Proposed Wind Farm

Based on the analysis of the results, the M&S team recommends the GE 2.75 MW-120 wind turbine model and a quantity of 73 units to PacifiCorp for the proposed 270 MW rated wind farm in Wyoming. Our results show that this wind turbine model and quantity would perform most effectively as it relates to the energy generation requirement and the land utilization. This recommendation does not consider the cost of procurement, installation, maintenance, storage, or any other related expenses.

12.2 Stretch Goals

The simulation is currently tailored to answer PacifiCorp's problem statement. It addresses the establishment of an onshore wind farm. However, this initiative has the potential to be expanded, made more robust, and made more computationally efficient. The M&S team identified the stretch goals outlined below:

- **Which turbine option would be the most cost-effective solution?** - At this time, the simulation provides an output that is related to land utilization across the specified plot size. Ultimately, by including more financial data, such as cost per turbine, the insights delivered by the model will be more valuable to PacifiCorp. The findings can be used as a basis for a business case.
- **What is the land size required to set up a wind turbine cluster of a particular model?** - If PacifiCorp already has a turbine preference, M&S could be used to calculate the estimated land use for that turbine model, and this provides added value to PacifiCorp.
- **What is the maximum achievable power output in this location?** - Outlines the highest attainable rated power that can be captured from the wind at this location.
- **Is the simulation scalable for a larger project?** - The simulation is effective working with small to moderate datasets. As the size of the data set increases and the scope of the simulation is expanded, the simulation may become slower and more resource intensive. Optimization methods can be employed to make the simulation more computationally efficient.
- **Can this model be applied to offshore wind energy?** - The simulation was designed to answer PacifiCorp's problem statement, but it can be adapted to address a new problem. An offshore wind farm initiative will likely require considerable time investment, but still less time than creating a model from scratch. Another key consideration would be the availability of reliable and recent data.

13 Summary

This project aimed to assist Wyoming's utility company, PacifiCorp, in the Planning phase of their newest project – the establishment of a 270 MW wind farm. They sought M&S services to aid in their design decisions. This specifically relates to the number of wind turbines that would be needed to meet the outlined energy generation output (700 GWh in a year) and fits within the 6 square miles plot of land they designated for this project.

The M&S team created a conceptual model of the problem statement, using the requirements as a basis, to illustrate the inputs and outputs of the model. For the purposes of this M&S project, the main inputs were Wind Attributes, Turbine Attributes, Power Requirement, and Risk Factor. The outputs were Number of Turbines Required, Total Energy Harnessed, and Land Use for wind farm.

The simulation model was created in MATLAB from scratch to answer PacifiCorp's problem statement. The simulation model leveraged the wind power equation, from which the energy generated in a single year can be ascertained. It considers data over the period of a year. The factor of cost is not included in this simulation as it is outside of the scope of the problem statement.

The verification and validation plan confirmed that the model was built correctly and that it answers PacifiCorp's problem statement with reasonable accuracy. This was achieved by using data from an already existing wind farm in Casper, WY in our model and comparing the results of the simulation model to the real-world data.

Once the M&S team confirmed that the simulation model performed reasonably, experimentation was initiated. There was a series of six experiments, where six different wind turbine models were evaluated across six years of wind data. The MATLAB simulation generated results for each trial run via a "User Data Summary," from which the M&S team was able to extract the relevant data and collate it onto two different plots. The first plot showed the number of turbines required to meet the target energy output while the second plot compared the land usage for a wind farm of a specified turbine type.

The results of the M&S analysis demonstrated that the GE Wind 2.75 MW-120 model outperformed the alternative models, both in number of turbines needed and in land utilization. That is, this model required the least amount of wind turbines that would still generate 700 GWh in a year. Furthermore, it is estimated to use only half of the available plot of land. Therefore, 73 units of the GE Wind 2.75 MW-120 is our recommendation to PacifiCorp for their new proposed wind farm.

14 Acknowledgements

Executing this project would not have been possible without the exceptional support of our mentors – Kayla Sanders, Professor Marshall Bronston, and Dr. Margaret Loper. The knowledge and attention to detail these individuals have dedicated to our project kept the M&S team on track and providing PacifiCorp the answer they needed within the tight timeline.

The M&S team would also like to thank the Subject Matter Experts (SMEs) at GE Renewable Energy (Wind Energy Division) – Matthew Rinaldi (Senior Commodity Leader), Rita Nerurkar (Senior Program Manager), and Neumann Ulrich (Principal Engineer). They dedicated their personal time to explain the basics of wind energy to the team and provided invaluable resources that helped us lay the foundation for the execution of this project and producing a reliable recommendation.

Thank you to all the individuals who supported this endeavor!

15 References

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16 Appendix A: Requirements Definition

Considerations for the simulation requirements came from several sources ranging from conversations with our key stakeholder (PacifiCorp) to consultations with Subject Matter Experts (SMEs) in the field of Wind Energy Generation. A search was performed for any relatable projects and the resulting literature was analyzed to understand if there were gaps in the M&S team's requirements for the proposed simulation.

The M&S team separated the high-level requirements into five categories as illustrated in Figure 20 below. The two letters that follow each category name within parenthesis indicate the identifier that's used to show which requirements belong to each category.

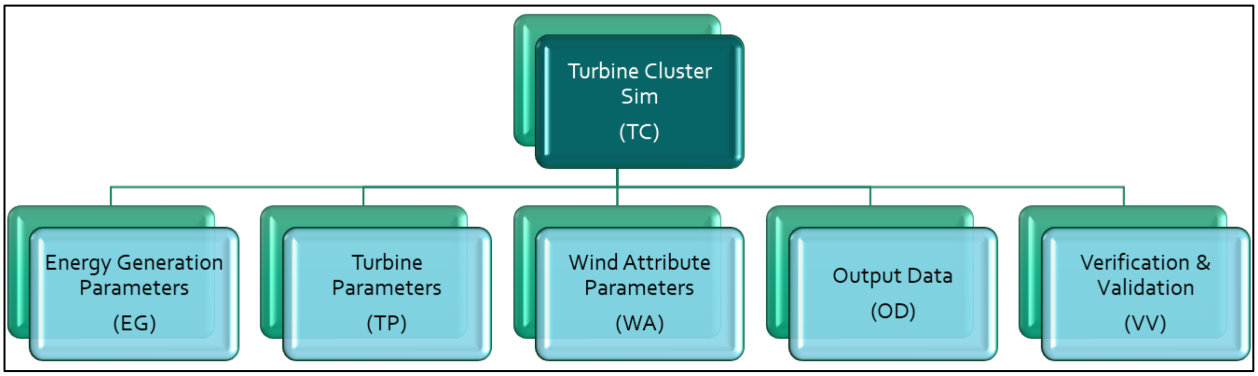


Figure 20 High-Level M&S Requirements Hierarchy

Table 5 defines the nature of each requirement category seen in the hierarchy map above.

Table 5 High-Level M&S Requirements Definition

Category	Definition
Turbine Cluster Simulation (TC)	Describes the general M&S and is the highest in hierarchy
Energy Generation Parameters (EG)	Input controls for Energy Generation (e.g., functional coefficients – Betz)
Turbine Parameters (TP)	Input controls related to the wind turbine (e.g., rotor diameter, cut-in velocity, rated velocity, efficiency factors)
Wind Attribute Parameters (WA)	Input controls related to the wind (e.g., wind speed)
Output Data (OD)	Output requirements from the simulation (e.g., total energy output calculated, total number of turbines)
Verification & Validation (VV)	Requirements to ensure that the model is coded correctly and accurately

17 Appendix B: Modeling & Simulation Timeline

PacifiCorp has set hard deadlines in line with their overall project. They need results of the refined Turbine Cluster Simulation in four weeks. As such, the M&S team developed the milestone schedule shown in Figure 21 below. The M&S team identified nine major milestones and estimated the time required for the successful completion of each one. As is evident, building the M&S and Programming will be the lengthiest of approximately 10 days.

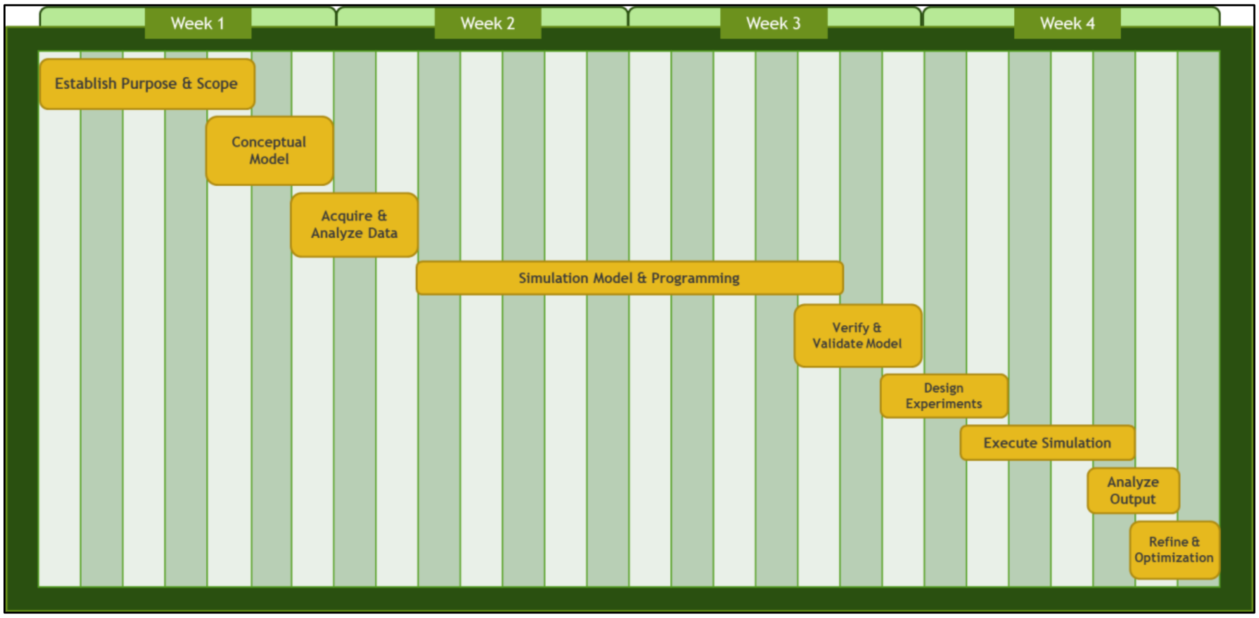
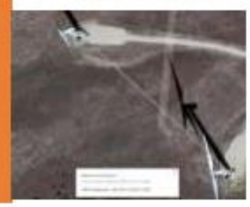


Figure 21 M&S Timeline

18 Appendix C: Turbine Spacing Factor Calculations

Start	End	Distance (X)	Distance/ Rotor Diameter	Average (Distance / Rotor Diameter)	
Turbine ID: 3029130 **Project Name:** Casper Wind Farm **Year Online:** 2009 **Rated Capacity:** 1.5 MW **Hub Height:** 80 m **Rotor Diameter:** 77.00 m **Total Height:** 118.60 m **Turbine Manufacturer:** GE Wind **Turbine Model:** GE1.5-77 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 42.883293 **Longitude:** -106.219688	**Turbine ID:** 3029129 **Project Name:** Casper Wind Farm **Year Online:** 2009 **Rated Capacity:** 1.5 MW **Hub Height:** 80 m **Rotor Diameter:** 77.00 m **Total Height:** 118.60 m **Turbine Manufacturer:** GE Wind **Turbine Model:** GE1.5-77 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 42.884693 **Longitude:** -106.221390	216 m	2.81	2.49	
Turbine ID: 3029127 **Project Name:** Casper Wind Farm **Year Online:** 2009 **Rated Capacity:** 1.5 MW **Hub Height:** 80 m **Rotor Diameter:** 77.00 m **Total Height:** 118.60 m **Turbine Manufacturer:** GE Wind **Turbine Model:** GE1.5-77 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 42.884392 **Longitude:** -106.233086	**Turbine ID:** 3033363 **Project Name:** Casper Wind Farm **Year Online:** 2009 **Rated Capacity:** 1.5 MW **Hub Height:** 80 m **Rotor Diameter:** 77.00 m **Total Height:** 118.60 m **Turbine Manufacturer:** GE Wind **Turbine Model:** GE1.5-77 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 42.883595 **Longitude:** -106.230888	200 m	2.60		
Turbine ID: 3029132 **Project Name:** Casper Wind Farm **Year Online:** 2009 **Rated Capacity:** 1.5 MW **Hub Height:** 80 m **Rotor Diameter:** 77.00 m **Total Height:** 118.60 m **Turbine Manufacturer:** GE Wind **Turbine Model:** GE1.5-77 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 42.890293 **Longitude:** -106.214790	**Turbine ID:** 3029131 **Project Name:** Casper Wind Farm **Year Online:** 2009 **Rated Capacity:** 1.5 MW **Hub Height:** 80 m **Rotor Diameter:** 77.00 m **Total Height:** 118.60 m **Turbine Manufacturer:** GE Wind **Turbine Model:** GE1.5-77 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 42.891392 **Longitude:** -106.216087	160 m	2.08		

Start	End	Distance (X)	Distance/ Rotor Diameter	Average (Distance / Rotor Diameter)	
Turbine ID: 3105683 **Project Name:** TB Flats I & II **Year Online:** 2021 **Rated Capacity:** 4.3 MW **Hub Height:** 82 m **Rotor Diameter:** 136.00 m **Total Height:** 150.00 m **Turbine Manufacturer:** Vestas **Turbine Model:** V136-4.3 **Attribute Confidence:** Low **Location Confidence:** High **Latitude:** 42.099319 **Longitude:** -106.099731	**Turbine ID:** 3105530 **Project Name:** TB Flats I & II **Year Online:** 2021 **Rated Capacity:** 4.3 MW **Hub Height:** 82 m **Rotor Diameter:** 136.00 m **Total Height:** 150.00 m **Turbine Manufacturer:** Vestas **Turbine Model:** V136-4.3 **Attribute Confidence:** Low **Location Confidence:** High **Latitude:** 42.095505 **Longitude:** -106.099174	426.5 m	3.14	2.77	
Turbine ID: 3107856 **Project Name:** TB Flats I & II **Year Online:** 2021 **Rated Capacity:** 4.3 MW **Hub Height:** 82 m **Rotor Diameter:** 136.00 m **Total Height:** 150.00 m **Turbine Manufacturer:** Vestas **Turbine Model:** V136-4.3 **Attribute Confidence:** Low **Location Confidence:** High **Latitude:** 42.046494 **Longitude:** -106.092613	**Turbine ID:** 3108365 **Project Name:** TB Flats I & II **Year Online:** 2021 **Rated Capacity:** 4.3 MW **Hub Height:** 82 m **Rotor Diameter:** 136.00 m **Total Height:** 150.00 m **Turbine Manufacturer:** Vestas **Turbine Model:** V136-4.3 **Attribute Confidence:** Low **Location Confidence:** High **Latitude:** 42.049274 **Longitude:** -106.092300	307.5 m	2.26		
Turbine ID: 3105377 **Project Name:** TB Flats I & II **Year Online:** 2021 **Rated Capacity:** 4.3 MW **Hub Height:** 82 m **Rotor Diameter:** 136.00 m **Total Height:** 150.00 m **Turbine Manufacturer:** Vestas **Turbine Model:** V136-4.3 **Attribute Confidence:** Low **Location Confidence:** High **Latitude:** 42.065636 **Longitude:** -106.148094	**Turbine ID:** 3105752 **Project Name:** TB Flats I & II **Year Online:** 2021 **Rated Capacity:** 4.3 MW **Hub Height:** 82 m **Rotor Diameter:** 136.00 m **Total Height:** 150.00 m **Turbine Manufacturer:** Vestas **Turbine Model:** V136-4.3 **Attribute Confidence:** Low **Location Confidence:** High **Latitude:** 42.069016 **Longitude:** -106.145905	398 m	2.93		
Turbine ID: 3012878 **Project Name:** Ponnequin (PSCo) **Year Online:** 2001 **Rated Capacity:** 0.66 MW **Hub Height:** 65 m **Rotor Diameter:** 47.00 m **Total Height:** 88.40 m **Turbine Manufacturer:** Vestas **Turbine Model:** V47-0.66 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 40.991692 **Longitude:** -104.805687	**Turbine ID:** 3012879 **Project Name:** Ponnequin (PSCo) **Year Online:** 2001 **Rated Capacity:** 0.66 MW **Hub Height:** 65 m **Rotor Diameter:** 47.00 m **Total Height:** 88.40 m **Turbine Manufacturer:** Vestas **Turbine Model:** V47-0.66 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 40.990894 **Longitude:** -104.806932	140.94 m	3.00	3.00	

Figure 22 Turbine Spacing Factor Calculation, Part 1

Start	End	Distance (X)	Distance/ Rotor Diameter	Average (Distance / Rotor Diameter)	
Turbine ID: 3029270 **Project Name: Northeastern Colorado Wind Energy Center** **Year Online:** 2009 **Rated Capacity:** 2.3 MW **Hub Height:** 80 m **Rotor Diameter:** 108.00 m **Total Height:** 134.00 m **Turbine Manufacturer:** Siemens Gamesa Renewable Energy **Turbine Model:** SWT-2.3-108 **Attribute Confidence:** Medium **Location Confidence:** High **Latitude:** 40.959991 **Longitude:** -102.899292	**Turbine ID:** 3029269 **Project Name:** Northeastern Colorado Wind Energy Center **Year Online:** 2009 **Rated Capacity:** 2.3 MW **Hub Height:** 80 m **Rotor Diameter:** 108.00 m **Total Height:** 134.00 m **Turbine Manufacturer:** Siemens Gamesa Renewable Energy **Turbine Model:** SWT-2.3-108 **Attribute Confidence:** Medium **Location Confidence:** High **Latitude:** 40.957592 **Longitude:** -102.902191	355 m	3.29	3.29	
Turbine ID: 3029276 **Project Name:** Northeastern Colorado Wind Energy Center **Year Online:** 2009 **Rated Capacity:** 2.3 MW **Hub Height:** 80 m **Rotor Diameter:** 108.00 m **Total Height:** 134.00 m **Turbine Manufacturer:** Siemens Gamesa Renewable Energy **Turbine Model:** SWT-2.3-108 **Attribute Confidence:** Medium **Location Confidence:** High **Latitude:** 40.946194 **Longitude:** -102.921288	**Turbine ID:** 3029275 **Project Name:** Northeastern Colorado Wind Energy Center **Year Online:** 2009 **Rated Capacity:** 2.3 MW **Hub Height:** 80 m **Rotor Diameter:** 108.00 m **Total Height:** 134.00 m **Turbine Manufacturer:** Siemens Gamesa Renewable Energy **Turbine Model:** SWT-2.3-108 **Attribute Confidence:** Medium **Location Confidence:** High **Latitude:** 40.946095 **Longitude:** -102.925491	355 m	3.29		
Turbine ID: 3092396 **Project Name:** Solomon Forks **Year Online:** 2019 **Rated Capacity:** 2.625 MW **Hub Height:** 85 m **Rotor Diameter:** 120.00 m **Total Height:** 145.10 m **Turbine Manufacturer:** Siemens Gamesa Renewable Energy **Turbine Model:** SG-2.625-120 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 39.321564 **Longitude:** -101.216812	**Turbine ID:** 3092412 **Project Name:** Solomon Forks **Year Online:** 2019 **Rated Capacity:** 2.625 MW **Hub Height:** 85 m **Rotor Diameter:** 120.00 m **Total Height:** 145.10 m **Turbine Manufacturer:** Siemens Gamesa Renewable Energy **Turbine Model:** SG-2.625-120 **Attribute Confidence:** High **Location Confidence:** High **Latitude:** 39.320492 **Longitude:** -101.220818	365	3.04	3.04	
				2.919344	Approximated to 3

Figure 23 Turbine Spacing Factor Calculation, Part 2

19 Appendix D: Power Curves for Wind Turbine Models

19.1 Experiment 1: GE Wind 1.5 MW-77

The corresponding power curve is shown in Figure 24.

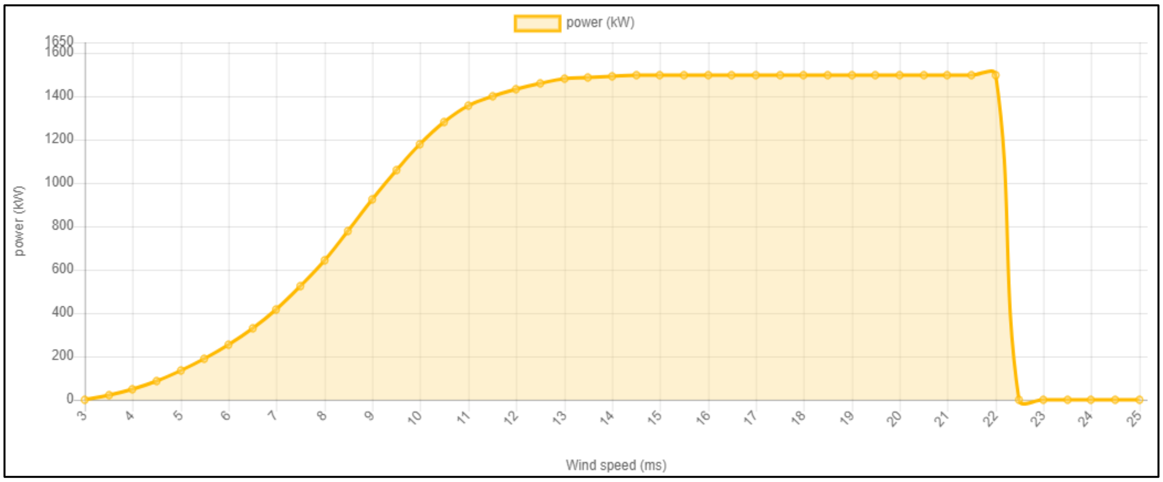


Figure 24 GE Wind 1.5 MW-77 Power Curve

19.2 Experiment 2: GE Wind 2.75 MW-120

The corresponding power curve is shown in Figure 25.

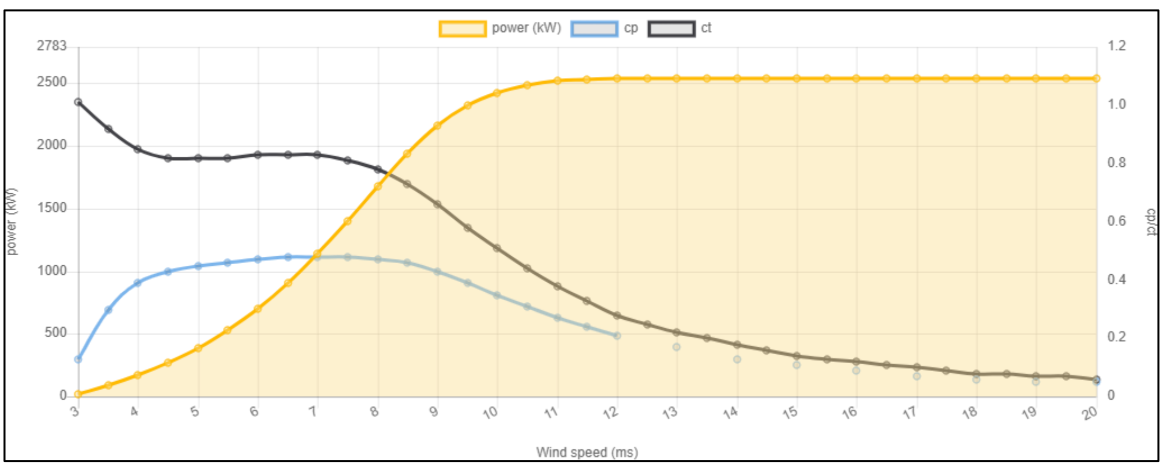


Figure 25 GE Wind 2.75 MW-120 Power Curve

19.3 Experiment 3: Vestas V100-1.8

The corresponding power curve is shown in Figure 26.

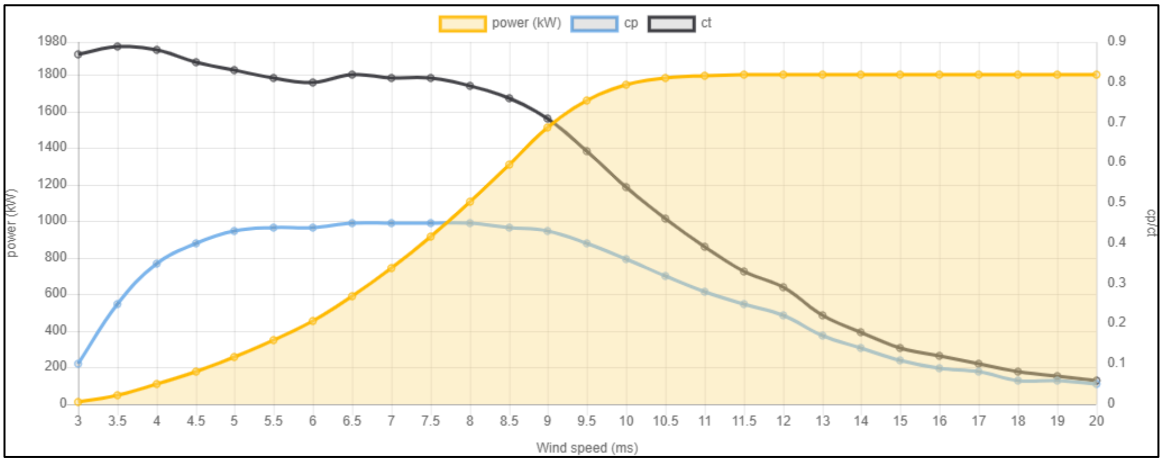


Figure 26 Vestas V100-1.8 Power Curve

19.4 Experiment 4: Vestas V136-3.45

The corresponding power curve is shown in Figure 27.

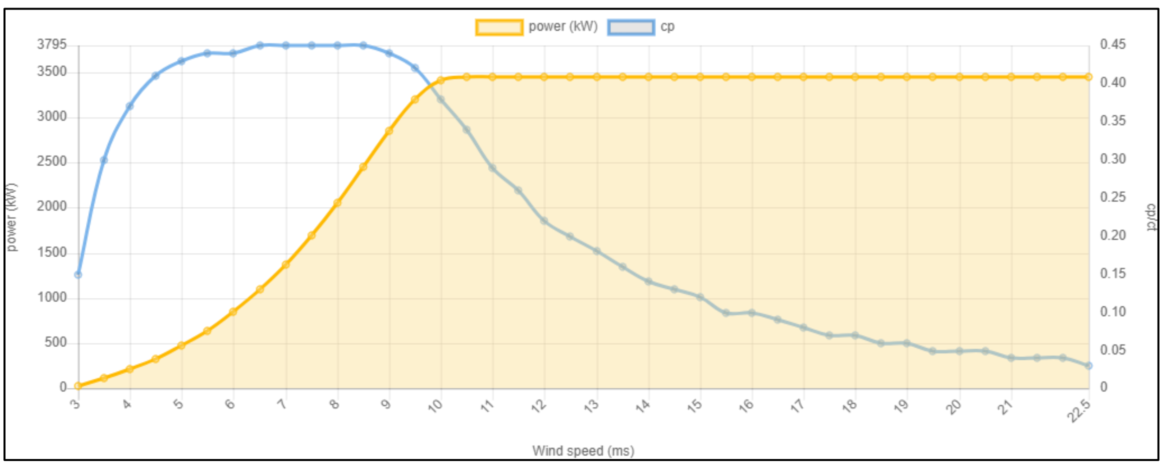


Figure 27 Vestas V136-3.45 Power Curve

19.5 Experiment 5: Siemens Gamesa G97-2 MW

The corresponding power curve is shown in Figure 28.

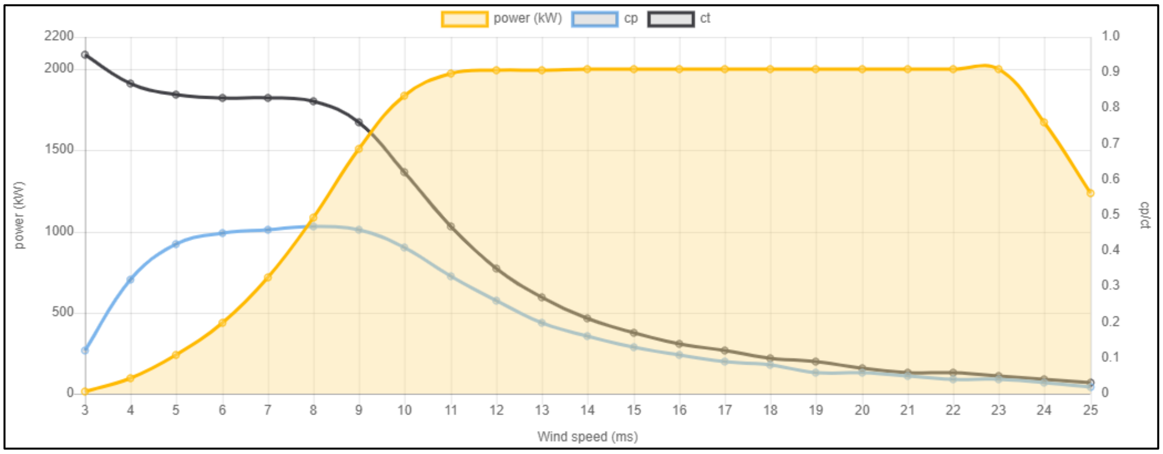


Figure 28 Siemens Gamesa G97-2 MW Power Curve

19.6 Experiment 6: Siemens Gamesa G126-2.5 MW

The corresponding power curve is shown in Figure 29.

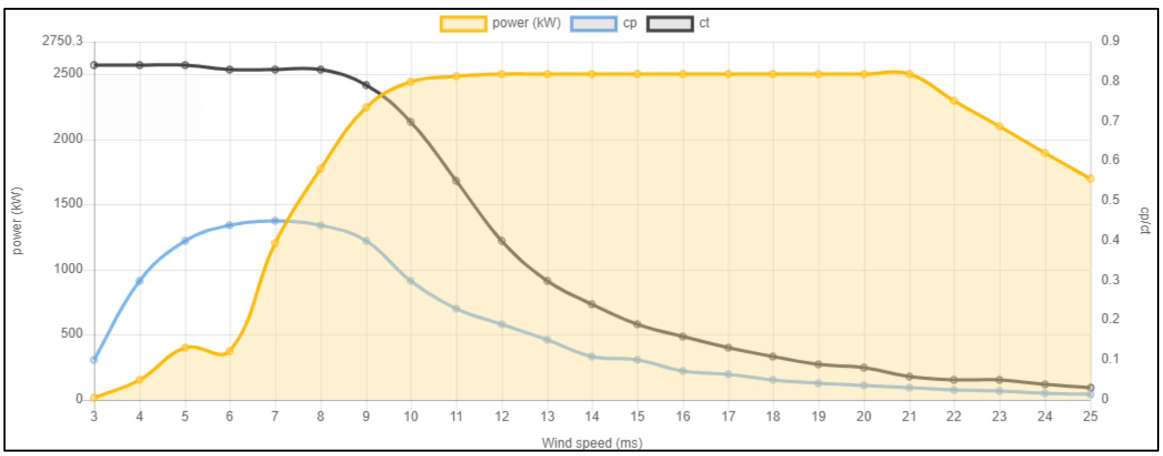


Figure 29 Siemens Gamesa G126-2.5 MW Power Curve

20 Appendix E: MATLAB Code

```
%NOTE FOR THE USER
%Change CSV file name in line 27 to pull in wind data from different
years

%Input GUI and Variable Assignment
clc;
clear;
GUIFields = {'Please Enter Wind Turbine Model:', 'Please Enter
Rotor Diameter (in m):', 'Please Enter Cut-in Velocity (in
m/s):','Please Enter Rated Velocity (in m/s):','Please Enter
Efficiency:'};
dlgtitle = 'Welcome to the Turbine Energy Simulator';
dims = [1 100];
definput = {'Vestas: V100','100','3','12','0.45'};
userInput = inputdlg (GUIFields,dlgtitle,dims,definput);
[Model, rD, vC, vR, n] = deal(userInput{:});

%Converting user input into numeric values
rD = str2double (rD); %Convert Rotor Diameter to RADIUS
%h = str2double (h); Not including Rotor height as a variable
since it doesn't impact the power calculation formula
vC = str2double (vC);
vR = str2double (vR);
n = str2double (n);

%Read Model Data can be added to simplify user input into just
the name and the values. This user input can then allow for the
Turbine model information to be pulled in from a known data
repository.

%Read Wind data: Currently reading from spreadsheet with hourly
distribution of wind speeds for a year. This function can be
expanded to enable reading a segment (shorter time duration)
from a large spreadsheet spanning large time intervals.

%Using this smaller dataset to test and setup the model
%[simTime, V] = readvars ('WindData_v1.xlsx');        %Small
Dataset
[simTime, V] = readvars ('Hourly Wind Speed - 2012 Capser
WY.csv');       %Large Dataset
dataPoints = size (V, 1);


%Power Formula (verify again with inclusion of Cp)
```

```
%Fixed air density at 20C of 1.204 kg/m^3
rho = 1.204;
P = zeros(dataPoints, 1);
currentPower = zeros(dataPoints, 1);



%Actual power achievable from a 270MW "rated" wind farm is
0.3*270 (since wind power capacity is 30% (Reference))
actualPower = 81;   %in MW

farmCapFactor = 1;    % Land-based wind farm capacity factor
assumption is ~30%. Leaving it at 1 since the true power factor
has already included this (above)
targetPower = actualPower * 365 * 24 * farmCapFactor;   % 270MW
for 365 days and 24 hours with a capacity factor of 25%
safetyFactor = 1.2;    % Variable used to capture maintenance
times, wind variability, other factors
reqPowerMW = targetPower * safetyFactor;   % Real required power
after considering assumptions / variability


%PLEASE NOTE that some variable names may be called Power or
Energy but may not pertain to the true type of variable.


for i = 1 : 500  %Loop to increase number of turbines. Make 500
as a large enough variable n that has to be minimized based on
Power needed

    for j = 1 : dataPoints
        instV = V (j,1);                          %Instantaneous
Velocity (per hour) extraction array

        %Stretch Goal: Also record time data to provide
information to the user as to when the required power is reached
            %instT = simTime (j,1);  %Instantaneous Time
extraction array
        %This requires datetime to double conversion. Modify
incoming spreadsheet to help with parsing this information
            %External script to convert the day and hour
information into 1 hour segments. SQL / Python may help with
that function

        %Conditions for Cut-in velocity and Rated velocity.
Turbine operates only within the sweet-spot
```

```
        if V(j,1) < vC | V(j,1) > vR
        instPower = 0;

        else
        instPower = (0.5 * pi * (rD/2) * (rD/2) * rho * n *
(instV ^ 3)) * i;

        end

        P (j) = instPower * 10^(-6);  %W to MW conversion
        currentPower = sum (P);

        if currentPower > reqPowerMW;
            break;

        else

        end

    end

        %Checking for total power for a given number of turbines
        totPower (i, :) = sum (P);

        if totPower (i,:) < reqPowerMW;

            i = i + 1;

        else
            numTurb = i;
            break;

        end

%          Plot the Power Output vs Number of Turbines
%          figure (2)
%          set(gcf,'position',[900,250,800,500])
%          Custom plot formatting
%          %plot (simTime, P, 'LineStyle', '-', 'Color',
'#0072BD', 'Marker', 'o', 'MarkerSize', 8, 'MarkerFaceColor',
'r', 'LineWidth', 2);
%          plot (i, P, 'LineStyle', '--', 'Marker', 'square',
'MarkerSize', 8, 'LineWidth', 2);
%          title('Number of Turbines vs Power Output');
%          xlabel('Number of Turbines');
%          ylabel('Power Generated (MW)');
```

```
%         legendInfo{i} = ['Power from ', num2str(i),
'turbine(s)'];
%         legend(legendInfo)
%         legend show
%         set(gca, 'Units','normalized',
'FontUnits','points','FontWeight','normal',
'FontSize',14,'FontName','Arial');
%         grid on
%         hold on


end

        %Plot the Power Output vs time (here, per hour)
        figure (1)
        set(gcf,'position',[100,360,1500,500])
        %Custom plot formatting
        plot (simTime, P, 'LineStyle', '-', 'Marker', 'o',
'MarkerSize', 1, 'LineWidth', 1);
        title('Power vs Time Distribution for Varying Wind
Speeds');
        xlabel('Time (hours)');
        ylabel('Power Generated (MW)');

        legendInfo = ['Power from ', num2str(i), 'turbine(s)'];
%Have i in legendInfo when in a loop
        legend (legendInfo);
        legend show
        set(gca, 'Units','normalized',
'FontUnits','points','FontWeight','normal',
'FontSize',14,'FontName','Arial');
        grid on
        grid minor
        hold on

%     CHECK THIS LOOP For Ouput Stopping @ Power Limit
%     if totP > 218000;
%             break;
%     end

    %Output to Excel File
    %writematrix (totP (:,i), Model (:,i),
'/Users/ashthomas/Library/Mobile
```

```
Documents/com~apple~icloud~applecorporate/Documents/Miscellaneou
s/GATech-Ash/ASE6003/GP1/WindOutput_Turbines.xlsx');


%~~~~~~~~~3D Plot to lay out random number of Turbines in a
land~~~~~~~~
% figure (3)
% [x,y] = meshgrid(0:1:499);
% zlim ([0 1]);
% z = ones (500) .* linspace(1,1,500);
%
% surf (x, y, z);
%
%     [xx,yy] = meshgrid(x,y);
%     zz = xx.*exp(-xx.^2-yy.^2);
%     [px,py] = gradient(zz,.2,.2);
%
%     quiver(x,y,px,py)
%     xlim([0 500]);
%     ylim ([0 500]);

%     wTurbine=imread('Wind-Turbine-580x386.jpeg');
%     plot([.1 .9],[.2 1]);
%     axis([0 1 0 1]);
%     hold on;
%     imagesc([.5 .5], [.6 .6], wTurbine);

%Power in GW;
reqPowerGW = reqPowerMW * (10^-3);
totPowerGW = totPower .* (10^-3);

%User Output
fprintf('<strong> User Data Summary </strong>\n');
fprintf(' --------------------\n');

%PLEASE NOTE that some variable names may be called Power or
Energy but may not pertain to the true type of variable.

formatPow1 = ' <strong>%3.0f turbine(s)</strong> would be
required to meet the required energy output of <strong>%3.0f
GWh.</strong> \n';
fprintf(formatPow1, numTurb, reqPowerGW);

formatPow2 = ' The net energy produced by %3.0f turbine(s) is
<strong>%5.2f GWh.</strong> \n';
fprintf(formatPow2, numTurb, totPowerGW(numTurb,:));
```

```
%Land Usage Measure
%Turbine spacing variable
tSpacing = 1.5 * rD; %Half of 3 x rD
landArea = 1.554e+7; %In m^2 (6 sq miles = 3840 acres = 1.554e+7
m^2)

turbCoverage = (pi * tSpacing * tSpacing);    %Turbine coverage
in m^2
turbCoverageAcres = turbCoverage * 0.000247105;   %Turbine
coverage conversion to acres
turbCoverageSqMiles = turbCoverage * 3.861e-7;   %Turbine
coverage conversion to Sq Miles

coveragePercentage = ((turbCoverage * numTurb) / landArea) *
100;


formatLand2 = ' Each turbine of this model takes up
<strong>%2.3f sq miles (%2.2f acres)</strong> of land area \n
(including inter-turbine spacing). \n';
fprintf(formatLand2, turbCoverageSqMiles, turbCoverageAcres);

formatLand3 = ' Overall land use is <strong>%2.2f%%</strong>
\n';
fprintf(formatLand3, coveragePercentage);

%Failure message if land size is exceeded
if coveragePercentage > 100;
formatFail = '
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~ \n The model <strong>%s is NOT
recommended</strong> since the target energy output cannot be
achieved within 6 sq miles. \n The allowable number of turbines
<strong>exceed wind farm size.</strong> \n';
fprintf(formatFail, Model);

%Success message if land size is within limit
else
formatSuccess = '
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~ \n The model %s <strong>may be used</strong> to
achieve required energy output. \n';
fprintf(formatSuccess, Model);

end
```

20.1 Code Operation

20.1.1 Input GUI

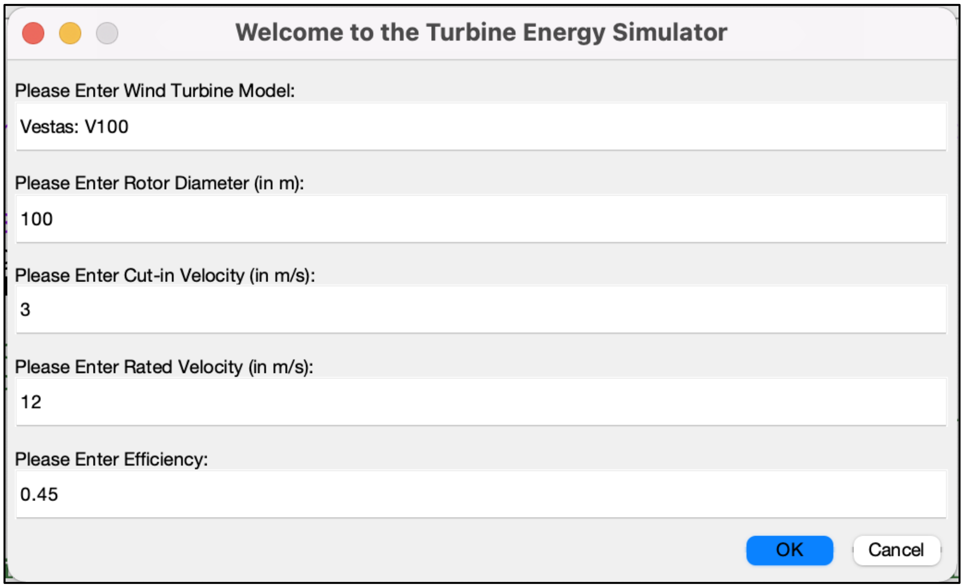


Figure 30 Input GUI

20.1.2 Output Power Plot

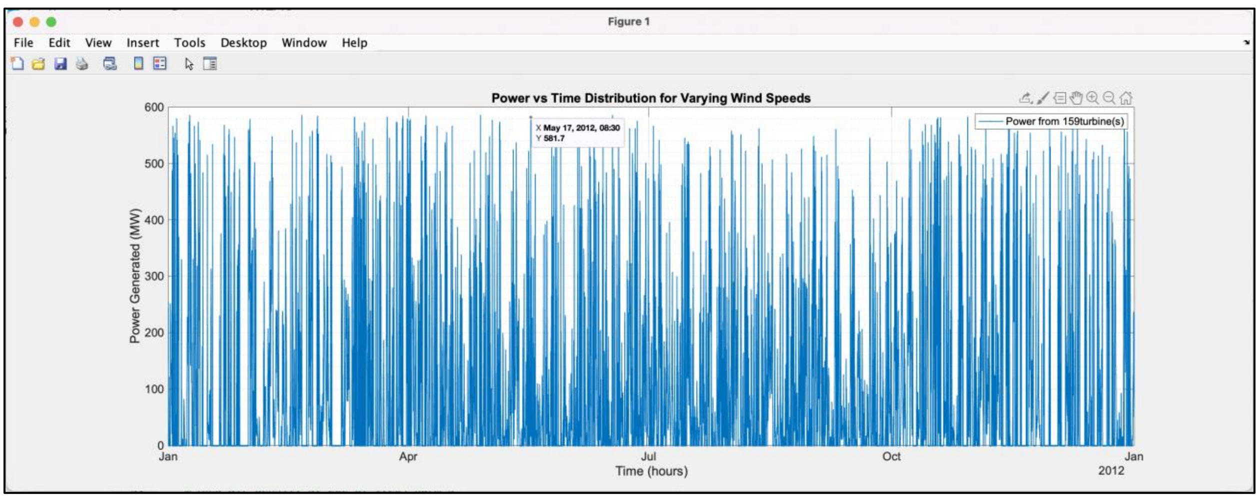


Figure 31 Sample Output Power Plot

20.1.3 Output Summary Message

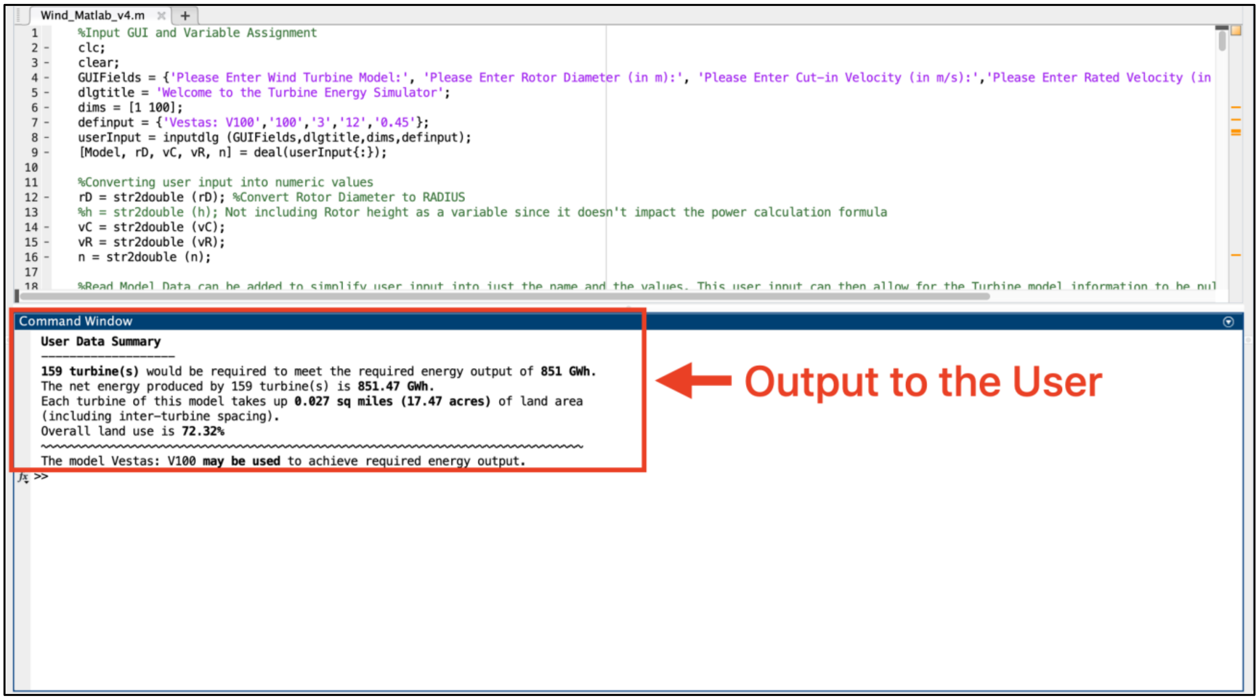
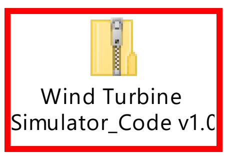


Figure 32 Sample Output Summary Message

The code for the simulation model and all the associated data sets are embedded below.



Model code and associated data sets

21 Appendix F: Additional Background Work

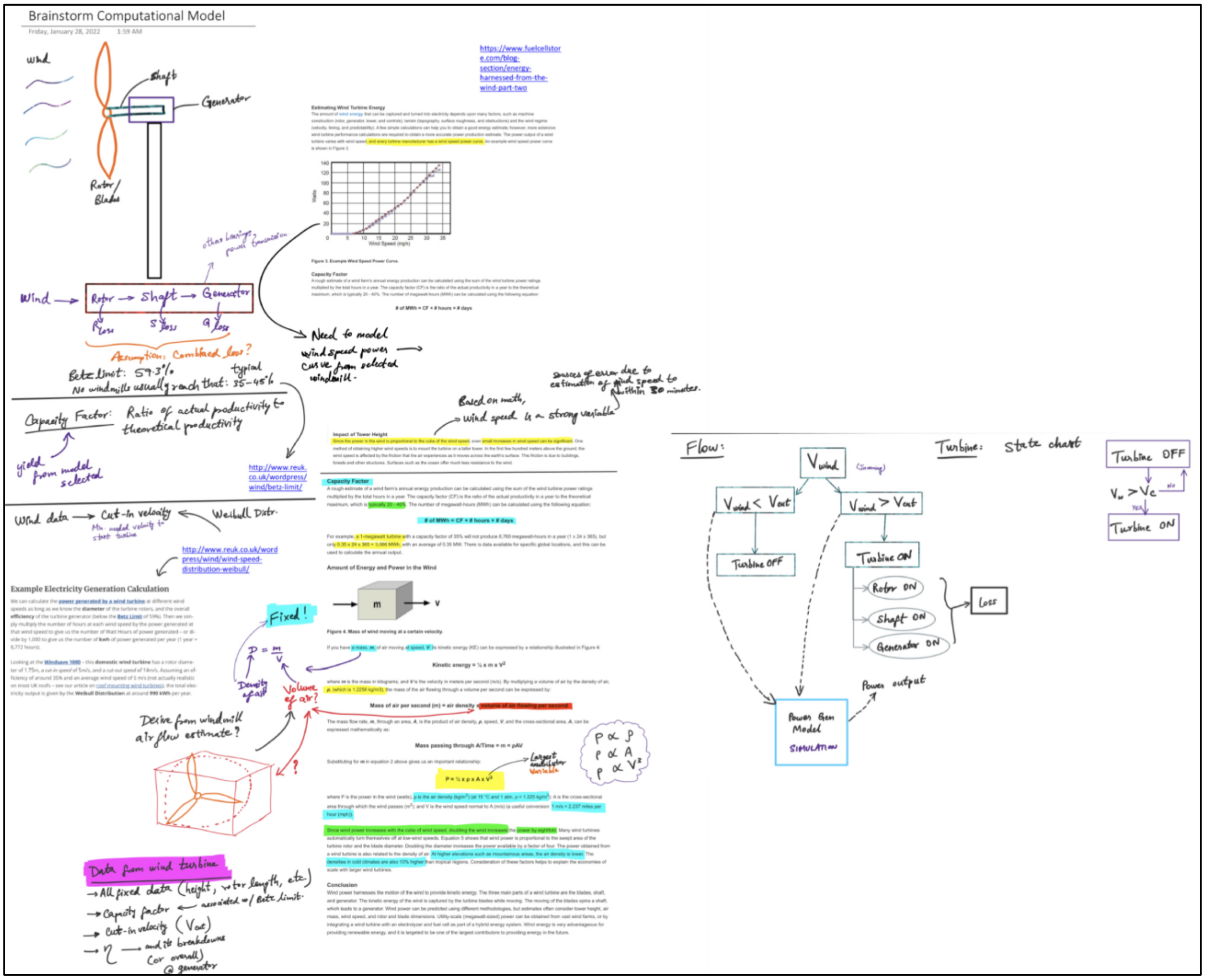


Figure 33 Background Notes

22 Appendix G: Literature Review

The M&S team reviewed two papers that were related to the project, as well as referenced the Georgia Tech Library. Reference Figure 34.

- Model of a Wind Turbine Using Discrete Events (using MATLAB)
- An Agent-Based Multi-Scale Wind Generation Model (using AnyLogic)

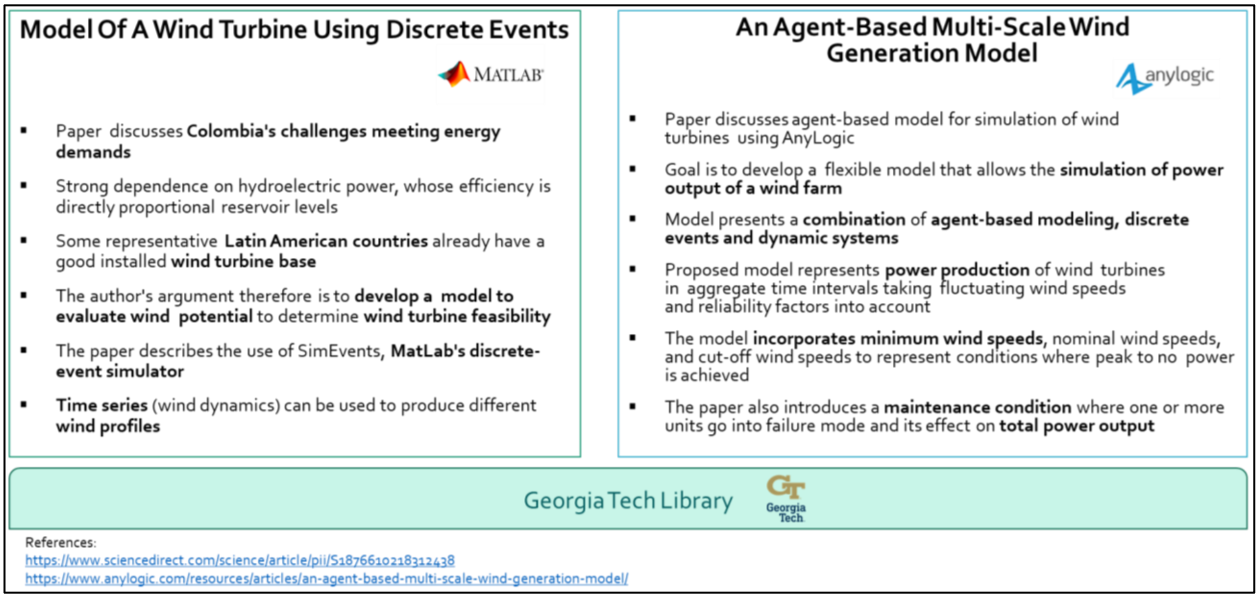


Figure 34 Literature Review