A SIMPLIFIED APPROACH TO ASSESS THE CAPACITY CREDIT OF WIND ELECTRIC CONVERSION SYSTEMS

By

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CHAPTER I

INTRODUCTION

1.1 Energy Scenario:

Economic development, quality of living environment and increased use of energy in various forms are highly interconnected. Accelerated by population growth with increasing expectations, global energy use has been growing dramatically. In particular, electricity generation and consumption has tripled over the past three decades as shown in Figure 1[1].

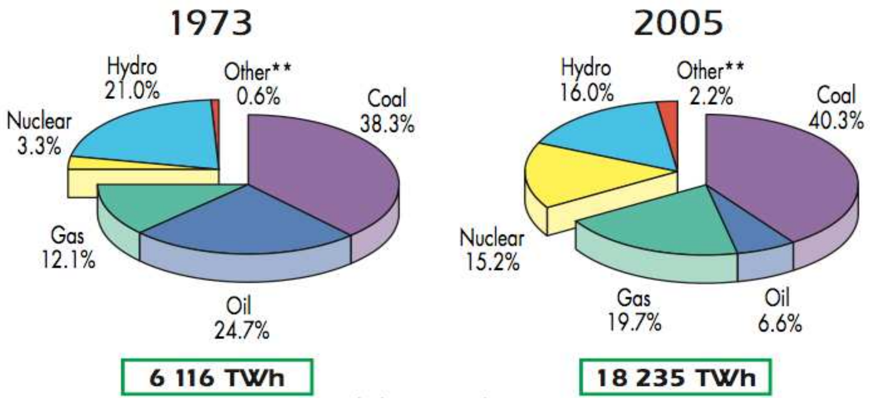


Figure 1: World Electricity Generation, Source: IEA key world energy statistics 2007

Other: Non-hydro renewable energy resources

Fossil fuels (coal, oil and natural gas) account for nearly two-thirds of electricity generation even as late as 2005. The associated emission of greenhouse gases (primarily carbon dioxide) and its impact on global climate change have attracted considerable attention during the past few years. Coupled with the economic and geopolitical implications of importation of fuels, the need to transfer some of the energy needs to renewable energy resources is becoming increasingly critical.

1.2 Renewable energy:

Energy Resources that are replenished on a short time scale (daily, seasonal, annual and a few years) are termed renewable. Examples of such resources are wind, incident solar radiation (insolation), hydro, tides, ocean waves and biomass. Most of these resources trace back to the sun. A major objective of the present day technical community is to decrease the emission of carbon dioxide and renewable energy has an important role to play towards this goal. The practical definition of renewable energy is a flow of energy that is not exhausted by being used [2]. They are dilute, stochastic and require considerable capital expenditure to convert them into useable forms-especially electricity.

High energy demands resulting from the use of highly sophisticated equipments and changing life style of humans due to advancements in technology led to the installation of new power plants using coal, oil, natural gas, nuclear etc. Lack of practical solutions to the problems of disposing spent nuclear fuels, costs involved in and the development of clean coal applications and global shortage of crude oil and natural gas resulting in disproportionate increase in price of crude oil have resulted in major attention towards harnessing renewable energy resources. As a result, a need emerged to harness renewable energy resources to generate grid-friendly electricity. Major attention was focused on harnessing wind and insolation.

The future share of renewable energy use (primarily hydro) may increase from the present 25%, primarily by increasing the contribution of solar, wind and advanced biomass conversion. In the long term and with inclusion of energy storage facilities, the share of renewable energy could be much higher. For the next few decades, a doubling of the renewable energy contribution to 50% would be a very ambitious goal, but one that is technically feasible [2].

Of all the renewable energy resources, wind energy has become very popular for electricity generation due to the following reasons:

- It has a long history of use by human beings.
- The footprint is very small since energy is captured perpendicular to ground surface.
- The resource base is very large and is distributed fairly evenly throughout the world
- Wind energy can be easily converted to rotary mechanical energy

1.3 Evolution of Wind Energy Systems:

Humans have exploited wind energy to enable them to perform various tasks such as separating husk, pumping water, grinding grain and cutting lumber for several millennia. Horizontal axis wind turbines and vertical axis wind turbines are the two major types of turbines in use today. However, most of the grid-connected commercial wind turbines in operation at present are built with a three-bladed propeller-type rotor on a horizontal axis. During the 1800s, use of small "windmills" with dc generators and battery energy storage in remote areas which have no access to the electrical grid was a common sight [3].

The earliest modern wind turbines designed for electricity generation were constructed in Denmark in the year 1891. Those wind-turbines were designed with plane slatted blades, with a swept area of up to 23m in diameter supported on steel lattice towers 23 m high and had power outputs of between 5 and 25 kW. In the United States during the winter of 1887-88 Brush built what is today believed to be the first automatically operating wind turbine for electricity generation [5].

Later on use of ac was very prevalent and feeding wind generated electrical energy into an existing grid posed a challenge because of the stochastic nature of the wind. Several experiments were carried out to obtain constant frequency output from a generator operating at variable speed [4] to maintain a high coefficient of performance for the aero turbine with the varying wind speed. With the advances in power electronics devices and power conversion technologies, all the modern MW- scale wind electric conversion systems (WECS) of today utilize variable speed operation to obtain utility grade ac for insertion into the power-grid.

Figure 2 gives a view of the progress in the output power ratings of wind turbines and the corresponding increases in their rotor diameters and hub heights. The enhancement in the power ratings of wind turbines is the result of efficient energy capture enabled by improved aerodynamic structures and flexibility in controls and operating speeds backed up by the improvement of technologies in power electronics.

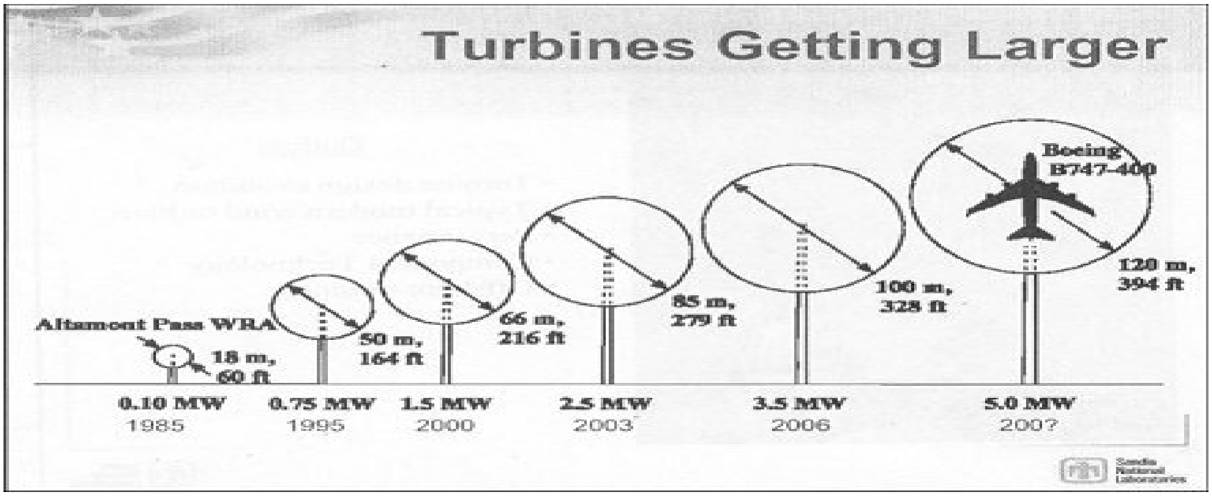


Figure 2: Wind Power Generation Progress [6]

Source: Sandia National Laboratories

At good wind sites, wind plants employing new turbine designs can produce energy at U.S. **$.04** to **$.06** per kWh (levelized/constant dollar). This makes wind power competitive with gas fired plants [7].

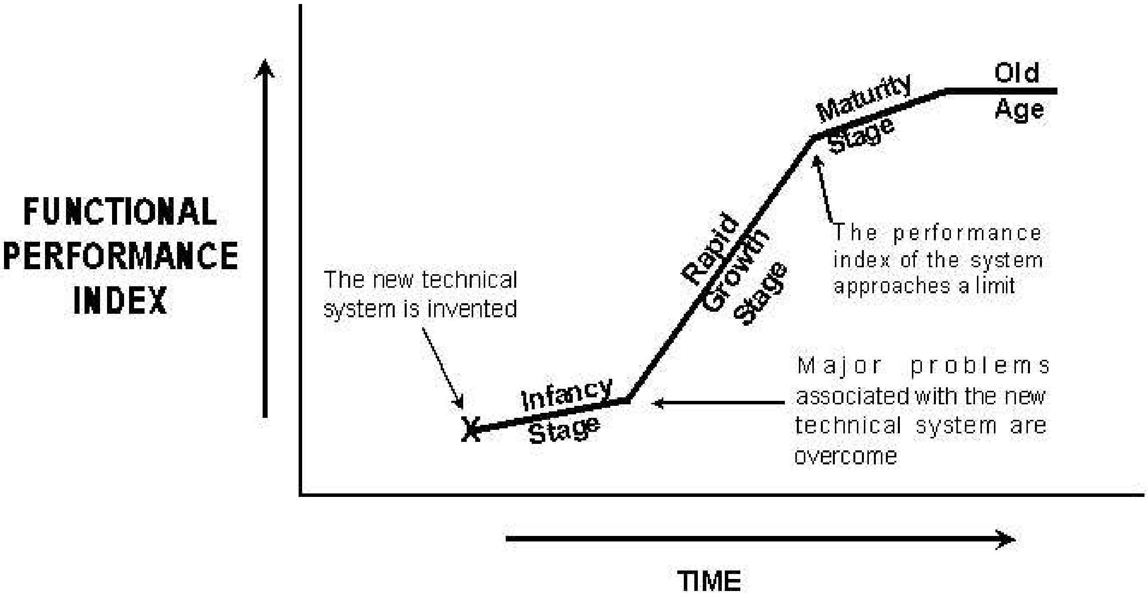


Figure 3: Life cycle of technologies [5]

Figure 3 enables the comparison of different renewable energy technologies: Hydraulic energy (Old Age period), Wind energy (Growth period), Solar energy (Infancy period), Geothermal energy (Infancy period), Biomass energy (Infancy period). It is seen that by comparing different renewable technologies, wind energy is in the growth period

1.4 Future of Wind Energy:

Future challenges to wind energy development are in the areas of design, installation (on shore and off-shore), size increase and integration of new technologies. Development and support for wind energy in Asia are critical due to population growth and lack of other alternatives. Advancement in technology implies operation of wind energy collectors over a wide range of wind regimes and finding ways to smooth wind farm outputs to conform to relatively uniform and regular demands.

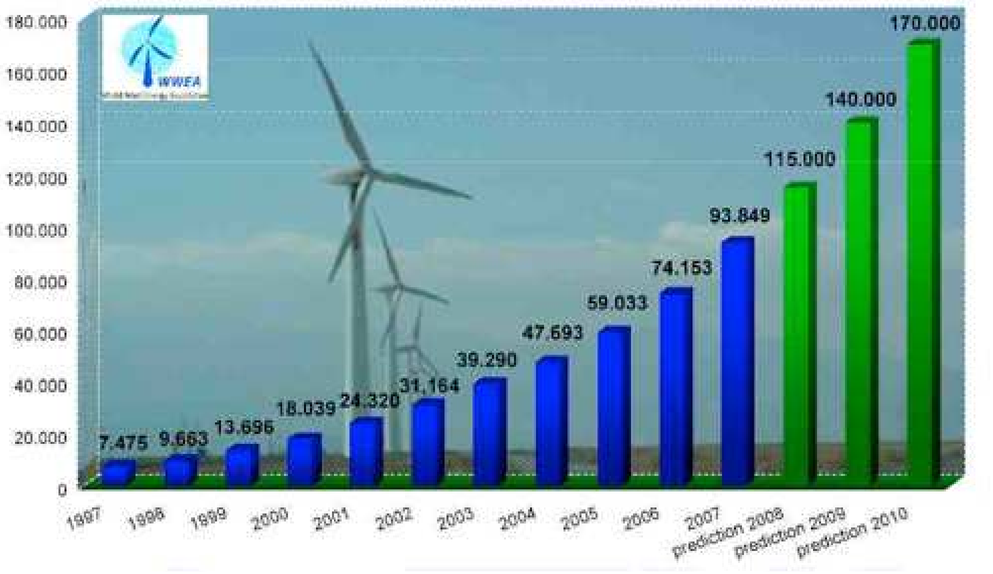
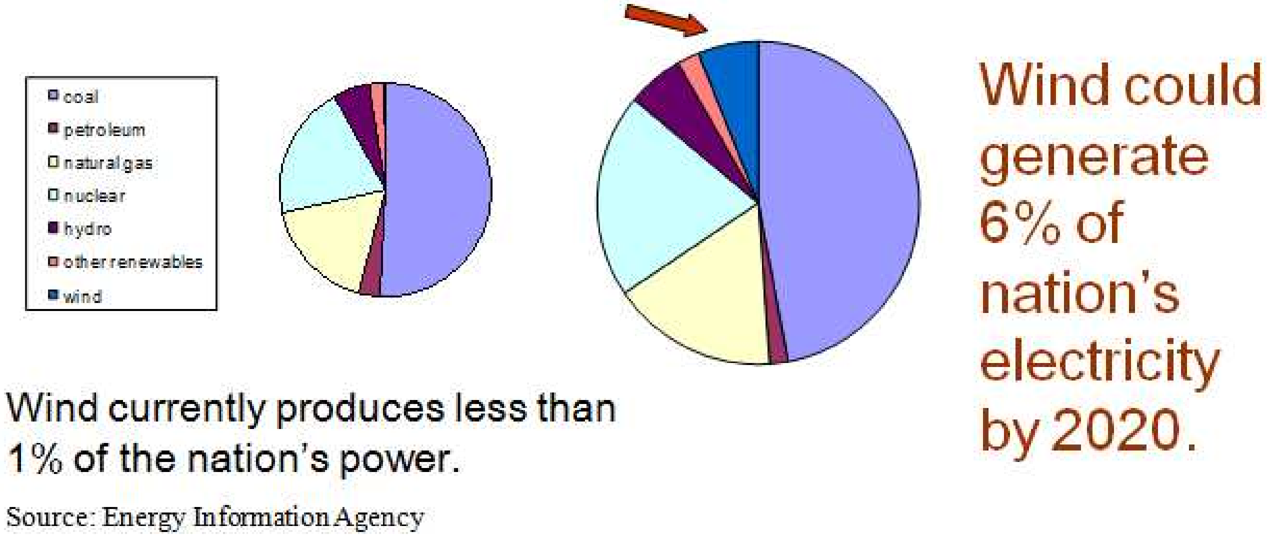


Figure 4: World Wind Energy: Total Installed Capacity and Prediction [8]

Figure 4 illustrates the progress of global wind power capacity since 1997 and the capacity predictions up to 2010 as estimated by the World Wind Energy Association. The world's wind industry could install as much as 1200 GW of turbine capacity by 2030 to meet the shortfall in oil and gas supplies according to the Global Wind Energy Council and Renewable Energy Systems [9]. Also, from Figure 5 it can be seen that wind currently produces 1% of the United State's electric power and is expected to generate 6 % of nation's electricity by 2020, a significant increase. Recently, the U.S. Department of Energy (U.S. DOE) is advancing a scenario to obtain 20% of electricity from wind by the year 2030.



Wind currently produces less than 1% of the nation's power.

Wind could generate 6% of nation's electricity by 2020.

Source: Energy Information Agency

Figure 5: Increasingly significant power source for the U.S. [10]

Wind generated electricity has shown significant growth over the last two decades. The cost of electricity from wind has dropped from $0.35 per kilowatt-hour (kWh) in 1980 to less than $0.05 per kWh today at good wind sites. DOE's goal is to improve the technology further to reduce costs to $0.03 per kWh for projects at low wind speed sites and to $0.05 per kWh for offshore sites by 2012. Environmental benefits include minimal overall pollution, no green house gases, no water pollution with mercury and no water needed for operations. Economic benefits of expanding Wind Power development include creation of jobs in rural communities, increased revenue tax and decreasing the outflow of money to import petroleum products.

1.5 Problem Areas:

Albeit the decreasing cost of wind generated electricity over the past few decades, profound amount of investment is needed for the large-scale installation of wind turbines. To get the best use of the resource in spite of limitations resulting due to the random nature of wind, wind farms should be rendered with energy storage and reconversion systems or additional reserves to insure the continuity and quality of supply to the connected loads.

Many potential wind farm sites are far from demand centers and hence they require very large investments for the construction of new transmission lines and substations to "evacuate" the wind-generated electrical energy. Existing transmission and distribution systems are all based on conventional power plant generation techniques and the addition of wind plants may disturb the operation of the system i.e., may result in overloading of some of the transmission lines. Redesigning the system will increase the overall cost.

Although energy production using wind resources is pollution free, wind plants need to be backed up with coal fired plants and/or nuclear power plants as supply of wind is intermittent. Wind turbine installations will result in a small increase in avian mortality. Mortality rate can be decreased with the advancements in technology and by operating the turbines at low rotational speeds. Leaking lubricating oil or hydraulic fluid running down turbine blades may be scattered over the surrounding area and in some cases could contaminate drinking water supplies.

Organization of the thesis:

Chapter II discusses the concepts of energy credit, capacity credit, and the factors that influence these important values. It also discusses the methods for calculating capacity credit and the economic impact of energy credit and capacity credit. A simplified approach to calculate capacity credit of wind electric conversion systems

(WECS) using effective forced outage rate (FOR) of WECS and loss of load probability (LOLP) calculations is developed in chapter III. The method for calculation of LOLP is explained by considering a simple example of a 2-unit plant. Chapter IV applies the approach presented to a study example. Sensitivity analyses of key factors which affect the capacity credit of WECS is performed and the results are presented in graphical form. In chapter V, the suggested simplified approach to evaluate capacity credit and the results of simulation are summarized. It also provides concluding remarks for this study and discusses avenues for future work. A mathematical reliability model to obtain the effective FOR of WECS using Weibull distribution and a MATLAB code for performing sensitivity analyses are documented in the Appendix A and B respectively.

CHAPTER II

ENERGY CREDIT AND CAPACITY CREDIT

2.1 Energy Credit:

Energy credit refers to the rating of a continuously operating conventional power plant a wind power plant can replace in terms of the energy generated per year. It is typically expressed in the form of an “energy production factor” or “plant factor” k, defined as

k = (kWh energy generated per year by the wind plant) / (name plate rating in kW*8760)

Renewable Energy Certificates (RECs), also known as Green tags, Renewable Energy Credits, or Tradable Renewable Certificates (TRCs), are tradable environmental commodities in the United States which represent proof that 1 megawatt-hour (MWh) of electricity was generated from an eligible renewable energy resource.

A Renewable Portfolio Standard (RPS) is a policy, according to which a proportion of power supplied by retail electricity providers be derived from approved renewable resources (e.g., wind and solar-photovoltaic generation).

Governments around the world have implemented or are in the process of implementing renewable portfolio standards to commit to an increasing renewable energy penetration by 5 to 25% within a certain period of time [11]. Wind energy is viewed as crucial player in meeting the renewable energy portfolio standard of the British government in 2010 and 2020 [12, 13].

2.1.1 Factors determining energy credit:

The energy value of wind power plants is highly dependent on the utility involved, wind turbine performance characteristics, and wind regime at the site. Because wind power typically displaces power generated by marginal units, the economic value of power displaced will vary throughout the day. The marginal generator during low-load periods typically has a lower fuel cost than a marginal unit during the system peak. Therefore, the timing of the wind power output has an important influence on the value of energy that is displaced. Wind sites that are highly correlated with load will have a higher economic value because higher-cost energy is displaced during the peak period.

2.2 Capacity Credit:

Electric power systems must have sufficient reserves so that generation is adequate to meet varying customer demand. Because electricity demand cannot be known in advance with certainty, and because generators can experience forced outages, a capacity margin requirement is necessary to maintain reliability [14]. Capacity Credit (CC) assigned to a renewable power plant is the fraction of its installed capacity by which conventional power generation capacity can be reduced without affecting the benchmark quality of supply [15]. In broad terms, it can be said to be the amount of conventional resources (mainly thermal) that could be ‘replaced’ by the renewable production, without making the system less reliable [16].

The preferred method for calculating capacity credit is in terms of equivalent load carrying capability (ELCC). It will rank the plants that are able to deliver during periods of high demand and ranks less reliable plants that are unable to meet the demand by assigning less capacity credit. Hourly load requirements and generator characteristics are required to calculate ELCC. Primary parameters for conventional generators are forced outage rates, rated capacity and maintenance schedules. For wind generators at least one year of hourly power output is required to assess capacity credit. Chronological reliability model and probabilistic reliability models are two approaches to determine capacity credit. Equivalent load carrying capability method is nothing but chronological reliability model method which will be discussed in detail next.

2.2.1 Chronological reliability model:

Three reliability models runs are required to calculate the capacity credit of WECS. In each run several iterations are required to achieve reliability targets. First the model is run until the reliability target is achieved, conventional generator is added or load is decreased to attain the reliability target. Next wind generator is added to the system and the associated decrease in Loss of Load Probability (LOLP) is observed. Wind generator is then removed from the system and the load is increased until reliability level matches the value calculated in the second step. This increase in load is the capacity value of wind.

Calculation of capacity credit using the ELCC technique is computationally intensive. Approximate methods are used sometimes to calculate capacity credit. These methods are known as non-iterative methods. The non-iterative method allows a simple estimating function to obtain reasonable estimates of a wind farm's effective load carrying capability. A summary of some of the results and comments on various wind capacity value assessments and approximate methods are listed in Table 1.

Region/Utility	Method	Note
CA/CEC	ELCC	Rank bid evaluations for RPS (mid 20s); 3-year near-match capacity factor for peak period used by CA PUC and CA ISO
CPUC	Peak Period	Three-year rolling average of the monthly average of wind energy generation between 12 and 6 p.m. for the months of May through September.
PJM	Peak Period	Jun-Aug HE 3 p.m. -7 p.m., capacity factor using 3-year rolling average (20%, fold in actual data when available)
MN 20% Study	ELCC	Found significant variation in ELCC: 4%, 15%, 25% and variation based on year
ERCOT	ELCC	ELCC based on random wind data, compromising correlation between wind and load (8.7%)
MN/DOC/Xcel	ELCC	Sequential Monte Carlo (26-34%)
NY ISO	Peak Period	Wind's capacity factor between 2-6 p.m., June through August, and 4-8 p.m., December through February
CO PUC/Xcel	ELCC	12.5% of rated capacity based on 10-year ELCC study. Load forecast algorithm compromised correlation between wind and load
PacifiCorp	ELCC	Sequential Monte Carlo (20%). Z-method 2006
MAPP	Peak Period	Monthly 4-hour window, median
PGE		5-15% (method not stated)
Idaho Power	Peak Period	4 p.m. -8 p.m. capacity factor during July (5%)
PSE and Avista	Peak Period	PSE will revisit the issue (lesser of 20% or 2/3 Jan C.F.)
SPP	Peak Period	Top 10% loads/month; 85th percentile
PNM	Peak Period	Capacity factor between 4-5 p.m. in July

Table 1: Various methods for calculating capacity credit of WECS [14]

Although ELCC is the preferred metric to evaluate the capacity value of a wind farm for generation expansion studies, the classical implementation of the ELCC concept requires substantial reliability modeling and a computationally-intensive iterative process [21]. Therefore a simplified approach to assess the capacity credit of wind electric conversion systems will be very useful and is discussed in detail in the coming chapters.

2.2.2 Factors determining capacity credit:

The factors determining of capacity credit are listed below:

- Penetration levels
- Amount of Spinning Reserve
- Wind parameters
- Base case reliability
- Voltage levels at which WECS are connected
- Proximity to the load centers
- Size of the power system
- Variability of the generator
- Order of correlation of the interconnected wind projects
- Correlation of WECS output and load

Distributed generators are rapidly increasing in electrical power systems. Due to low operation and maintenance costs and rapidly maturing technology, wind-electric generation is becoming the primary choice among all renewable energy systems. Capacity credit variation with factors such as base case reliability of the network, voltage levels at which the WECS are connected and their proximity to load centers are discussed in [11]. Capacity credit does not vary with base case reliability. Generators connected at higher voltage levels will result in higher capacity credit values. Generators located near load centers will also have capacity credit.

Load Carrying Capability (LCC) of WECS can be calculated using probabilistic approach and stochastic models which are computer intensive. One approach that has been proposed to estimate LCC from power plants is the constant z-statistic method [18]. This method is used for assessing load carrying capability of resources and can be directly applied to diverse power systems.

Larger power systems will contribute to a greater capacity contribution from a given power plant than that realized with smaller power systems, generators with greater variability over peak demand hours result in a lesser contribution to meeting peak loads, and capacity contribution from correlated wind projects depends on the order of interconnection [19].

Capacity credit decreases as the effective forced outage rate increases. Capacity credit decreases with an increase in wind penetration. With an increase in spinning reserve capacity credit increases. Capacity credit variation with spinning reserve, wind penetration, wind parameters is discussed in detail in the coming chapters.

2.3 ECONOMIC IMPACT:

Economic Impact of adapting a Renewable Portfolio Standard will create thousands of jobs. The renewable energy industry will generate economic activity, increased income and tax revenue. Since most of these plants will be located in rural areas, they will foster rural economic development and economic growth.

Because wind turbines and access roads occupy about 4% or less of the land area required for a wind project, the previous use of the land (e.g., farming, ranching) typically can continue. The continued use of the land essentially creates a “no-cost” option for the landowner to receive additional revenues.

CHAPTER III

A SIMPLIFIED APPROACH TO ASSESS CAPACITY CREDIT

3.1 General and simplified approach to FOR:

Wind power is an intermittent energy source that behaves quite differently than conventional energy sources. For the success of WECS projects, overall reliability of the electric power system is a key factor. Poor reliability of WECS units results in increased O&M costs and reduced system availability; it also directly affects the revenue from the project. LOLP will increase with the increasing penetration of wind generated electrical power into conventional power systems. A simplified method to evaluate the forced outage rate of WECS and the LOLP calculation can be used to evaluate capacity credit.

3.2 Forced Outage Rate:

Forced Outage Rate sets the expected level of unplanned outages, resulting in a partial or complete loss of generating capability during certain periods of time. The Forced Outage Rate is one of the most important parameters in the estimation of component reliability. The long-term probability of finding the component in the down state is called its ‘Forced Outage Rate’ (FOR).

3.2.1 FOR of Conventional Generating Units:

The FOR of a generating unit is also termed as ‘unavailability’ of that unit. By definition, unavailability is the probability that an item will not operate correctly at a given time and under specified conditions. The long-term or steady-state value of this is the FOR. In the case of conventional generating units, emergency conditions may arise due to customer demand, component failures or system behavior. Successful prediction of load is known as load forecasting. Load forecasting plays a vital role in power system planning and operating decisions. Sometimes, these techniques cannot predict the load precisely which results in overloading and consequent loss of load.

Forced Outage Rate is given by

$$FOR = \frac{\lambda}{\lambda + \mu} = \frac{\sum down\ time}{\sum down\ time + \sum up\ time}$$

Where λ and μ are the constant failure and repair rates of a generating unit respectively. Typical FOR value for a conventional generating unit is around 0.02.

3.2.2 FOR of a Wind-Electric System:

The FOR of a wind-electric system is comparatively higher than that of conventional generating units due to the stochastic nature of wind, operating characteristic of the system and mechanical components failure which may result in zero output power. In such cases, if sufficient reserve is not available, the power system may not be able to meet the load which, in fact, increases the LOLP.

FOR of WECS can be calculated by considering the characteristics of the wind resource, output curve of the WECS and mechanical failure data. Then the FOR can be used to calculate the LOLP and estimate the capacity credit of WECS under assumed conditions as outlined in this thesis.

From the power output curve of WECS shown in Figure 6, it can be seen that wind-electric system starts generating electric power at a wind speed known as cut-in speed (V_{ci}), reaches rated power (P_r) at rated wind speed (V_r) and continues to produce rated power until it reaches cut-out speed (V_{co}). Beyond the cut-out value, the turbine is shut down completely for safety reasons. By approximating the non-linearity in the power curve for wind speeds between V_{ci} to V_r by a straight line, an equation for the power output can be obtained for use in FOR calculations. FOR of a WECS and reliability model of WECS are discussed in detail in Appendix A.

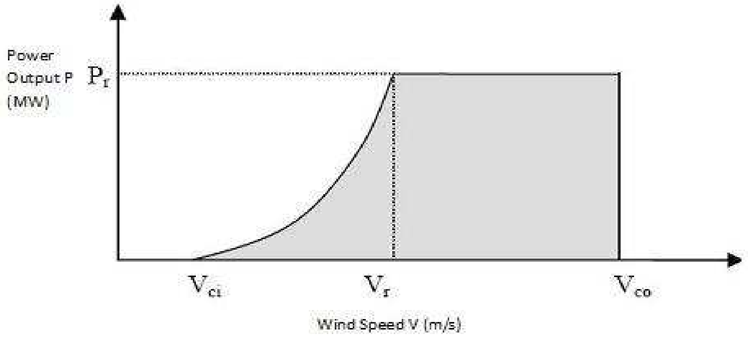


Figure 6: WECS Power Output Characteristic

3.3 Use of FOR and LOLP to obtain Capacity Credit:

Life history of a repairable electric power system component during its life period can be represented by a simple two state model, the two states being the ‘up’ or ‘available’ and the ‘down’ or ‘unavailable’. Therefore ‘up’ state is nothing but ‘capacity-in’ and ‘down’ state is nothing but ‘capacity-out’. Some of the other parameters involved are listed and defined below.

Required Load (□):

Power system planning and operation have to be done properly to meet the expected load obtained using load forecasting.

Capacity in (C_{in}):

C_{in} is the capacity of the generation system that is in service.

Capacity out (C_{out}):

C_{out} is the capacity of the generation system that is not in service.

Probability (P):

Probability value used for calculation of LOLP is the probability of exactly the indicated amount of capacity in service.

Load Loss (L):

Failure of meeting the target i.e., if capacity in is greater than the required load then load loss will be zero otherwise load loss is the difference between required load and capacity in.

Loss of Load Probability:

A loss of load occurs when system load exceeds the available generating capacity. The overall probability that there will be a shortage of power is called the loss of load probability.

Expected Loss of Load:

This is the expected value of the loss of load and it is obtained by summing the products of the amounts of load lost and the probability of losing it.

Considering the case of a 2-unit plant, there are four system states. For each state, C_{in}, C_{out}, P and L are calculated. Then the expected loss of load can be expressed as

E [loss of load] = (P1*L1) + (P2*L2) + (P3*L3) + (P4*L4)

3.3.1 Case of a 2-unit plant:

Truth table		C_{in}	C_{out}	P	**L**
Unit-1	Unit-2				
Down	Down	0	Total capacity of plant	P1	L1
Down	Up	Capacity of unit-1	Capacity of unit-2	P2	L2
Up	Down	Capacity of unit-2	Capacity of unit-1	P3	L3
Up	Up	Total capacity of plant	0	P4	L4

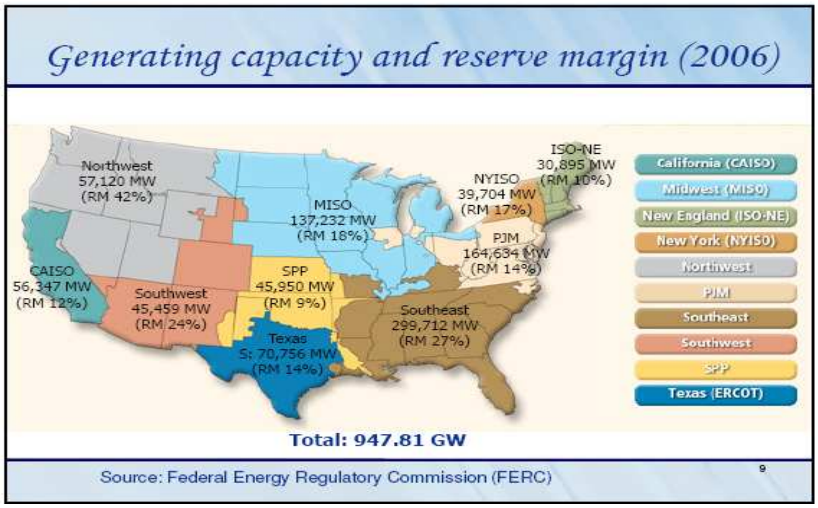
Table 2. Expected Loss of Load Calculation

After finding the expected loss of load of a system with conventional generators, wind generator is added to the system and the decrease in expected loss of load is found. Next wind generator is replaced by a conventional generator and the capacity of the conventional generator is varied until the expected loss of load matches the one obtained with the wind generator. This capacity is the capacity credit that can be assigned to WECS.

3.4 Factors influencing capacity credit:

3.4.1 Spinning reserve:

Spinning reserve is one of the determining factors of capacity credit. With the increase in spinning reserve capacity credit decreases. The generating capacity and the reserve margin of various regions in the United States is shown in Figure 7.



Generating capacity and reserve margin (2006)

Total: 947.81 GW

Source: Federal Energy Regulatory Commission (FERC)

Figure 7: Generating capacity and reserve margin (2006) [20]

3.4.2 Wind penetration:

Capacity credit variation with wind power penetration can be seen in Figure 8. Clearly, as wind penetration increases, capacity credit decreases.

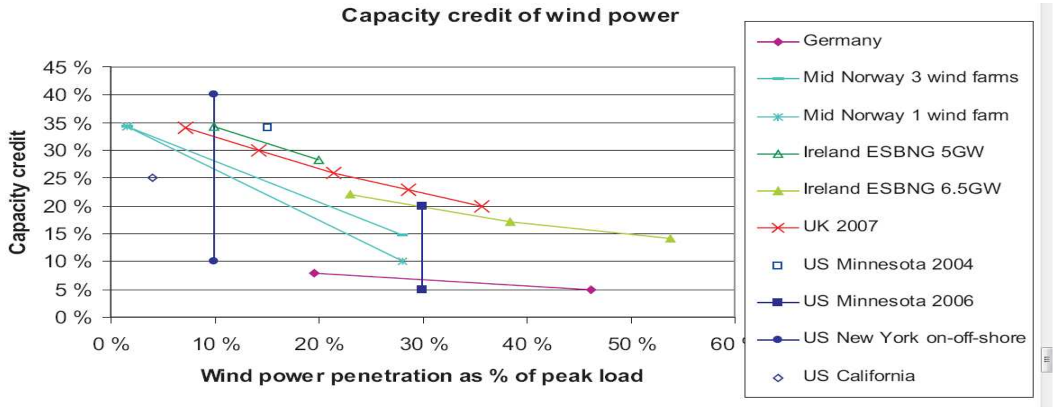


Figure 8: Capacity credit versus Wind power penetration [21]

3.4.3 Wind parameters:

Weibull distribution has been used to model the wind resource. It is one of the most widely used probability distributions for wind resource. It is a two parameter distribution namely, a “scale parameter” (α) having unit m/s and a “shape parameter” (β). Weibull Cumulative Distribution Function is given by

$$F(V) = 1 - \exp\left[-\left(\frac{V}{\alpha}\right)^{\beta}\right]$$

Weibull Cumulative Density Function is given by

$$f(V) = \frac{\beta * V^{\beta-1}}{\alpha^{\beta}} \exp\left[-\left(\frac{V}{\alpha}\right)^{\beta}\right]$$

Where,

V = wind speed (m/s)

Hence, using CDF function the probability that the wind speed V m/s is between any two values say V1 and V2 can be written as,

$$\begin{aligned} P\left(V_1 \le V \le V_2\right) &= F(V_2) - F(V_1) \\ &= \exp\left[-\left(\frac{V_1}{\alpha}\right)^{\beta}\right] - \exp\left[-\left(\frac{V_2}{\alpha}\right)^{\beta}\right] \end{aligned}$$

Variation of wind parameters with capacity credit will be discussed in detail in sensitivity analyses.

CHAPTER IV

EXAMPLE STUDIES

In this chapter, the concepts of FOR and Loss of Load Probability are applied to assess the capacity credit of wind electric systems. In the example studies below, the published failure data for wind power systems operating in Sweden are used.

4.1 FOR of WECS:

For the study, three different wind regimes, labeled as low, medium and high are used and their corresponding Weibull parameters are listed in Table 3 [22]. Values of cut-in, rated and cut-out wind speeds are chosen as 3.6 m/s, 8m/s and 21 m/s respectively. Table 4 lists failure data for various components as documented in published literature [24]. Table 5 lists the values of WECS reliability and FOR for the three different wind regimes. As expected, high speed wind regime results in render high unit reliability and the lowest effective FOR value.

Wind Speed	**α(m/s)**	**β**
Low	5.07	1.31
Moderate	9.7	2.00
High	15.55	3.10

Table 3. Wind Specific Data

Component	**Failure Rate(1/yr)**	**Repair Time(hrs/yr)**	**MTTR(hrs)**
Structure	0.006	0.6	100.00
Yaw System	0.026	6.6	253.85
Hydraulics	0.061	2.6	42.62
Mechanical Brakes	0.005	0.6	120.00
Gears	0.045	11.6	257.78
Sensors	0.054	2.7	50.00
Drive Train	0.004	1.2	300.00
Controls	0.050	9.2	184.00
Electric System	0.067	7.2	107.46
Generator	0.021	4.5	214.29
Blades	0.052	4.7	90.38
Hub	0.001	0.0	0.00

Table 4. Component Failure Data [24]

Wind Speed	**Low**	**Moderate**	**High**
FOR_{Mech}	0.0059	0.0059	0.0059
R	0.1653	0.5885	0.7892
FOR_{Wind}	0.8347	0.4115	0.2108

Table 5. FOR of WECS [23]

4.2 System Configuration:

Using the FOR values of WECS listed in Table 5, capacity credit is calculated for a system consisting of conventional generators and a WECS generator.

Step 1: Consider a system as shown in Figure 9 consisting of three conventional coal fired generators. Each of the generators has a rating of 100 MW. The forced outage rate of a coal fired plant is taken as 0.02 and the system load is taken as 240 MW.

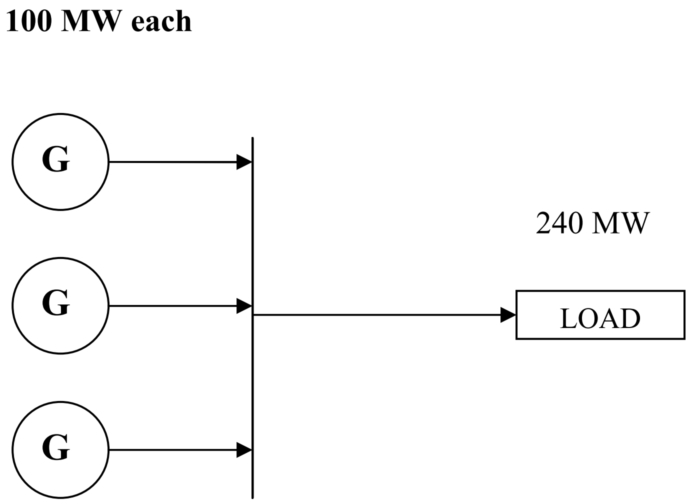


Figure 9: Case of Three Conventional Generators

The expected loss of load of the system is calculated to be 2.4715 MW using the MATLAB code given in Appendix B.

Step 2: A wind generator is added to the system; now the system shown in Figure 10 consists of three conventional coal fired generators and WECS. With the same system load, the new value of expected loss of load is equal to 0.559 MW. As expected, the simulation results show a decrease in expected loss of load with the addition of a wind generator.

100 MW each

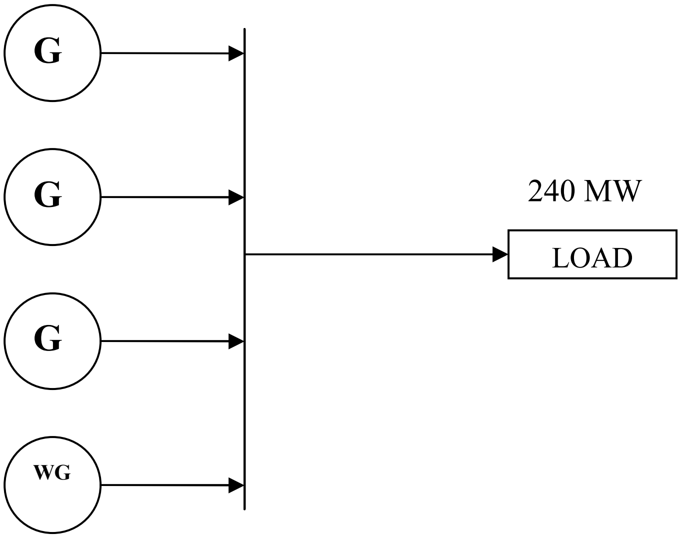


Fig 10: Case of Three Conventional Generators and one WECS

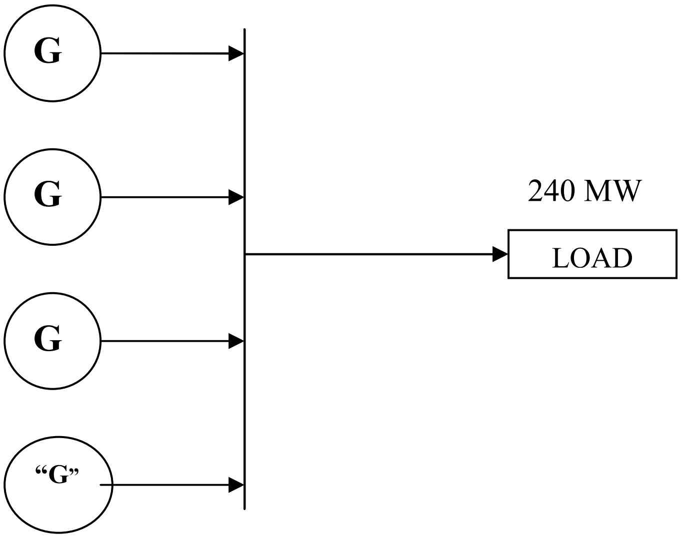


Figure 11: WG replaced by a variable "G"

Step 3: Now the wind generator is replaced by a conventional generator. The capacity of the conventional generator is varied until the same expected loss of load is obtained

(0.559 MW in this case). By using the MATLAB code given in Appendix B the capacity of a conventional generator is found out to be 33.17 MW. Based on this, a capacity credit of 0.3317 can be assigned to the wind system.

4.3 Assumptions:

- Load is kept constant throughout the study.
- Wind specific data i.e., cut in speed, cut out speed, rated speed, shape parameter and scale parameter are kept constant throughout the study.
- The Forced outage rate of a conventional generator is assumed to be 0.02
- Three wind regimes are considered : low speed wind regime, moderate speed wind regime and high speed wind regime

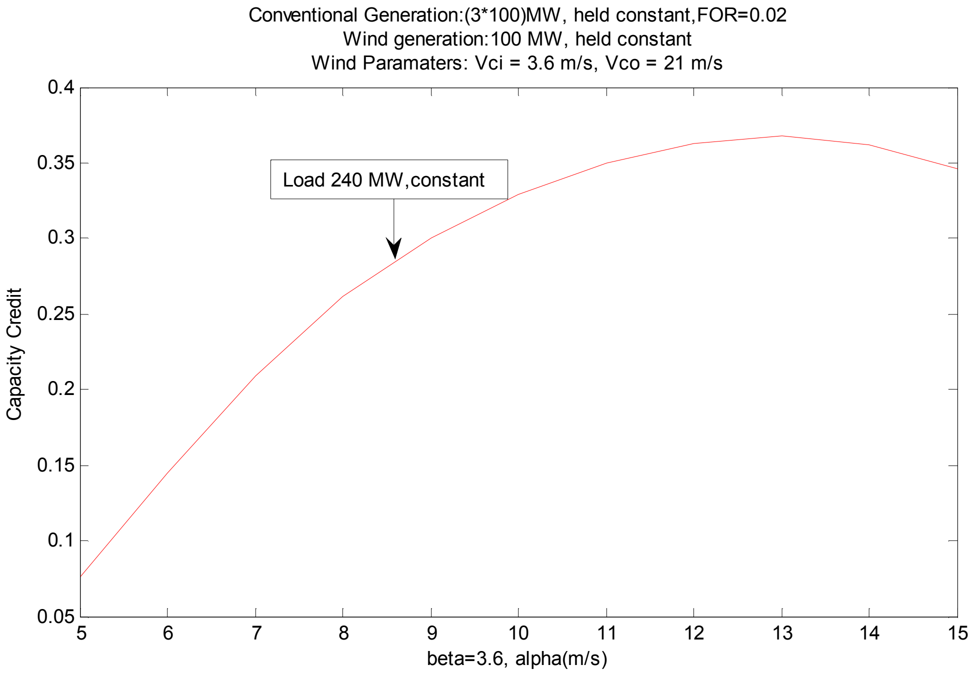


Figure 12: β = 3.12, Varying α

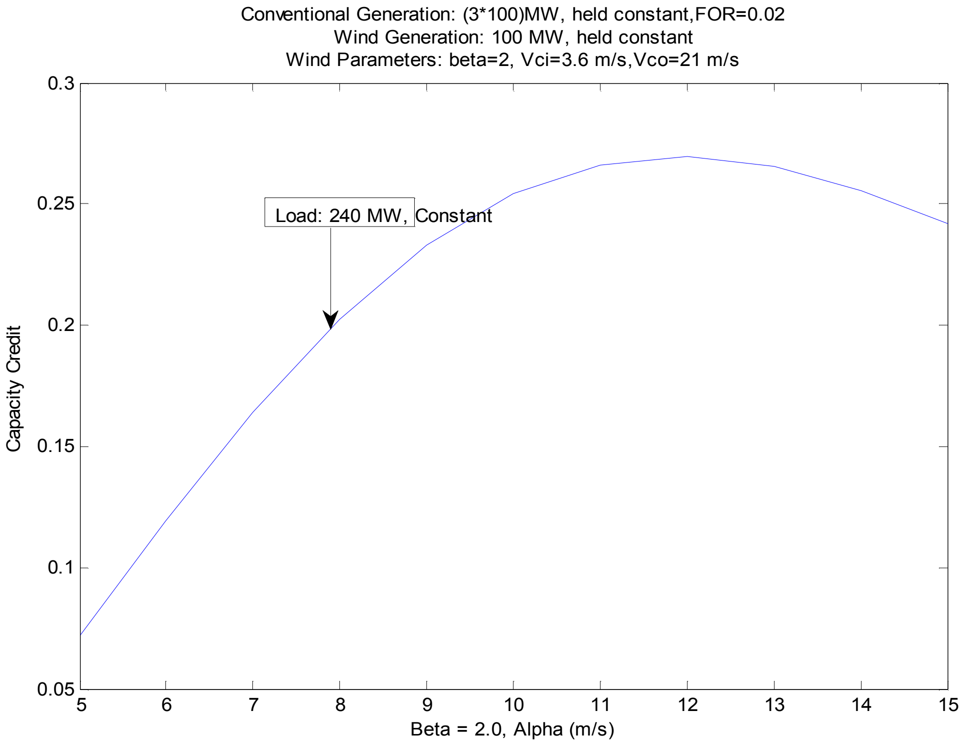


Figure 13: β = 2, Varying α

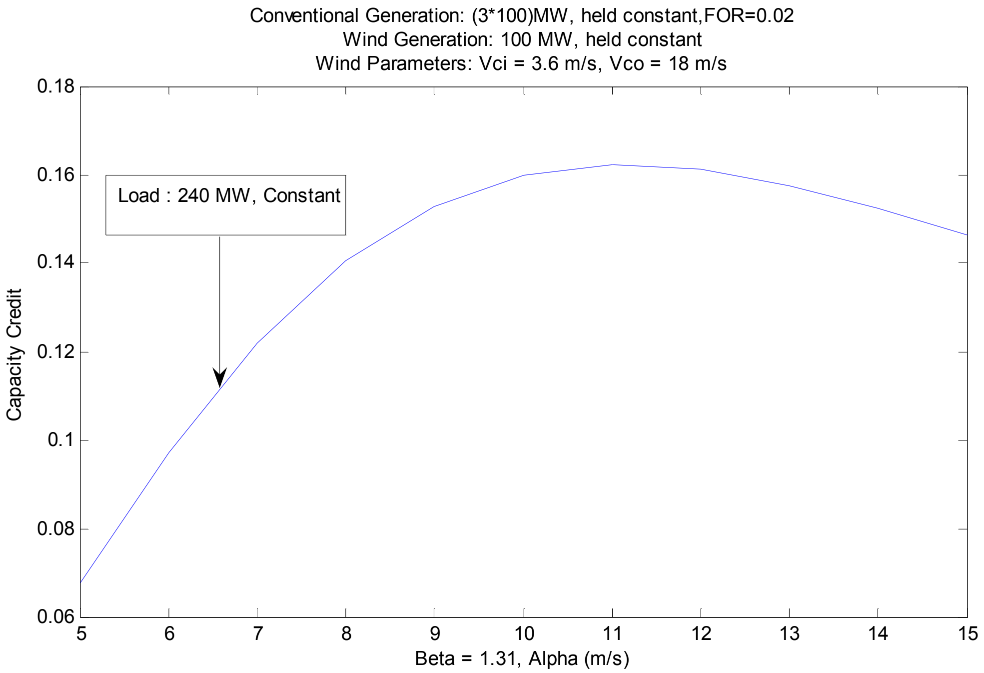


Figure 14: β = 1.31, Varying α

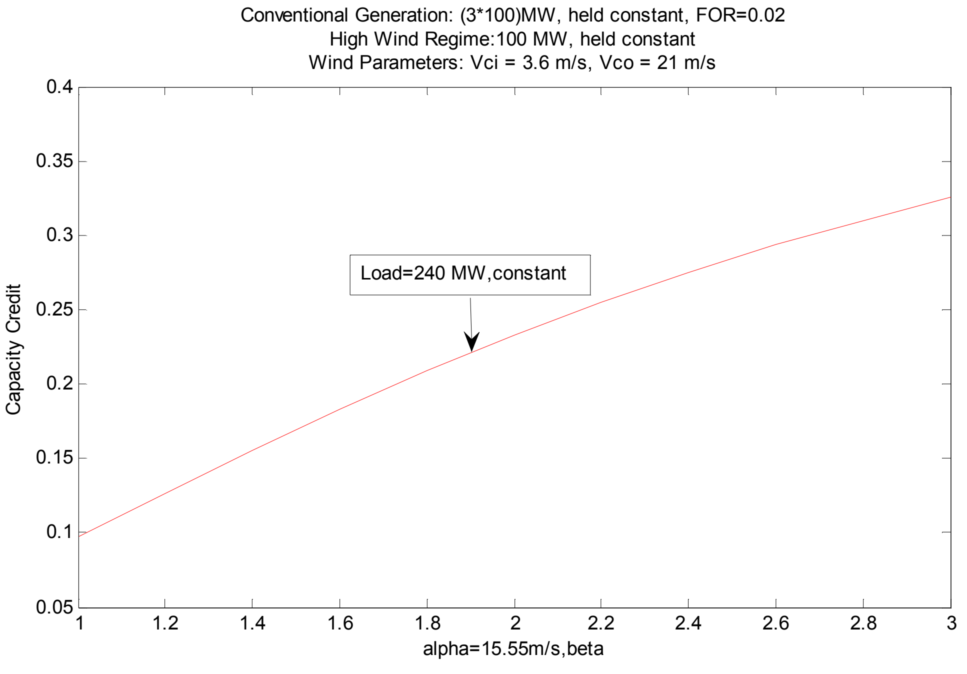


Figure 15: High Wind Speed – α = 15.55 m/s, Varying β

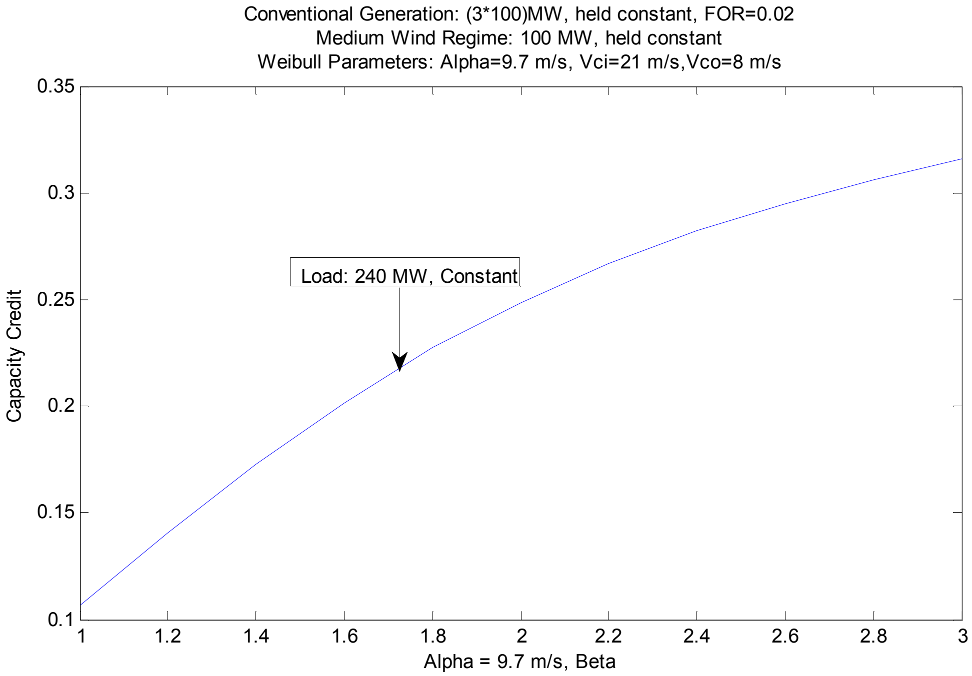


Figure 16: Moderate Wind Speed – $\alpha = 9.7$ m/s, Varying β

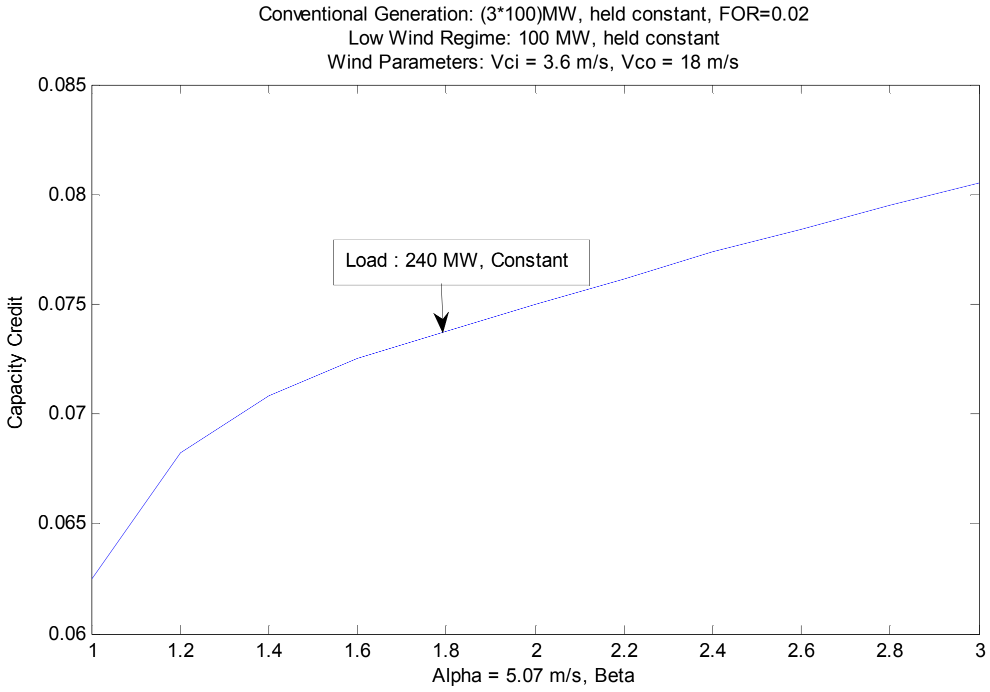


Figure 17: Low Wind Speed – $\alpha = 5.07$ m/s, Varying β

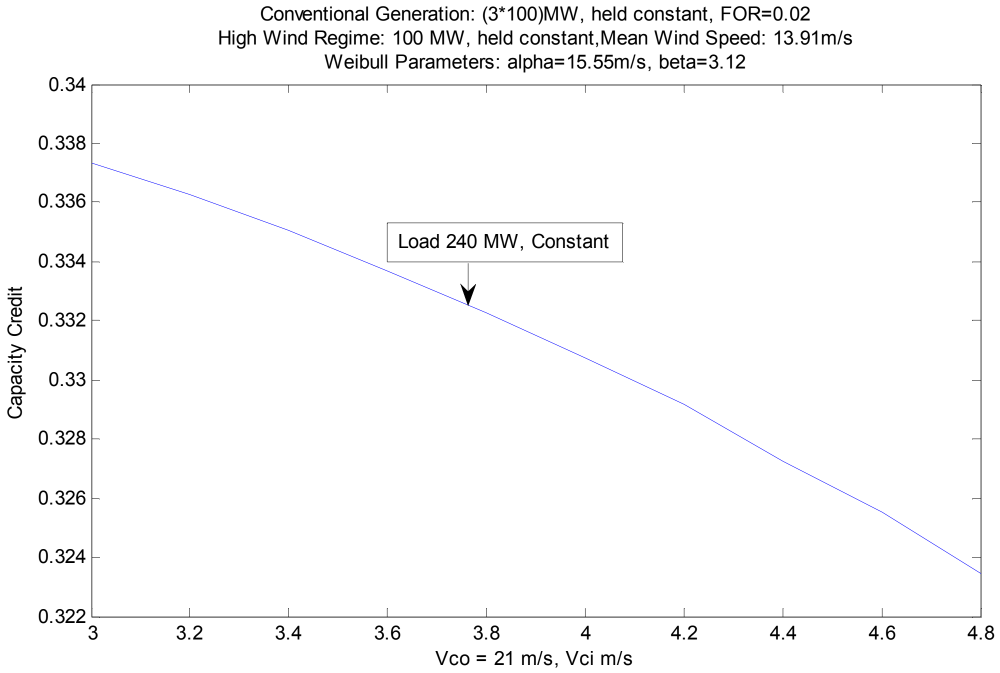


Figure 18: High Wind Speed – Varying V_{ci} constant V_{co}

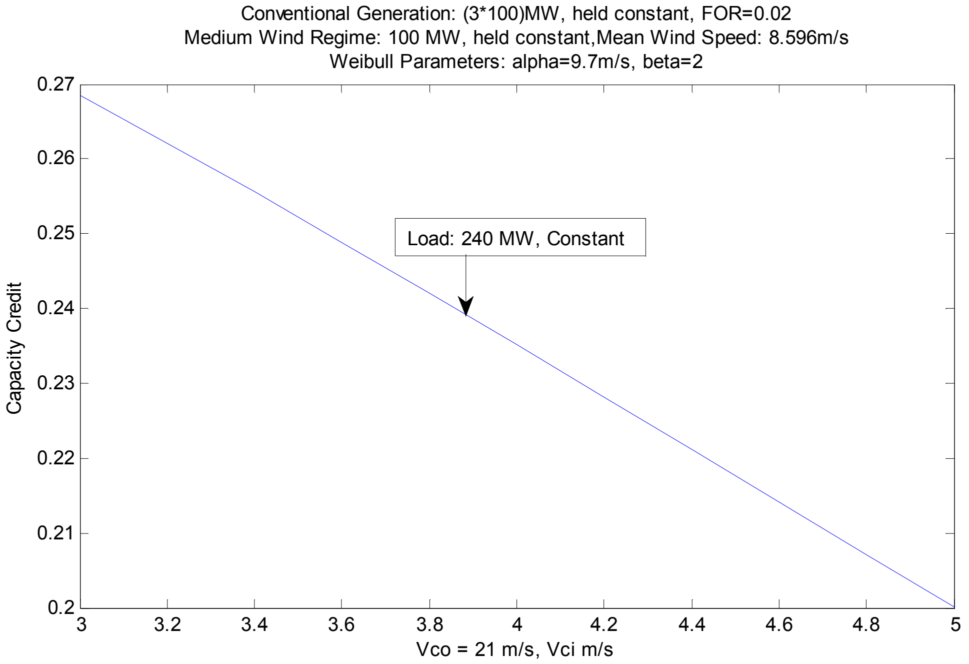


Figure 19: Moderate Wind Speed – Varying V_{ci} constant V_{co}

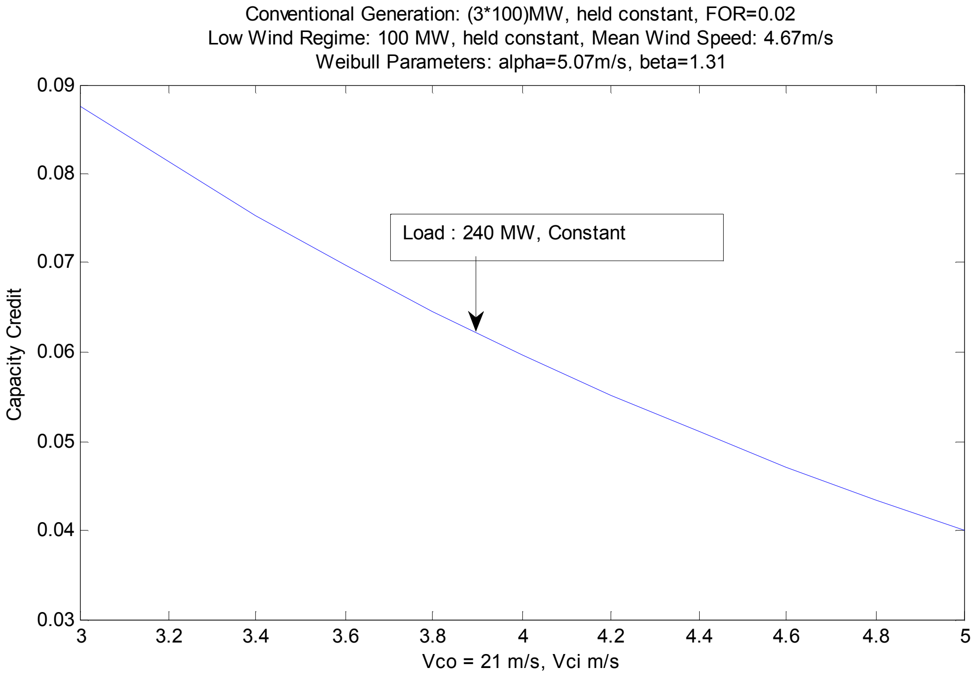


Figure 20: Low Wind Speed – Varying V_{ci} constant V_{co}

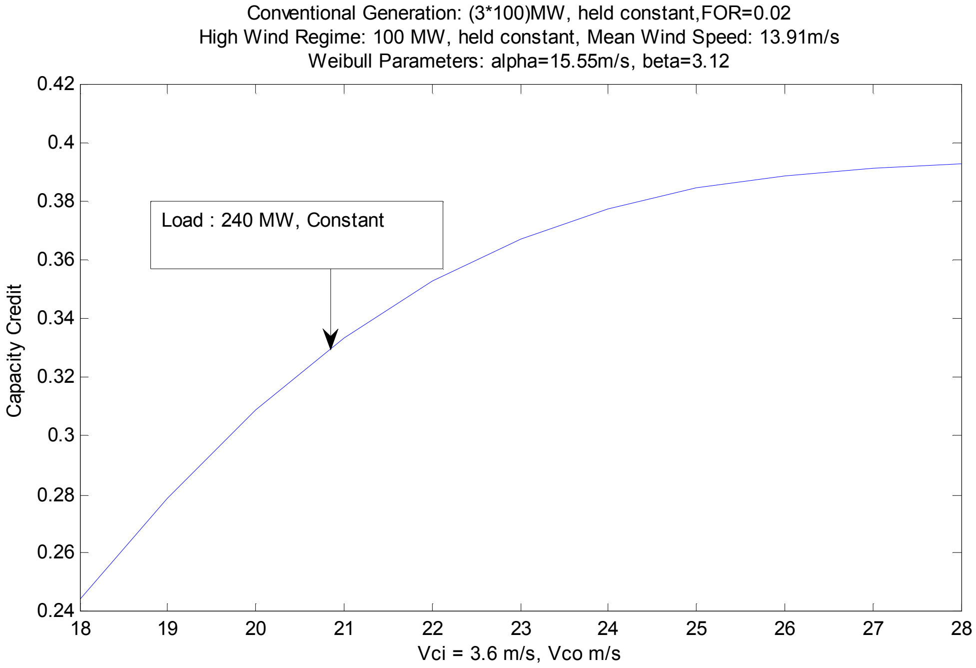


Figure 21: High Wind Speed – Varying V_{co} constant V_{ci}

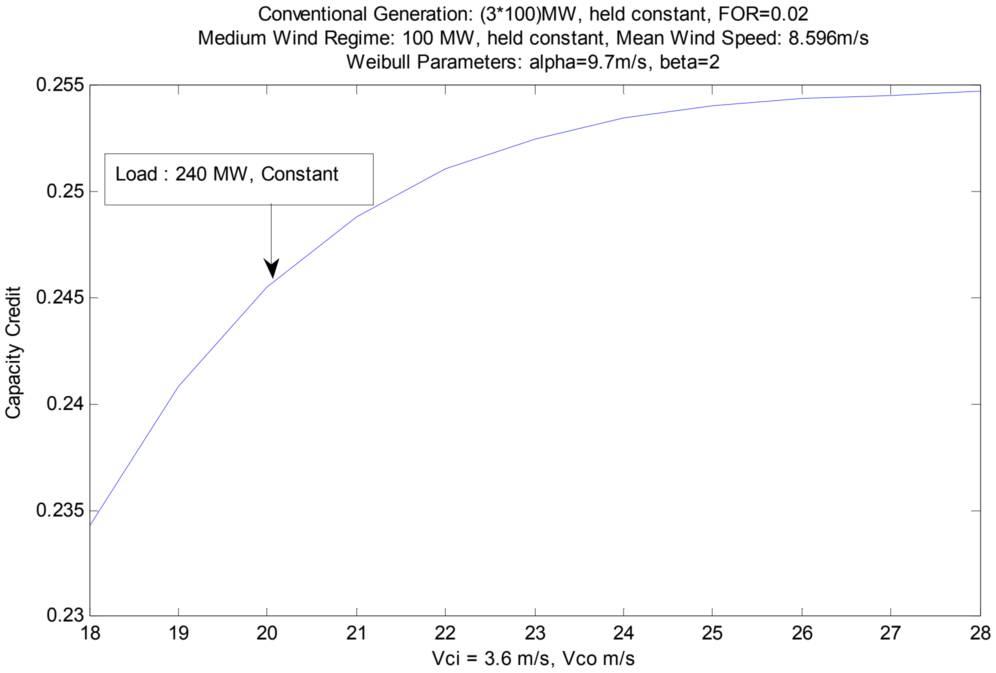


Figure 22: Moderate Wind Speed – Varying V_{co} constant V_{ci}

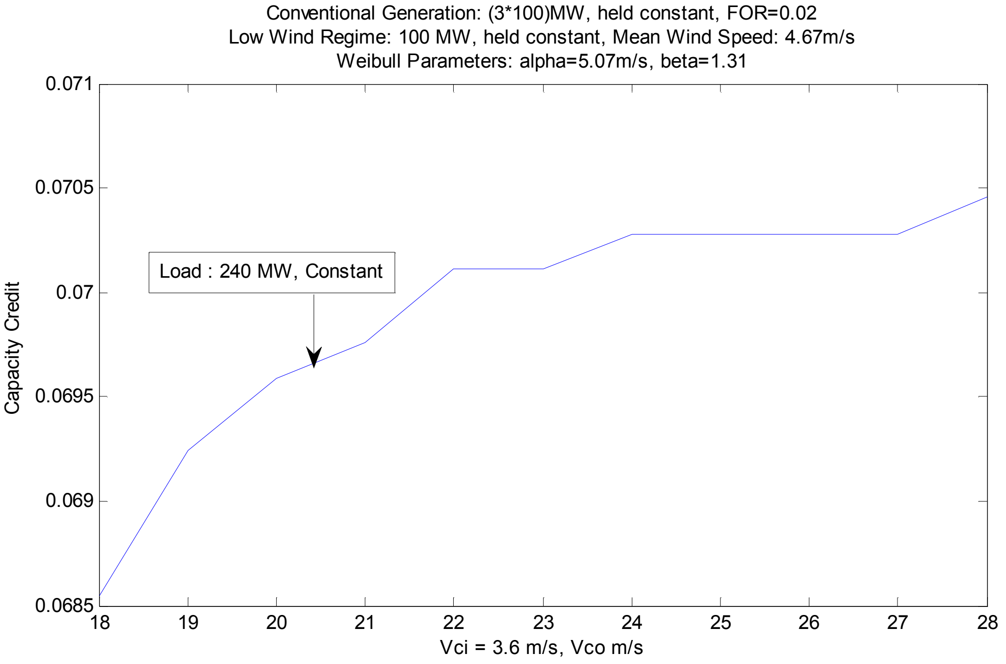


Figure 23: Low Wind Speed – Varying V_{co} constant V_{ci}

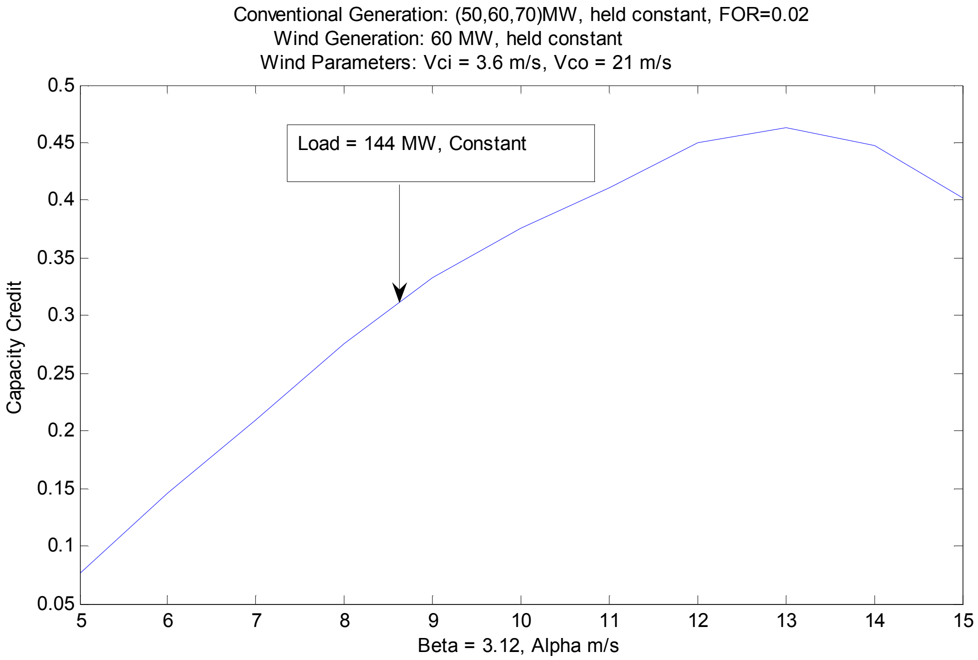


Figure 24: β = 3.12, Varying α

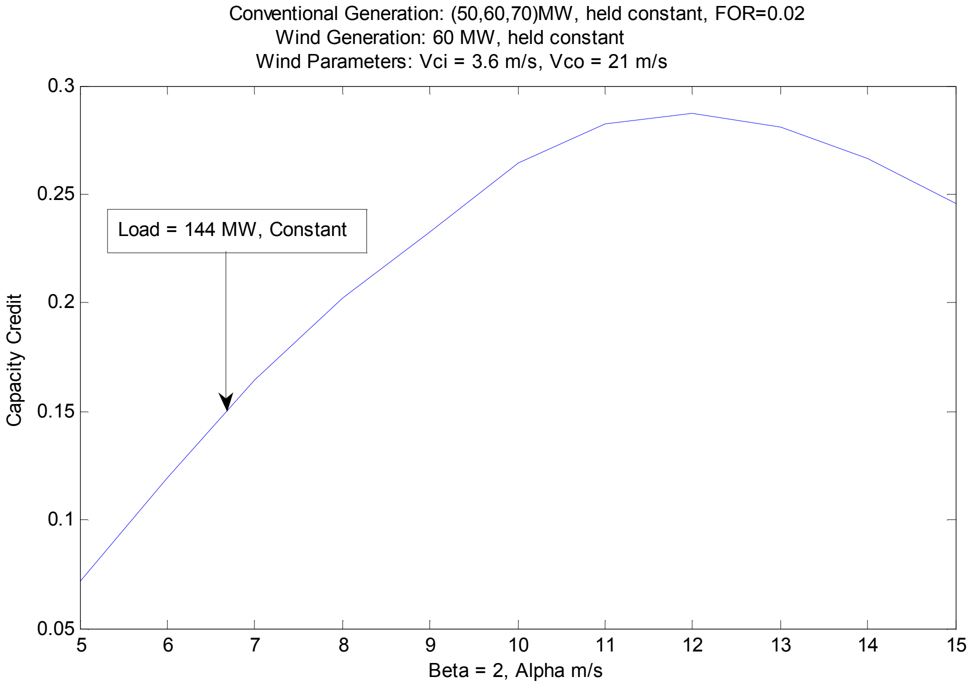


Figure 25: β = 2, Varying α

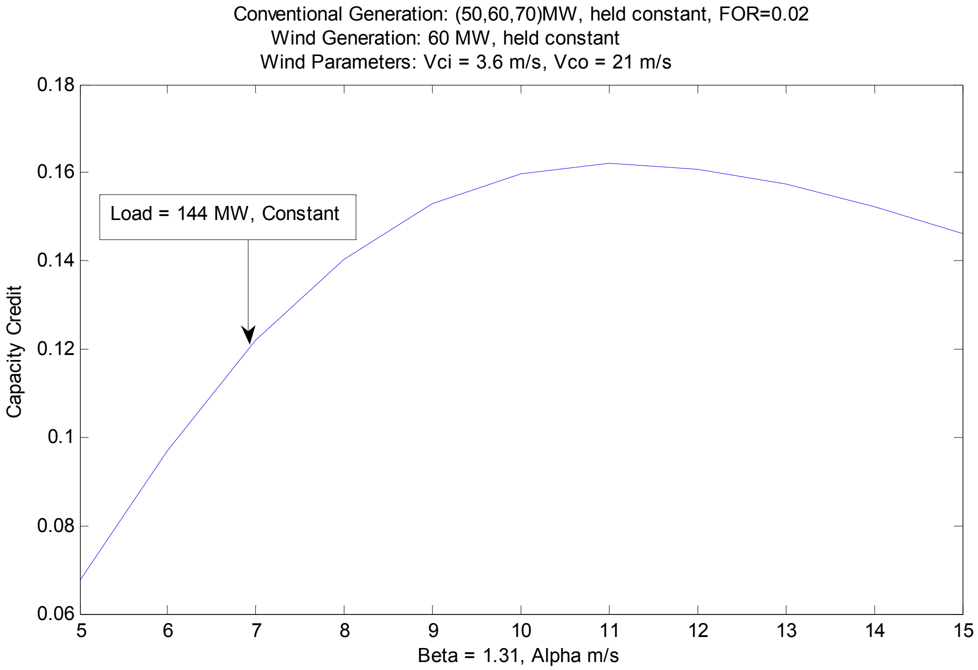


Figure 26: β = 1.31, Varying α

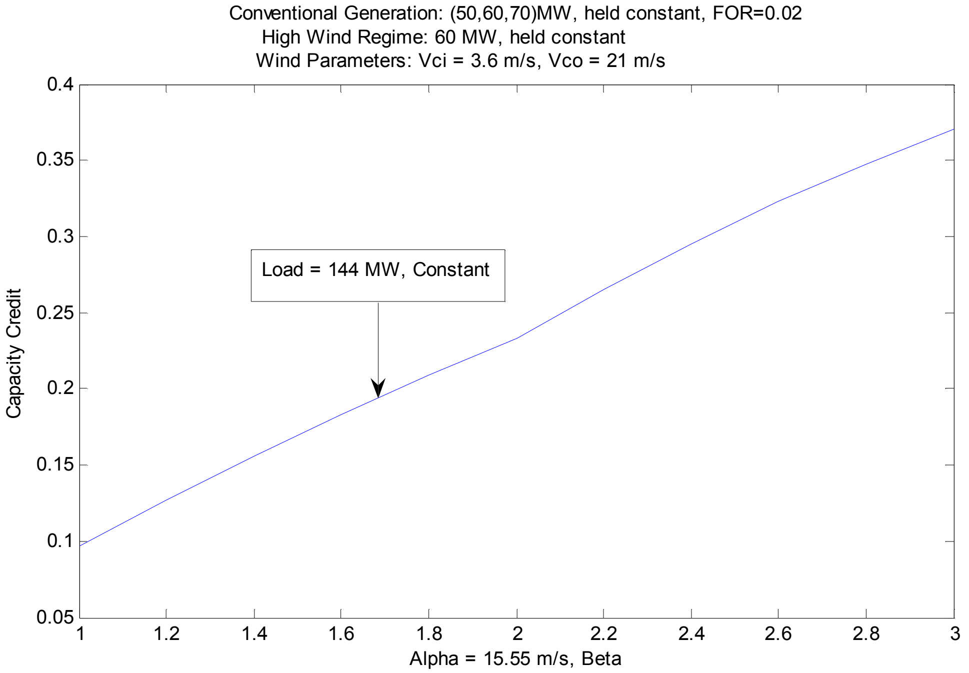


Figure 27: High Wind Speed – α = 15.55 m/s, Varying β

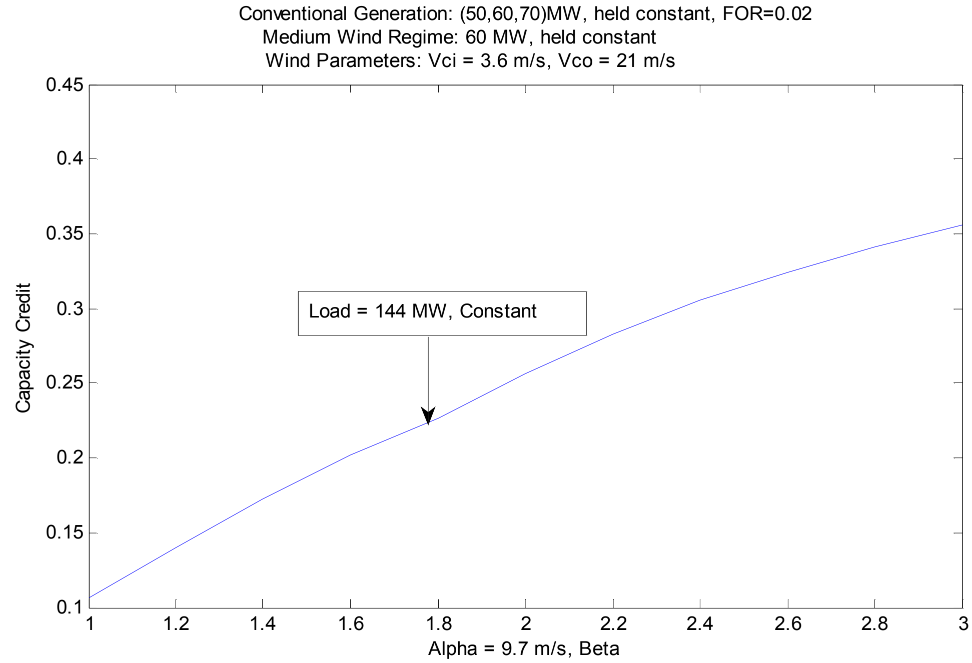


Figure 28: Medium Wind Speed – α = 9.7 m/s, Varying β

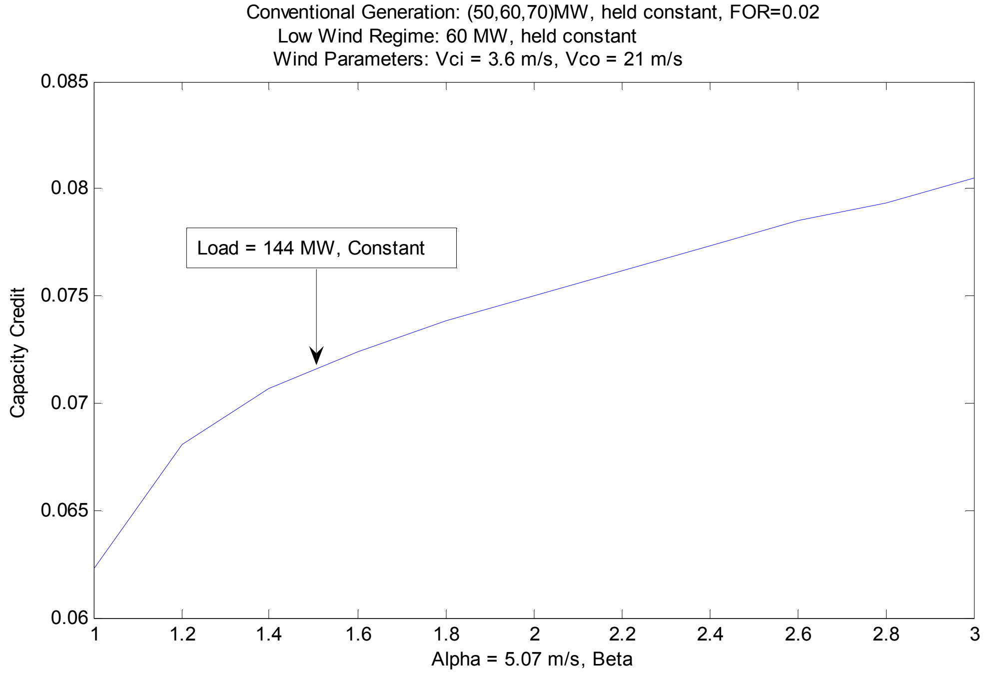


Figure 29: Low Wind Speed – α = 5.07 m/s, Varying β

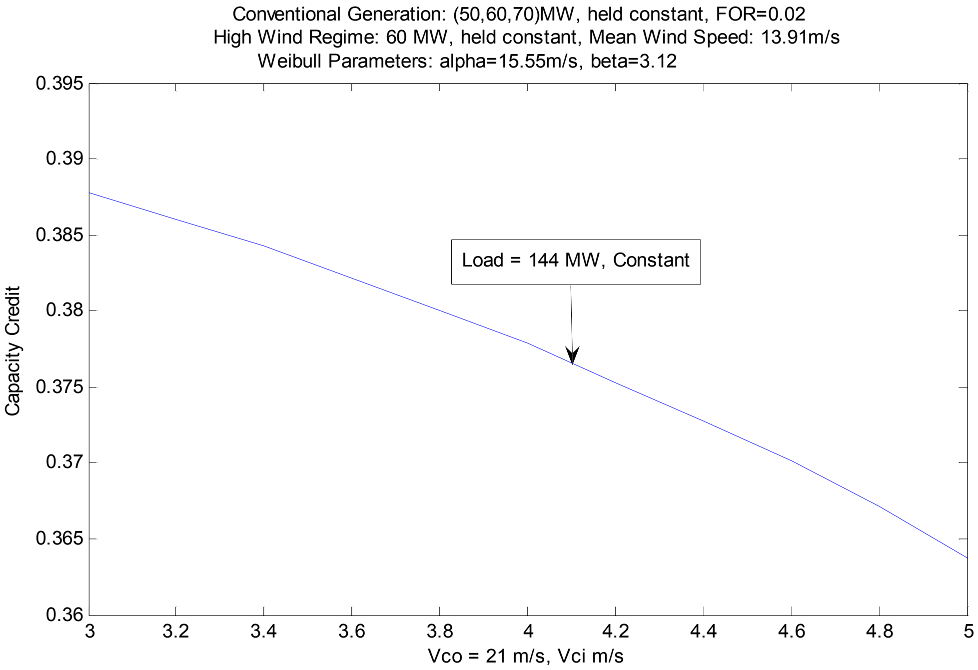


Figure 30: High Wind Speed – Varying V_{ci} constant V_{co}

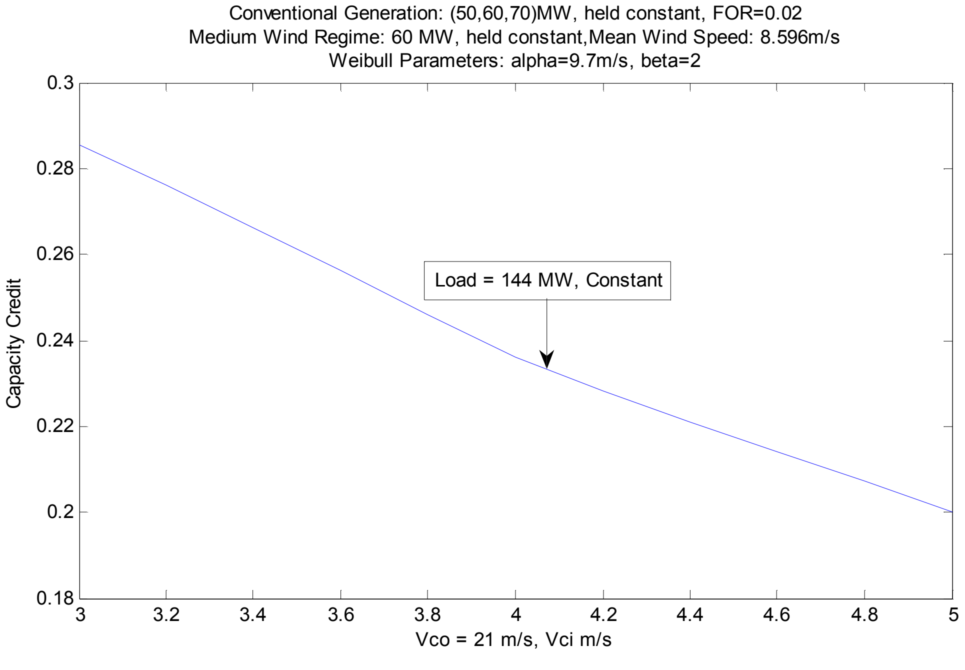


Figure 31: Medium Wind Speed – Varying V_{ci} constant V_{co}

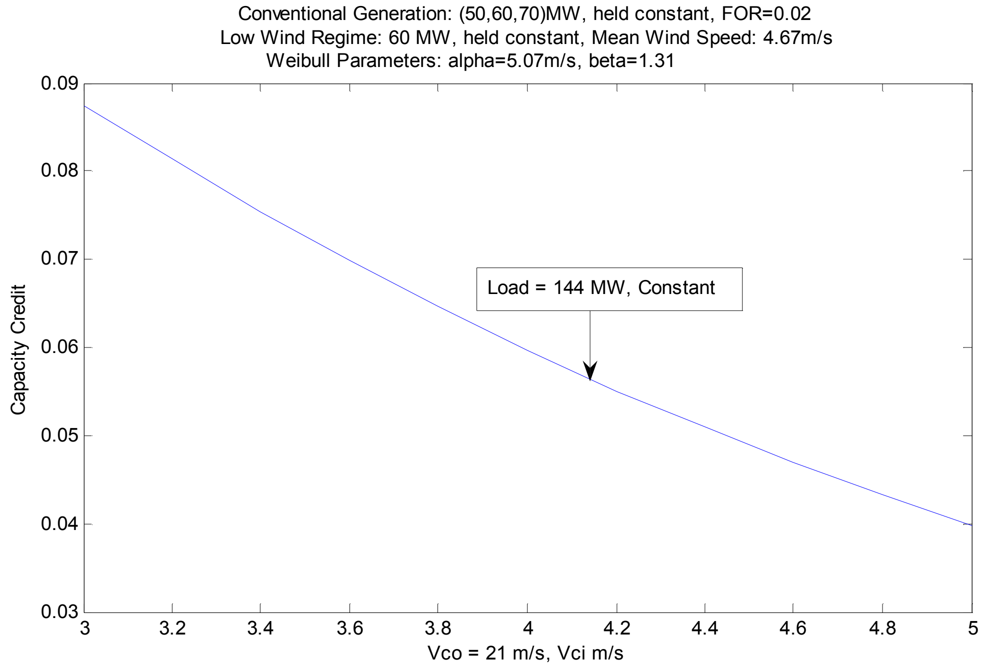


Figure 32: Low Wind Speed – Varying V_{ci} constant V_{co}

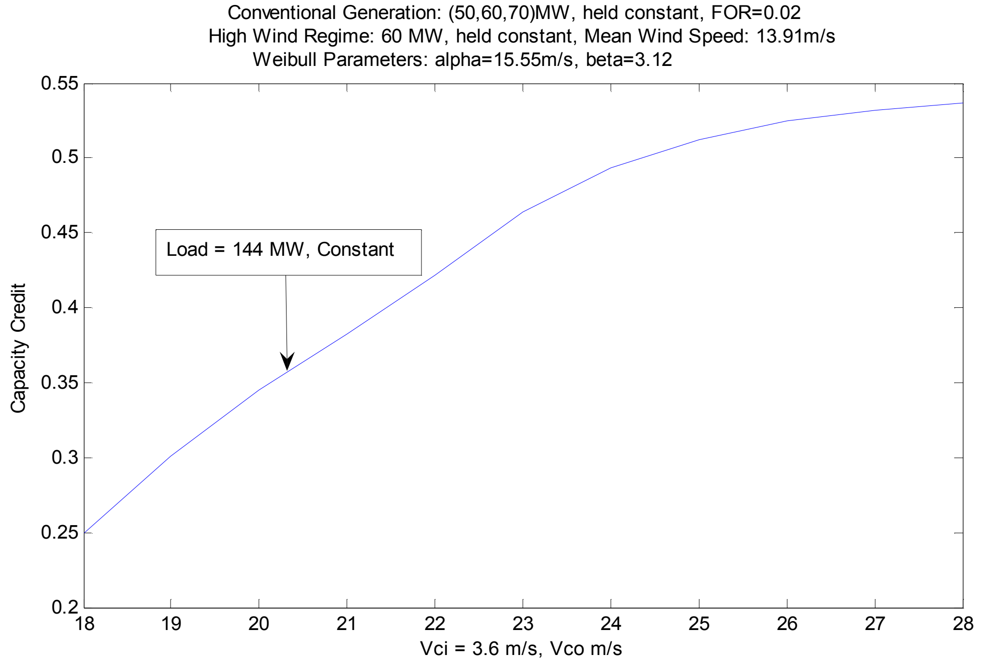


Figure 33: High Wind Speed – Varying V_{co} constant V_{ci}

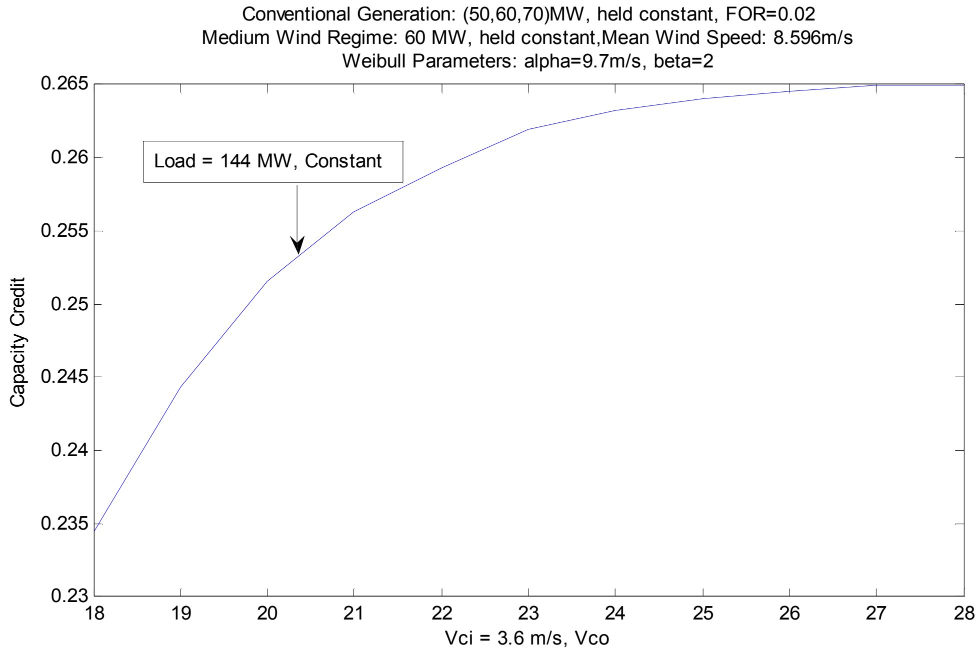


Figure 34: Medium Wind Speed – Varying V_{co} constant V_{ci}

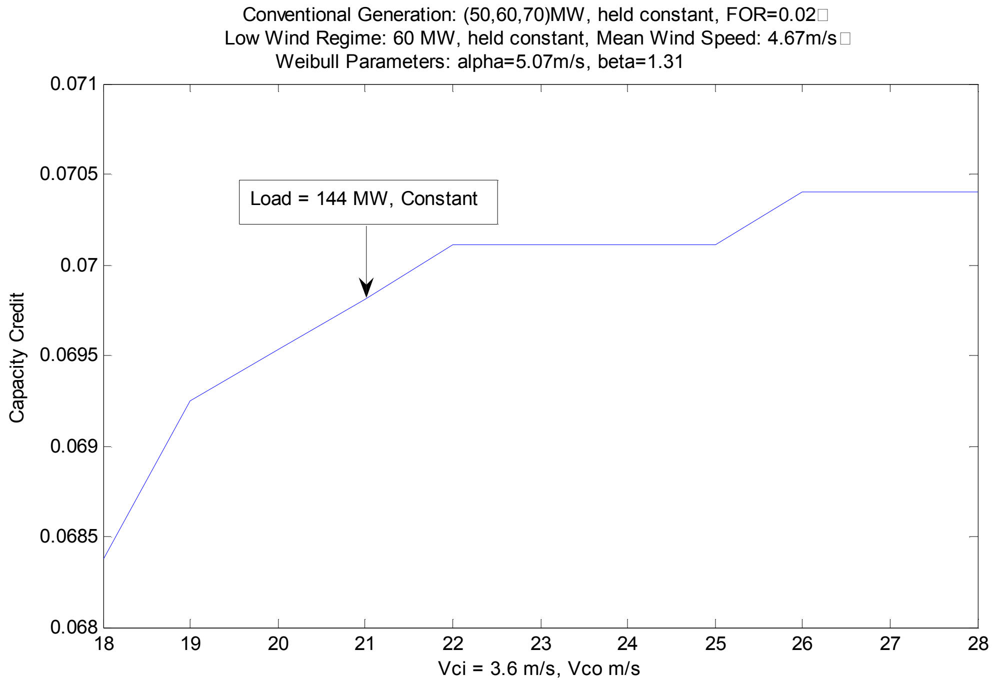


Figure 35: Low Wind Speed – Varying V_{co} constant V_{ci}

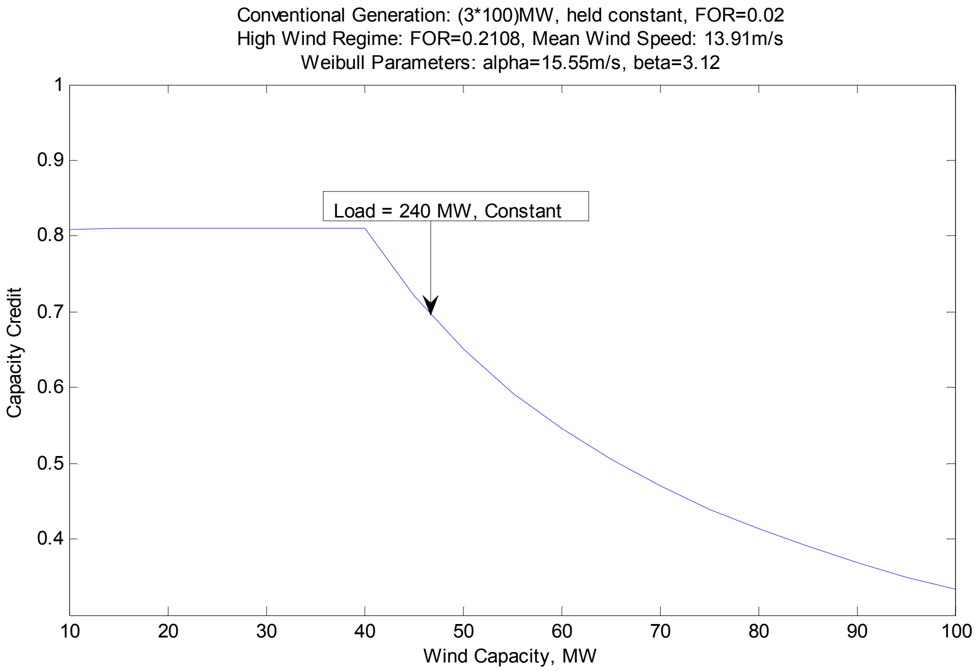


Figure 36: High Wind Speed – Varying wind capacity, constant load

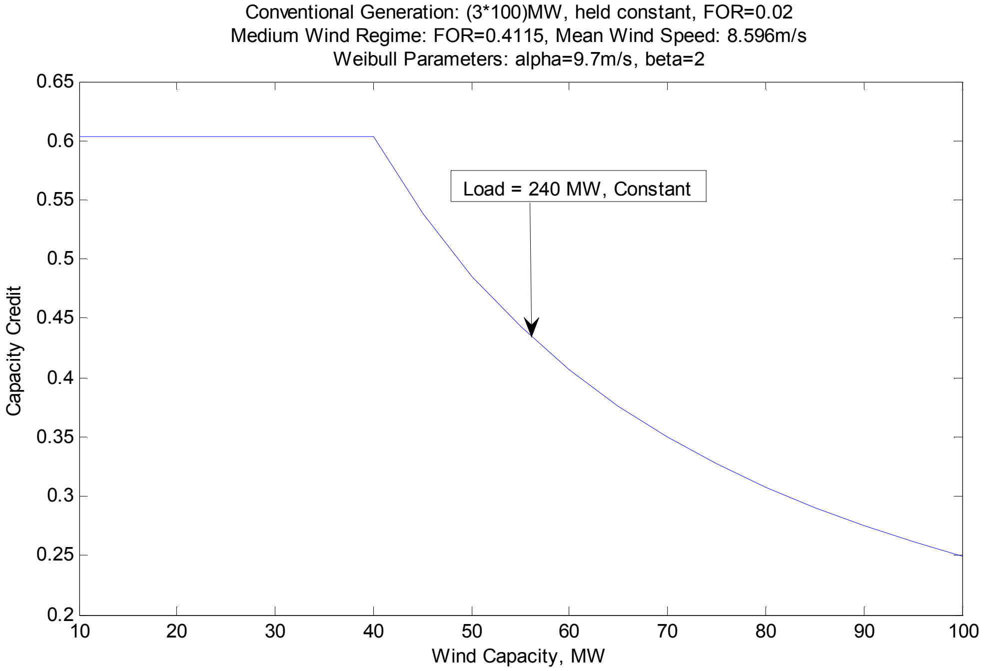


Figure 37: Medium Wind Speed – Varying wind capacity, constant load

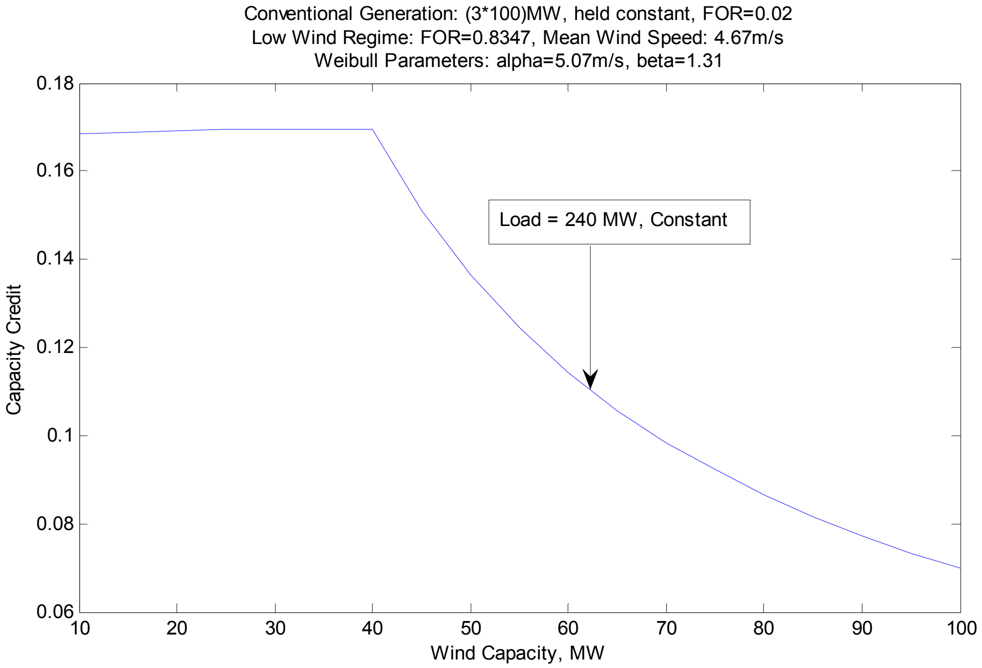


Figure 38: Low Wind Speed – Varying wind capacity, constant load

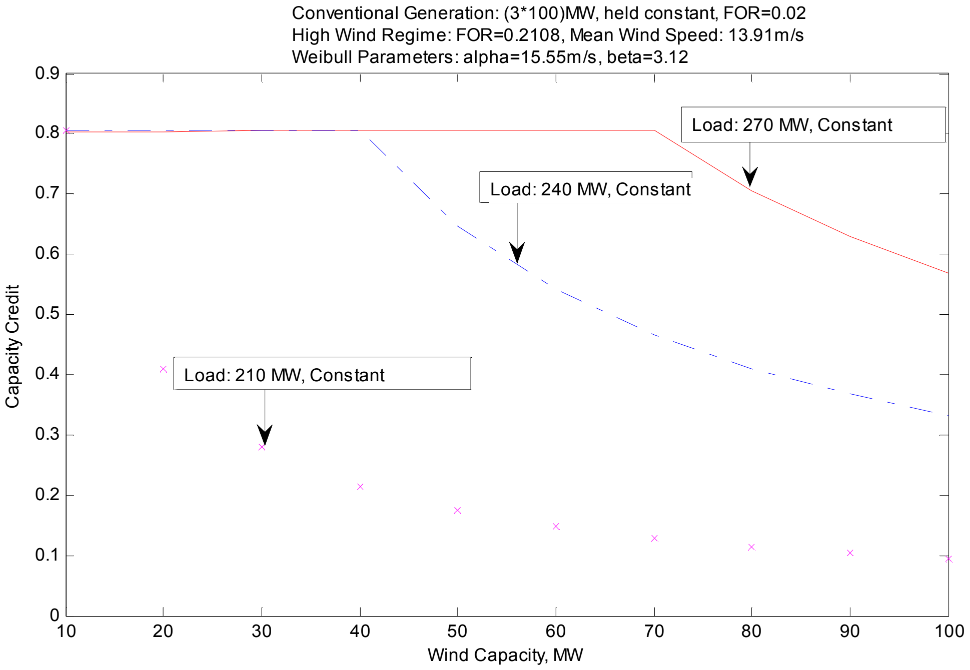


Figure 39: High Wind Speed – Varying Spinning Reserve

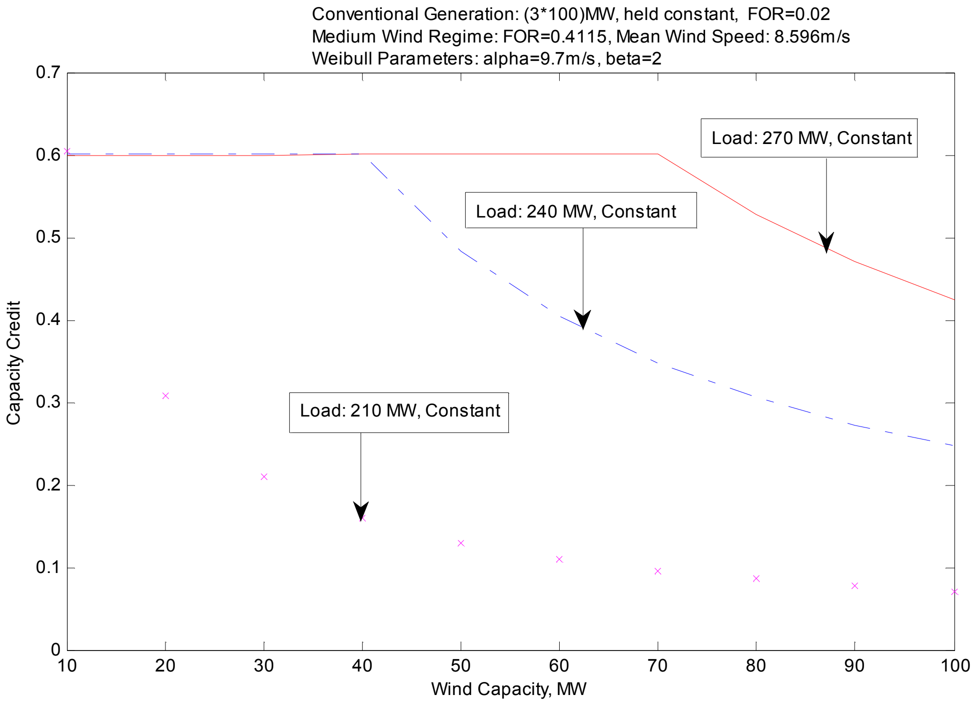


Figure 40: Medium Wind Speed – Varying Spinning Reserve

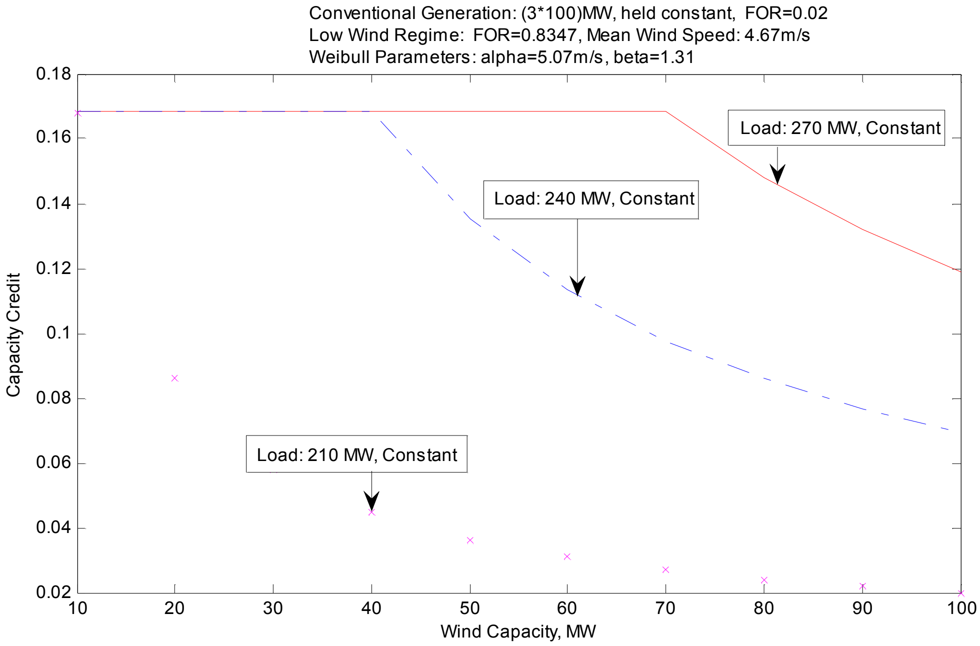


Figure 41: Low Wind Speed – Varying Spinning Reserve

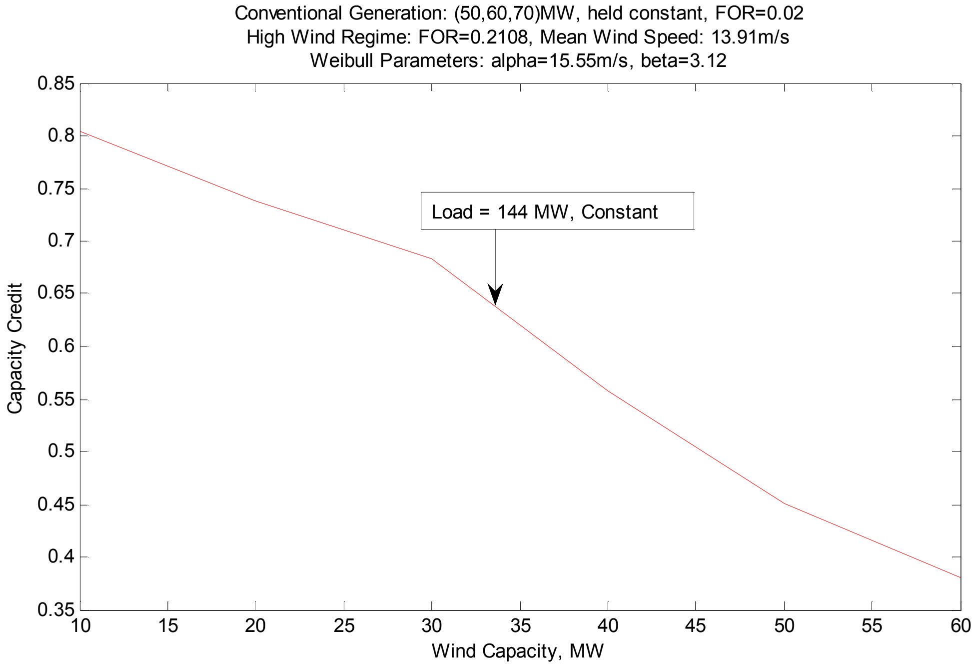


Figure 42: High Wind Speed – Varying wind capacity, constant load

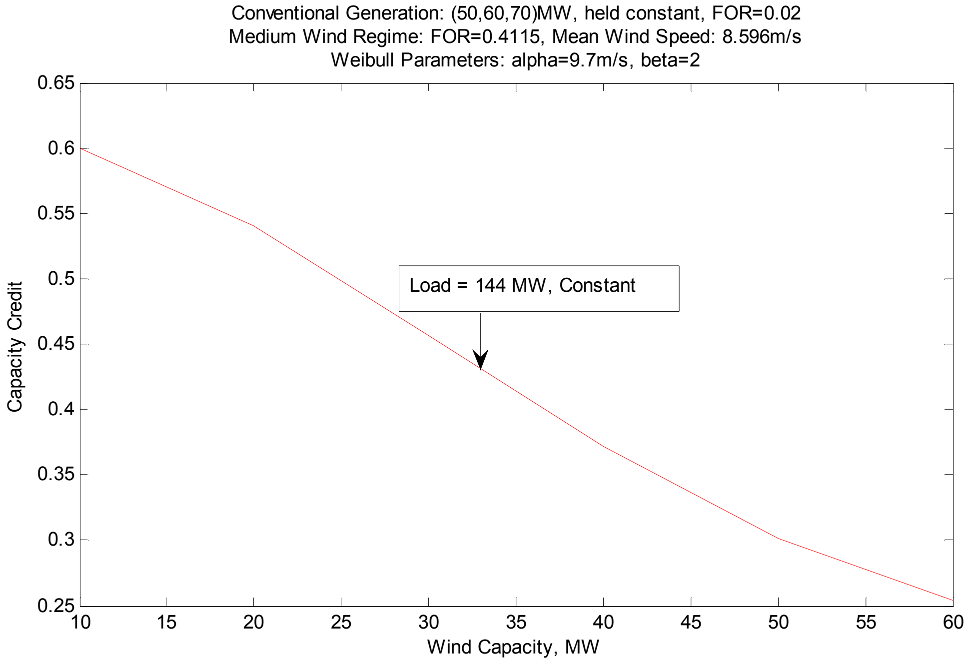


Figure 43: Moderate Wind Speed – Varying wind capacity, constant load

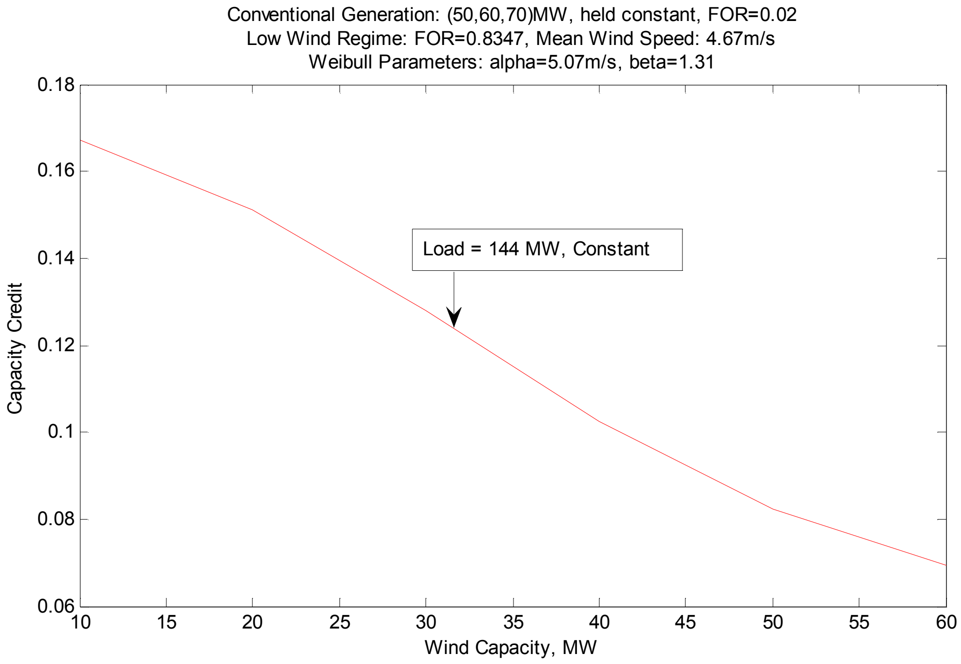


Figure 44: Low Wind Speed – Varying wind capacity, constant load

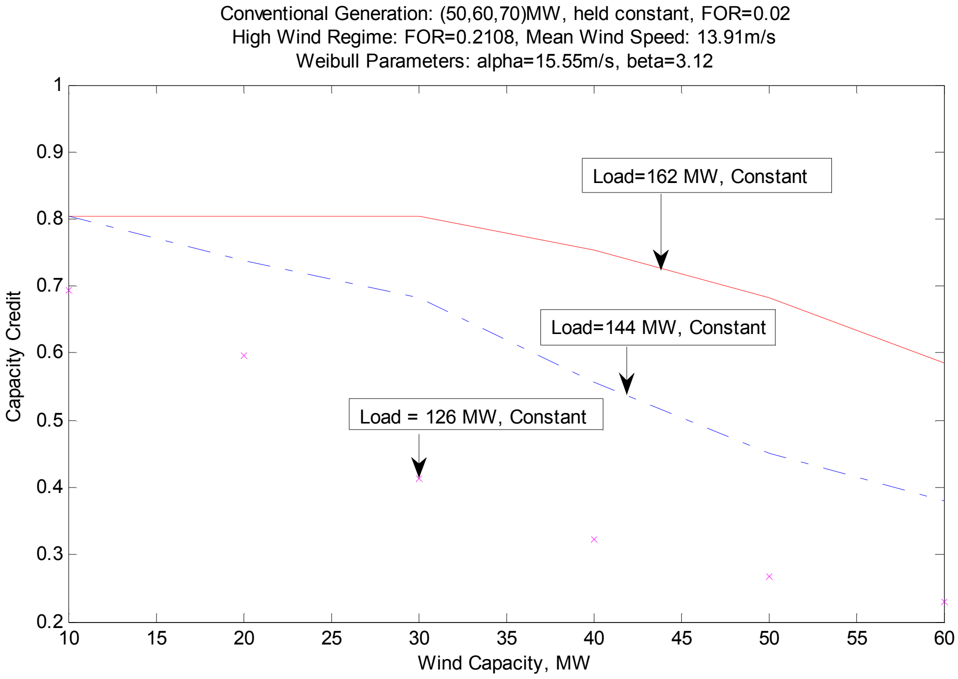


Figure 45: High Wind Speed – Varying Spinning Reserve

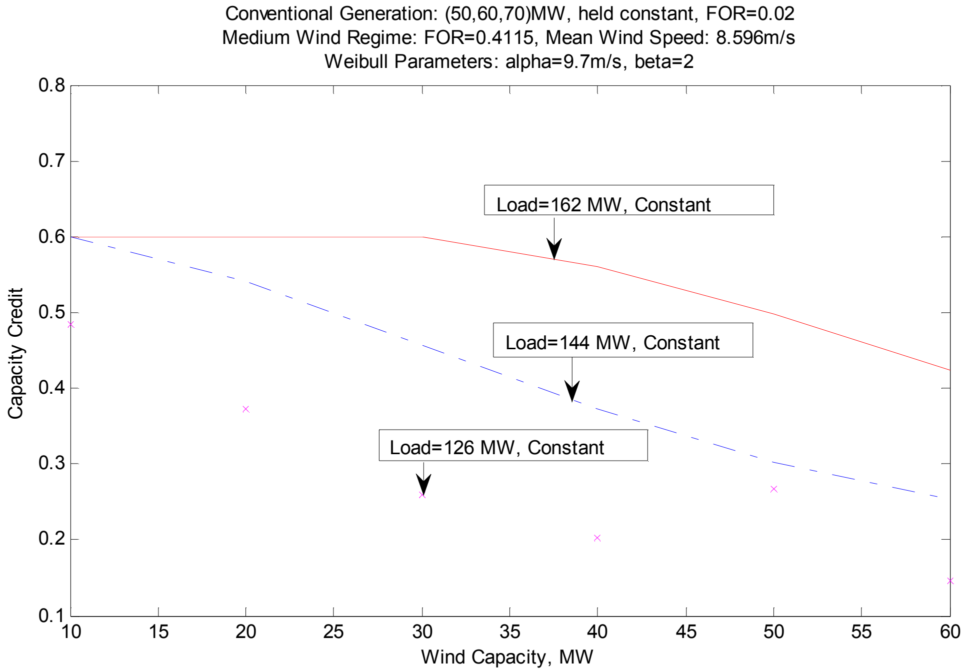


Figure 46: Moderate Wind Speed – Varying Spinning Reserve

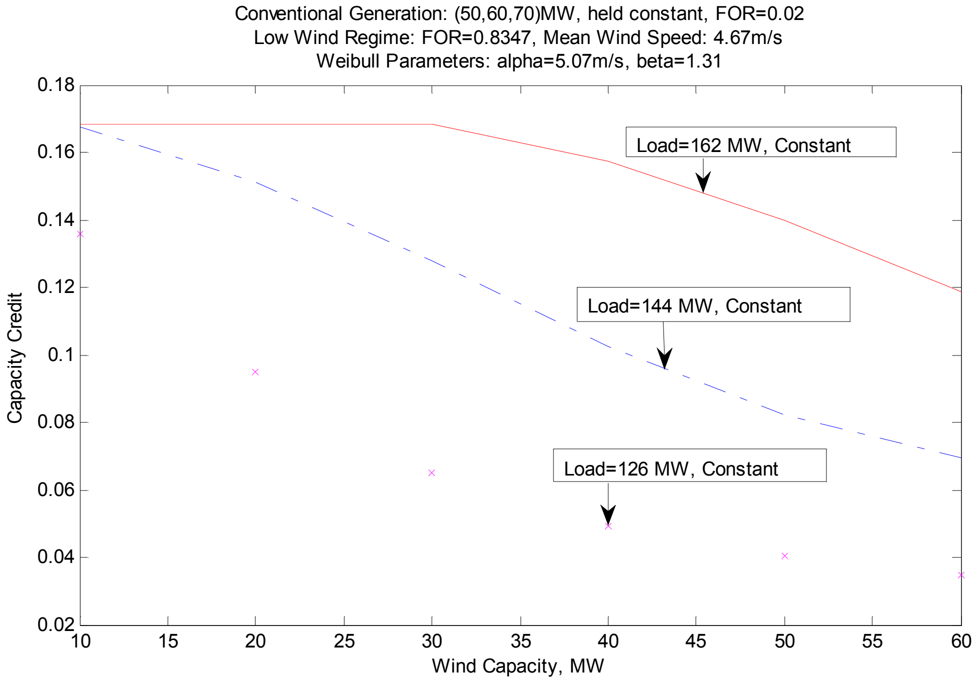


Figure 47: Low Wind Speed – Varying Spinning Reserve

4.4 Discussion of Simulation Results:

The study was undertaken to quantify the impact of wind parameters, wind penetration, amount of spinning reserve, and wind turbine output characteristics on capacity credit.

The results are presented in Figures 12-47 for the three chosen wind regimes. As the scale factor α increases, the capacity credit increases initially and then decreases for high values of α as shown in Figures 12-14. Figures 15-17 shows a steady rise in capacity credit with increasing β at all the three wind speeds. As V_{ci} increases, the capacity credit decreases because the wind availability factor decreases with the increase in V_{ci} for all three wind regimes as shown in Figures 18-20. With increasing $V_{co,}$ the operational wind speed range increases, rated power is available over a larger range of wind speeds and hence capacity credit increases as shown in Figures 21-23. The same results apply for dissimilar conventional generators as shown in Figures 24-35.

The impact of wind power on system adequacy increases significantly as the capacity of the connected wind farm is increased. Figures 36-38 shows that the capacity credit of a wind farm decreases rapidly as more wind capacity is added to the system for all three wind regimes. The results were obtained by adding gradually more wind capacity without changing the reliability level of the system. Figures 42-44 show the same results as explained above for the system consisting of dissimilar conventional generators.

The variation of capacity credit with change in spinning reserve is shown in Figures 39-41. As spinning reserve increases, capacity credit decreases for all three wind regimes. For smaller values of spinning reserve the capacity credit remains the same for smaller values of wind capacity and decreases gradually as wind capacity increases. The same is true for the system consisting of dissimilar conventional generators as can be seen from the Figures 45-47.

CHAPTER V

SUMMARY AND CONCLUDING REMARKS

5.1 Summary and Concluding Remarks

Generation of electricity from wind has become commonplace over the last few decades and its impact on overall system operation is becoming increasingly important at various levels. Quantification of capacity credit is very important because of its direct economic impact. This study has presented a simple approach to assess the capacity credit of wind electric conversion systems. The method employs the effective forced outage rate of a wind generator and uses the classic loss of load probability calculations to estimate the capacity credit of WECS.

Variation of capacity credit with penetration levels, amount of spinning reserve, wind parameters and wind turbine output characteristics are studied. A simple generation system model is used to calculate the capacity credit in three steps using matlab code. In the generation system, WECS and conventional generators are assumed to have a rating of 100 MW each and a system load of 240 MW is considered.

In addition to being simple, the approach is general enough to consider units of any rating and any location. The influence of Weibull parameters, cut-in speed, cut-out speed, wind penetration, and spinning reserve are presented graphically for different low, medium and high wind regimes. The graphs show the sensitivity of capacity credit to different key parameters. The range of capacity credit obtained in this study is between 0.07 and 0.81. The high value of 0.81 is for an excellent (high) wind regime and low wind penetration and the low value of 0.07 is for a poor (low) wind regime and high wind penetration.

The approach presented can be used to obtain initial estimates of capacity credit for use in preliminary reserve planning. More detailed analyses will be necessary in a practical situation.

5.2 Scope for Future Work

The study assumes a constant load but in reality load also changes. The impact of variable load on the capacity credit is left for future work. The correlation, if any, between wind availability and load curve is an important factor. This can be included only with chronological simulation. In practice, wind parameters (both shape and scale parameters) will be changing throughout the day in addition to seasonal variations. The net effect of such variations on the capacity credit value needs further examination and study.

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APPENDIX A

FOR of Wind Electric Conversion Systems

By approximating the non-linearity in the power curve for wind speeds between V_{ci} to V_r to a straight line, equation for the power output can be obtained as follows

$$P = \begin{cases} P_r\left(\dfrac{V - V_{ci}}{V_r - V_{ci}}\right) & for\ V_{ci} \le V \le V_r \\ P_r & for\ V_r \le V \le V_{co} \\ 0 & elsewhere \end{cases}$$

Using P_r as the base value, equation (2) is normalized as

$$P = \begin{cases} \left(\frac{V - V_{ci}}{V_r - V_{ci}}\right) & for\ V_{ci} \le V \le V_r \\ 1 & for\ V_r \le V \le V_{co} \\ 0 & elsewhere \end{cases}$$

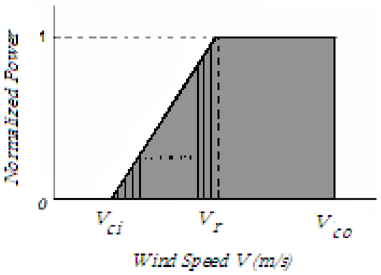

Figure 48: Approximated Power Output Curve

To determine FOR, wind availability factor, constant power output factor and variable power output factor should be calculated.

***Wind Availability Factor* (P_{WA}):** It is defined by the probability that wind speed is between cut-in and cut-out values.

$$\text{Wind Availability Factor} = P\left(V_{ci} \le V \le V_{co}\right) = P_{WA}$$

$$P_{WA} = \exp\left[-\left(\frac{V_{ci}}{\alpha}\right)^{\beta}\right] - \exp\left[-\left(\frac{V_{co}}{\alpha}\right)^{\beta}\right]$$

***Constant Power Output Factor* (P_{Const}):** Since rated power output results for wind speeds between V_r and V_{co}, the expected normalized power output in this speed range will be the probability of the wind speed lying in this speed range.

$$P_{Const} = \exp\left[-\left(\frac{V_r}{\alpha}\right)^{\beta}\right] - \exp\left[-\left(\frac{V_{co}}{\alpha}\right)^{\beta}\right]$$

***Variable Power Output Factor* (P_{Var}):** Expected value of normalized power output over the speed range from V_{ci} to V_r can be calculated by dividing the region from V_{ci} to V_r into n small intervals as shown in Figure 2. The probability that the wind speed is between any two values, say V_1 and V_2 (Figure 3), will be

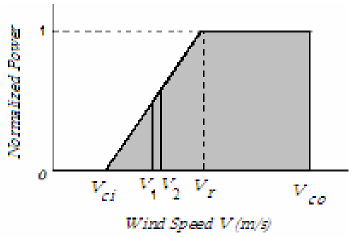

Figure 49: Expected Power Output Calculation for the Variable Portion

$$a_1 = P\left(V_1 \le V \le V_2\right) = \exp\left[-\left(\frac{V_1}{\alpha}\right)^{\beta}\right] - \exp\left[-\left(\frac{V_2}{\alpha}\right)^{\beta}\right]$$

Then, the expected normalized power output over the speed range from V_{ci} to V_r will be

$$P_{var} = \sum E\left(P_{1,2}\right)$$

$$E(P_{1,2}) = a1 * \frac{\left(\frac{V1+V2}{2}\right) - V_{ci}}{(V_r - V_{ci})}$$

Factor for mechanical failures (P_{mech}): Forced outage rate for a mechanical component with a constant failure rate of 'λ' per hour and a mean repair time of 'r' hours is given by,

Forced outage rate = λ*r

$$FOR_{Mech} = \sum_i \lambda_i r_i$$

$$P_{Mech} = 1 - FOR_{Mech}$$

Reliability Model for WECS:

Reliability R for a WECS can be expressed as $R = P_{WA} * E\left(P\right) * P_{Mech}$

Where $E(P) = P_{Var} + P_{Const}$

Then, the overall forced outage rate for the WECS output will be

$$FOR_{Pow} = 1 - R$$

Thus the forced outage rate for wind-generated electricity is determined based on the approximated power output curve for WECS and the failure and repair rates of mechanical components. Using the Weibull probability density function and cumulative distribution function equations; general key factors are defined and expressed mathematically.

APPENDIX B

MATLAB CODE FOR SENSITIVITY ANALYSES

B.1 Program Listing

```
function Forced_Outage_Rate_Power =

Forced_Outage_Rate(Alpha,Beta,Vci,Vr,Vco,FailuresPerYear,RepairHoursPerFailure)

Interval = (Vr-Vci)/50;

V=Vci;

for i=1:50

   V_New=V+Interval;

   Probability(i,:)=exp(-(V/Alpha)^Beta) - exp(-(V_New/Alpha)^Beta);

   Power(i,:)= ((V_New+V)/2-Vci)/(Vr-Vci);

   V=V_New;

end


%%%Calculate different factors affecting availability of WECS output

Variable_Output_Factor=Probability'*Power;

Constant_Output_Factor=exp(-(Vr/Alpha)^Beta) - exp(-(Vco/Alpha)^Beta);

Expected_Power_Output=Variable_Output_Factor+Constant_Output_Factor;

Wind_Availability_Factor=exp(-(Vci/Alpha)^Beta) - exp(-(Vco/Alpha)^Beta);

Failure_Rates=FailuresPerYear./8760;
```

```
Forced_Outage_Rate_Mech=RepairHoursPerFailure*Failure_Rates';

Reliability_Power=Wind_Availability_Factor*(1-

Forced_Outage_Rate_Mech)*Expected_Power_Output;

Forced_Outage_Rate_Power=1-Reliability_Power;

function truth_table = truthtable(nb_possibles)

truth_table = [];

for k = 0:(nb_possibles -1)

    x = dec2binvec(k,log2(nb_possibles));

    truth_table = [truth_table; x];

end

truth_table = flipud(truth_table);

function out = dec2binvec(dec,n)

out = dec2bin(dec,n);

pre = logical(str2num([fliplr(out);blanks(length(out))]')');

out = pre(end:-1:1);


%%% calculate expected loss of load

no_generators=input('Enter Number of generators: ');

Alpha=input('Enter the value of Alpha: ');

Beta=input('Enter the value of Beta: ');

Vci=input('Enter the value of Cut In Voltage: ');

Vco=input('Enter the value of Cut Out Voltage: ');

Vr=input('Enter the value of Rated Voltage: ');
```

```
FailuresPerYear=input('Enter the number of failures per year: ');
RepairHoursPerFailure=input('Enter the number of Repair Hours per failure: ');
no_entries=2^no_generators;
Cin=zeros(no_entries,1);
Cout=Cin;
Pro=Cin;
Pro2=Cin;
Loadloss=Cin;
Truth_Table=zeros(no_entries,no_generators);
Cap=zeros(1,no_generators);
Forced_Outage=Cap;
for i=1:no_generators-1
   Cap(1,i)=input('Enter the value of the capacity of generator: ');
   Forced_Outage(1,i)=input('Enter the value of the Forced Outage rate of the generator : ');
end
min_wind=10;
Wind_Cap=input('Enter the value of the capacity of wind generator: ');
max_wind=roundn((sum(Cap)+Wind_Cap)/4,0);
Cap(1,i+1)=min_wind;
Wind_range=zeros(1,roundn((max_wind-min_wind)/5,0)+1);
Wind_Forced_Outage_Rate=Forced_Outage_Rate(Alpha,Beta,Vci,Vr,Vco,FailuresPerYear,RepairHoursPerFailure);
```

```
L=input('Enter the value of Required Load: ');

k=0;

for x=min_wind:5:max_wind

   k=k+1;

   Cap(1,no_generators)=x;

   Forced_Outage(1,no_generators)=Wind_Forced_Outage_Rate;

   Truth_Table=truthtable(no_entries);

   Pro1=zeros(no_entries,no_generators);


%%% Calculate Probability Matrix


   for i=1:no_entries

      for j=1:no_generators

         if Truth_Table(i,j)== 0

            Pro1(i,j)=Forced_Outage(1,j);

         else

            Pro1(i,j)=1-Forced_Outage(1,j);

         end

      end

   end

   Pro2 = prod(Pro1,2);


%%% Calculate Capacity In
```

```
   Cin=Truth_Table*Cap';


%%% Calculate Capacity Out

    Cout=flipud(Cin);


%%% Calculate Load Loss

  for i=1:no_entries

      if Cin(i,1)> L

          Loadloss(i,1)=0;

      elseif Cin(i,1)<L

          Loadloss(i,1)=L-Cin(i,1);

      else

          Loadloss(i,1)=0;

      end

   end

   Expected_Loadloss=Pro2'*Loadloss;

   fprintf('Expected loss of load is %f\n',Expected_Loadloss);


%%%  Calculate Capacity Credit



   Forced_Outage(1,no_generators)=0.02;

   Required_Loadloss=Expected_Loadloss;
```

```
RLL=roundn(Required_Loadloss,3);

Cap(1,no_generators)=0;

while(1)

Cin1=zeros(no_entries,1);

Cout1=Cin1;

Pro21=Cin1;

Loadloss1=Cin1;

Truth_Table1=zeros(no_entries,no_generators);

Truth_Table1=truthtable(no_entries);

Pro12=zeros(no_entries,no_generators);

for i=1:no_entries

   for j=1:no_generators

      if Truth_Table1(i,j)== 0

         Pro12(i,j)=Forced_Outage(1,j);

      else

         Pro12(i,j)=1-Forced_Outage(1,j);

      end

   end

end

Pro21 = prod(Pro12,2);

Cin1=Truth_Table1*Cap';

Cout1=flipud(Cin1);

for i=1:no_entries
```

```
        if Cin1(i,1)> L
            Loadloss1(i,1)=0;
        elseif Cin1(i,1)<L
            Loadloss1(i,1)=L-Cin1(i,1);
        else
            Loadloss1(i,1)=0;
        end
    end
    fprintf('\n');
    Expected_Loadloss1=Pro21'*Loadloss1;
    ELL=roundn(Expected_Loadloss1,3);
    fprintf('Expected loss of load is %6f\n',Expected_Loadloss1);
    fprintf('rounded Expected loss of load is %6f\n',ELL);
    fprintf('The required capacity of the added conv generator is
%6f\n',Cap(1,no_generators));
    if(ELL~=RLL)
      Cap(1,no_generators)=Cap(1,no_generators)+1/1000;
    else
        break;
    end
    end
    fprintf('The required capacity of the added conv generator is
%6.9f\n',Cap(1,no_generators));
```

```
    capacity_credit=Cap(1,no_generators)/x;

    fprintf('The capacity credit is: %6.9f\n',capacity_credit);

    Wind_range(k)=capacity_credit;

end

fprintf('Minimum wind capacity is: %f\n',min_wind);

fprintf('Max. wind capacity is: %f\n',max_wind);

x=min_wind:5:max_wind;

y=Wind_range(1,:);

plot(x,y);
```

VITA

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Title of Study: A SIMPLIFIED APPROACH TO ASSESS THE CAPACITY CREDIT OF WIND ELECTRIC CONVERSION SYSTEMS

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Scope and Method of Study: The purpose of this study is to develop a simplified method to evaluate the capacity credit of wind electric conversion systems (WECS). The simplified approach presented in this study employs an effective forced outage rate for a wind generator and uses the classic loss of load probability calculations to estimate the capacity credit. The result is a good estimate of capacity credit and it can be followed by detailed calculations as needed. The study presented employs a simplified reliability model for the output of a WECS in the capacity credit evaluation of a hybrid (conventional and wind) system. Results of sensitivity analyses are presented to study the impact of penetration levels, amount of spinning reserve, wind parameters and wind turbine output characteristics. The method can be extended to include the effect of seasonal changes, and the impact of variable load on capacity credit. The approach presented can be used in reserve capacity planning in which a fraction of coal-fired plants will be replaced by WECS.

Findings and Conclusions: A simplified approach to assess the capacity credit of wind electric conversion systems (WECS) has been presented. Sensitivity of the capacity credit value for several key parameters are studied using MATLAB 8.1 program. Capacity credit decreases as more wind capacity is added to the system. Capacity credit decreases with an increase in spinning reserve and cut-in speed. Capacity credit increases with an increase in shape parameter and cut-out speed. Capacity credit increases initially and then decreases with an increase in scale parameter. Range of capacity credit obtained is between 0.07 to 0.81.

ADVISER’S APPROVAL: Dr. R. G. Ramakumar