A SIMPLE APPROACH TO ESTIMATE THE CAPACITY CREDIT OF WIND ELECTRIC CONVERSION SYSTEMS AND ITS ECONOMIC ASPECT

By

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NOMENCLATURE

a = Plant factor for conventional power plant

$\alpha_{i,}$ β_i = wind parameters where i = 1 to 12

C_{AC} = Annual installment payment for conventional power plant

C_f = Fuel cost in $ per Ton

C_{ft} = Total fuel cost at the end of first year

CV= Heating value of Coal in MJ/Kg

CC_i = Capacity credit of wind farm

Ci= Capacity credit for the i^{th} load step

CC_{av} = Average monthly capacity credit of wind farm

C_{AW} = Annual installment for wind power plant

C_w = Capital cost for wind power plant in $ per MW of installation

Cs = Subsidy on wind in $ per MWh of energy generation

C_{TW} = Total initial capital cost of wind power plant for P_w in MW

C_{AW} = Annual installment for wind power plant

C_{wm} = Maintenance cost of wind power plant in $ per MWh

C_{awm} = Annual maintenance cost of wind power plant in $

C_x= Total annual expenditure on wind power plant

C_c = Capital cost for conventional power plant in $ per MW of installation

C_{TC} = Total initial capital cost of conventional power plant of capacity P_c

$Coal_{wt}$ =Amount of coal used in a year in tons

$Carb_{emit}$ = Total amount of carbon emitted in atmosphere

C_{tax} = Annual carbon tax on conventional power plant

C_{cm} = maintenance cost of conventional power plant in \$ per MWh

C_{cm1} = Total maintenance cost of conventional power plant in \$ at the end of first year

C_y = Total expenditure on conventional power plant at the end of first year

C_T= Total annual expenditure on the system.

C_P= Energy generation cost per MWh

E_{wa} = Average annual energy production from wind farm in MWh

E_{ca}= Average annual energy produced from conventional plant in MJ

□ = efficiency of the plant

n_1 = Payback period for wind power plant

n_2= Payback period in years for conventional power plant

R_1 = Annual interest rate for wind power plant

R_2= Annual interest rate for conventional power plant

P_w = Total installed capacity of wind farm in MW

Pi = Probability of occurrence of the i^{th} load step

P_{wm} = Average monthly effective capacity from wind farm in MW

P_c = Installed capacity of a conventional power plant in MW

P_T= Total annual energy generation by the system.

CHAPTER I

INTRODUCTION

Economic development and quality of life are highly interconnected with the use of energy in various forms. Rapid increases in world population lead to an increase in energy demand. As our conventional resources are depleted and environmental issues such as CO_2 emission and global warming start to gain importance, the need to harness clean, renewable and non pollutant sources of energy is becoming clear [1].

In recent years, remarkable growth and development in the area of harnessing renewable energy sources has emerged. Figure 1 shows the share of renewable sources in the United State's energy supply in 2008. Renewable energy share in 2008 has risen upto 7% from a meager 3% in 2005. Fossil fuels (coal, oil and natural gas) account for nearly two-thirds of electricity generation. The associated emission of greenhouse gases (primarily carbon dioxide) and their impact on global climate change have attached considerable attention during the past few years. The need to transfer some of the energy to renewable energy needs resources is becoming increasingly critical [1].

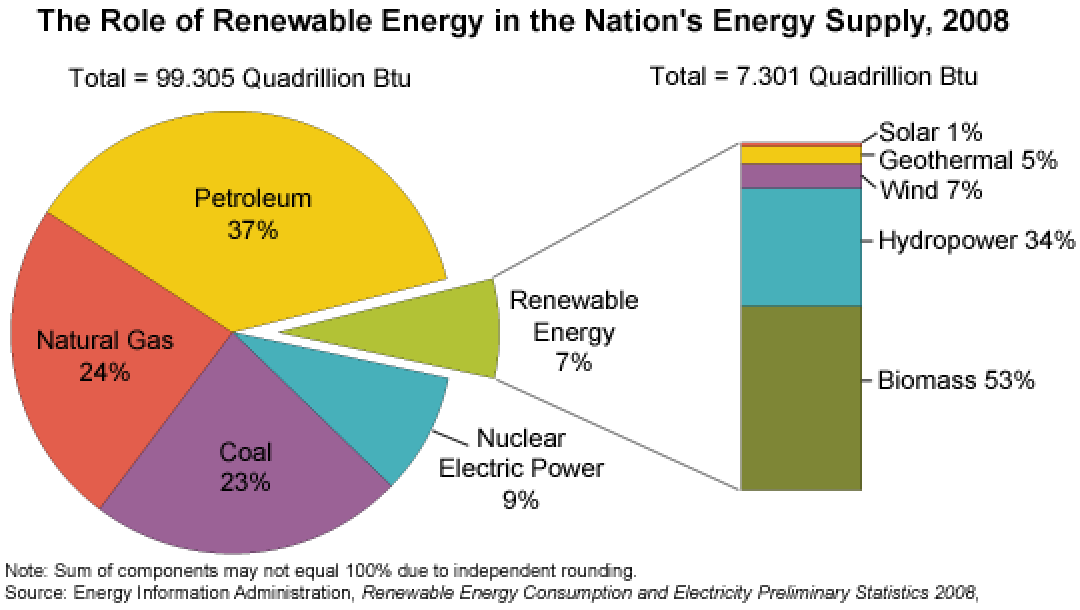

Figure 1: Share of renewable energy in United States energy supply in 2008

In 2006, the share of renewables in electricity generation was around 18% with 15% coming from hydroelectricity and the rest coming from renewable technologies such as wind, solar, geothermal, etc. which are growing rapidly. The renewable energy market is growing steadily due to higher oil prices, climate change concerns and strong government support, though some renewable energy technologies are criticized for being unsightly. The world's main renewable energy sources are briefly discussed next.

I.1 Solar energy

The energy emanating from the sun in the form of solar radiation is known as isolation (incident solar radiation). Electricity generation from solar power relies on photovoltaic and solar thermal technologies. Solar thermal technologies are mainly characterized as passive solar or active solar depending on the way they process solar energy.

Though at present solar power provides only about 1% of the total energy needs of the U.S., it has the potential to provide almost 1000 times the total energy consumption in 2008. It has the promise to become a dominant energy source if its use continues to double in every two to three years. One of the largest solar-thermal-electric power plants has an installed capacity of 354 MW (SEGS- Solar Energy Generating System) and is located in the Mojave Desert in Nevada, USA [2].

Several MW-scale grid-connected photovoltaic systems are successfully operating around the world.

I.2 Hydroelectric Power

The potential energy of water stored at a height can be harnessed and used to generate electricity. Hydroelectricity is the production of electricity through the use of the gravitational force of falling water. It is the oldest and most widely used renewable energy form. It is also an indirect form of solar energy. The main advantage of hydroelectricity is that once its infrastructure is constructed, the project produces no direct waste and has low level of CO_2 emission. As no fossil fuel is consumed, direct production of CO_2 is negligible [2].

In 2006, worldwide installed capacity of hydroelectricity was 777 GW and it supplied 2998 TWh of hydroelectricity; this amounted to approximately 20% of the world's electricity needs and about 88% of electricity derived from renewable sources. Three Gorges dam in China is the world's largest hydroelectric installation with a total capacity of 22,500 MW.

Some of the major advantages of hydroelectricity are the elimination of fuel costs and very low operating costs. Hydroelectric plants also have long lifetimes (some plants were built 50-100 years ago) as compared to fossil fuel plants.

I.3 Geothermal Energy

The word Geothermal comes from the Greek root Geo meaning earth and Thermos meaning heat. In other words it is the power extracted from heat stored in the interior of the earth. Geothermal energy originates from radioactive decay of minerals in the earth's core.

Around 24 countries around the world generated a total of 56,786 GWh from geothermal resources as in 2005 and the output is growing by 3% annually. In 2007, the worldwide capacity of geothermal plants to generate electricity was about 10 GW or 0.3% of global electricity demand [2].

Geothermal power is reliable, environmentally friendly and cost effective but is geographically limited to areas near tectonic plate boundaries (Figure 2). Due to recent technology advancements, range and size of viable resources have expanded dramatically. Though greenhouse gases trapped deep within the earth are released from geothermal wells, these emissions are much lower compared to consumption of fossil fuels. Geothermal power indeed has a potential to help mitigate global warming up to a certain level [2].

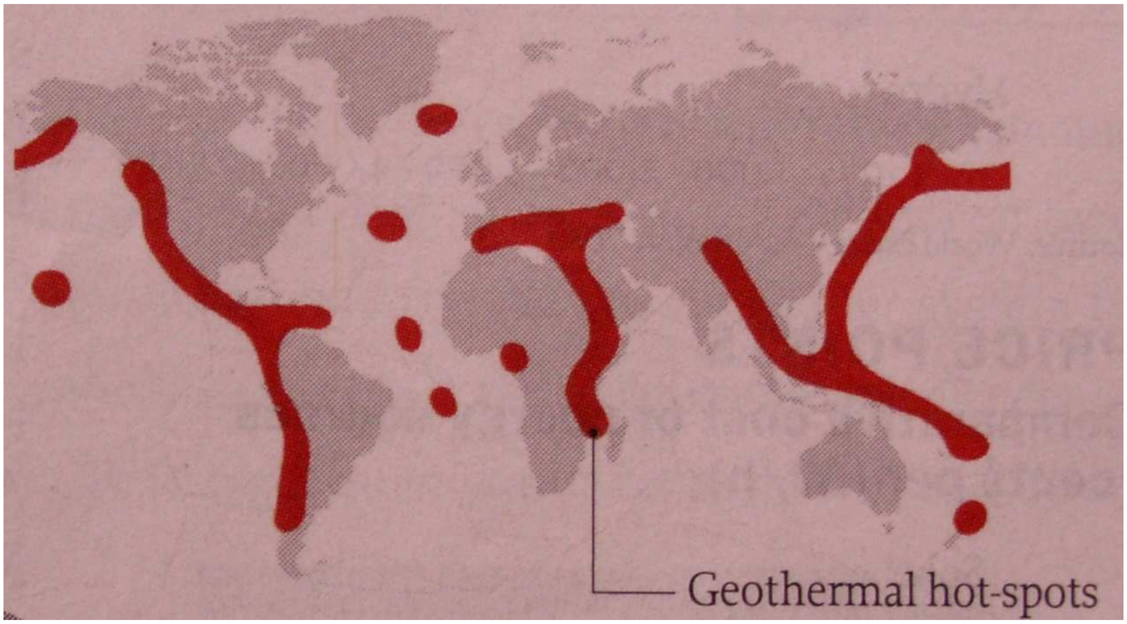

Figure 2. Geothermal hot-spots around the world; Source: Article “Geothermal Electricity”, en.wikipedia.org

I.4 Biofuels

One of the major renewable sources of energy is biofuels. It represents a wide range of fuels which are derived from various biomass resources such as solid biomass, liquid forms and gaseous forms. Due to incessant oil price hikes, biofuels are gaining increased attention. Biodiesel is a type of biofuel which is made from vegetable oils and animal fats. It can be used as a fuel for vehicles in its pure form. It is mostly used as a diesel additive to reduce levels of particulates and carbon monoxide from diesel powered vehicles. It is the most common biofuel in Europe.

Bioethanol is also a type of biofuel which is an alcohol made mostly from sugarcane and starch corps. Ethanol can be used as a fuel for vehicles in its pure form. Bioethanol is widely used in the USA and Brazil [2].

In 2008, biofuels provided 1.8% of the world’s transportation fuel. Investment in biofuels has exceeded $4 billion worldwide in 2007 and is growing continuously.

I.5 Tidal Energy

Tidal energy or tidal power is a form of hydropower which converts energy from tides into electricity. Though not being used widely at present, tidal power has the potential to generate considerable amount of electricity in the future because of its better predictability as compared to wind and solar. The first tidal power station was the Rance tidal power plant built over a period of 6 years in 1966 in France with a capacity of 240 MW.

I.6 Wave Power

It is the transport of energy by ocean surface waves which is converted into electricity by suitable hardware. Wave power is different from the steady gyre of ocean currents and the diurnal flux of tidal power. It is currently not widely used for commercial energy generation but there have been attempts to using it since 1890.

I.7 Wind Power

Wind is air in motion initiated by the uneven heating of the atmosphere by the sun. This is an indirect form of solar energy.

Conversion of wind energy into useful form of energy such as electricity is the fastest growing generation technology at present. Wind is a very abundant but highly unreliable source of energy. However, it is regarded as a valuable addition to conventional electric power generation. Benefits of wind power are listed below.

Environmental:

- Minimal overall pollution
- No greenhouse gas emissions
- No water pollution
- No water needed for operation
- Very small footprint

Economic:

- At good wind sites, generation costs are competitive with fossil- fueled alternatives.
- Creation of jobs in rural communities.
- Decreasing the outflow of money to import petroleum products

At the start of 2009, aggregated worldwide nameplate capacity of wind power plants was approximately 122 GW and energy production was around 260 TWh, which was about 1.5% of the worldwide electricity usage. In May 2009, around 80 countries were using wind power on a commercial basis. Countries such as Denmark and Spain have achieved relatively high levels of wind penetration into their power systems. World's total installed wind capacity has increased by almost 10 times since the year 2000 [3] as shown in Figure 3.

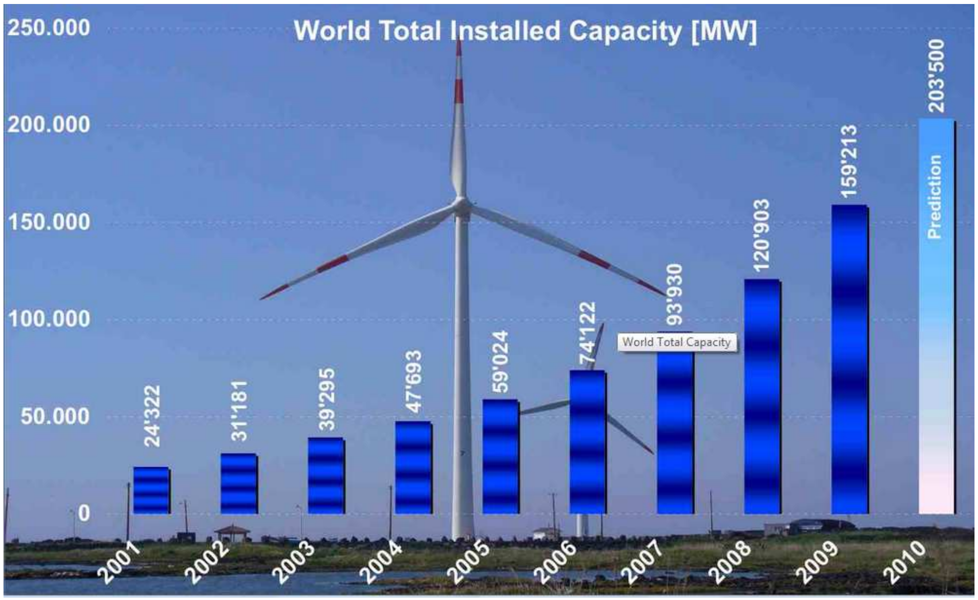

Figure 3. World wind energy installed capacity.

Source: World wind energy report 2009, www.wwindea.org

Among all the renewable sources, wind power has made the most remarkable growth in the past decade. Because of increasing interests and a impressive growth in the area of wind, penetration of electricity produced from wind energy into conventional power system is increasing significantly. This increasing wind penetration has brought to focus various issues related to wind power production such as quality of output and reliability. One of the key parameter used to assess the viability of wind power is 'capacity credit'. This thesis deals with a simplified method to evaluate capacity credit of Wind Electric Conversion System (WECS) and its economic implications.

I.8 Organization of the thesis

Chapter II gives a brief overview of the growth of wind power capacity and various performance parameters involved in assessing performance. Chapter III discusses the significance of wind energy capacity credit and various approaches proposed to evaluate it. A simplified approach to evaluate capacity credit of WECS is presented in

Chapter IV. A brief look at the economic aspect of capacity credit is given in Chapter V. Example studies and simulation results are documented and discussed in Chapter VI along with suggestions for further work.

CHAPTER II

GROWTH OF WIND ENERGY AND PERFORMANCE PARAMETERS

The significance of renewable energy is becoming clear to the present world. Of the various energy sources discussed in the previous chapter, wind energy has exhibited a significant growth in the recent past. This chapter gives a brief overview of the growth of wind energy and the various performance parameters involved in its assessment.

II.1 GROWTH OF WIND ENERGY

Of all the renewable energy resources, wind energy has exhibited the fastest growth in the area of electricity generation in the recent past. It is gaining increasing importance throughout the world. At the beginning of modern industrialization, the use of fluctuating wind energy resources was limited to smaller units in remote areas for pumping water and charging batteries. After the first oil price shock in 1973, interest in wind energy re-emerged [4]. Since then the focus has increasingly been on wind power for generation of electricity. After 1970's, technology started improving steadily and by 1990, wind energy emerged as one of the most important sustainable energy resources. In the past few decades, installed wind capacity has almost doubled every three years. The cost of electricity from wind has decreased by a factor of six since 1980. In the US the installed capacity of wind power increased by 50% during 2008 [5]. According to the U. S. Department of Energy, wind power is capable of becoming a major contributor of electricity to America in three decades [5]. A scenario of 20% of electricity from wind by 2030 is proclaimed as a national goal.

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 at present at good wind sites. The Department of Energy'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 greenhouse gas emissions, small footprint, no water pollution with mercury and no water needed for operation. Economic benefits of expanding wind power development include creation of jobs in rural communities, increased tax revenue and decreased outflow of money to import petroleum products [5].

II.2 GLOBAL FACTS AND FIGURES RELATED TO DEVELOPMENT OF WIND POWER IN RECENT YEARS [see ref. 3]

- Total energy production from wind in 2008 was 260 TWh, which is 1.5% of the energy usage.
- In recent years, United States has added more wind energy to its grid than any other country, A list of top leading countries in wind power installation are shown in Table 2.
- Countries such as Denmark and Spain have considerable share of wind in energy generation sector with shares of 19% and 13% respectively.
- China had originally set a generation target of 30,000 MW by 2020 from renewable energy sources and reached 22,500 MW by the end of 2009 with a potential to surpass 30,000 MW by the end of 2010.

- According to the US Department of Energy, United States is capable of generating 20% of its electrical energy from wind by the year 2030.
- 80 countries around the world are using wind power on commercial basis.

TABLE 1
TOP FIVE COUNTRIES IN WIND POWER INSTALLATION IN MW

#	NATION	2005	2006	2007	2008	2009
1	**United States**	**9,149**	**11,603**	**16,819**	**25,170**	**35,159**
2	**Germany**	**18,428**	**20,622**	**22,247**	**23,903**	**25,777**
3	**China**	**1,266**	**2,599**	**5,912**	**12,210**	**25,104**
4	**Spain**	**10,028**	**11,630**	**15,145**	**16,740**	**19,149**
5	**India**	**4,430**	**6,270**	**7,850**	**9,587**	**10,925**

Source: World Wind Energy Report 2009, World Wind Energy Association.

II.3 PERFORMANCE PARAMETERS

There are many factors on influencing the performance of wind electric conversion systems. As the penetration of wind generated electricity into conventional power systems increases rapidly, it becomes critical to study the effect of these factors on the wind power output and its influence on the overall power system. This section discusses a few of the important performance parameters in brief.

II.3.1 WECS Power Output Characteristics

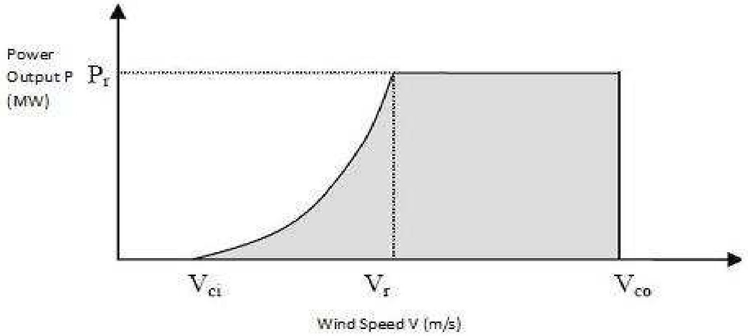

Figure 4: Typical WECS Power Output Characteristic

Electric power output is available from a wind turbine only for a certain range of wind speeds as shown in Figure 4. Wind-electric system starts generating electric power at a wind speed known as 'cut-in speed' (Vci). It reaches rated power (Pr) output at 'rated wind speed' (Vr) and continues to produce the rated output until the wind speed reaches the 'cut-out' value (Vco). Beyond Vco, the turbine is completely shut down to avoid any damage to its components.

II.3.2 Reliability

Wind electric conversion, in spite of its extraordinary progress, faces major hurdles due to lack of adequate transmission facilities and variability of output. Because of the intermittent nature of wind power, it is difficult to determine an appropriate penetration level to ensure specific reliability requirements.

The overall reliability of power systems with wind generated electricity has attracted considerable attention in the past. Poor reliability might result due to reduced system availability and the lack of coincidence between wind resources and load demand. It also affects the revenue of the project. Loss of load probability (LOLP) is a well known measure used in evaluating reliability of electric power supply. With an increase in wind penetration into the conventional power system, the LOLP will tend to increase because the availability of WECS is not as high as conventional units [6].

Forced outage rate (FOR) is one of the 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’. A component experiences forced outage if there is an emergency related to the component which forces it out of service. The FOR value for a wind power plant is much higher as compared to conventional power plant [6] because a lack of wind input will result in zero output just as a component failure will lead to no output.

II.3.3 Economic Aspects

Cost of wind generated electricity has declined noticeably over the last few decades even though a significant amount of investment is still involved in the manufacturing and installation of wind turbines. To overcome the limitations resulting from the stochastic nature of wind resource, wind farms are equipped with additional energy storage or reserves to ensure continuity of supply. Also, complex power electronic circuitry and controls are used in modern wind turbines to maintain superior power quality. Use of these sophisticated components increases the overall cost significantly.

Existing transmission and distribution systems are designed based on conventional power generation techniques. Connecting wind power plants to these existing grids will disturb the operation of conventional grids and may even result in overloading and reverse power flows. Redesigning the power system may improve the overall stability and efficiency, but it will also involve higher investments [6].

II.3.4 Energy Credit

Energy credit can be defined as the rating of continuously operating conventional power plant a wind plant can replace in terms of energy generated per year. It is typically expressed as "plant factor" or energy production factor (K) [6].

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

The energy value of a wind power plant is highly dependent on wind turbine performance, wind regime at the site, utility involved at its load profile. As wind power is typically expected to displace power generated by marginal units, the economic value of power displaced will vary widely. The fuel cost of marginal generators operated during peak hours is much higher than that of base load plants operating during low-load periods hence the timing of wind power output has an important influence on the value of energy that is dispatched [6].

II.3.5 Capacity Credit

Power systems must have sufficient reserves so that generation is adequate to meet customer demand at all times. As electricity demand cannot be accurately known in advance, a capacity margin requirement is necessary to maintain reliability [7]. Capacity Credit (CC) assigned to a wind power plant is the fraction of its installed capacity by which conventional generation capacity can be reduced without affecting the benchmark quality of supply [8]. In other words, it can be thought of as the amount of conventional generation capacity that could be 'replaced' by the renewable production, without affecting the overall systems reliability [9].

The concept of capacity credit and various methods used to evaluate it are briefly summarized in the next chapter.

CHAPTER III

EVALUATION OF CAPACITY CREDIT

A simple definition of capacity credit of WECS can be given as [10]:

“The amount of conventional generation that could be ‘replaced’ by generation from wind without making the system less reliable”

In other words, capacity credit refers to the capability of the new power plant to increase the reliability of the system. There is always a certain risk of capacity deficit in the existing power system and it is quantified as loss of load probability (LOLP) in which case some load will not be met. If a new plant is introduced in the system, the chances of meeting the load often increase. This implies that the introduction of a new power plant increases the system reliability. The concept of capacity credit refers to the capability of the new plant to increase the reliability of the system [see ref. 5].

Many methods have been developed to assess the capacity credit of WECS. Some of them are briefly discussed next.

III.1 Effective Load Carrying Capacity Approach [11-12]

One of the most popular and widely used reliability-based approaches to evaluate wind capacity credit is Effective Load Carrying Capacity (ELCC). The key parameter in assessing capacity credit with ELCC approach is Loss of Load Expectation (LOLE).

LOLE is the number of hours in a given period (month, year etc.) during which the generating system cannot satisfy the overall system demand.

In this approach different reliability models are employed for several iterations to arrive at the capacity credit of WECS. At first, the LOLE of original generating system without WECS is calculated. Then the WECS is added to the system and the significant drop in LOLE is observed. Next the system (with WECS) peak load is gradually increased until the original LOLE values are obtained. This increased value of the system peak load is the capacity credit value of the WECS.

It is the most comprehensive approach and the values of calculated capacity credit obtained from this approach are widely used.

III.2 Capacity Factor Approach [13-15]

The capacity factor approach compares actual energy output of a plant for a given period of time with the output of the plant if it operated at its 100% capacity over the same period. This is the same as the plant factor discussed in Chapter II.3.4. This approach can be used to measure productivity of any WECS or any power generating system. PJM and NYISO define capacity credit as the capacity factor during the daily peak load hours of the peak load months. Definition of peak load hours and peak load months may vary for different companies. PJM peak load hours and peak load months are 3-6 pm for the month of June, July and August.

The wind speed and wind power output at peak hours for the peak months (June-August) are obtained. The peak hour wind power outputs are obtained using the functional relationship between wind speed and the power output of the wind turbine generator (WTG). With the help of simulation tools, the summed peak load hour wind power output (or the energy output) during the peak load months over a significant period of time is calculated. This summed peak hour wind power output value is divided by wind power that would have been produced if the WECS operated at the maximum output to obtain capacity factor.

Wind capacity values in this method will vary with the definition of peak load hours and peak load months.

III.3 DAFORW Approach [15]

Derating Adjusted Forced Outage Rate (DAFOR) or the Equivalent Forced Outage Rate (EFOR) is the probability of a unit residing in its complete down state. The DAFOR is obtained using a method in which the residence times of the actual derated states are apportioned between the up (normal) and down (outage) states. The effect of wind variability can be aggregated to produce a DAFOR statistic similar as for conventional generating units.

For an example, from the data obtained from Regina wind site located in the Province of Saskatchewan, Canada, the DAFOR for the two 20 MW WECS are 0.7576 and 0.7656. Based on this, the wind capacity credit comes to 20* (1-0.75716) = 4.9MW (20%).

The DAFORW method uses the probability distribution of the annual wind power instead of the particular time period profile used in the Capacity Factor method.

III.4 Simplified approach [16]

This approach employs an effective forced outage rate of a wind generator and uses the loss of load probability calculations to estimate the capacity credit of WECS, and the load is kept constant throughout.

In this approach, the expected loss of load of a system with conventional generators is obtained first. Wind generator is added to the system and the decrease in expected loss of load is calculated. After obtaining the expected loss of load with the added wind generator, the 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 second value. This capacity is the capacity credit that can be assigned to WECS.

III.5 Weighted Capacity Credit Method [17]

This method extends the simplified approach to estimate the capacity credit under variable load conditions. It is based on replacing the annual load duration curve by a stepped function and calculating the capacity credit for each of the load steps. A weighted average of these values using the probability of the various load steps as weighting factor is proposed as an estimate of the overall capacity credit.

At every load step, the capacity credit is calculated considering load to be constant. The forced outage rate, loss of load probability (LOLP) and expected loss of load are the important parameters used in assessing capacity credit at a constant load by the procedure described in section III.4.

The next chapter discusses the weighted capacity credit in detail approach in detail.

CHAPTER IV

SIMPLIFIED APPROACH TO ASSESS CAPACITY CREDIT OF WIND ELECTRIC CONVERSION SYSTEM

In this chapter, a simple approach to estimate the capacity credit of WECS under variable load condition is presented. It is based on replacing the annual load duration curve by a stepped function and calculating the capacity credit for each of the load steps [16]. A weighted sum of these values using the probability of occurrence of the various load steps as weighting factors is proposed as an estimate of the overall capacity credit. Step-by-step procedure is explained next.

IV.1 Load Model Representation

This section presents the load model representation employed in this study for assessment of overall capacity credit. In the previous method for calculation of capacity credit, the load is considered to be constant [16]. This approach proposes a method to evaluate capacity credit under variable load condition. The annual load duration curve is replaced by a sequence of steps and the capacity credit is calculated for each load step assuming it to be constant. Weighted sum of these values is proposed as the capacity credit under varying load condition. Probabilities of occurrence of the steps are used as weighting factor.

The annual load duration curve is a plot of load versus the number of hours the load equaled or exceeded that value. This concept is commonly used in analyzing generation systems, especially in planning stages.

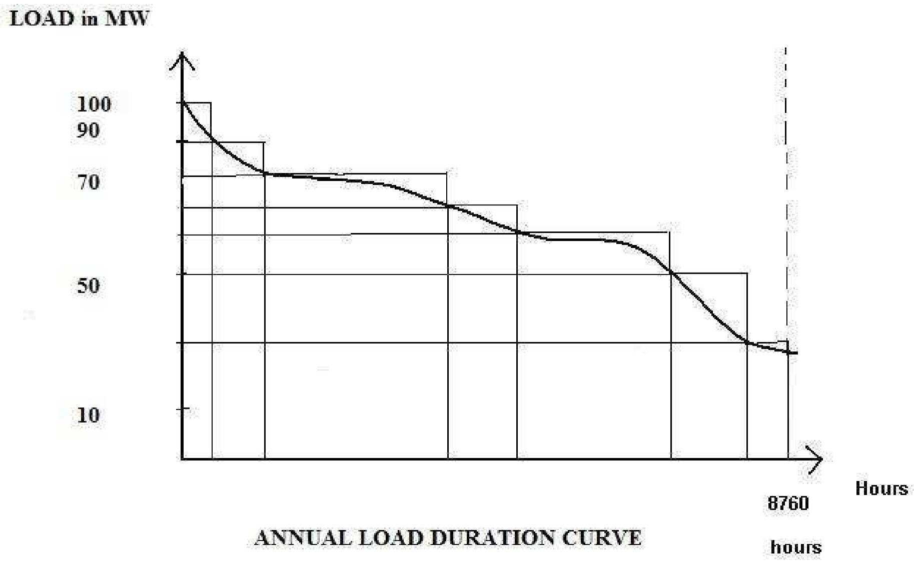

Figure 5. Annual Load Duration Curve

As shown in Figure 5, the annual load duration curve gives an overall representation of the system load. The X-axis represents the number of hours the load equaled or exceeded the load demand in MW as shown along Y-axis. The annual load duration curve is replaced by a sequence of load steps from base load to peak load as shown. Each load step will have its demand on the generation side for a particular duration in a year. The probability of occurrence of each load step can be calculated by dividing the duration of that load step by the total number of hours in a year (8760).

As shown in Figure 5, each step corresponds to a certain load value and its duration in hours can be found along the X-axis. For example, if the peak load on the system is 100MW, the duration for which the system load is 100 MW is found to be 738 hours. Hence the probability of occurrence is 738/8760 = 0.0842.

TABLE 2
PARAMETERS FOR CAPACITY CREDIT ASSESSMENT

Annual load duration curve	The annual load duration curve is a plot of load versus the number of hours the load equaled or exceeded that value.
Probability of occurrence	The probability of occurrence of each load step can be calculated by dividing the duration of that load step by the total number of hours in a year
Capacity credit	Capacity credit Ci for the load step Li, assuming it to be constant.
Weighted capacity credit	$\sum_{i=1}^{n} PiCi$ For i = 1, 2, 3, ---, n for the n-step representation of the annual load duration curve.

IV.2 Weighted Capacity Credit

The annual load duration curve is replaced by a stepped function with the different load levels as given above. The capacity credit (C) is calculated for every load step assuming the load to be constant. The probability of occurrence (P) of every level is calculated. For every step, capacity credit value is multiplied by the probability of that step. Finally, weighted capacity credit value is calculated by summing all the product values obtained.

Capacity credit is calculated for every load step assuming the load to be constant by the procedure documented in [16]. For every step, capacity credit value is multiplied by the probability of that step. Finally, weighted capacity credit value is calculated by summing all the products values.

$$\text{Weighted Capacity Credit} = \sum_{i=1}^{n} PiCi \qquad \text{….(4.1)}$$

Where,

Pi= Probability of occurrence of the ith load step

Ci= Capacity credit for the ith load step

for i = 1, 2, 3, ---, n for the n-step representation of the annual load duration curve.

This approach to assess weighted capacity credit is explained in detail with the aid of numerical examples for different wind regimes and wind penetration levels in Chapter VI.

CHAPTER V

ECONOMIC ASPECT OF WIND ENERGY CAPACITY CREDIT

In the previous chapter a simplified approach to evaluate capacity credit of WECS under varying load conditions was presented. This chapter deals with the significance of this capacity credit in assessing the economics of WECS versus conventional generation options.

With the help of wind data collected over several years at the proposed wind farm site and the installed capacity of the wind farm, the average annual energy production can be estimated. The total annual expenditure incurred by the wind power plant and the total annual expenditure for the complete power generation system (WECS and conventional) can also be estimated. This can be used to analyze economic as well as environmental impacts of wind energy penetration into the conventional system. The step-by-step procedure to evaluate per unit generation cost of the energy produced by the complete system is discussed next.

V.I Assessment of average annual energy production from wind power plant (E_{wa})

The first step is to estimate the annual energy production from wind power plant. The wind data collected at the proposed wind farm site is useful to characterize the average monthly wind regime (Low, Moderate, High). Once the average monthly wind regime is obtained, the capacity credit of WECS for each month can be assessed as illustrated in the previous chapter. The average monthly capacity credit of WECS (CC_{av}) is obtained as,

$$CC_{av} = \sum_{i=1}^{12} CCi \,/\, 12 \qquad \text{….(5.1)}$$

Once the average monthly capacity credit of WECS is obtained, the average effective capacity (P_{wm}) of WECS is calculated as,

$$P_{wm} = CC_{av} * P_w \quad \text{in MW} \qquad \text{….(5.2)}$$

The average annual energy production from wind plant is obtained as,

$$E_{wa} = P_{wm} * 365 * 24 \quad \text{in MWh} \qquad \text{….(5.3)}$$

V.2 Determination of total annual expenditure on wind power plant (C_x)

This section gives the procedure to obtain the total annual expected expenditure on wind power plant.

The total installed cost for wind power plant (C_{TW}) is obtained as,

$$C_{TW} = C_w * P_w \quad \text{in \$} \qquad \text{….(5.4)}$$

This amount is borrowed at an annual interest rate of R_1% with payback period of n_1 years.

The annual cash flow for wind power plant is obtained with the help of amortization formula which is given below,

$$C_{AW} = [C_{TW} \times R_1]/[1-(1/(1+R_1))n_1] \qquad \text{…..(5.5)}$$

Annual maintenance cost of wind power plant is obtained as,

$$C_{awm} = C_{wm} * E_{wa} \quad \text{in \$} \qquad \text{….(5.6)}$$

Governmental wind subsidy is given on the basis of the energy generated.

Total annual subsidy received by the wind plant is given as,

$$C_{sub} = Cs * E_{wa} \quad \text{in \$} \qquad \text{....(5.7)}$$

Where, Cs is the subsidy for wind generation in \$ per MWh.

The total annual expenditure on wind power plant is given as,

$$C_x = C_{AW} + C_{awm} - C_{sub} \quad \text{in \$} \qquad \text{....(5.8)}$$

V.3 Determination of total annual expenditure on conventional power plant (C_y)

This section deals with the determination of total annual expected expenditure on a conventional power plant. Let the total conventional power capacity in the system be Pc. The total initial capital cost of the conventional power plant (C_{TC}) will be,

$$C_{TC} = C_c * P_c \quad \text{in \$} \qquad \text{....(5.9)}$$

Where, C_c = Capital cost for conventional power plant in \$ per MW of installation

With the use of amortization formula the annual installment (C_{AC}) to repay the borrowed amount to install conventional power plant with an annual interest rate of R_2% with payback period of n_2 years will be,

$$C_{AC} = \frac{C_{TC} \times R_2}{1-(\frac{1}{1+R_2})^{n2}} \qquad \text{....(5.10)}$$

The annual energy generation from the conventional power plant will be,

$$E_{ca} = Pc*365*24*a*3600 \quad \text{in MJ} \qquad \text{....(5.11)}$$

As 1 MWh = 3600 MJ

Annual fuel cost (C_{ft}) is obtained as,

$$C_{ft} = \frac{C_f \times E_{ca}}{CV \times \eta} \quad \text{in \$} \qquad \text{.........(5.12)}$$

(Ideally the heating value of coal is assumed as 24000 KJ/kg, efficiency of coal fired power plant as 0.42)

The amount of coal used in a year is given by,

$$Coal_{wt} = \frac{E_{ca}}{CV \times \eta} \quad \text{in \$} \qquad .....(5.13)$$

Total amount of carbon emitted in atmosphere will be,

$$Carb_{emit} = Coal_{wt} * 3.67 \quad \text{tons} \qquad ....(5.14)$$

Since burning 1 Kg of Coal produces 3.67 Kg of CO_2.

Annual carbon tax on the conventional power plant will be,

$$C_{tax} = Carb_{emit} * Carb_{unit} \quad \text{in \$} \qquad ....(5.15)$$

where, $carb_{unit}$ is tax in \$ on per ton of carbon dioxide emitted in atmosphere

Annual maintenance cost (C_{m1}) is given as,

$$C_{m1} = C_{cm} * E_{ca} \quad \text{in \$} \qquad ....(5.16)$$

Finally, the total annual expenditure on conventional power plant is given as,

$$C_y = C_{AC} + C_{ft} + C_{cm1} + C_{tax} \quad \text{in \$} \qquad ....(5.17)$$

The total annual expenditure on the system will be,

$$C_T = Cx + Cy \quad \text{in \$} \qquad ....(5.18)$$

The total annual energy generation from the system will be,

$$P_T = E_{wa} + E_{ca} \quad \text{in MWh} \qquad ....(5.19)$$

The generation cost per MWh of the complete system will be,

$$C_P = C_T / P_T \quad \text{in \$} \qquad ....(5.20)$$

This gives the energy generation cost per MWh for the combined system. Impact of various parameters such as wind penetration, carbon tax and wind subsidy on the energy generation cost of the system is discussed in detail with the help of case studies in the next chapter.

V.4 Factors affecting generation cost of energy:

The following are the primary factors affecting the energy generation cost of the system,

V.4.1 Capacity Credit (CC) of WECS: Capacity credit value directly affects the generation cost. If CC is low (low wind regime), the possible energy generation cost will be high and vice-versa.

V.4.2 Fuel cost for conventional power plant: Annual expenditure increased for the conventional power plant significantly depends on the type and cost of fuel used. If the fuel cost is large the annual expenditure of conventional power plant will increase and energy generation cost will increase (Fuel cost for wind power plant is zero).

V.4.3 Wind penetration (Installed capacity): As mentioned in the previous chapter, capacity credit (CC) of WECS decreases as the wind penetration in the power system increases (for same wind regime). As the installation capacity of proposed wind power plant increases, its CC decreases and eventually increases the generation cost.

V.4.4 Plant factor of the conventional power plant: The energy production from the conventional power plant depends upon its plant factor, if the availability is low, energy production will be less. With the installed capacity constant, average generation cost will increase.

CHAPTER VI

EXAMPLE STUDIES

This chapter is divided into two sections: the first section deals with the assessment of weighted capacity credit and second section considers the significance of wind energy capacity credit in the context of assessing certain economic and environmental aspects of introducing WECS into a conventional power system.

VI.1 Weighted capacity credit

Three different wind regimes and four penetration levels (10, 20, 30 and 40%) are considered in the example studies. The wind regimes are designated as High, Moderate and Low. Table 3 shows the three different wind regimes and their corresponding Weibull parameters.

TABLE 3: Wind regimes considered

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

The cut-in, cut-out and rated wind speed values for the WECS are taken as 3.6 m/s, 21 m/s and 8 m/s respectively. The values are in the range of parameters for modern large MW-scale wind energy systems.

VI.1.1 System with 20% wind penetration

Step-by-step calculations of weighted capacity credit with variable load and with 20 % wind penetration are detailed next.

The annual load duration curve, shown in Figure 6, is replaced by a stepped function with six steps as shown. Table 4 lists the number of hours the load is at different load levels (steps) and the probability of occurrence of each load step.

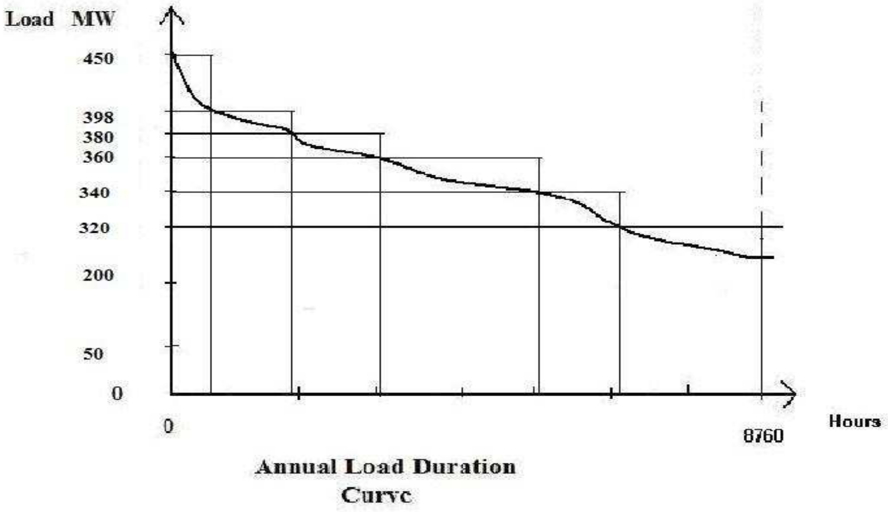

Fig.6 . Annual load duration curve

TABLE 4
STEP BY STEP REPRESENTATION OF THE ANNUAL
LOAD DURATION CURVE

Load Level	Duration (hours)	Probability
450	**702**	**0.0801**
398	**1150**	**0.1312**
380	**1245**	**0.1421**
360	**2368**	**0.2705**
340	**1125**	**0.1284**
320	**2170**	**0.2477**
	∑ = 8760 Hours	**∑ = 1.0**

Step 1:

A system consisting of 4 conventional generators and a wind generator is considered as shown in Figure 7. The total capacity of the system is 500MW and the equivalent wind generator is rated at 100 MW which corresponds to a 20% penetration level.

FOR value for the conventional generator is assumed to be 0.02 and the equivalent FOR for the wind system under low, moderate and high wind regimes are calculated to be 0.7989, 0.4096 and 0.2115 respectively (see Appendix A for details). The expected loss of load is obtained with the help of MATLAB program.

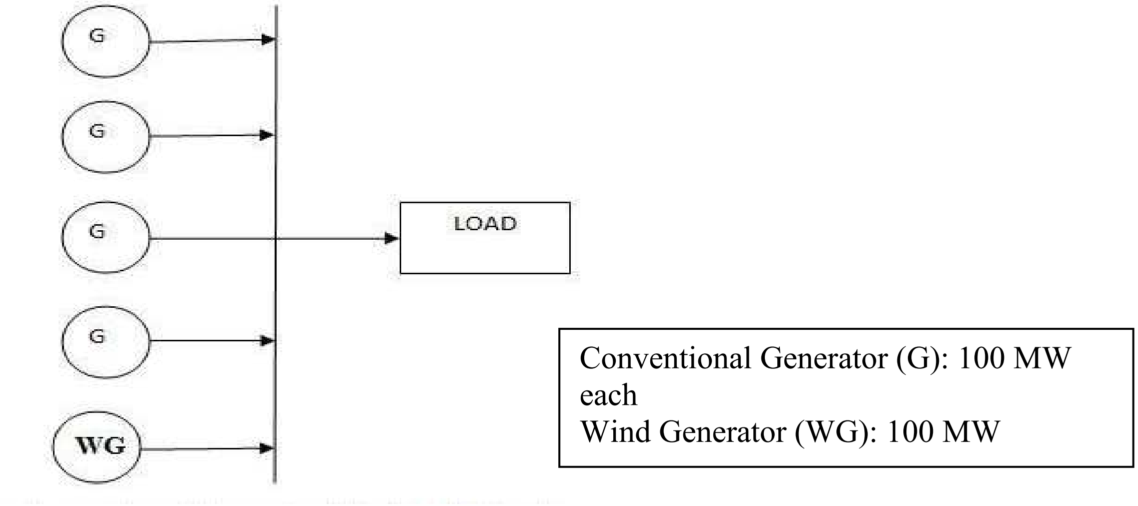

Fig. 7. 20% wind penetration example.

Step 2:

The equivalent wind generator is replaced by a conventional generator G1 of variable capacity as shown in Figure 8 and its capacity is varied until the value of expected loss of load matches with the value obtained in the first step. This capacity of

G1 divided by the capacity of WG in step 1 is the equivalent capacity credit for WECS. This is repeated for every load step and every wind regime.

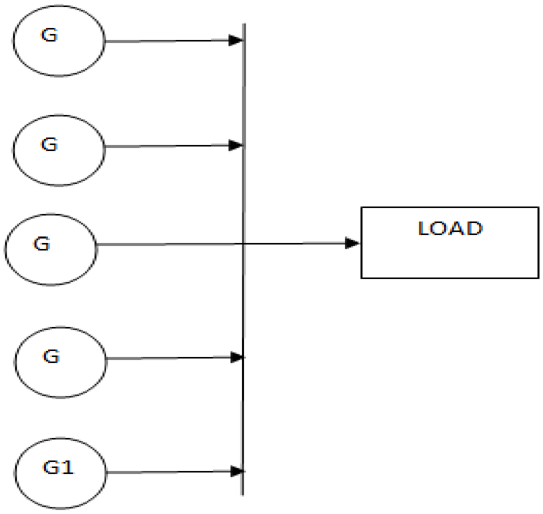

Fig. 8. Wind generator 'WG' is replaced by a variable capacity conventional generator 'G1'.

Step 3:

The capacity credit values obtained for different load steps are then multiplied by their probabilities of occurrence. All the products are summed together to obtain the weighted capacity credit for 20% wind penetration in the power system.

The step by step calculation of weighted capacity credit with variable load is presented in Table 5.

TABLE 5
STEP BY STEP REPRESENTATION OF WEIGHTED CAPACITY CREDIT ASSESSMENT WITH 20% WIND PENETRATION
(Moderate Wind Regime)

Load Level	**Probability of occurrence *(Pi)***	**Capacity credit *(Ci)***	***Pi×Ci***	$\sum_{i=1}^{n} PiCi$
450	**0.0801**	**0.3220**	**0.02579**	**0.2820**
398	**0.1312**	**0.5720**	**0.07504**	
380	**0.1421**	**0.3880**	**0.05513**	
360	**0.2705**	**0.3150**	**0.08520**	
340	**0.1284**	**0.2430**	**0.03120**	
320	**0.2477**	**0.039**	**0.00966**	

For this example, the weighted capacity credit value with variable load for the moderate wind regime is found to be 0.2820 or 28.2%.

Similar procedure is followed for 10, 30 and 40% wind penetration levels under different wind regimes and the weighted capacity credit values obtained are tabulated in Table 6.

TABLE 6
EQUIVALENT CAPACITY CREDIT VALUES

WIND PENET. (%)	**TOTAL SYSTEM CAPACITY in MW**	**WIND CAP. in MW**	**WEIGHTED CAPACITY CREDIT VALUES @ WIND REGIMES**		
			Low	**Moderate**	**High**
40	**300**	**120**	**0.0361**	**0.2097**	**0.2246**
30	**400**	**120**	**0.0177**	**0.2588**	**0.3478**
20	**500**	**100**	**0.0467**	**0.2820**	**0.3521**
10	**500**	**50**	**0.0603**	**0.3357**	**0.4293**

VI.2 Simulation Results

In this section simulation results are presented in graphical form to illustrate the sensitivity of the capacity credit to various parameters involved. The parameters considered are wind penetration, wind regimes and wind parameters (α, β).

1. 20% wind penetration

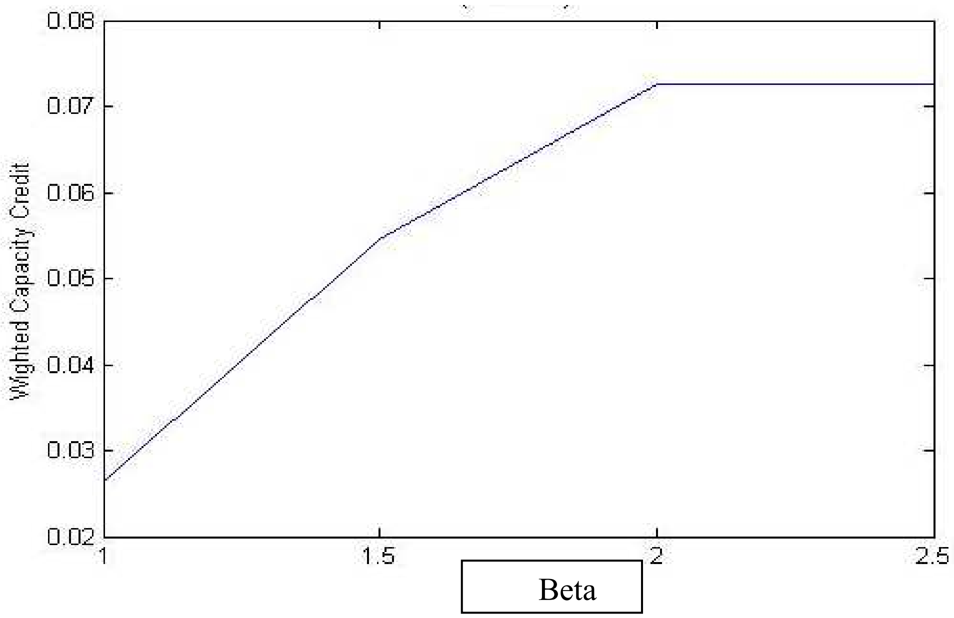

Figure 9 . 20% wind penetration, Low wind regime- α= 5.07 m/s, varying β

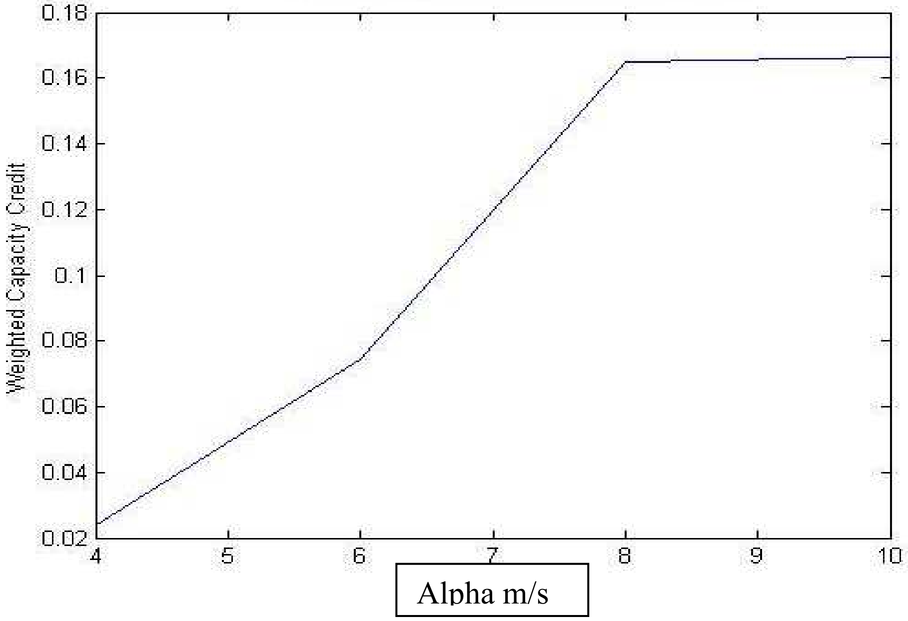

Figure 10. 20% wind penetration, Low wind regime- β = 1.31, varying α

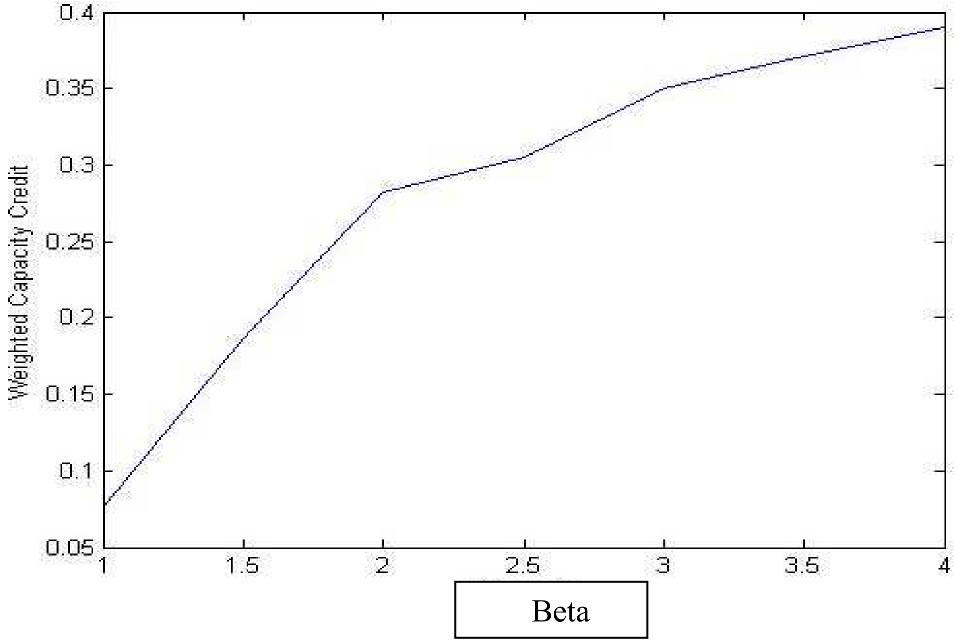

Figure 11. 20% wind penetration, Moderate wind regime- α =9.07 m/s, varying β

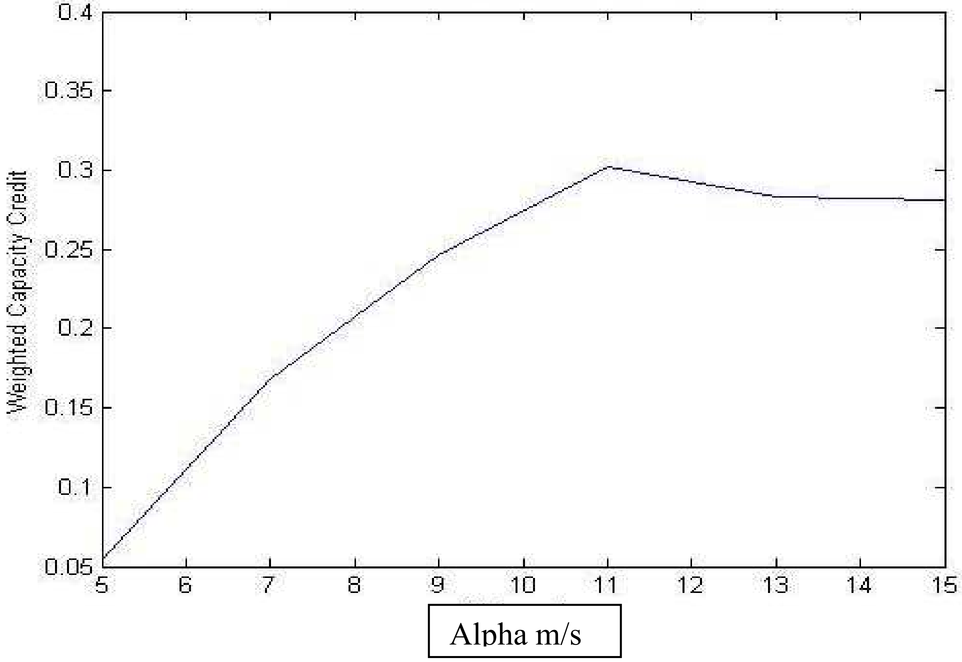

Figure 12 . 20% wind penetration, Moderate wind regime- $\beta = 2$, varying α

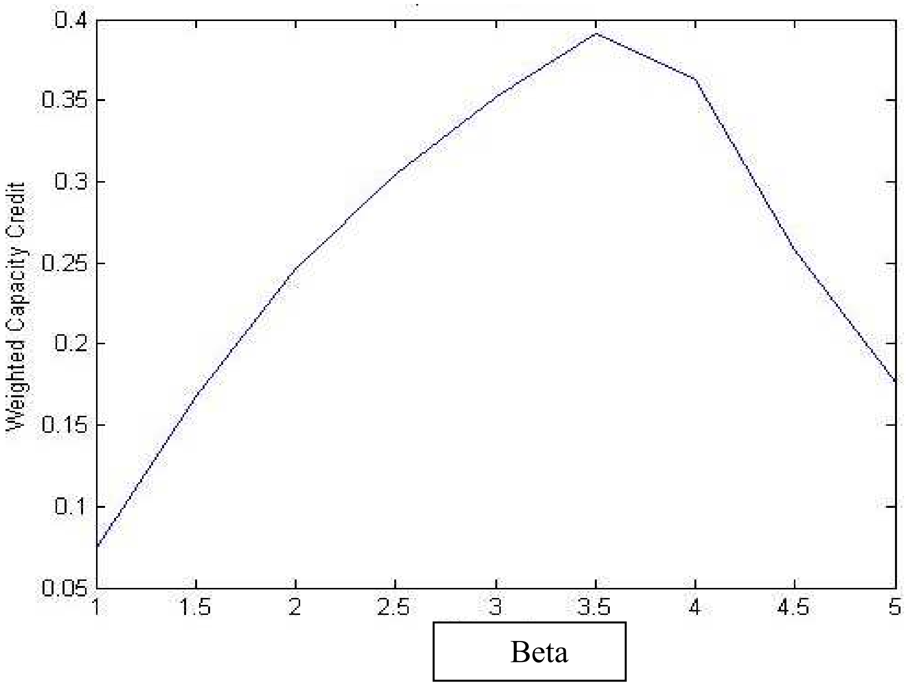

Figure 13. 20% wind penetration, High wind regime- $\alpha = 15.55$ m/s, varying β

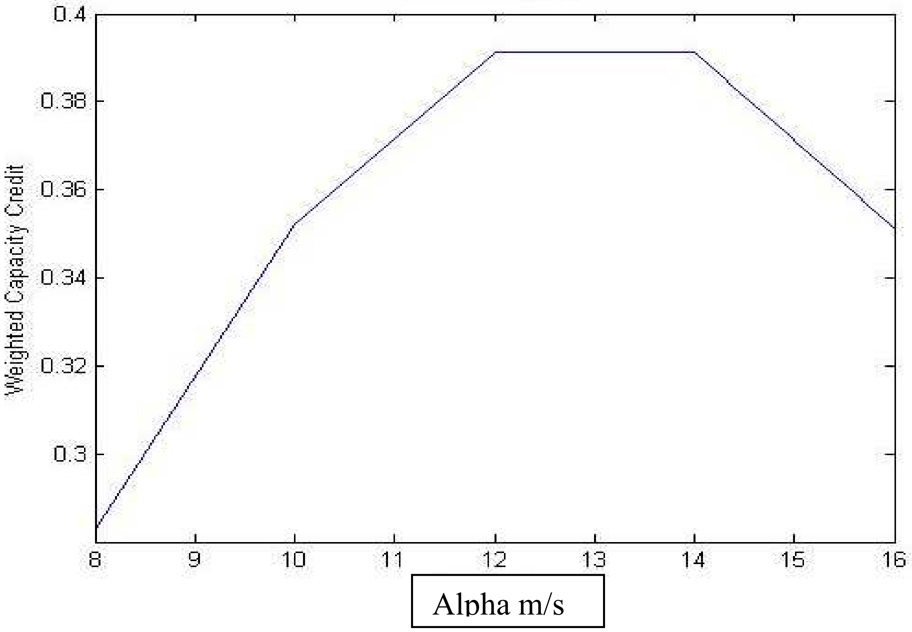

Figure 14 . 20% wind penetration, High wind regime- β = 3.1, varying α

2. 10 % wind penetration

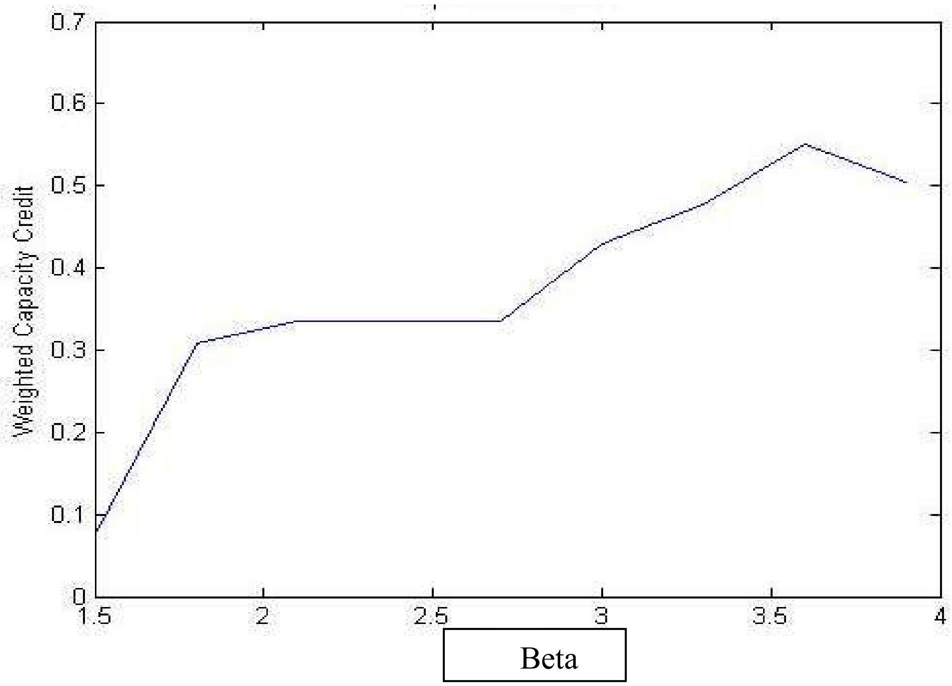

Figure 15 . 10% wind penetration, High wind regime- α =15.55 m/s , varying β

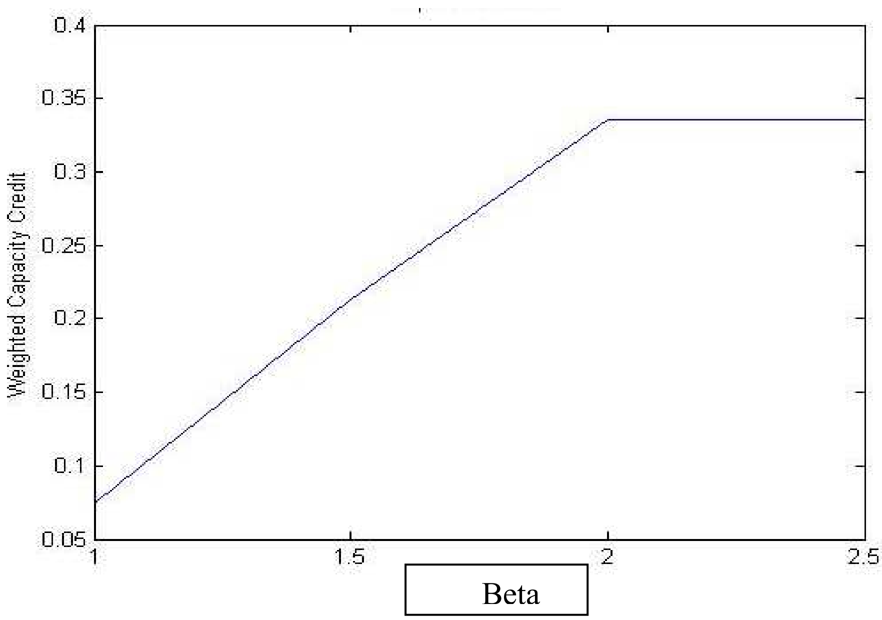

Figure 16 . 10% wind penetration, Moderate wind regime- α =9.7 m/s , varying β

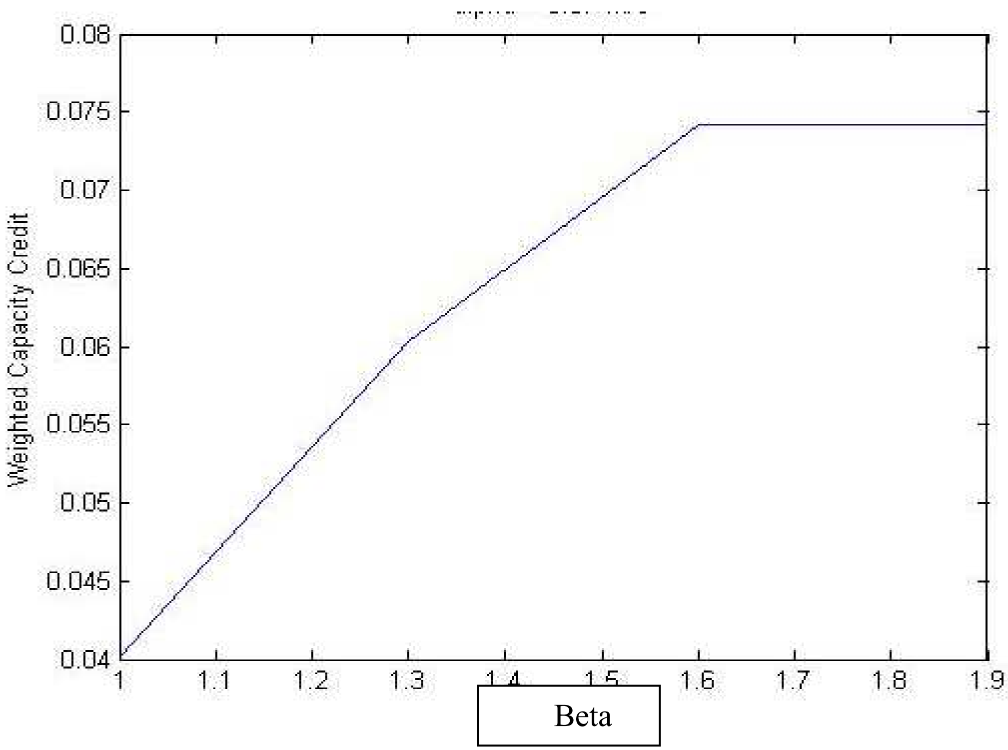

Figure 17. 10% wind penetration, Low wind regime- α =5.07 m/s , varying β

VI.3 Economic aspect of capacity credit

This section makes an effort to employ the CC value of WECS to predict and study possible economic and environmental impacts on overall energy generation with increasing wind penetration into conventional power system. A simple framework to accomplish this is presented. Examples are included to illustrate the approach with the following assumptions.

- System consists of coal fired plants as a primary base load generation.
- Total system capacity is kept constant at 500 MW.
- WECS penetration levels and wind regimes are varied.
- Variations of overall system's parameters are studied for different wind penetration levels.
- Detailed specification of power plants is given in Table 7.

TABLE 7

DETAILED SPECIFICATION FOR ECONOMIC ASSESSMENT

Energy Source	Wind	Conventional (Coal Fired)
Capital Cost	1,797,000 \$ per MW	1,923,000 \$ per MW
Fixed Annual Cost	176,271 \$/ MW	162,822 \$/ MW
Variable O & M cost	6 \$/MWh	4.59 \$/MWh
Fuel Cost	-----	38.53 \$/ Ton
Plant Factor	Included in the Capacity Credit value	0.92
Efficiency	-----	0.42
Annual Interest Rate	7.5%	7.5%
Payback period	20 years	30 years
CO_2 emission	-------	3.67 kg /Kg coal
Heating Value	--------	24000 KJ/kg
Subsidy	23.37 \$/MWh	-------
Carbon Tax	---------	12.5 \$/ ton of CO_2

Sources: U.S. Energy Information Administration, website: www.eia.gov and www.carbontax.org

Example 1. 10 % Wind Penetration

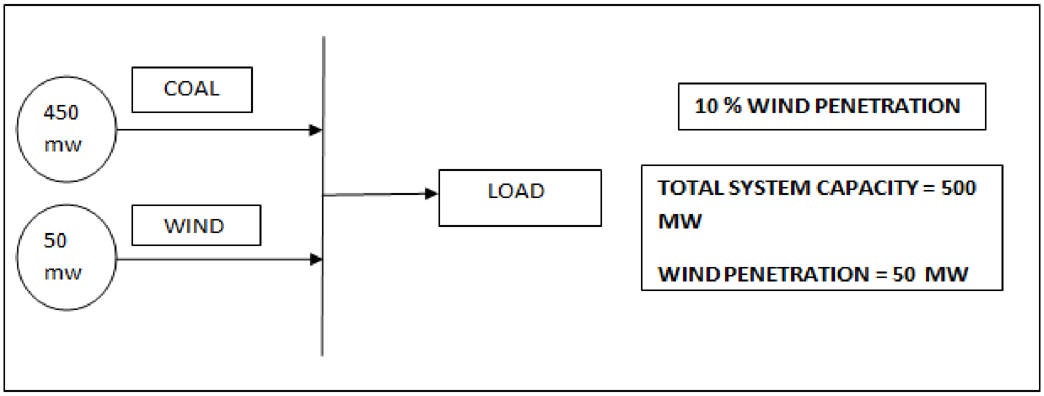

Figure 18. 10 % wind penetration in the system

Wind Calculations:

Assuming moderate wind regime,

Average annual capacity credit from section 1,

CCav = 0.3357

Annual energy production from wind = 0.3357*50*365*24 =147,036 MWh

Annual fixed cost= 50*176271= $ 8,813,550

Variable cost = 147,036*6 = $ 882,219

Annual subsidy on wind energy = 147,036*23.37 = $ 3,436,245

Annual expenditure on wind = $ 6,259,524

Coal Calculations:

Annual energy production from coal = 450*365*24*0.92 = 3,262,640 MWh

Annual fixed cost = 162,822 * 450 = $ 73,269,900

Total coal used = 1,295,228 tons

Total fuel cost = $ 49,218,664

Total carbon emitted= 4,753,488 tons

Total carbon tax = $ 59,418,610

Total maintenance cost = $ 16,646,277

Annual expenditure on coal plant = $ 198,553,451

Total system calculations:

Total annual expenditure on the system (Coal+wind)= $ 204,812,975

Total energy produced in a year by the system = 3,773,676 MWh

Generation cost to 1 MWh energy = 54.274 $/ MWh

Example 2. 20 % Wind Penetration

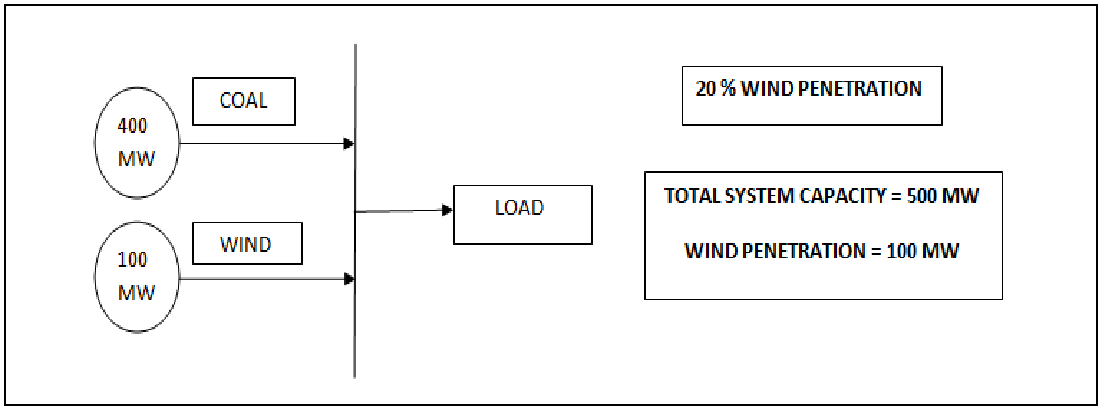

Figure 19. 20% wind penetration in the system

Wind Calculations:

Assuming moderate wind regime,

Average annual capacity credit= 0.2820

Annual Energy production from wind = 0.2820*100*365*24 =247,032 MWh

Annual fixed cost= 100*176271= $ 17,627,100

Variable cost = 247,032*6 = $ 882,219

Annual subsidy on wind energy = 247,032*23.37 = $ 5,773,137

Annual expenditure on wind = $ 13,336,154

Coal Calculations:

Annual energy production from coal = 400*365*24 *0.92= 3,223,680 MWh

Annual fixed cost = 162,822 * 400 = $ 65,128,800

Total coal used = 1,151,314 tons

Total fuel cost = $ 43,749,932

Total carbon emitted= 4,225,323 tons

Total carbon tax = $ 52,816,542

Total maintenance cost = $ 14,796,691

Annual expenditure on coal plant = $ 176,491,965

Total system calculations:

Total annual expenditure on the system (Coal+wind)= $ 189,828,119

Total energy produced in a year by the system = 3,470,712 MWh

Generation cost of 1 MWh energy = 54.7 $/ MWh

The above procedure is also followed for systems with only coal fired plants and only WECS. The results are summarized in Table 8.

TABLE 8: ECONOMIC ASSESSMENT RESULTS

System	**Coal**	**Coal + 10% wind (Moderate wind regime, CC=0.3357)**	**Coal + 20% wind (Moderate wind regime, CC=0.2820)**	**Wind (Moderate wind regime,CC=0.2820)**
System Capacity (total 500 MW)	500 MW Coal	450 coal + 50 wind	400 coal + 100 wind	100 MW
Annual Energy Generation	4,029,600 MWh	3,773,676 MWh	3,470,712 MWh	294,073 MWh
Coal used	1,439,142 tons	1,295,228 tons	1,151,314 tons	------
CO_2 emitted	5,281,651 tons	4,753,488 tons	4,225,323 tons	------
Fixed annual cost	$ 88,135,500	$ 82,083,450	$ 82,755,900	$ 17,627,100
Variable cost	$ 18,495,864	$ 17,528,496	$ 16,278,883	$ 1,764,436
Fuel cost	$ 54,686,428	$ 49,218,664	$ 43,749,932	-----
Annual CO_2 tax	$ 66,020,639	$ 59,418,610	$ 52,816,542	-----
Total annual expenditure	$ 227,520,431	$ 204,812,975	$ 189,828,119	$ 19,391,536
Generation cost / MWh	56.46 $/MWh	54.27 $/MWh	54.7 $/MWh	42.57 $/MWh
Generation cost / MWh (No CO_2 tax)	40.03 $/MWh	38.52 $/MWh	39.47 $/MWh	---------
Generation cost /MWh(No subsidy)	-----------	55.18 $/MWh	56.36 $/MWh	65.94 $/MWh
Generation cost /MWh(No subsidy and no CO_2 tax)	40.03 $/MWh	39.44 $/MWh	41.14 $/MWh	65.94 $/MWh

VI.4 Additional Simulation Results In the Realm of Economics

In this section additional simulation results are presented in a graphical form to illustrate the effect of capacity credit of WECS on total system's generation cost and to assess environmental impact of introduction of WECS into conventional system.

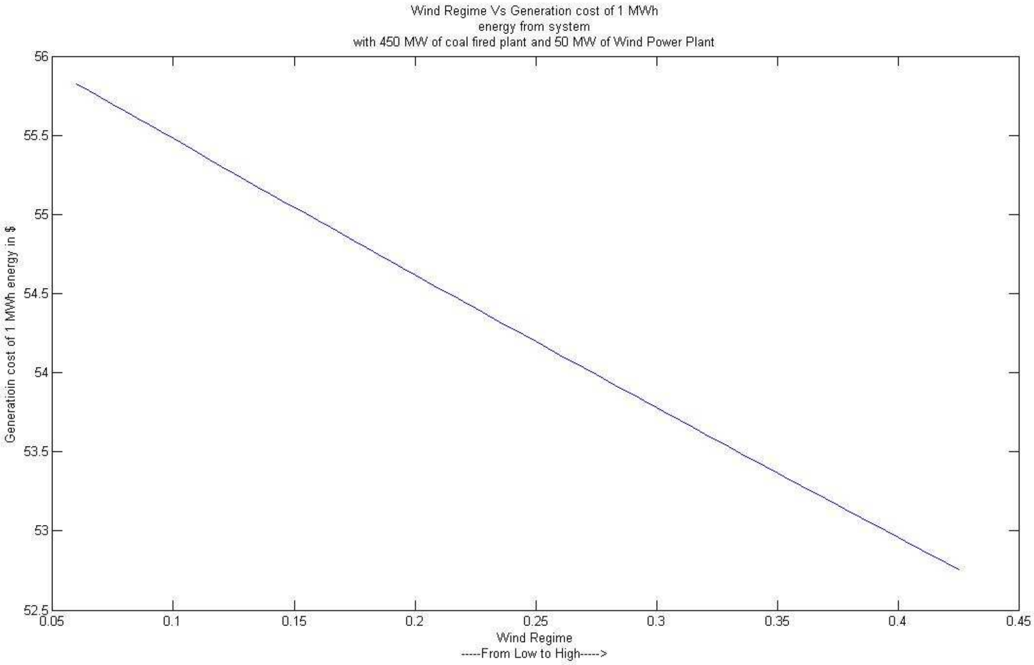

Figure 20. 10% wind penetration, capacity credit Vs per unit generation cost

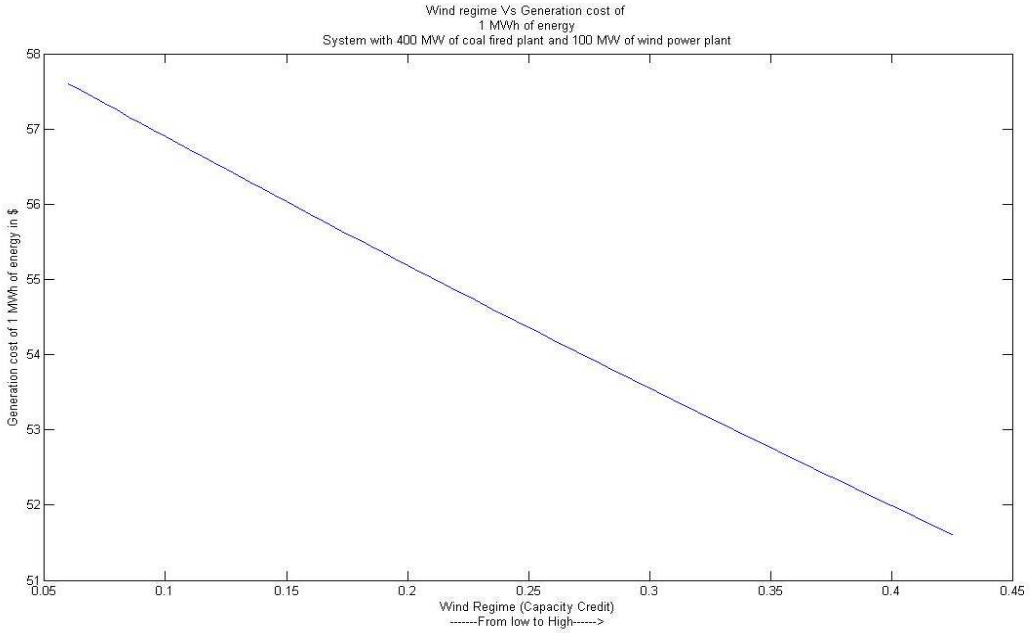

Figure 21. 20% wind penetration, capacity credit Vs per unit generation cost

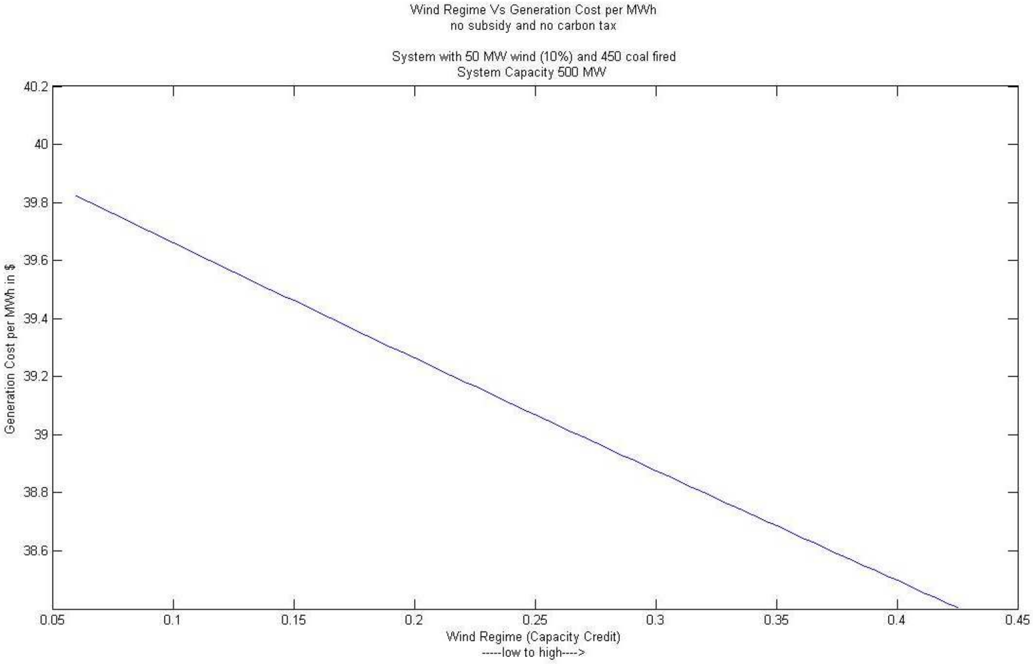

Figure 22 . 10% wind penetration, capacity credit Vs per unit generation cost

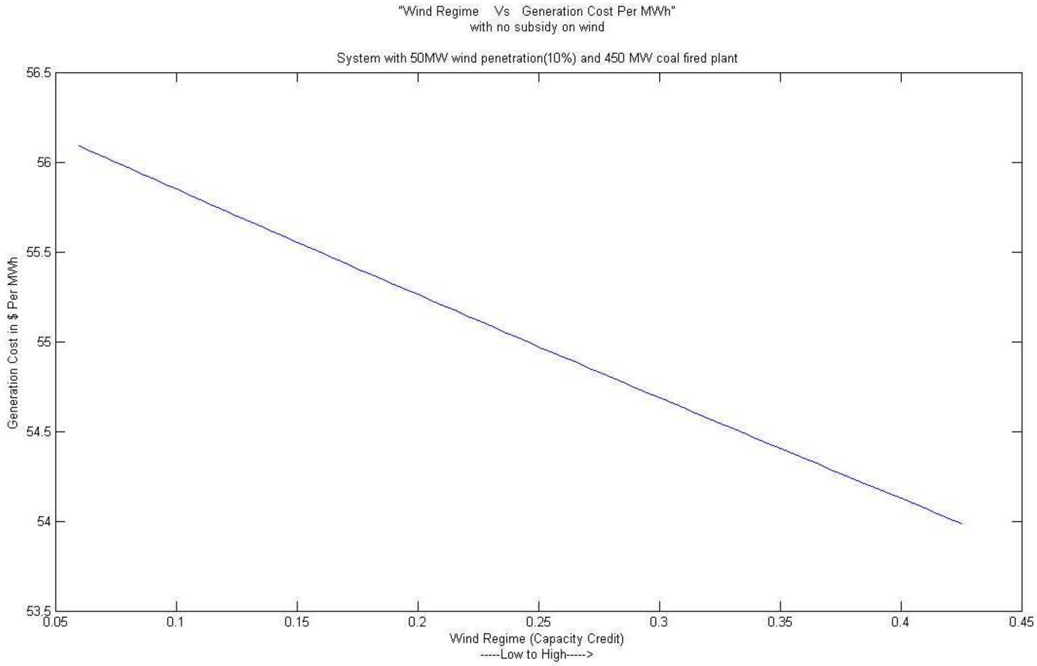

Figure 23. 10% wind penetration, No subsidy on wind, capacity credit Vs per unit generation cost

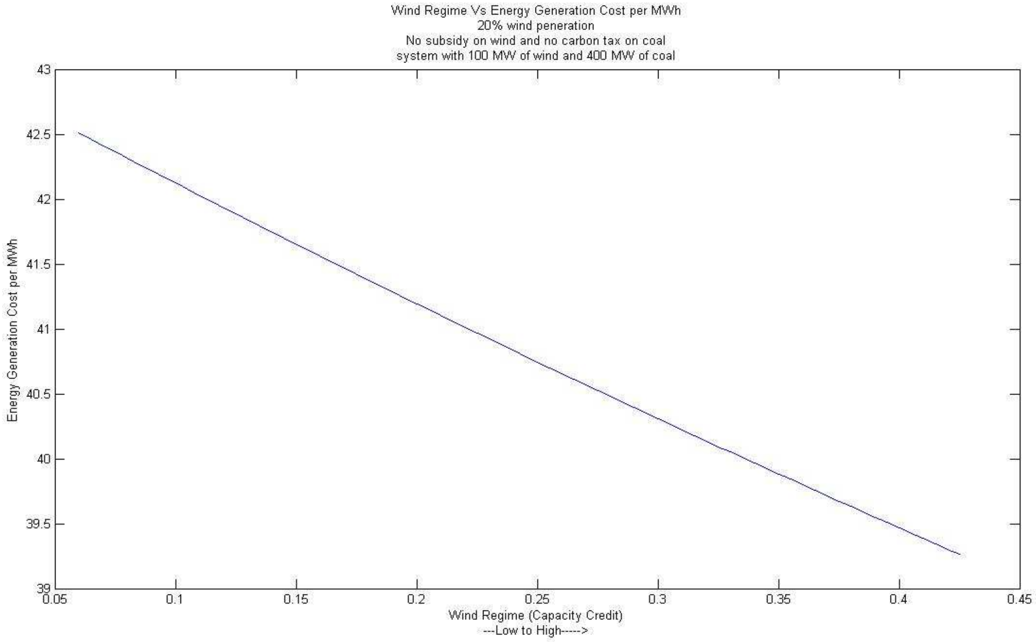

Figure 24. 20% wind penetration, No subsidy on wind and no carbon tax on coal Capacity credit Vs per unit generation cost

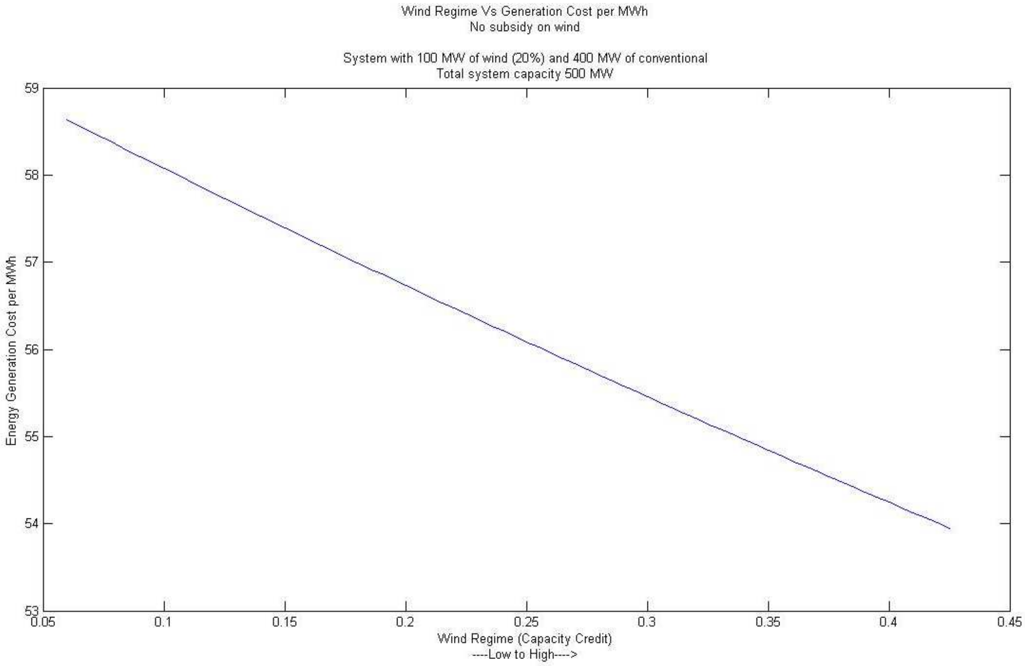

Figure 25. 20% wind penetration, No subsidy on wind, capacity credit Vs per unit generation cost

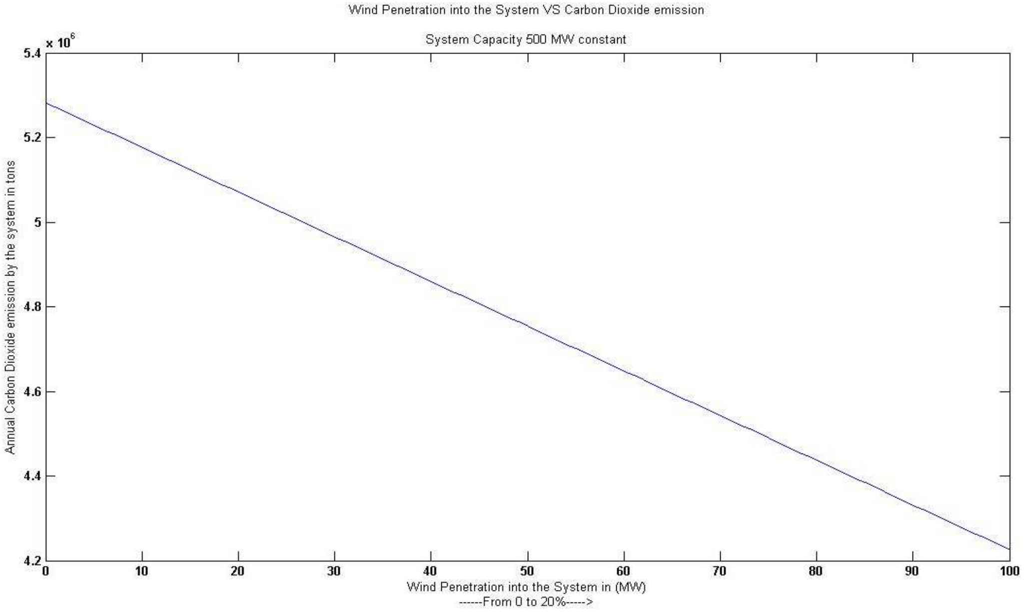

Figure 26. % wind penetration Vs Annual carbon dioxide emission

VI.5 Discussion of simulation results:

a. Weighted Capacity credit:

This part of the study was undertaken to quantify the impact of wind parameters and wind penetration on weighted capacity credit of WECS.

Results presented in Figures 9-14 are for 20% wind penetration into conventional power system. They show the dependence of capacity credit on variation in wind parameters (α, β) for different wind regimes (low, medium, high). For high and low wind regimes, as the wind parameters (α, β) increase, the capacity credit increases initially and then decreases for high values of both α and β as shown in Figures 9-10 and 13-14. Figure 11 for 20% wind penetration shows a steady rise in capacity credit with increase in β. However with the same 20% penetration, dependence on α shown in Figure 12 exhibits an initial steady rise in capacity credit value and become constant after certain high value of α.

Results presented in Figures 15-17 are for 10% wind penetration into conventional power system. The results show variation in capacity credit with change in wind parameter β for different wind regimes. All the results show initial steady increase in capacity credit value and then remain constant with increase in β for low and moderate wind regimes. But for high wind regime it increases first and then decreases for large β values.

b. Economic aspect of capacity credit:

This part of the study was undertaken to examine possible economic and environmental impacts of introducing WECS into a conventional power system.

Figures 20-25 shows variation of the overall system's generation cost with capacity credit value of WECS over the various parameters such as wind penetration, subsidy on wind and carbon tax on CO_2 emission from coal for 10% and 20% penetration levels.

From the results, overall system's generation cost for 10% wind penetration varies from 52.8 \$/MWh to 55.7 \$/MWh as wind regime varies from high to low with subsidy, and with no subsidy on wind it varies from 54 \$/MWh to 56 \$/MWh. Similarly, for 20% wind penetration it varies from 52 \$/MWh to 57.5 \$/MWh with subsidy and with no wind subsidy the generation cost varies from 54 \$/MWh to 58.5 \$/MWh.

Figure 26 show a considerable decrease in annual CO2 emission from the overall generation system with a steady increase in wind penetration. Results show an annual decrease of up to 1.1 million tons (approximately 20%) in CO_2 emission by the total system with 20 % wind penetration into the system.

CHAPTER VII

SUMMARY AND CONCLUDING REMARKS

VII.1 Summary and concluding remarks

Wind generated electricity has shown significant growth over the last few decades. Because of its direct economic impact, quantification of capacity credit is very important. This study has presented a simple approach to assess the capacity credit of wind electric conversion systems under variable load conditions. It is based on replacing the annual load duration curve by a stepped function and calculating the capacity credit for each of the load steps. A weighted average of these values using the probability of the various load steps as weighting factor is proposed as an estimate of the overall capacity credit. This method is applied at different penetration levels of wind generated electric power and also for different wind regimes (low, moderate, high).

Capacity credit values are obtained for 10%, 20%, 30% and 40% wind penetration. For 10% penetration, system consisting of 3 conventional generators of 150 MW each and a wind generator of 50 MW is considered. The total capacity of the system is 500 MW and capacity of wind generated electric power is 50 MW. The weighted capacity credit value for 10% wind penetration with moderate wind regime is obtained as 0.3357. Similarly, weighted capacity credit values for 20%, 30% and 40% values at moderate wind regime are estimated to be 0.2820, 0.2588 and 0.2097 respectively. All the results in this area are summarized in Table 6.

Results show a pattern for all wind penetration values. Weighted capacity credit values decrease as penetration increases in the system. Also, weighted capacity credit value increases as the wind regime improves. Although this approach can be refined, it enables a rapid initial assessment of the capacity credit that can be used for planning purposes.

As a next step, capacity credit is incorporated in a simple economic study with wind and coal-fired plants. Systems with different wind penetration levels are compared with the system with only conventional power plant (coal) in terms of various parameters such as annual energy production, generation cost and annual system CO_2 emission etc. keeping the total system capacity constant. Results show that although the system's total annual energy production decreases with an increase in wind penetration, system generation cost / MWh is lower than the system with only coal fired plants. Also, there is a considerable decrease in CO_2 emission with increasing in wind penetration. Results obtained in this part of the study are summarized in Table 8.

VII.2 Scope for future work

The study aggregates all wind energy conversion units in a wind farm into an equivalent wind capacity equal to the sum of all individual capacities. In reality, units will be spread over a large area and the wind incident on individual units will not be same for all the wind turbines at a particular time. Detailed analysis and study will be needed to effectively aggregate the outputs. Also, profile of the wind incident on a turbine will vary from season to season over the year. Therefore the procedure developed should be repeated over the different seasons with applicable load models.

Another significant issue to be considered is the correlation between wind availability and load depend on the system. Sudden drop of wind over an extended wind farm can initiate dynamic instability, lower the overall power quality and may also lead to blackouts depending on the time of occurrence. Provision of backup generation and/or energy storage and reconversion subsystems will significantly add to the overall generation cost. Quantifications of these factors would involve a considerable amount of further and detailed investigation.

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APPENDIX A

FOR of Wind Electric Conversion Systems

Procedure for calculating an effective forced outage rate (FOR) for WECS is documented in references [6]. A brief summary is presented here.

A. Forced Outage Rate

The Forced Outage Rate is one of the most important parameters in the assessment of capacity credit. The long-term probability of finding the component in the down state is called its ‘Forced Outage Rate’ (FOR).

1. 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. Typical FOR for the conventional generator is considered to be 0.02

FOR of WECS can be calculated by considering the characteristics of the wind resource, output curve of the WECS and mechanical failure data. This FOR value can be used to calculate the LOLP and estimate the capacity credit of WECS.

From the power output curve of WECS shown in Figure 27 , 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.

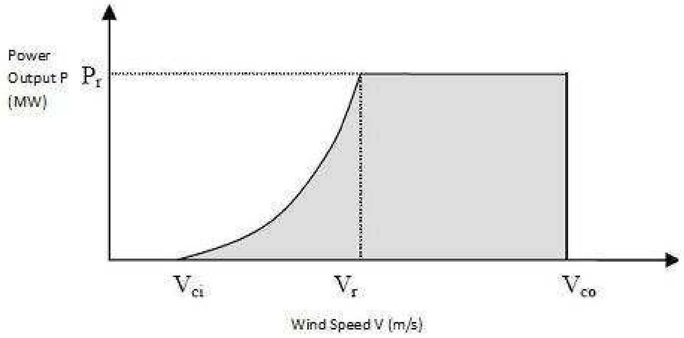

Fig. 27. Typical WECS Power Output Characteristic

2. Reliability Model for WECS

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

Where,

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

Then, the overall forced outage rate for the WECS output will be $FOR_{Pow} = 1 - R$

Where,

$\boldsymbol{P_{WA}}$= Wind Availability Factor

It is defined by the probability that wind speed is between cut-in and cut-out values.

P_{mech} = Factor for mechanical failures

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 summing over all the components logically in series.

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

Where, FOR *Mech* is FOR for Mechanical system.

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

P_{Const} = Constant Power Output Factor

Since rated power output results for wind speeds between Vr and Vco, the expected normalized power output in this speed range will be the probability of the wind speed lying in this speed range.

P_{Var} = Variable Power Output Factor

It is the expected value of normalized power output over the speed range from Vci to Vr

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.

Example:

List of all the parameters used in the process of calculation of effective FOR for WECS with moderate wind regime are tabulated below in Table 9

.

TABLE 9

LIST OF PARAMETERS INVOLVED IN CALCULATION OF EFFECTIVE ‘FOR’ FOR WECS

FOR_{Mech}: 0.0027	**P_{WA}: 0.8621**
$P_{Mec}h$: 0.99729	**$E(P)$: 0.6867**
P_{Const}: 0.49729	**R: 0.5904**
P_{var}: 0.18940	**FOR_{POW}: 0.4096**

Where,

FOR_{POW} is the effective FOR of WECS.

VITA

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Scope and Method of Study: In this study, an effort has been made to develop a simple approach to estimate the capacity credit under variable load condition. It is based on replacing the annual load duration curve by a stepped function and calculating the capacity credit for each of the load steps. A weighted average of these values using the probability of the various load steps is proposed as an estimate of the overall capacity credit.

As a next step, capacity credit is incorporated in a simple economic study with wind and coal-fired plants. Systems with different wind penetration levels are compared with the system with only conventional power plant (coal) in terms of various parameters such as annual energy production, generation cost and annual system CO_2 emission etc. keeping the total system capacity constant.

Findings and Conclusions: A simplified approach to assess the capacity credit of wind electric conversion systems (WECS) and its economic aspect has been presented. Results for weighted capacity credit show a pattern for all wind penetration values. Weighted capacity credit values decrease as penetration increases in the system. Also, weighted capacity credit value increases as the wind regime improves. Although this approach can be refined, it enables a rapid initial assessment of the capacity credit that can be used for planning purposes.

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