

Capacity Value of Wind Generation in India - An Assessment



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Table of Contents

Acknowledgements.....	3
Executive Summary.....	1
1 Introduction	6
1.1 Power System Reliability and Capacity Value Concept	7
1.2 Factors affecting Capacity Value Calculation	7
2 Review of international practices in estimating the Capacity Value for Wind Generation.....	9
2.1 Risk-Based Methods.....	9
2.1.1 Risk Based Method 1: California RPS Method	10
2.1.2 Risk-Based Method 2: Garver’s Approximation.....	10
2.2 Time-Period Methods	11
2.2.1 Time Period Method 1: Peak Period method	11
2.2.2 Time Period Method 2: Z-Statistic method.....	11
3 Approach for Calculating the Capacity Value of Wind.....	14
3.1 Calculation of Critical hours	14
3.1.1 Scenario 1.....	15
3.1.2 Scenario 2.....	15
3.1.3 Scenario 3.....	16
3.1.4 Scenario 4.....	16
3.2 Model Assumptions and Limitations.....	17
3.3 Selection of wind turbine and calculation of wind power generation.....	18
4 Modeling Results	20
4.1 Tamil Nadu	20
4.1.1 Scenario 1.....	21
4.1.2 Scenario 2.....	21
4.1.3 Scenario 3.....	21
4.1.4 Scenario 4.....	22
4.2 Gujarat	22
4.2.1 Scenario 1.....	23
4.2.2 Scenario 2.....	24

4.2.3	Scenario 4.....	24
4.3	Andhra Pradesh (AP).....	24
4.3.1	Scenario 1.....	25
4.3.2	Scenario 2.....	25
4.3.3	Scenario 4.....	26
4.4	Maharashtra.....	26
4.4.1	Scenario 1.....	27
4.4.2	Scenario 2.....	27
4.4.3	Scenario 4.....	28
4.5	Karnataka.....	28
4.5.1	Scenario 1.....	29
4.5.2	Scenario 2.....	29
4.5.3	Scenario 4.....	30
4.6	Rajasthan.....	30
4.6.1	Scenario 1.....	31
4.6.2	Scenario 2.....	31
4.6.3	Scenario 4.....	31
5	Scenario 1, Scenario 2 and Scenario 4 - Comparison of results for the six selected States.....	32
5.1	Scenario 1 (Met Load – Chronological with respective State’s Demand).....	33
5.2	Scenario 2 (Met Load – top 10% hours).....	34
5.3	Scenario 4 (Met Load – Chronological with Pan-India Demand).....	35
5.4	Wind Profile of States wrt State’s demand profile.....	36
5.5	Wind Profile of States wrt Pan-India demand profile.....	39
6	Overall capacity contribution of wind to national generation mix over next five Planning periods.....	42
7	Factors affecting capacity value of wind and limiting the results of this study.....	44
8	The Way forward and Recommendations.....	46
9	Annexure 1 – Details of formulae used in the analysis.....	48
10	Annexure 2 – Stochastic Resource Adequacy Model.....	51

List of Tables

Table 1 Capacity Value of Wind Generation for six key wind states	4
Table 2 Wind capacity at the end of each planning period (in MW)	5
Table 3 Wind capacity contribution at the end of each planning period (in MW).....	5
Table 4 Time of Day (ToD) hours for each state and Pan-India.....	17
Table 5 Wind States and specific sites covered under study.....	18
Table 6 Analysis results for Mupandal.....	20
Table 7 Analysis results for Coimbatore.....	20
Table 8 Analysis results for Kutch	23
Table 9 Analysis results for Saurashtra.....	23
Table 10 Analysis results for Ramasagaram.....	24
Table 11 Analysis results for Anapur.....	25
Table 12 Analysis results for Satara	26
Table 13 Analysis results for Somnath Nagar	27
Table 14 Analysis results for Chitradurg	28
Table 15 Analysis results for Gadak	29
Table 16 Analysis results for Jaisalmer	30
Table 17 Analysis results for Ludurwa.....	30
Table 18 Summary of Wind Capacity Value from modeling analysis	32
Table 19 Estimated overall wind potential and capacity contribution at National level...	42
Table 20 Wind capacity addition at the end of each planning period (in MW)	43
Table 21 Wind capacity contribution at the end of each planning period (in MW)	43

List of Figures

Figure 1 Broad classification of methods for capacity value calculation	9
Figure 2 List of Capacity Value calculation methods used in different US utilities	12
Figure 3 Capacity Value calculation approach.....	14
Figure 4 Power Curve for Gamesa G97 - 2.0 MW Machine	19
Figure 5 Frequency distribution of top 10% load hours under Scenario 2 and 3.....	22
Figure 6 Graphical representation of Scenario 1 results	33
Figure 7 Graphical representation of Scenario 2 results	34
Figure 8 Graphical representation of Scenario 4 results	35
Figure 9 Tamil Nadu annual wind and power demand profile	36
Figure 10 Karnataka annual wind and power demand profile	36
Figure 11 Maharashtra annual wind and power demand profile	37
Figure 12 Gujarat annual wind and power demand profile.....	37
Figure 13 Andhra Pradesh annual wind and power demand profile.....	38
Figure 14 Rajasthan annual wind and power demand profile.....	38
Figure 15 Tamil Nadu wind and Pan India demand profile	39
Figure 16 Karnataka wind and Pan India demand profile.....	39
Figure 17 Maharashtra wind and Pan India demand profile	40
Figure 18 Gujarat wind and Pan India demand profile.....	40
Figure 19 Andhra Pradesh wind and Pan India demand profile.....	41

Figure 20 Rajasthan wind and Pan India demand profile.....	41
Figure 21 Wind capacity contribution to overall generation - NAPCC wind capacity target compliant case	43
Figure 22 Data table for sample calculation of wind power generation.....	48
Figure 23 Data table for sample calculation of capacity value.....	50
Figure 24 SRAM Process	51

List of Abbreviations

AEMO	Australian Energy Market Operator
CAISO	California Independent System Operator
CEA	Central Electricity Authority
C-WET	Centre for Wind Energy Technology
DISCOM	Distribution Company
ELCC	Effective Load Carrying Capability
ERCOT	Electricity Reliability Council of Texas
ISO	Independent System Operators
JNNSM	Jawaharlal Nehru National Solar Mission
LDC	Load Duration Curve
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
NAPCC	National Action Plan on Climate Change
NY ISO	New York Independent System Operator
PJM	Pennsylvania-Jersey-Maryland Independent System Operator
RE	Renewable Energy
RLDC	Regional Load Dispatch Center
RTO	Regional Transmission Organization
SLDC	State Load Dispatch Center
SRAM	Stochastic Resource Adequacy Model
ToD	Time of Day

Executive Summary

A two fold increase in the conventional generation capacity over last decade in India is accompanied by an eight fold increase in the installed renewable energy (RE) capacity. Today, India stands at the 5th position globally in the wind power generation installed capacity. The officially estimated wind power potential at 80m hub height is 102 GW¹. However, a number of recent independent reports suggest that this potential could well be beyond 1000 GW. Further, solar is regarded as a resource with unconstrained potential. With the launch of Jawaharlal Nehru National Solar Mission (JNNSM) launched in 2010, the installed solar capacity has increased multi-fold reaching 1.8 GW in July 2013. The ever increasing power demand in the country coupled with energy security, energy access and environmental concerns strongly suggest increasing the contribution of renewable energy sources in the overall generation mix. It is noteworthy that in the year 2013, installed wind and solar capacities constitute about 13% of the total electricity generation capacity in the country and are expected to hold significant share in future too. In 2012-2013, RE plants in the country contributed 4.7% to the overall generation mix.

The renewable energy markets in India can be transformed if we work to solve issues such as unstable policy environment, absence of land procurement frameworks, inadequate transmission network and its planning, absence of supportive grid integration rules, and limited state-centre coordination.

Motivation for the study

Even though wind and solar power contribute significantly to India's electricity generation mix, these resources are not attributed a capacity value in the capacity addition plans of the Government of India. The 12th five-year plan targets to add 15,000 MW of wind capacity over 2012-17. It also recommends of a National Wind Mission to accelerate tapping the huge wind potential of the country. The JNNSM aims to add another 9000 MW of solar in the second phase of the mission, that is, 2013-17. Above all these, Government of India's National Action Plan on Climate Change (NAPCC) envisages to achieve 15% RE in India's electricity generation mix by 2020. However, these targets are additional to the required capacity and are only valued in energy terms. Attributing a capacity value to RE sources assume importance primarily because of the following reason: if the capacity value of wind generation is estimated at say 15% in a particular region (for 100 MW of installed wind capacity), this implies that instead of 1000 MW of base load capacity required to be installed; now 985 MW will need to be deployed as 15 MW will be met through wind.

Looking at the increasing contribution of RE sources to the national energy mix, and their potential to solving India's environmental concerns, it is essential that these sources, particularly wind and solar, be ascertained a capacity value while formulating our power sector plans. While

¹ At 80m level, source: http://www.cwet.tn.nic.in/html/departments_ewpp.html

this phenomenon is common in several other countries, it still needs to make place in India's planning framework.

Therefore, this analysis focuses on assessing capacity value of wind generation mainly because it is considered to be more variable than solar. However, a similar analysis is equally imperative case for solar as well.

Objective

The study aims to address the following major objectives:

- To estimate the contribution of wind power in meeting the base load requirement and electricity shortages
- To attribute "certainty" value to wind generation so that capacity addition plans can be optimized by substituting appropriate percentage of installed and planned wind capacity with equivalent conventional capacity
- To facilitate integration of RE with India's power sector planning by mainstreaming RE into the power sector

Methodology

Understanding the variability in power generation from RE sources and accounting for the contribution of RE generation in meeting the peak demand is becoming important in developed countries as the installed capacity of RE based power plants is increasing. The methodology followed in this study for estimation of capacity contribution of wind power is an adaptation of the methodologies used internationally for this purpose and is considered appropriate, given the data constraints. This study assesses the capacity value of wind generation in India to quantify its contribution in meeting the peak power demand. It is noteworthy that a similar term 'capacity factor' is the ratio of the actual energy produced by a generator in a given period, to the hypothetical maximum possible, i.e. running full time at rated power whereas capacity value implies a different meaning as already explained.

The approach followed for the study involves determining correlation between wind generation and the state's peak power demand in six key wind-rich states over three financial years (FY10, FY11 and FY12). The analysis has been carried out in various scenarios² differing in methodology for calculating the critical hours of power demand in these three years. Hours in power demand is highest or is needed the most have been referred as critical hours.

Further, capacity contribution of wind generation for the overall wind resource base in the country and wind capacity planned at the end of each five-year planning period has been estimated. Also, the planned conventional generation capacities (as per the targets laid down in NAPCC) that could potentially be replaced by the estimated capacity value of wind at the end year of 12th, 13th, 14th and 15th planning period have been estimated.

² explained in detail in the main report

Modelling Assumptions

For the study, it is assumed that in all the selected states – Rajasthan, Gujarat, Maharashtra, Karnataka, Andhra Pradesh and Tamil Nadu, there is 100% power evacuation from wind plants. It is assumed that all inter-state transmission constraints will be resolved in the coming years (by end of 12th Five Year Plan) thus no such constraints between states have been incorporated in the modelling. ToD definition of peak hours represents the best estimate of critical hours for system reliability under scenarios considered for calculation of capacity value of wind. Average hourly generation of wind plants for all three years (FY10 to FY12) has been computed using wind resource data obtained from AWS Truepower. The wind frequency distribution and density has been converted into potential power generation for each wind area by using the power curve of G97 Gamesa wind turbine as it represents the wider turbine installation base in India. However, other turbines similar in capacity, hub-heights and size could also be used to carry out this analysis. Hub-height of 90m has been considered for the calculation. Representative sites in each state have been assumed to represent average wind capacity value of all the wind plants in the state.

Limitations

Met load data has been used as substitute to unrestricted demand data for all states except Tamil Nadu, for which load shedding data for one year is available. For the estimation of critical hours under scenario 1 as defined in the section below, Time of Day (ToD) tariff hour definition by respective DISCOMs has been considered. For states where ToD tariff is unavailable, peak hour definition from respective Regional Load Dispatch Centre (RLDC) has been considered. In addition, the results derived in the analysis are limited by some factors listed below³:

- Long term monthly power demand pattern and overall demand scenario
- Long term power supply scenario
- Daily load profile or change in peak hour definition as per ToD
- Transmission or power evacuation constraints
- Size and efficiency of turbine
- Wind farm site selection
- Additive effect of wind generation within a wind farm
- Curtailment of wind energy
- Wake effect in wind farm
- Scenario with firming up of wind power with other sources
- Impact of grid integration

³ explained in detail in the main report

Scenario Definitions

The analysis has been undertaken under four scenarios, which differ mainly on the method of critical hour calculation. In the **first scenario**, critical hours were estimated based on time periods having lowest system reliability by taking ToD tariff definition of Peak hours from respective states while in the **second scenario** critical hours were estimated by considering top 10% hours in Load Duration Curve (LDC) plotted using Met Load data. The **third scenario** could be worked out only for Tamil Nadu because of data constraints. In this scenario, critical hours were estimated by considering top 10% hours in LDC plotted using Met plus Un-Met demand data.

In addition to these, a **fourth scenario** was also analyzed to understand the contribution of wind power from each of the six states to the national-level peak power demand. The pan India demand constituted demand of 14 states (Maharashtra, Andhra Pradesh, Tamil Nadu, Uttar Pradesh, Gujarat, Karnataka, Rajasthan, Madhya Pradesh, Punjab, West Bengal, Haryana, Delhi, Orissa and Kerala) which accumulate to 90% of national demand. The critical hours were estimated based on common ToD hours of above mentioned 14 states.

Results

Based on the above assumptions and scenario definitions, capacity values of wind for the sites under study in the six key wind rich states have been calculated through MS Excel based model. The table below summarizes the results:

Table 1 Capacity Value of Wind Generation for six key wind states

S. No.	State	Site	Capacity Value Scenario 1	Capacity Value Scenario 2	Capacity Value Scenario 3	Capacity Value Scenario 4
1	Tamil Nadu	Muppandal	24-31%	21-28%	18-19%	~24%
		Coimbatore	19-24%	20-23%	15-16%	~22%
2	Gujarat	Kutch	22-23%	~25%	-	~29%
		Saurashtra	25-28%	~26%	-	~30%
3	Andhra Pradesh	Ramasagaram	25-27%	~17%	-	~25%
		Anantapur	20-29%	~18%	-	~26%
4	Maharashtra	Satara	18-36%	~18%	-	~25%
		Somnath Nagar	14-28%	~26%	-	~21%
5	Karnataka	Chitradurg	30-31%	~25%	-	~29%
		Gadak	18-19%	~17%	-	~19%
6	Rajasthan	Jaisalmer	16-17%	~20%	-	~22%
		Ludurwa	13-15%	~17%	-	~19%

Wind power plant capacity addition as per National Action Plan on Climate Change (NAPCC) targets for 2020-2030 and its contribution that could potentially replace the conventional capacity at the end year of 12th, 13th, 14th and 15th planning period is shown in Table 2 and Table

3 below. Wind power contribution has been calculated based on the capacity value of wind estimated in Scenario 4 analysis.

Table 2 Wind capacity at the end of each planning period (in MW)

Capacity (Wind)	2011*	2012	2016	2021	2026	2031
NAPCC Complaint	14,986	17,986	35,266	75,266	1,40,266	2,25,266

* ending year of the corresponding National Five Year Plan

Table 3 Wind capacity contribution at the end of each planning period (in MW)

Capacity Contribution (Wind)	2011*	2012	2016	2021	2026	2031
NAPCC Complaint	3,583	4,323	8,668	18,536	33,928	54,373

* ending year of the corresponding National Five Year Plan

Thus, the potential contribution of wind power to national generation capacity has been estimated to be about 54 GW by 2031.

The Way Forward

This study lays a foundation for developing an understanding of the Wind Capacity Value concept in the Indian scenario. In view of the emerging RE sector, the study explains the importance of quantifying wind power share and estimates the wind capacity value range for various wind rich sites in the country. It strengthens the role of wind power in meeting national peak power demand and hence establishes the need to incorporate wind power to India's National power capacity planning. However, this analysis is developed with some assumptions and power shortage data limitations as mentioned above. Thus, a more detailed study through pertinent probabilistic models is recommended for determining the accurate capacity value contribution of the installed and planned wind generation capacity in the country. Such a comprehensive study would involve significant data requirement and stakeholder's involvement. Data on a number of parameters such as unrestricted demand, shortage, and unrestricted load profile for each state at hourly level, monthly forced outage rate of generators, conventional and non-conventional plant average monthly availability etc will be needed. The resulting extensive analysis would aid in realizing higher capacity value of renewable energy resources and avoiding larger conventional generation capacity through a number of policy and regulatory measures.

1 Introduction

As power from renewable energy sources like wind and solar achieves higher installation base in India, it becomes pertinent to understand their contribution to the overall system adequacy. The intermittent nature of power from these sources makes it difficult to analyze the capacity they provide to the grid. The ratio of the electrical energy produced by a RE based generating unit in a given period, to the maximum it could produce at continuous full power operation during the same period is called the generating unit's Capacity Factor, while, the contribution of the generating unit to power system adequacy is defined as its Capacity Value. Even though, presently the value of renewable sources is as an energy resource, but at higher installed capacities, it is important to determine the extent to which they contribute towards capacity requirements. Planning agencies all over the world typically allocate some capacity value to RE based power generation, although at a lower level than other generation types because of RE's variable nature.

The capacity value for wind/solar is determined as the correlation of wind/solar generation with system load, along with the adjustments for power outage rates and forecasting errors. If the wind/solar power output has high correlation with the load, it can be regarded as supplying power when it is most needed and thereby a high capacity value can be assigned to the generation source.

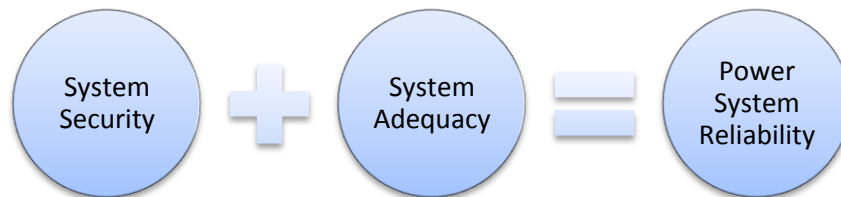
In India, the power sector planning agencies do not consider any contribution from wind and solar in meeting the peak demand, they rather account only the energy contribution of these RE sources. Any capacity contribution of wind and solar generation can directly help in avoiding the additional conventional capacity in the system, thus leading to direct savings. Therefore, if in a region with 1000 MW of capacity requirement to meet its reliability target and capacity value of wind and solar generation is 20%(for 100 MW of installed wind/solar capacity), it implies that 980 MW of base load capacity is required to be installed Instead of 1000 MW to meet the requirement.

This study focuses on estimating the capacity value of wind power generation in India and similar analysis for estimating the contribution of solar power can also be conducted at a later stage. The study aims to address the following major objectives:

- To estimate the contribution of wind power in meeting the base load requirement and electricity shortages
- To attribute "certainty" value to wind generation so that capacity addition plans can be optimized by substituting appropriate percentage of installed and planned wind capacity with equivalent conventional capacity
- To facilitate integration of RE with India's power sector planning by mainstreaming RE into the power sector

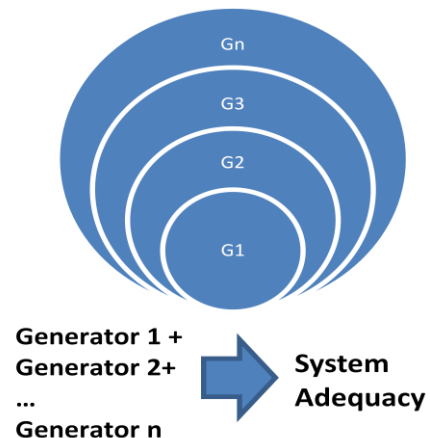
1.1 Power System Reliability and Capacity Value Concept

A Power System is referred to as secure and reliable if it can withstand the loss (or potentially multiple losses) of key power supply components such as generators or transmission links. Similarly, a system is referred to as adequate if it has sufficient installed capacity to meet the power demand. A combination of these two aspects together determines Power System Reliability.



System adequacy is achieved with a combination of different generators that may have significantly different characteristics. The contribution that a given generator makes to overall system adequacy is referred to as its Capacity Value. It can be defined as the amount of additional load that can be served due to the addition of the generator, while maintaining the existing levels of reliability.

The metrics that are used for adequacy evaluation include the loss of load probability (LOLP) and the loss of load expectation (LOLE). LOLP is the probability that the load will exceed the available generation at a given time. LOLE is the expected number of hours or days, during which the load will not be met over a defined time period. While LOLP criterion gives only an indication of generation capacity shortfall and lacks information on the importance and duration of the outage; the contribution that any given generator makes to overall system adequacy, as measured by LOLE, or similar reliability metric is called the Effective Load Carrying Capability (ELCC). A generator's ELCC is the additional load which the system can support on the addition of the new generation, while maintaining the same LOLE level. ELCC is the standard metric by which the capacity value is judged.



1.2 Factors affecting Capacity Value Calculation

Capacity Value of a generator depends on various factors which tend to be different in case of thermal and wind power plants. For thermal units, the primary characteristics that influence the overall system adequacy are the units' available capacity and forced outage rates (FORs). The data on long term FORs are available for different size and type of power plants and is compiled from a large data set of similar units.

With respect to wind power, the relationship between the wind and the load is a key factor impacting the capacity value calculation. The correlation between power from wind and load is site dependent. In some areas there is a diurnal and/or seasonal wind pattern. Although the hourly correlation between wind and load in some areas can be very low, there may be a considerable correlation among wind and load data when grouped according to rank. This implies the existence of systematic patterns of wind generation during system peaks and other time periods that cannot be ignored. Capacity Value can be determined as correlation of wind generation with system load, along with the adjustments for outage rates and forecasting errors. Capacity Value of a wind plant is dependent not only on the method employed but also on the specific characteristics of the region/country. In particular, the characteristics of the wind regime and the characteristics of the demand profile, e.g. whether peak demand occurs in winter or summer.

Thus, factors like wind resource forecast for that location, technology characteristics of the wind turbine, geographic location of the wind plant, change in load profile can affect the potential delivery and timing of wind generation to the grid and hence the capacity value of the wind plant. These have been discussed in more detail in Section 7 under 'Factors affecting capacity value of wind and limiting the results of this study'.

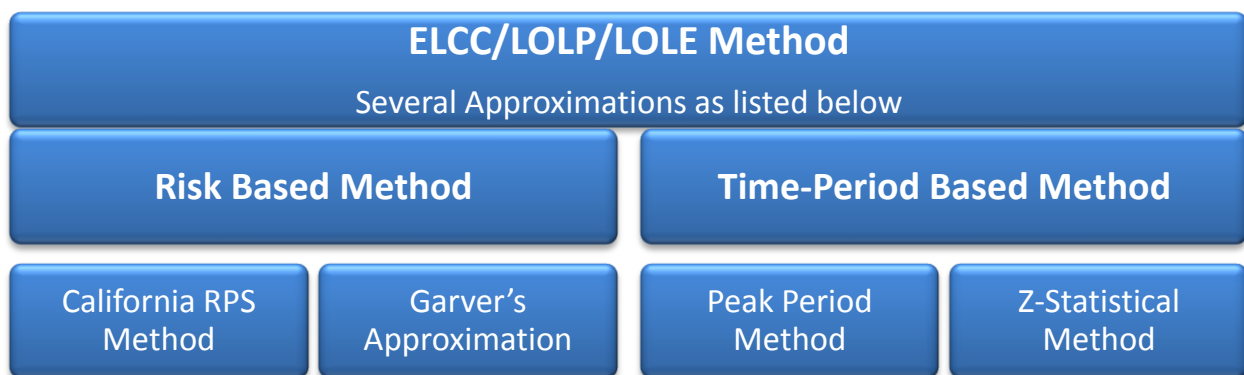
2 Review of international practices in estimating the Capacity Value for Wind Generation

Various methods are employed by different utilities across the globe for computation of capacity value for wind generation. Interest in simpler methods has emerged over the past several years because of potential difficulty in assembling the appropriate database to use for the ELCC calculation. Although several methods can be used to approximate ELCC, it is important to note that they are indeed approximations. However, in cases where ELCC can't be calculated because of data or other limitations, these methods can be useful. The following section provides an introduction to several techniques that are currently in practice.

On a broad level, the approximation techniques fall into two categories - Risk based and Time Period based. Risk-based techniques develop an approximation to the utility's LOLP curve throughout the year. Time-period-based methods attempt to capture risk indirectly, by assuming a high correlation between hourly demand and LOLP. Although this relationship generally holds, it can be compromised by scheduled maintenance of other units and hydro conditions.

A further limitation of time-period-based methods is that all hours considered for analysis by the method are generally weighted evenly, whereas ELCC and other risk-based methods place greater weight on high-risk hours and less weight on low risk hours. However, time-period based methods are much simpler and relatively easier to implement & explain. Time-period based methods are used by many utilities, Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) in the United States for assessing wind capacity value.

Figure 1 Broad classification of methods for capacity value calculation



2.1 Risk-Based Methods

Risk-based methods utilize hourly LOLP information either from an actual reliability model run or as an approximation. The two widely used techniques are summarized below:

2.1.1 Risk Based Method 1: California RPS Method

Investor owned utilities (IOUs) in California are required to acquire 20% of their energy mix from renewable sources by 2017 as per state's Renewable Portfolio Standard (RPS). The California Energy Commission developed the RPS method as an approximation to ELCC approach to calculate capacity value for all renewable generators and renewable technologies under the RPS requirements. The method contains several steps and is based on the output of a reliability model execution that does not consider the renewable generator of interest. The approach proceeds as follows:

- First, data for hourly LOLP, system load, and wind generation are collected for the top 10% of load hours for the year.
- A logarithmic risk metric that is a variation of LOLE over this discontinuous period is calculated and normalized. This provides a measure of risk over the top 10% of load hours that is normalized to one. This new metric is called the risk share, and for each hour, represents the fraction of risk occurring in that hour.
- For each of these hours, the wind generator output is multiplied by the risk share, and the total of all of these hourly values represents the relative risk contribution of the wind plant. This is converted to a percentage of the rated capacity of the wind plant.

This approach develops a set of load-ratio shares over the top 10% of load hours. These hourly share values are also normalized and multiplied by the hourly wind generation in the appropriate hour. This can be converted to a percentage of the rated capacity of the wind plant. This calculates the ratio of the standard deviation to the mean for the wind plant, also known as the coefficient of variation (COV), over the top 10% of load hours. When applied to wind generation at the three resource areas in California (Altamont, San Geronio, Tehachapi), selected solar and selected geothermal resources, the method had a mean absolute percentage error of 1.2% of the actual ELCC value. These results could not be obtained when the hydro system was included and thus the method may only be applicable to systems in which hydro generation is not significant.

2.1.2 Risk-Based Method 2: Garver's Approximation

In 1966 Garver proposed a simplified, approximate graphical approach for calculating the ELCC of an additional generator. This has been an important method in the calculation of capacity values but has been superseded by advances in computing power. The methodology underlying Garver's graphical approach can be used to estimate the ELCC of a wind generator added to a given power system. The technique is based on the development of a risk-approximation function, and in some respects it is similar to the California RPS method.

The approach approximates the declining exponential risk function (LOLP in each hour, LOLE over a high-risk period). It requires a single reliability model run to collect data to estimate

Garver's constant, known as m . Once this is done, the relative risk for an hour is calculated by the following equation:

$R' = \text{Exp} \{-(P-L)/m\}$, where P = annual peak load, L = load for the hour in question, R' is the risk approximation (LOLP), measured in relative terms (peak hour risk = 1). A spreadsheet can be developed to calculate R' for the top loads. Then values of L by are modified by subtracting the wind generation in that hour.

2.2 Time-Period Methods

To avoid using a reliability model altogether, it is possible to collect only hourly load and wind data for at least 1 year and use it to calculate an approximation to ELCC. This approach is comparatively simple, but it does not capture the potential system risks that are part of the other methods discussed above. Though an approximation, the method is quite effective and provides a fair assessment of capacity value of wind.

2.2.1 Time Period Method 1: Peak Period method

Peak Period method is a quite simplified approach to calculate capacity value of wind. This approach does not differentiate between criticality of hours, i.e. all hours are equally critical. This approach has many variations and is easy to implement. The variation is primarily dependent on selection of approach for the calculation of critical hours.

The approach follows simple steps. First, critical hours are determined based on either or all of the below mentioned criteria:

- Peak hour definition of the region during certain months
- Hours that has high system demand like top 10% peak hours
- Hours with maximum amount of load shedding as they generally reflect hours with lowest reliability or hours critical for system stability
- Hours with high merchant power prices
- Hours when system had lowest operating reserve margin

Second step involves calculation of average capacity factor or dispatch factor of wind plant in those critical hours. The calculated capacity factor represents average availability of wind plant during the hours when system reliability was lowest or capacity value of wind plant. The criteria for the selection of critical hours can vary from region to region, depending on importance of one or more factor listed above.

2.2.2 Time Period Method 2: Z-Statistic method

Some time-period methods succumb to the problem of using a percentile to calculate wind capacity value. For example, if the wind generation that occurs at least 85% of the time during a peak period is used for the capacity value, then all of the capacity generated that is below the

percentile is excluded. The implication is that a forced outage rate (applied in the simplified method) that exceeds 15% does not have any contribution to system adequacy. This variation of time-period is also called Z-statistic method and is recommended with some reservation as it results in loss of capacity value of wind.

The z-statistic method is based on taking the difference between available resources and load over peak demand hours (surplus availability) as a random variable with an associated probability distribution. The z-statistic for that distribution (mean divided by standard deviation) is taken as the primary system adequacy metric. The incremental load carrying capability for an added power plant is taken to be the load addition that keeps the z-statistic constant. For small changes in the overall system, keeping the z-statistic constant is equivalent to maintaining a constant LOLP. This approach is therefore an approximate method for annual peak ELCC calculation.

An observation of some of the methodologies being employed by ISOs and RTOs in the US and Canada reveals that most of the ISOs (in US) use peak period methodology for the determination of capacity value of wind plants. The flexibility in methodology allows for yearly revision in capacity value of wind and the approach adopted by most of the ISOs also allows for variable capacity value of wind plants i.e. capacity value of plants to be dependent on site/state. Similarly, the Australian Energy Market Operator (AEMO) follows Z-statistic method for assessing the contribution of generation to peak load in South Australia. A summary of methods used by different utilities in North America and that in Australia is provided in the table below:

Figure 2 List of Capacity Value calculation methods used in different US utilities

Region/Utility	Method	Details
CAISO	Peak Period	For three years, plant output that equals or exceeds 70% of period between 4:00 and 9:00 p.m. for Jan-March, and Nov. and Dec.; and between 1:00 and 6:00 p.m. from April through October. (Diversity benefit adder if wind area capacity credit higher than individual wind project. Various adjustments if wind project operating less than three years)
PJM	Peak Period	Jun-Aug Hour Ending 3 p.m.-7 p.m., local time, capacity factor using 3-year rolling average (13%, fold in actual data when available).
ERCOT	ELCC	ELCC based on random wind data, compromising correlation between wind and load (8.7%)
NY ISO	Peak Period	Wind's capacity factor between 2-6 p.m., June through August, and 4-8p.m., December through February

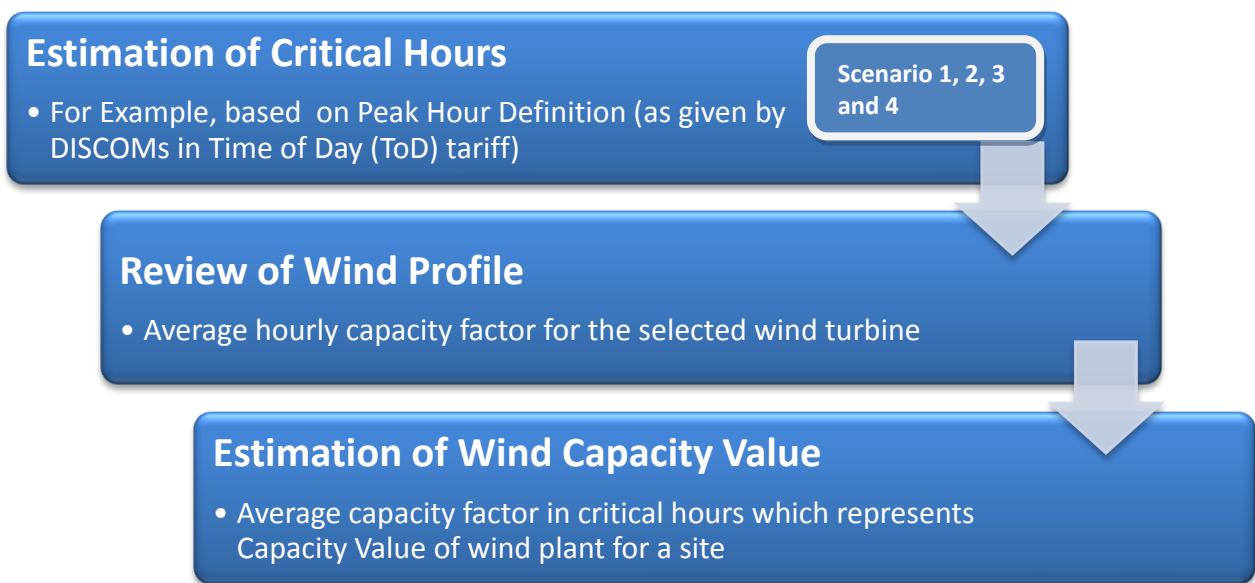
Southwest Power Pool	Z-Statistic Method	Top 10% loads/month; 85th percentile
Mid-west ISO	ELCC	Capacity credit currently 12.9% of rated capacity in 2011 and 14.9% in 2012.
New England ISO	Peak Period	For existing wind: wind's capacity factor between 2-6 p.m., June through September and 6-7 p.m. from October through May. For new wind: based on summer and winter wind speed data, subject to verification by ISO New England and adjusted by operating experience.
Alberta ESO	Peak Period	The capacity value for wind power has been given a 20% value until further studies determine a better value or method.
AEMO (South Australia)	Z-Statistic Method	Top 10% loads/month; 85th percentile Average wind contribution to peak in Summer – 8.3%, in Winter – 7.5%

3 Approach for Calculating the Capacity Value of Wind

Given the limited availability of data (especially the unrestricted demand data for different states), we have used Peak Period based methodology for calculating the capacity value of wind.

In the first step, critical hours for each state under consideration have been calculated by applying either Time of Day (ToD) criteria (as given by DISCOMs) or by plotting the Load Duration Curve (LDC). The selection of load data for this step has led to development of three different scenarios as explained in section 3.1 below. In the second step, hourly wind generation and capacity factor for the selected wind turbine has been computed. In the final step, capacity value for the wind plant located at the site under consideration has been estimated by analysing the correlation in wind generation and the peak load hours. A broad overview of the approach followed is presented in the figure below:

Figure 3 Capacity Value calculation approach

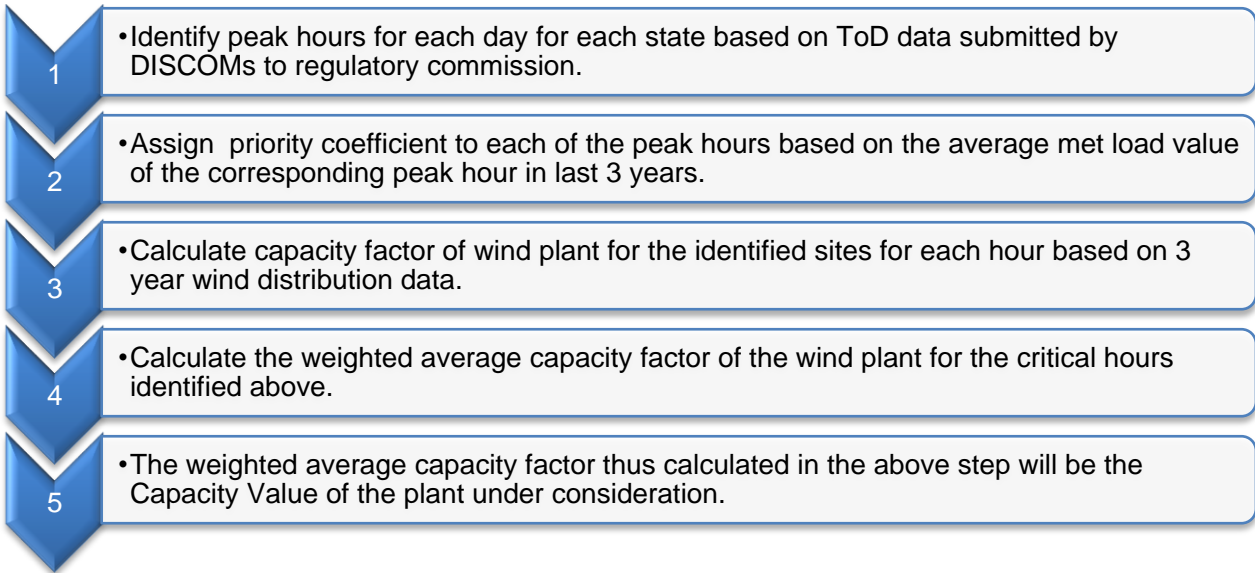


3.1 Calculation of Critical hours

The analysis has been undertaken under three scenarios, which differ mainly on the method of critical hour calculation. In Scenario 1, 2 and 3 capacity value of wind has been estimated by correlating wind power generation of each state with the peak power demand of the same state. In the fourth scenario, wind power generation of each state has been co-related with pan India power demand to understand the national level capacity value of wind. The steps and details of the analysis carried out under the four scenarios are explained below:

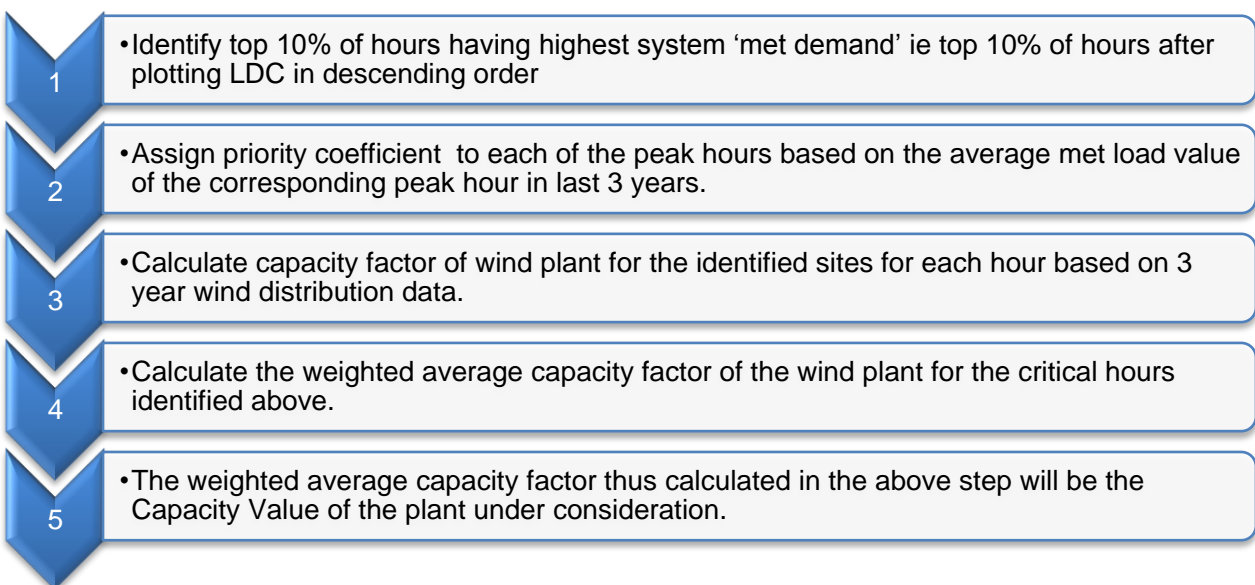
3.1.1 Scenario 1

For this scenario, critical hours were estimated based on time periods having lowest system reliability by taking Time of Day tariff definition of Peak hours from respective states:



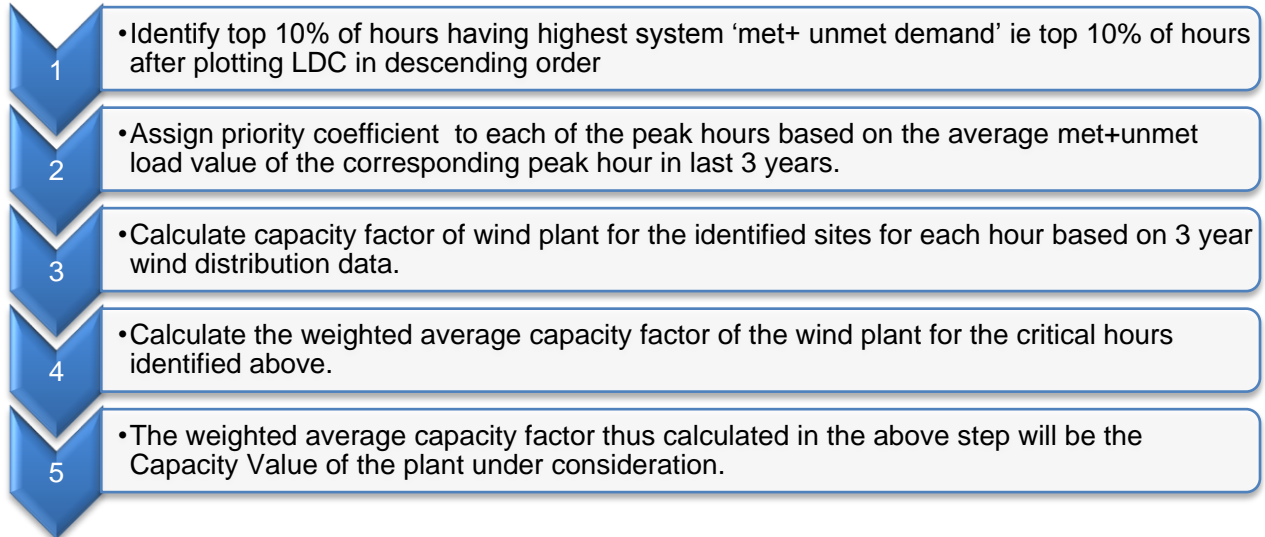
3.1.2 Scenario 2

For this scenario, critical hours were estimated by considering top 10% hours in Load Duration Curve (LDC) plotted using Met Load data:



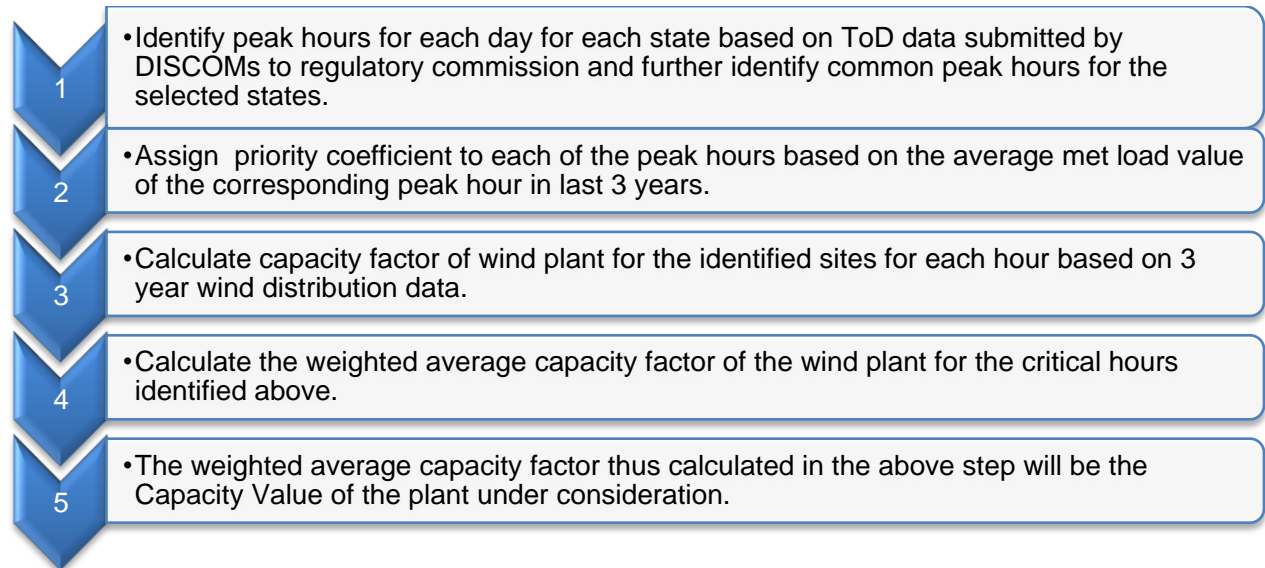
3.1.3 Scenario 3

For this scenario, critical hours were estimated by considering top 10% hours in LDC plotted using Met + UnMet demand data. This scenario could be worked out only for Tamil Nadu because of data constraints:



3.1.4 Scenario 4

For this scenario, critical hours were estimated based on time periods having lowest system reliability by taking common hours from the ToD tariff definition of Peak hours for selected states.



The pan India power demand in this scenario constituted demand of 14 states (Maharashtra, Andhra Pradesh, Tamil Nadu, Uttar Pradesh, Gujarat, Karnataka, Rajasthan, Madhya Pradesh,

Punjab, West Bengal, Haryana, Delhi, Orissa and Kerala) which accumulate to 90% of national power demand.

Estimation of critical hours for Scenario 4 has been done by considering Time of Day (ToD) tariff hour definition for the selected 14 states as given by their respective DISCOMs. For states where ToD tariff is unavailable, peak hour definition from respective Regional Load Dispatch Centre (RLDC) has been considered. The table below shows ToD hours for all selected 14 states and for Pan-India estimated on the basis of the former.

Table 4 Time of Day (ToD) hours for each state and Pan-India

Day-Hour	India	TN	GJ	RJ	KT	AP	MH	MP	PB	WB	HY	DL	OR	KE	UP
1															
2															
3															
4															
5															
6															
7		1													
8		1	1												
9		1	1												
10	1		1	1			1								
11	1		1	1			1								
12				1			1								
13				1											
14															
15															
16															
17															
18										1		1			
19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1		1	1	1	1	1	1	1	1	1	1	1
22	1	1	1		1	1	1	1	1	1	1	1	1	1	1
23	1	1								1		1	1		
24															

3.2 Model Assumptions and Limitations

The scenario analysis mentioned above is based on the following assumptions:

- There is 100% power evacuation for the wind generation in the state. Though, practically it is observed that in states like Tamil Nadu, the grid penetration of the wind generation reduces with an increase in wind generation.

- In scenario 1, 2 and 3 inter state transmission congestion has been assumed and state demand has been considered for computation of capacity value. In scenario 4, it is assumed that all inter-state transmission constraints will be resolved in the coming years (by end of 12th Five Year Plan) thus no such constraints between states have been incorporated in the modelling
- ToD definition of peak hours represents the best estimate of critical hours for system reliability under scenario 1 and 4
- Average hourly generation of wind plants for all three years (FY10 to FY12) has been computed using wind resource data obtained from AWS Truepower
- The wind frequency distribution and density has been converted into potential power generation for each wind area by using the power curve of G97 Gamesa wind turbine as it represents the wider turbine installation base in India.
 - Hub-height of 90m has been considered for the calculation
- Representative sites in each state has been assumed to represent wind capacity value of all the wind plants in the state

The scenario analysis mentioned above is based on the following limitations:

- Met load data has been used due to un-met load data unavailability. In ideal case we would have preferred to use 'unrestricted demand data' which is sum of 'met load' and 'power shortages'. Since power shortage data is estimated and not readily available, obtaining accurate unrestricted demand data estimates from Government offices like SLDCs appears significantly time intensive
- For Scenario 2, use of met load data could present a potential error in estimation of Critical hours as it does not include shortage or scheduled outages. In case shortages (or load shedding) are quite significant, use of met load data can result in significant error in estimating critical hours.

3.3 Selection of wind turbine and calculation of wind power generation

The six key wind states selected for this analysis represent about 85% of the wind resource potential in the country⁴. Further, the states and specific sites within them have been selected in a way that captures the geographic diversity in the wind resource. In all, twelve wind sites in six states have been analysed. The selected sites are listed in the table below:

Table 5 Wind States and specific sites covered under study

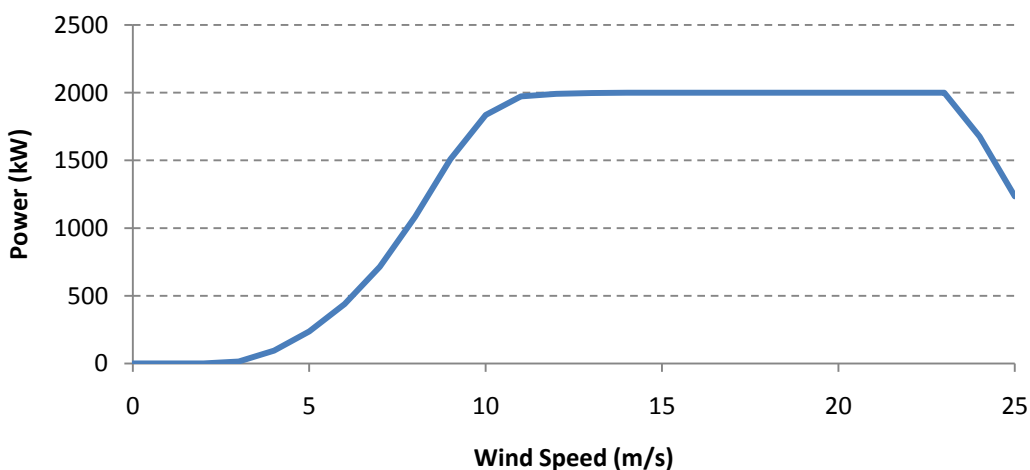
S. No.	State	No. of sites	Major Wind Farm Areas
1	Rajasthan	2	Jaisalmer
			Ludurwa
2	Gujarat	2	Kutch
			Saurashtra

⁴ As per C-WET revised estimates of the wind resource potential in India

3	Tamil Nadu	2	Mupandal
			Coimbatore
4	Andhra Pradesh	2	Anantapur
			Ramasagaram
5	Maharashtra	2	Satara
			Somnath Nagar
6	Karnataka	2	Chitradurgh
			Gadak

The analysis covers three financial years – FY10, FY11 and FY12. The average hourly generation of wind plants for all three years under study has been computed using wind resource data obtained from AWS Truepower⁵. The wind frequency distribution and density has been converted into potential power generation for each wind area by using the power curve of G97 Gamesa wind turbine as it represents the wider turbine installation base in India. It is noteworthy that any other such turbine typical in Indian market could also be used for such used for the analysis. Hub-height of 90m has been considered for the calculation. Power curve for this machine is presented in the figure below:

Figure 4 Power Curve for Gamesa G97 - 2.0 MW Machine



(Source: <http://www.gamesacorp.com/en/>)

⁵ <http://www.awstruepower.com/>

4 Modeling Results

The modeling results along with observations on the results so obtained for each site are discussed in the section below:

4.1 Tamil Nadu

Peak hours identified (for Scenario 1) as per Time of Day (ToD) tariff of Tamil Nadu DISCOM: 6 AM to 9 AM + 6 PM to 11 PM (total of 8 hours per day)

Table 6 Analysis results for Mupandal

Quarter	Scenario 1 Capacity Value_Met Load	Scenario 2 Capacity Value_top 10% Met Load	Scenario 3 Capacity Value top 10% Met + UnMet Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	45.6%	54.1%	49.7%	45.9%	45.5%
Q2	43.3%	50.8%	46.6%	43.6%	43.4%
Q3	31.4%	28.3%	32.2%	31.5%	31.0%
Q4	24.3%	21.5%	16.7%	23.8%	23.2%
Annual	36.3%	48.0%	18.8%	36.0%	35.8%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Table 7 Analysis results for Coimbatore

Quarter	Capacity Value_Met Load	Capacity Value_top 10% Met Load	Capacity Value top 10% Met + UnMet Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	42.9%	55.3%	47.2%	43.2%	42.1%
Q2	41.4%	53.3%	48.8%	42.0%	41.2%
Q3	23.9%	22.7%	25.1%	26.7%	23.7%
Q4	19.4%	20.3%	14.0%	22.2%	17.0%
Annual	32.2%	49.6%	15.6%	33.3%	31.1%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Observations and Comments

4.1.1 Scenario 1

- Tamil Nadu has high availability of wind during months of April to September (i.e. Q1 and Q2)
- Average Capacity Factor (CF) for wind plant during months of Q1 and Q2 is around 41% to 46% depending on the site/location
- Historically, months of April to September have seen relatively lower power shortage levels as compared to Q4 and Q3 months
- Also, unrestricted demand, estimated based on unmet load data or shortages and met load, is highest during Q4 months
- Thus Q4 months become more critical when it comes to reliability planning for grid operations
- Thus based on Scenario 1 calculations (Q4), we estimate that capacity value of wind for **Mupandal is ~24%** and for **Coimbatore is ~19%**
- Capacity value calculated for each quarter represents ~8% of hours in a year

4.1.2 Scenario 2

- In Q3 and Q4, Tamil Nadu experiences very high level of load shedding/shortages resulting in low “demand met”
- Whereas in Q1 and Q2, with low levels of power demand and high wind availability “demand met” is significant
- If we were to take results of Scenario 2 as they are, capacity value of wind would be around 50% to 55% and this would be incorrect representation
- Thus, based on estimations of unrestricted demand level, average capacity value in Q4 better represents capacity value of wind plants
- Capacity value of wind for **Mupandal is in the range of 21% to 22%** and for **Coimbatore is ~20%**
- In this scenario, limitation due to unavailability of proper power shortage data, which can be used to estimate unrestricted demand, poses a challenge and could lead to significant error in estimating capacity value of wind. This can be observed from results of Scenario 3

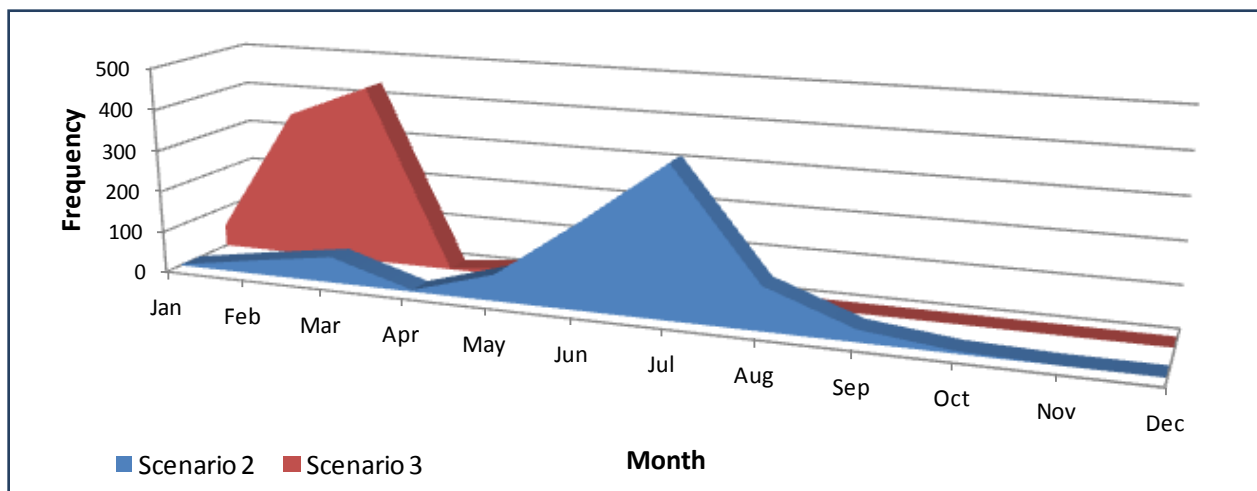
4.1.3 Scenario 3

Since the Un-Met load data for Tamil Nadu was available, a third scenario comparing wind generation and the (Met + Un-Met) load has been developed

- The results for this scenario are quite interesting and in-line with observations made in Scenario 2

- **Annual Capacity value for plants in Mupandal and Coimbatore is in the range of 15% to 20%**
- As can be seen in the graph below, frequency distribution of the top 10% load hours (of a year) over different months differs significantly in the two scenarios.
- In Scenario 2, months May to Aug represents the maximum load hours which match well with wind generation and hence result in higher capacity value compared to Scenario 3 in which Jan to March months happens to represent maximum load hours.
- This scenario indicates the importance of shortage data in better estimation of capacity value of wind plants.

Figure 5 Frequency distribution of top 10% load hours under Scenario 2 and 3



4.1.4 Scenario 4

- As observed in historical trends, India's total met energy demand peaks in last quarter of a financial year ie in Q4 thus Q4 becomes critical quarter for this scenario
- Thus Q4 months become more critical when it comes to reliability planning for grid operations
- **Annual Capacity value for plants in Mupandal is ~24% and Coimbatore is ~22%**
- Capacity value calculated for each quarter represents ~7% of hours in a year

4.2 Gujarat

Peak hours identified (for Scenario 1) as per Time of Day (ToD) tariff of Gujarat's DISCOMs: 7 AM to 11 AM + 6 PM to 10 PM (total of 8 hours per day)

Table 8 Analysis results for Kutch

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	41.9%	42.4%	42.4%	42.9%
Q2	29.2%	29.8%	29.2%	30.5%
Q3	22.4%	15.9%	23.4%	22.5%
Q4	27.0%	31.2%	28.5%	26.9%
Annual	30.1%	24.9%	30.8%	30.7%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Table 9 Analysis results for Saurashtra

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	41.1%	42.1%	41.6%	42.1%
Q2	30.4%	33.1%	30.2%	31.7%
Q3	25.8%	18.1%	26.7%	25.2%
Q4	28.6%	30.9%	29.5%	28.3%
Annual	31.4%	26.3%	32.0%	31.8%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Observations and Comments

4.2.1 Scenario 1

- Gujarat has high wind availability during months of March to August (ie Q1 and most of Q2)
- Average CF for wind plant during months of April to September is around 30% to 43% depending on site/location.
- Historically, months of October to December (or Q3) have seen highest power demand levels. It is noteworthy that Gujarat has quite high agricultural load and the power demand patterns in the state can shift depending on monsoon
- Thus Q3 becomes most critical quarter when it comes to reliability planning for grid operations.

- Based on Scenario 1 calculations, estimated capacity value of wind for **Kutch is in the range of 22% to 23%** and for **Saurashtra is in the range of 25% to 26%**
- Capacity value calculated for each quarter represents ~8% of hours in a year.

4.2.2 Scenario 2

- Under Scenario 2, each quarter represents only 2.5% of hours of a year
- Gujarat has very low levels of power shortages, therefore met load is almost equal to unrestricted load (which is sum of met load and estimated shortages). Thus Scenario 2 results closely represent capacity value of wind during top 10% of unrestricted peak demand hours.
- For Gujarat, annual values best represent capacity value of wind.
- Based on calculation under Scenario 2, estimated capacity value of wind plants in **Kutch is around 25%** and that of plants in **Saurashtra is around 26%**

4.2.3 Scenario 4

- As observed in historical trends, India's total met energy power demand peaks in last quarter of a financial year ie in Q4 making it critical quarter for this scenario
- Thus Q4 months become more critical when it comes to reliability planning for grid operations
- **Annual Capacity value for plants in Kutch is around 31% and that of plants in Saurashtra is around 32%**
- Capacity value calculated for each quarter represents ~7% of hours in a year

4.3 Andhra Pradesh (AP)

Peak hours identified (for Scenario 1) as per Time of Day (ToD) tariff of AP's DISCOMs: 6 PM to 10 PM (total of 4 hours per day)

Table 10 Analysis results for Ramasagaram

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	42.2%	26.9%	42.3%	40.7%
Q2	35.2%	27.8%	36.2%	35.3%
Q3	25.0%	14.9%	24.2%	20.3%

Q4	26.6%	20.3%	24.8%	19.6%
Annual	32.2%	17.2%	31.7%	29.0%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Table 11 Analysis results for Anantapur

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	35.3%	18.2%	35.4%	33.1%
Q2	40.9%	33.4%	42.5%	41.8%
Q3	20.0%	12.8%	19.4%	16.1%
Q4	28.6%	24.5%	26.3%	19.5%
Annual	31.2%	17.8%	30.8%	27.7%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Observations and Comments

4.3.1 Scenario 1

- Andhra Pradesh has high availability of wind during months of April to September (ie Q1 and Q2)
- Average CF for wind plant during months of Q1 and Q2 is around 33% to 42% depending on site/location
- Historically, months of May to August have seen relatively lower power shortage levels as compared to Q3 and Q4 months
- Also, unrestricted demand, estimated based on unmet load data or shortages and met load, is highest during Q3 and Q4 months.
- Thus Q3 and Q4 become more critical months when it comes to reliability planning for grid operations
- Thus based on Scenario 1 (Q3 & Q4) calculations, the capacity value of wind for **Ramasagaram is in the range of 25% to 27%** and for **Anantapur is in the range of 20% to 29%**
- Capacity value calculated for each quarter represents ~4% of hours in a year

4.3.2 Scenario 2

- Analysis limitations due to unavailability of power shortage data, which can be used to estimate unrestricted demand, pose a challenge and could lead to significant error in estimating capacity value of wind

- Andhra Pradesh has high demand met and high peak shortages in Q3 and Q4 months. Thus annual results from Scenario 2 can be used for estimation of capacity value of wind. The annual top 10% peak hours lie mostly in Q3 and Q4 months
- And based on Scenario 2 calculations, Capacity value of wind for **Ramasagaram is around 17%** and for **Anantapur capacity value is around 18%**

4.3.3 Scenario 4

- As observed in historical trends, India's total met power demand peaks in last quarter of a financial year ie in Q4 thus Q4 becomes critical quarter for this scenario
- Thus Q4 months become more critical when it comes to reliability planning for grid operations
- **Annual Capacity value for plants in Ramasagaram is around 25% and for Anantapur capacity value is around 26%**
- Capacity value calculated for each quarter represents ~7% of hours in a year

4.4 Maharashtra

Peak hours identified (for Scenario 1) as per Time of Day (ToD) tariff of Maharashtra's DISCOMs: 9AM to 12PM + 6 PM to 10 PM (total of 7 hours per day)

Table 12 Analysis results for Satara

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	40.7%	36.4%	39.6%	39.5%
Q2	36.3%	25.1%	35.8%	37.1%
Q3	21.9%	15.4%	21.9%	23.9%
Q4	25.4%	24.8%	24.7%	23.7%
Annual	31.0%	30.3%	30.4%	31.1%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Table 13 Analysis results for Somnath Nagar

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity factor
Q1	33.2%	31.9%	32.9%	32.6%
Q2	27.8%	15.4%	28.2%	28.7%
Q3	16.4%	10.3%	17.8%	17.3%
Q4	20.7%	22.0%	20.6%	18.5%
Annual	24.5%	25.8%	24.8%	24.3%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Observations and Comments

4.4.1 Scenario 1

- Maharashtra has high availability of wind during months of April to September (ie Q1 and Q2)
- Average CF for wind plant during months of Q1 and Q2 is around 28% to 42% depending on site/location
- Historically, Maharashtra has seen significant peak shortages (of around 20% to 25%) with maximum shortages in Q1 and Q4
- Also, unrestricted demand, estimated based on unmet load data or shortages and met load, is highest during Q1 and Q4 months
- Thus Q1 and Q4 become most critical months when it comes to reliability planning for grid operations as they have highest shortages and met load
- The wind pattern is in sync with demand in Q1 ie Q1 has significantly high wind generation and is peak demand quarter as well. Thus capacity value of wind for MH is expected to be higher.
- If load pattern of Maharashtra is to change, the capacity value of wind will change as well.
- Thus based on Scenario 1 calculations, we estimate that capacity value of wind for **Satara is in the range of 26% to 41%** and for **Somnath Nagar is in the range of 21% to 33%**
- Capacity value calculated for each quarter represents ~7.3% of hours in a year

4.4.2 Scenario 2

- Analysis limitations due to unavailability of power shortage data, which can be used to estimate unrestricted demand, poses a significant threat and could lead to error in estimating capacity value of wind

- Maharashtra has high demand met and high peak shortages in Q1 and Q4 months. The annual top 10% peak hours lie mostly in Q1 and Q4 months. Thus annual results from Scenario 2 can be used for estimation of capacity value of wind
- And based on Scenario 2 calculations, Capacity value of wind for **Satara is around 30%** and for **Somnath Nagar capacity value is around 26%**

4.4.3 Scenario 4

- As observed in historical trends, India's total met power demand peaks in last quarter of a financial year ie in Q4 thus Q4 becomes critical quarter for this scenario
- Thus Q4 months become more critical when it comes to reliability planning for grid operations
- **Annual Capacity value for plants in Satara is around 25% and for Somnath Nagar capacity value is around 21%**
- Capacity value calculated for each quarter represents ~7% of hours in a year

4.5 Karnataka

Peak hours identified (for Scenario 1) as per Time of Day (ToD) tariff of Karnataka's DISCOMs: 6 PM to 10 PM (total of 4 hours per day)

Table 14 Analysis results for Chitradurg

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	50.4%	35.8%	49.5%	48.0%
Q2	46.8%	45.6%	46.0%	44.7%
Q3	35.8%	35.6%	35.6%	32.6%
Q4	30.5%	26.0%	29.3%	26.5%
Annual	40.4%	24.6%	39.9%	38.0%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Table 15 Analysis results for Gadak

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	42.0%	27.3%	40.0%	37.6%
Q2	35.1%	33.0%	34.6%	34.0%
Q3	19.6%	22.6%	21.5%	20.6%
Q4	18.5%	18.9%	18.9%	16.1%
Annual	28.4%	16.8%	28.6%	27.1%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Observations and Comments

4.5.1 Scenario 1

- Karnataka has high availability of wind during months of April to September (ie Q1 and Q2)
- Average CF for wind plant during months of Q1 and Q2 is around 34% to 48% depending on site/location
- Historically, months of April to September (Q1 and Q2) have seen relatively lower power shortage levels as compared to Q4 months
- And Q3 has seen relatively lower level of power demand. Implying, unrestricted demand, estimated based on unmet load data, is highest during Q4 months
- Thus Q4 months become more critical when it comes to reliability planning for grid operations
- Thus based on Scenario 1 calculations, estimated capacity value of wind for **Chitradurg is in the range of 30% to 31%** and for **Gadak is in the range of 18% to 19%**
- Capacity value calculated for each quarter represents ~4% of hours in a year

4.5.2 Scenario 2

- Analysis limitations due to unavailability of proper power shortage data, which could be used to estimate unrestricted power demand, poses a challenge and could lead to significant error in estimating capacity value of wind
- Fortunately, Karnataka has high met demand and high peak shortages in Q4 months. The annual top 10% peak hours lie entirely in Q4 months. Thus annual results from Scenario 2 can be used for estimation of capacity value of wind.
- And based on Scenario 2 calculations, Capacity value of wind for **Chitradurg is around 25%** and for **Gadak capacity value is around 17%**

4.5.3 Scenario 4

- As observed in historical trends, India's total met power demand peaks in last quarter of a financial year ie in Q4 making it critical quarter for this scenario
- Thus Q4 months become more critical for reliability planning of grid operations
- **Estimated capacity value for plants in Chitradurg is around 29% and for Gadak capacity value is around 19%**
- Capacity value calculated for each quarter represents ~7% of hours in a year

4.6 Rajasthan

Peak hours identified (for Scenario 1) as per Time of Day (ToD) tariff filling by Rajasthan's DISCOMs (though ToD is under approval stage, a preliminary analysis was done to find peak hours): 9 AM to 1 PM + 6 PM to 8 PM (total of 6 hours per day)

Table 16 Analysis results for Jaisalmer

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	31.7%	38.4%	34.9%	36.0%
Q2	22.0%	31.0%	26.5%	25.7%
Q3	16.0%	20.0%	21.8%	19.7%
Q4	17.3%	19.8%	21.5%	21.2%
Annual	21.3%	19.7%	26.1%	25.7%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Table 17 Analysis results for Ludurwa

Quarter	Scenario 1 Capacity Value Met Load	Scenario 2 Capacity Value top 10% Met Load	Scenario 4 Capacity Value_National Load	Capacity Factor
Q1	29.0%	36.4%	32.4%	33.5%
Q2	20.7%	29.5%	25.1%	24.4%
Q3	13.4%	16.9%	17.8%	16.5%
Q4	15.2%	17.3%	18.7%	18.8%
Annual	19.1%	17.1%	23.4%	23.3%

Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

Observations and Comments

4.6.1 Scenario 1

- Rajasthan has high availability of wind during months of April to September (ie Q2 and Q1)
- Average CF for wind plant during months of Q1 and Q2 is around 17% to 36% depending on site/location.
- Historically, months of April to September (Q1 and Q2) have seen relatively lower power requirement levels (even after adding shortages) as compared to Q3 and Q4 months
- Implying, unrestricted demand, estimated based on unmet load data or shortages and met load, is highest during Q3 and Q4 months.
- Thus Q3 and Q4 become more critical months when it comes to reliability planning for grid operations.
- Thus based on Scenario 1 calculations, estimated capacity value of wind for **Jaisalmer is in the range of 16% to 17%** and for **Ludurwa is in the range of 13% to 15%**
- Capacity value calculated for each quarter represents ~6.25% of hours in a year

4.6.2 Scenario 2

- Analysis limitations due to unavailability of power shortage data, which could be used to estimate unrestricted demand, poses a challenge and could lead to significant error in estimating capacity value of wind
- Fortunately, Rajasthan has high unrestricted demand in Q3 and Q4 months. Thus annual results from Scenario 2 can be used for estimation of capacity value of wind. The annual top 10% peak hours lie entirely in Q3 and Q4 months
- Based on Scenario 2 calculations, Capacity value of wind for **Jaisalmer is around 20%** and for **Ludurwa capacity value is around 17%**

4.6.3 Scenario 4

- As observed in historical trends, India's total met power demand peaks in last quarter of a financial year ie in Q4, making it critical quarter for this scenario
- Thus Q4 months become more critical when it comes to reliability planning for grid operations
- **Annual Capacity value for plants in Jaisalmer is around 22% and for Ludurwa capacity value is around 19%**
- Capacity value calculated for each quarter represents ~7% of hours in a year

5 Scenario 1, Scenario 2 and Scenario 4 - Comparison of results for the six selected States

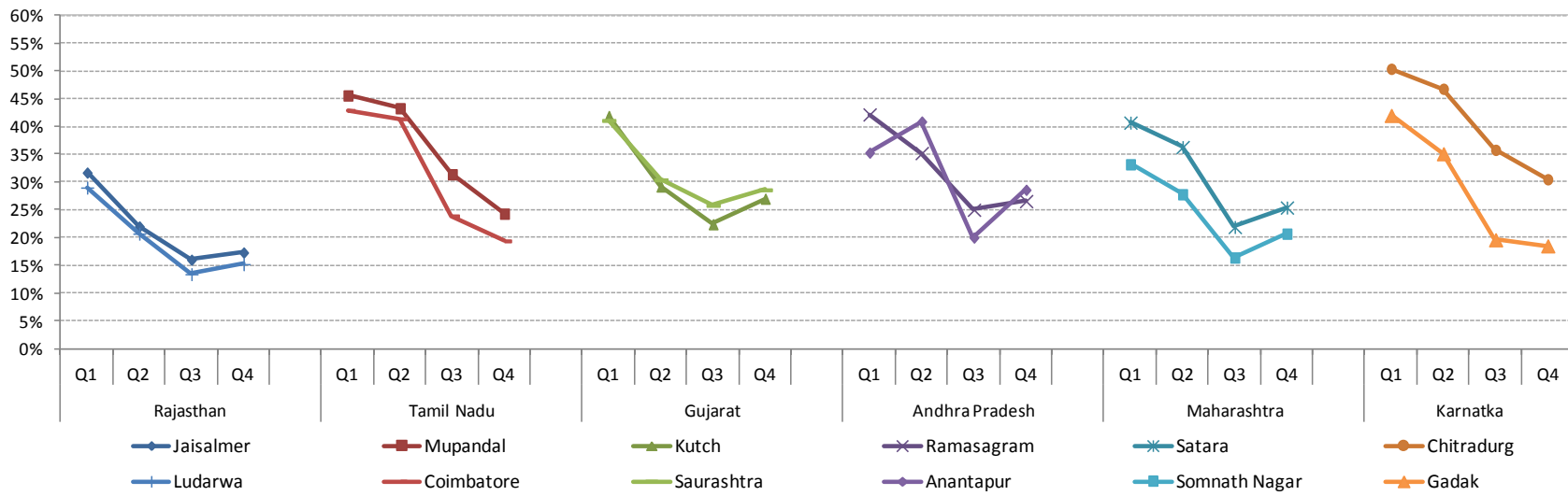
An integrated qualitative-quantitative approach has been adopted to capture the dynamics of wind power generation and power demand and to address the specific objectives of the study.

Table 18 Summary of Wind Capacity Value from modeling analysis

S. No.	State	Site	Capacity Value Scenario 1	Capacity Value Scenario 2	Capacity Value Scenario 3	Capacity Value Scenario 4
1	Tamil Nadu	Muppandal	24-31%	21-28%	18-19%	~24%
		Coimbatore	19-24%	20-23%	15-16%	~22%
2	Gujarat	Kutch	22-23%	~25%	-	~31%
		Saurashtra	25-26%	~26%	-	~32%
3	Andhra Pradesh	Ramasagaram	25-27%	~17%	-	~25%
		Anantapur	20-29%	~18%	-	~26%
4	Maharashtra	Satara	26-41%	~30%	-	~25%
		Somnath Nagar	21-33%	~26%	-	~21%
5	Karnataka	Chitradurg	30-31%	~25%	-	~29%
		Gadak	18-19%	~17%	-	~19%
6	Rajasthan	Jaisalmer	16-17%	~20%	-	~22%
		Ludurwa	13-15%	~17%	-	~19%

5.1 Scenario 1 (Met Load – Chronological with respective State’s Demand)

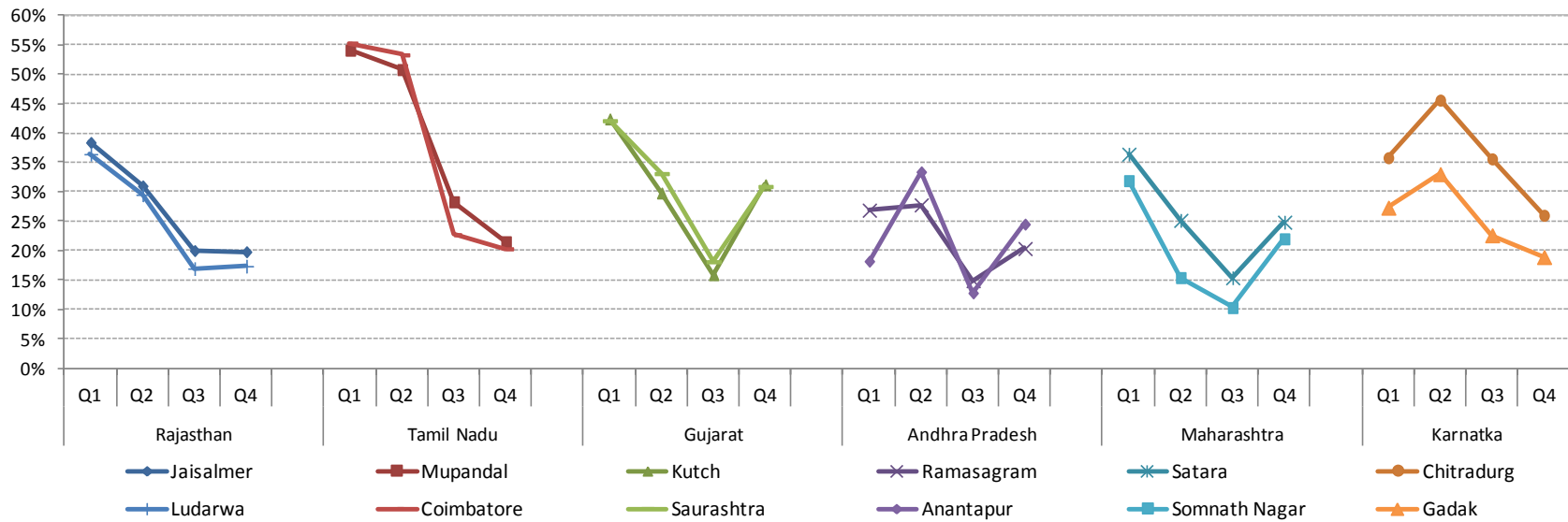
Figure 6 Graphical representation of Scenario 1 results



Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

5.2 Scenario 2 (Met Load – top 10% hours)

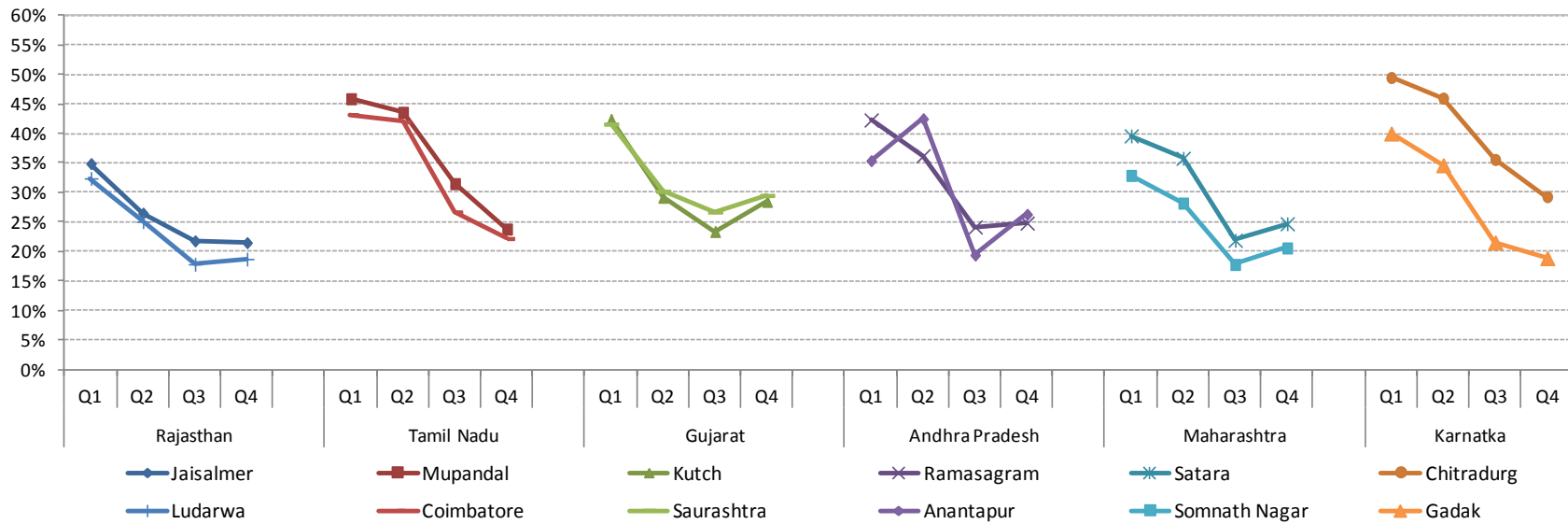
Figure 7 Graphical representation of Scenario 2 results



Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

5.3 Scenario 4 (Met Load – Chronological with Pan-India Demand)

Figure 8 Graphical representation of Scenario 4 results



Q1: Apr-Jun; Q2: Jul-Sep; Q3: Oct-Dec; Q4: Jan-March

5.4 Wind Profile of States wrt State's demand profile

Figure 9 Tamil Nadu annual wind and power demand profile

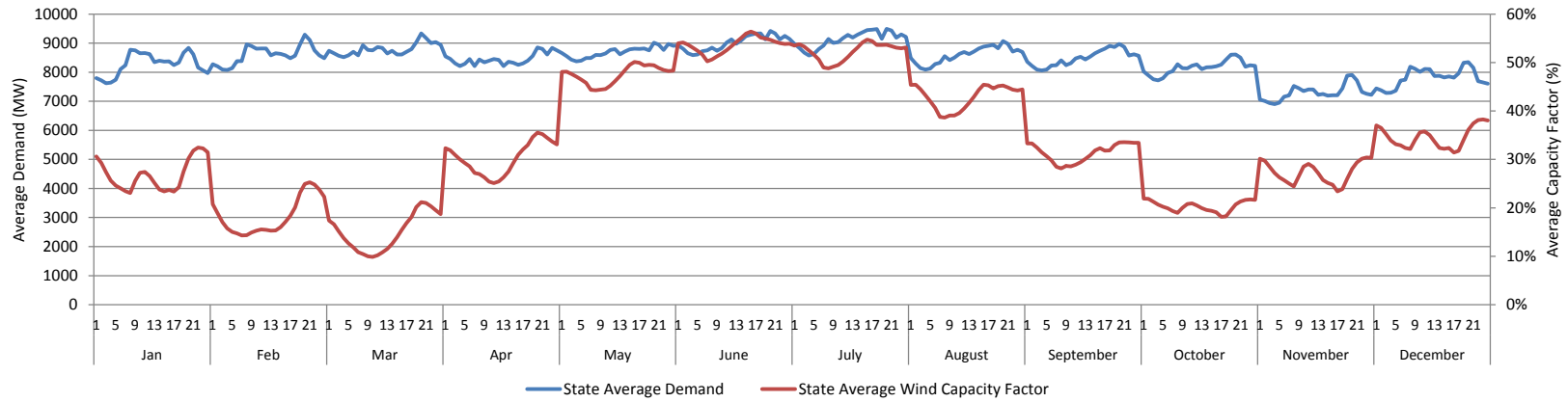


Figure 10 Karnataka annual wind and power demand profile

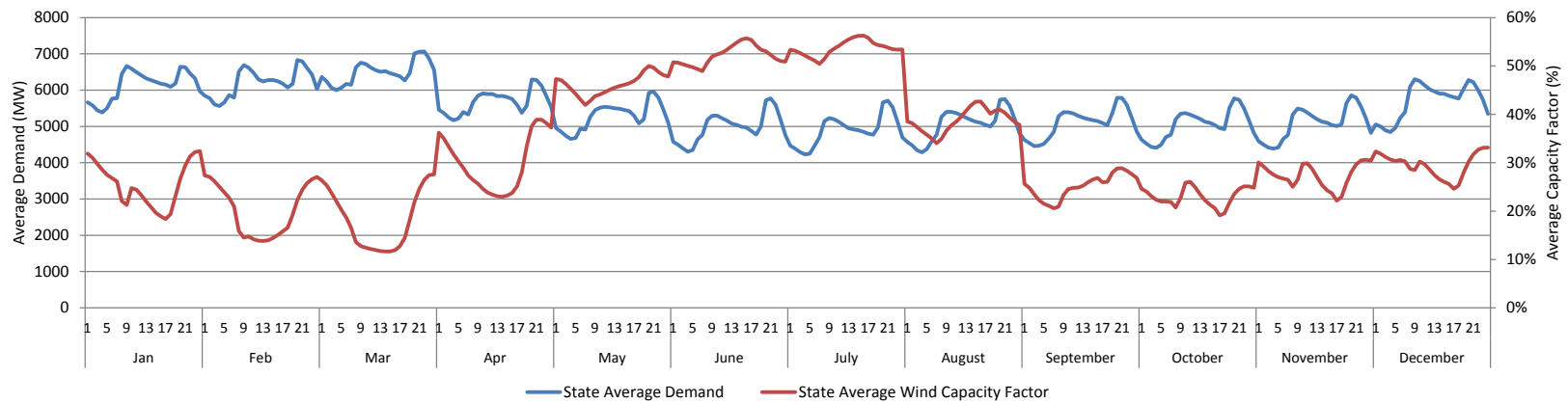


Figure 11 Maharashtra annual wind and power demand profile

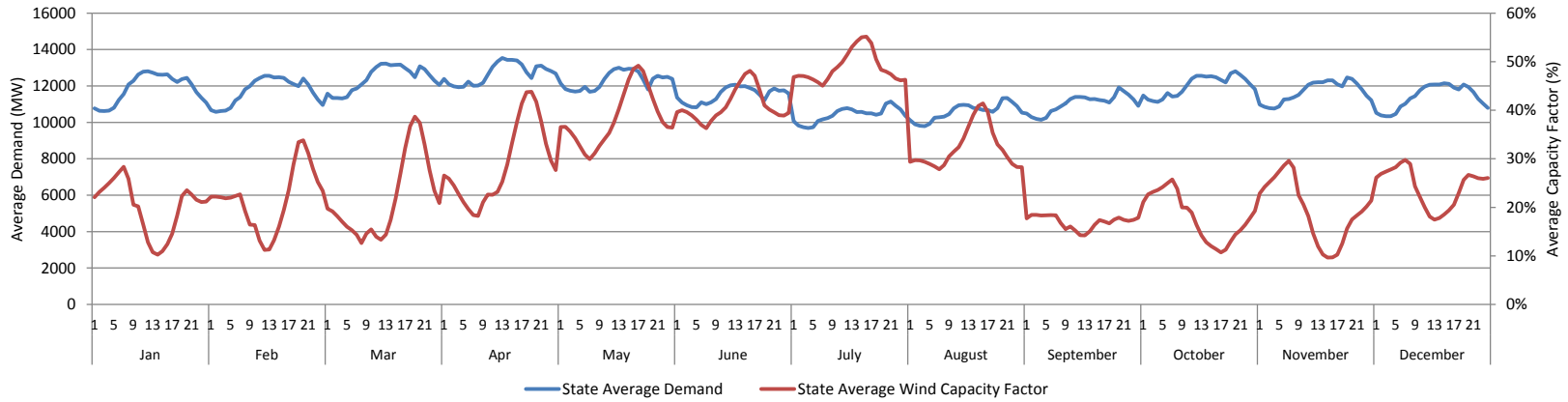


Figure 12 Gujarat annual wind and power demand profile

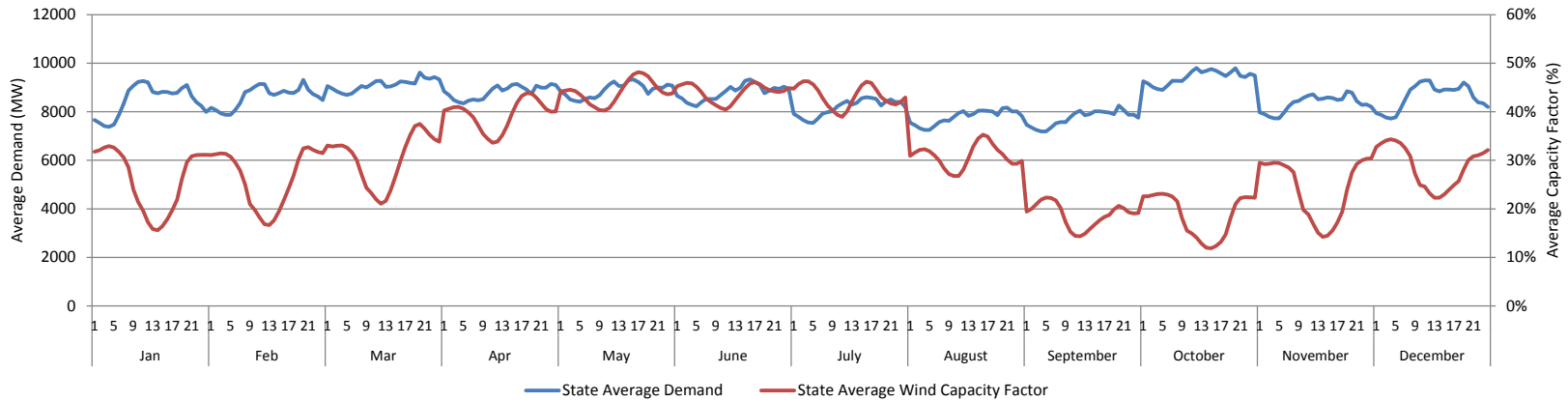


Figure 13 Andhra Pradesh annual wind and power demand profile

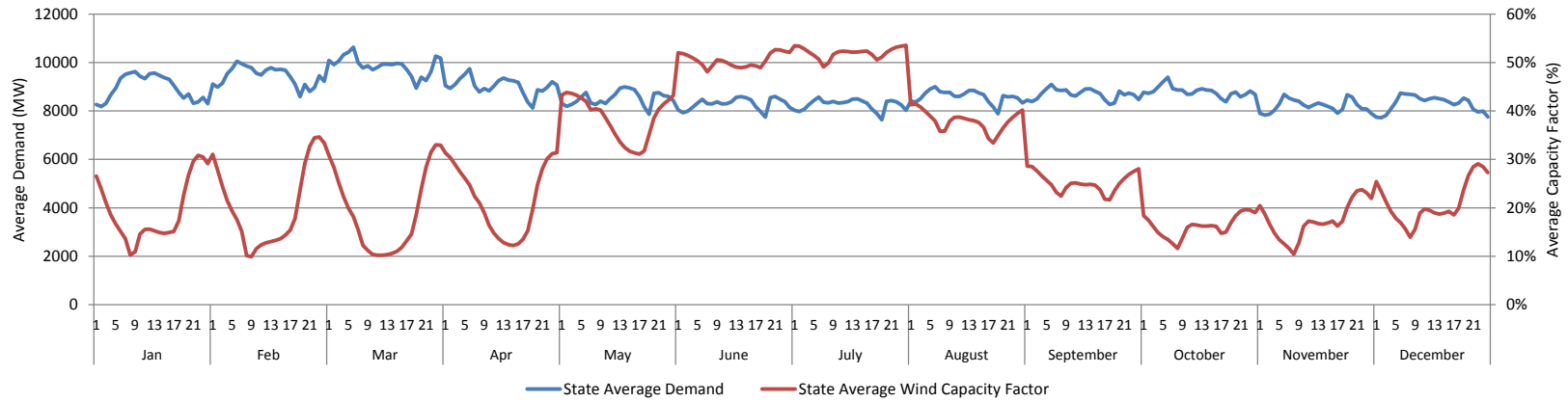
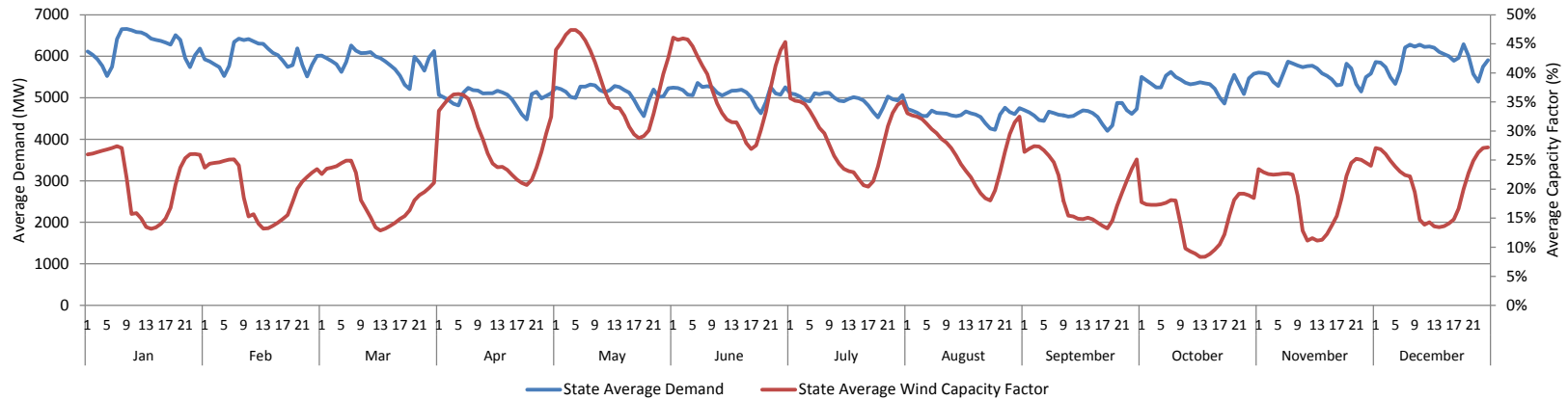


Figure 14 Rajasthan annual wind and power demand profile



5.5 Wind Profile of States wrt Pan-India demand profile

Figure 15 Tamil Nadu wind and Pan India demand profile

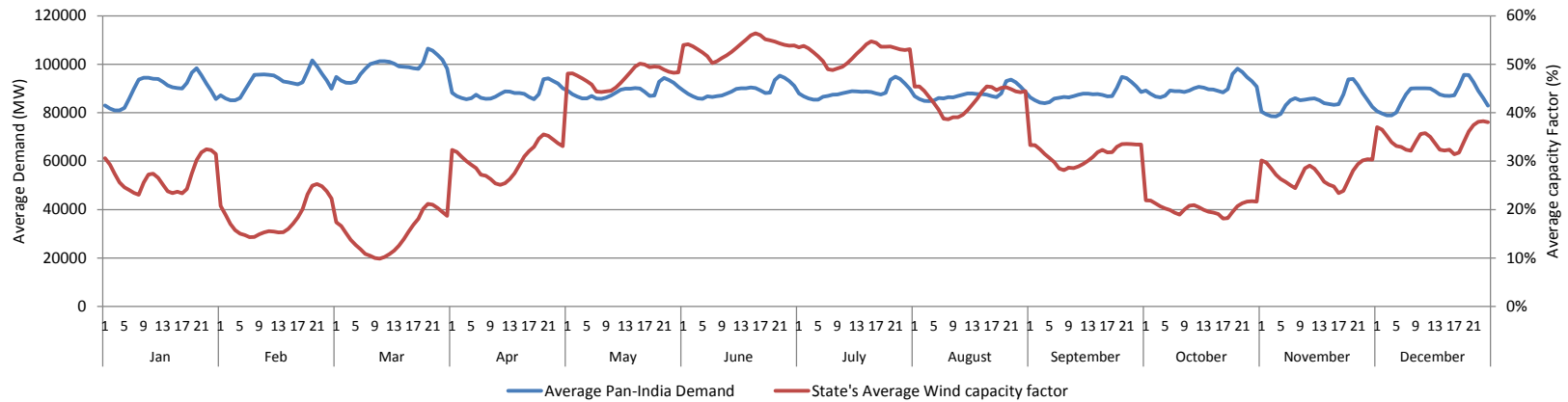


Figure 16 Karnataka wind and Pan India demand profile

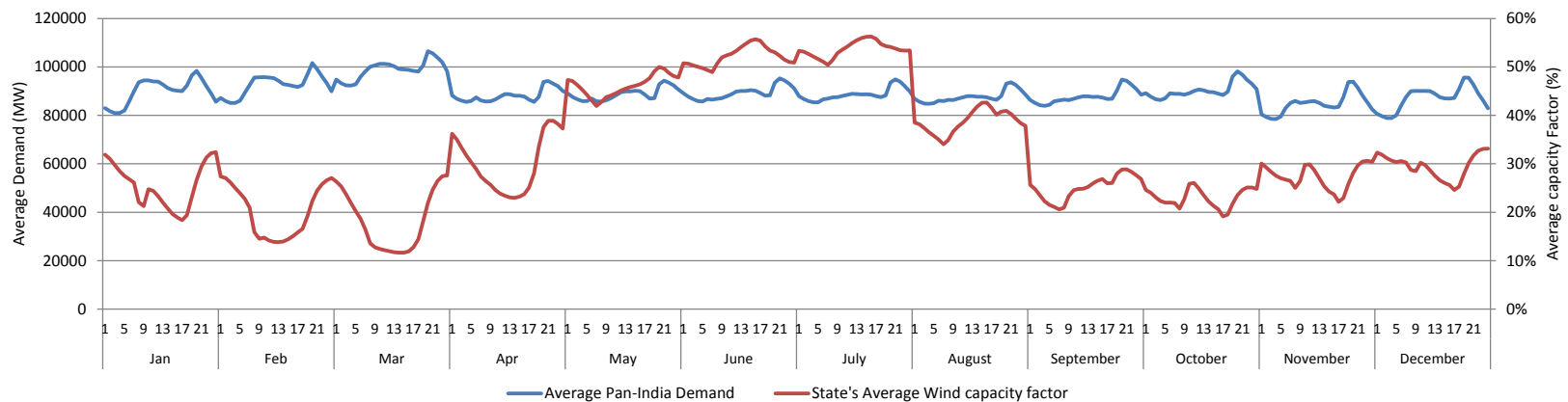


Figure 17 Maharashtra wind and Pan India demand profile

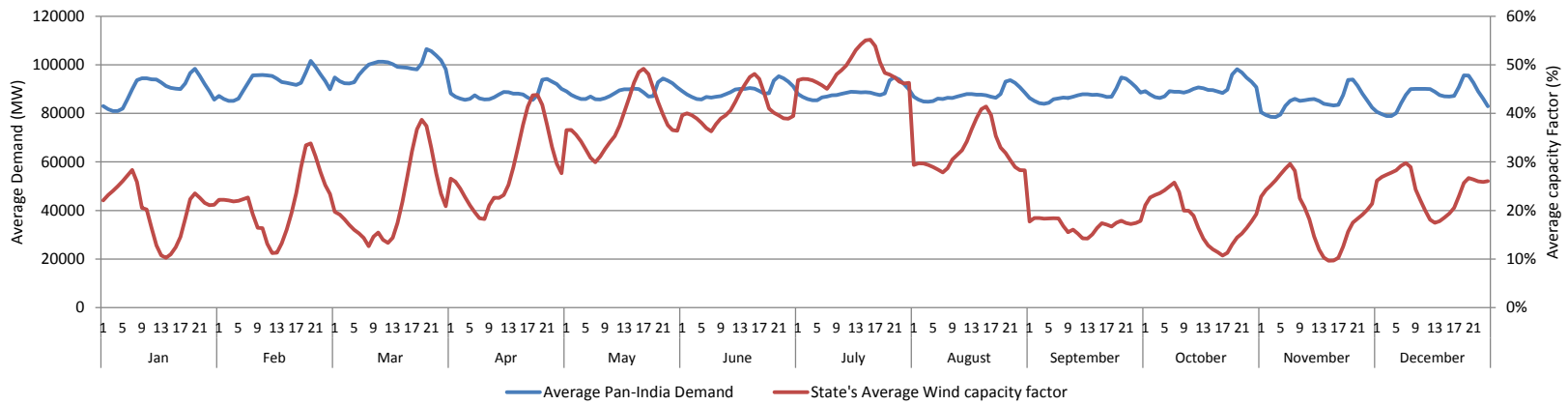


Figure 18 Gujarat wind and Pan India demand profile

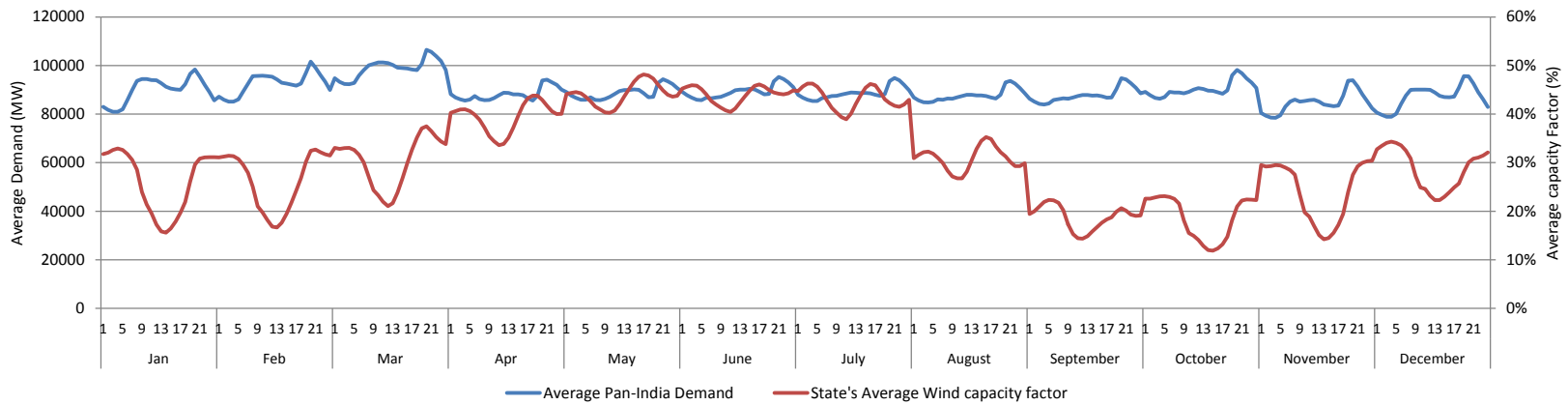


Figure 19 Andhra Pradesh wind and Pan India demand profile

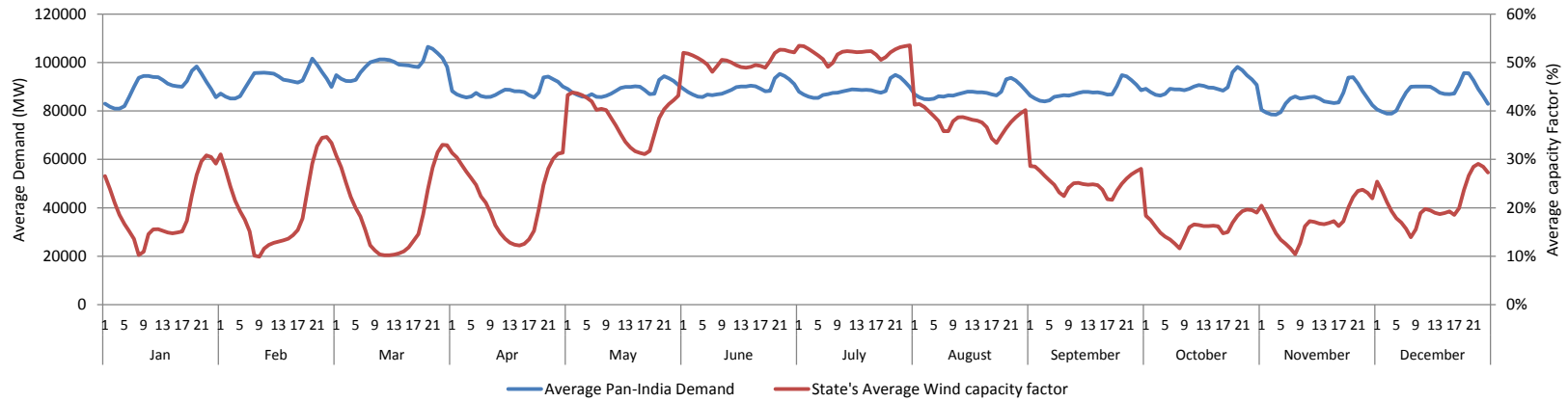
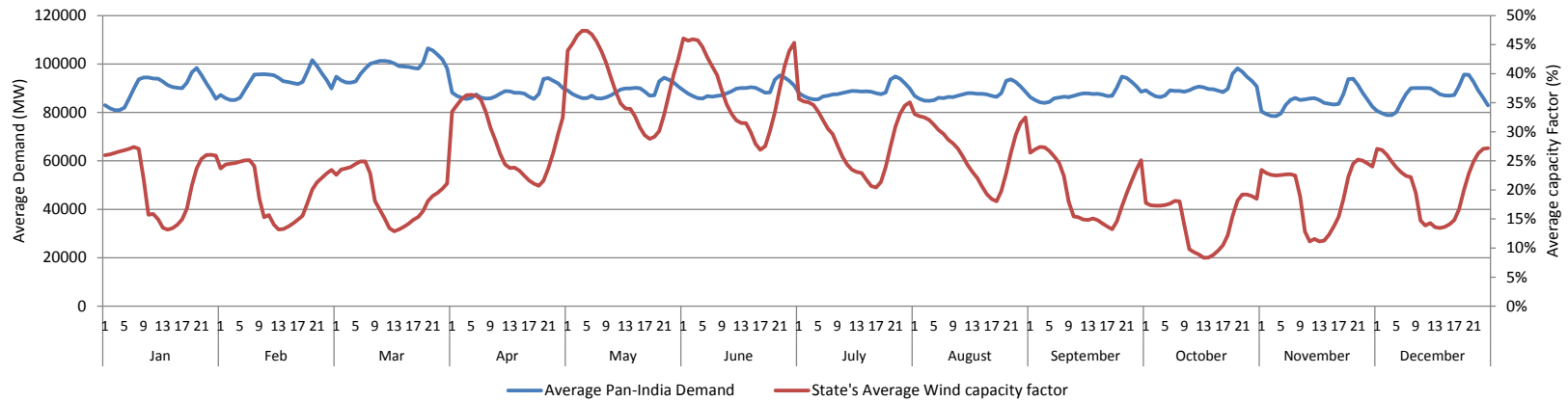


Figure 20 Rajasthan wind and Pan India demand profile



6 Overall capacity contribution of wind to national generation mix over next five Planning periods

The wind energy potential of India has been estimated by various agencies and it far exceeds the potential estimated by C-WET. Potential as high as 2006 GW at 80 m hub-height has been reported by the Lawrence Berkeley National Laboratory, US⁶. However, as per C-WET estimate, which is currently under validation, installable wind power potential at 80 m hub-height in India is about 102 GW.

The table below shows installable wind potential at 80 m hub-height as per C-WET's assessment of wind potential and potential generation capacity contribution for the six states under study. The capacity value considered under for calculating the generation capacity contribution corresponds to Scenario 4 analysis results.

Table 19 Estimated overall wind potential and capacity contribution at National level

State	Estimated Potential at 80 m (MW)	Capacity Value (%)	Capacity Contribution (MW)
Andhra Pradesh	14497	25.5%	3,697
Gujarat	35071	29.5%	10,346
Karnataka	13593	24.0%	3,262
Maharashtra	5961	23.0%	1,371
Rajasthan	5050	20.5%	1,035
Tamil Nadu	14152	23.0%	3,255
Others	14464	24.0%	3,471
Total	102788		26,438

Wind power plant capacity addition as per National Action Plan on Climate Change (NAPCC) targets for 2020-2030 and its contribution that could potentially replace the conventional capacity at the end year of 12th, 13th, 14th and 15th planning period is shown in Table 20 & Table 21 below. Wind power contribution has been calculated based on the capacity value of wind estimated in Scenario 4 analysis.

⁶Reassessing Wind Potential Estimates for India: Economic and Policy Implications
<http://newscenter.lbl.gov/feature-stories/2012/03/21/wind-energy-in-india/>;
<http://www.shaktifoundation.in/cms/uploadedImages/indiawindpotentialassessmentrevisedfinal.pdf>

Table 20 Wind capacity addition at the end of each planning period (in MW)

Installed capacity (Wind)	2011*	2012	2016	2021	2026	2031
NAPCC Compliant	14,986	17,986	35,266	75,266	1,40,266	2,25,266

* ending year of the corresponding National Five Year Plan

Table 21 Wind capacity contribution at the end of each planning period (in MW)

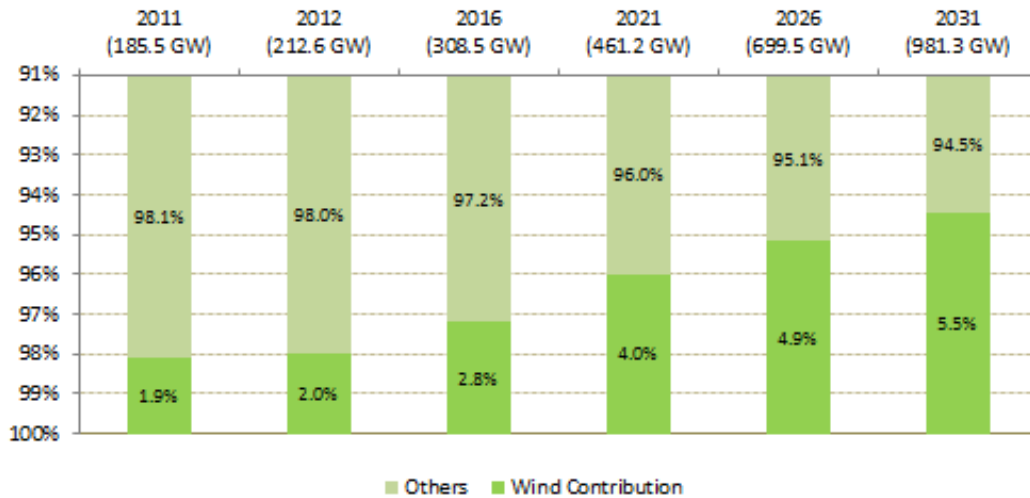
Capacity Contribution of Wind	2011*	2012	2016	2021	2026	2031
NAPCC Compliant	3,583	4,323	8,668	18,536	33,928	54,373

* ending year of the corresponding National Five Year Plan

Thus, the potential contribution of wind power to national generation capacity has been estimated to be around 54 GW by 2031.

The wind capacity contribution for NAPCC wind capacity target compliant case during the end year of 5 year planning periods till 2031 are shown in the graphs below:

Figure 21 Wind capacity contribution to overall generation - NAPCC wind capacity target compliant case



7 Factors affecting capacity value of wind and limiting the results of this study

This study has been undertaken with limited availability of power demand data. Since all states, except Gujarat, considered in this analysis represent a power deficit scenario, the actual power demand of the states could be potentially higher. In an ideal scenario, a correlation of unrestricted demand (un-met + met) power demand with wind power generation should have been used for estimation of wind capacity value. Some of these factors that would affect the results of a capacity value study are as follows –

1. **Long term monthly power demand pattern and demand scenario:** A change in diurnal power demand pattern will result in change in the capacity value of the wind plant contributing to power supply to the pertinent demand/load. Similarly, change in the overall demand scenario at state or regional level will result in change in the capacity contribution of wind for corresponding state or region.
2. **Long term power supply scenario:** With the development in power sector and addition of generation capacity, the system shortages are expected to decrease and eventually phase out in the coming years. Such a scenario of no-shortage already exists in Gujarat. As other states achieve self sufficiency over next few years, the state level as well as national level capacity value of wind will change. In such case, methodology for calculation of critical hours will depend more on parameters such as load profile, ToD tariff hours, high demand hours, low operating reserve margin hours etc.
3. **Daily load profile or change in peak hour definition as per ToD:** Critical hours are dependent on load profile, thus a change in load profile or peak hour will result in change in capacity value of wind
4. **Transmission or power evacuation constraints:** Capacity value remains sensitive to grid's capability to evacuate wind power. If the capability to evacuate increases, the wind capacity value also increases.
5. **Size and efficiency of turbine:** Capacity value of wind tends to increase with increase in size of turbine or with improved efficiency of turbine. This study considers generation from G97 - 2.0 MW turbines. The use of generation from turbines with higher efficiency and size may have better effect on capacity value of wind.
6. **Wind farm site selection:** Since wind resource availability varies across sites, the average wind resource profile for a reasonable sample of sites should be considered for the estimation of average wind capacity value for the state. This study has considered only two key wind sites in each of the six wind resource rich states.

-
7. **Additive effect of wind generation within a wind farm:** When a larger sample of sites are considered for wind generation profile, a possible smoothening of variable wind generation curves is possible as the diverse generation curves of individual turbines are analysed cumulatively.
 8. **Curtailement of wind energy:** Any dispatch-down of wind generation occurring from variety of reasons such as system stability requirements, operating reserve requirements, voltage control requirements etc have not been considered in this study. Inclusion of such factors in the analysis would negatively impact the wind generation and also the wind capacity value.
 9. **Wake effect in wind farm:** Adjustments for factors like directionally dependent wake interference, other non-directional losses and the non-availability of units have not been considered in this study. Such consideration will result in lower wind generation and hence lower capacity value.
 10. **Scenario with firming up of wind power with other sources:** In case power generation from wind is firmed up using generation from flexible sources such as pumped hydro, solar etc to achieve stable round-the-clock (RTC) generation profile, then the capacity value of wind/hybrid source would change and can be expected to be higher.
 11. **Impact of grid integration:** The study provides an estimate of capacity value at state level only under scenario 1, 2 and 3 assuming that the current inter-state and inter-region congestion persists. Under scenario 4, the study also provides an estimate of capacity value at national level assuming that both inter-state and inter-region congestion subsides. However, a situation may arise where in the inter-region congestion may persist for longer term though there may not be inter-state congestion within a region. The study has not calculated the capacity under such a scenario.

8 The Way forward and Recommendations

The Twelfth Plan targets to set up 88 GW of new generation capacity to meet the growing demand of electricity in the country. Renewable Energy (RE) sources, especially Wind and Solar Energy are already contributing significantly to the national generation mix and their share is likely to increase manifold under this Plan period. Renewable Energy resources are also poised to play an important role in the generation planning for the 13th planning period.

Requirement of a detailed study

The current study provides an estimate of the range of Wind Capacity Value for various wind rich sites in the country and reinforces the need for incorporating wind power contribution to the India's National power capacity planning. However, the study is based on several assumptions as discussed in the section above. In order to precisely compute the capacity value contribution of the installed and planned wind generation capacity in the country, there is need for a more detailed and stochastic study through pertinent probabilistic models. Such detailed study should estimate the capacity contribution of all RE sources including Wind Solar and Solar-Wind hybrid.

A number of such probabilistic models are available that can be employed for the comprehensive analysis on capacity contribution. These models provide a reasonably accurate value of capacity contribution as they consider the impact of multiple uncertainties (such as those in load forecasts, generator forced outages and variable energy resources on system reliability) simultaneously. The model makes extensive use of data around random variables like forced outage rate of generators, wind turbine dispatch profiles, load uncertainty etc. The details of one such model (SRAM) and its fundamentals is provided in Annexure.

Significant data requirement and stakeholder's involvement

To carry out a robust analysis using a model, at the minimum, the following data may be required:

- a) Unrestricted demand data for each state at hourly level
- b) Shortage data for each state at hourly level
- c) Unrestricted load profile of each state at hourly level
- d) Monthly average forced outage rate of generators
- e) Hourly wind turbine dispatch profile for each of the wind turbine installed in the country
- f) Conventional and non-conventional plant average monthly availability
- g) Historical data on plant wise mean time to failure and mean time to repair

If the above data is not available, the reasonable assumptions around these data points need to be developed. These assumptions need to dovetail in the overall long term power planning scenarios being considered by the Planners. Significant stakeholder's discussions are required to under these variables in the overall context of the power sector.

Policy and Regulatory Support

A higher capacity value of wind and thus a larger avoidable coal capacity can be achieved through a number of policy and regulatory measures. Few such measures would include the following –

- **Structuring of larger balancing areas:** As suggested, a larger balancing area can help to harness the wind capacity during all possible peak demand periods. There is a requirement to consider an optimal dispatch of state, central and private sector plants together with a single system operator at least at a regional level. Such a mechanism will help to increase the availability of wind generation and also help to overcome the variability. This is expected to lead to higher capacity contribution from RE sources including wind.
- **Development of system operation protocols for a high RE system:** A greater penetration of RE needs to be supported by the forecasting, scheduling and accounting protocols by the SLDCs and RLDCs. Such systems would help to provide a higher availability of RE with a substantial decrease in the instances of back down of RE generators. An estimation of capacity value of RE would also help to establish a bare minimum generation schedule that can be available from RE units during peak demand period in any state.

9 Annexure 1 – Details of formulae used in the analysis

Wind power generation calculation

Below is the table that shows calculation for hourly capacity factor for wind turbine at a particular site for one day of a year. As mentioned before, for this analysis, power curve of G97 Gamesa wind turbine has been used. Using power curve for the turbine shown in Figure 4 Power Curve for Gamesa G97 - 2.0 MW Machine, wind speed data for the site has been converted to generation.

Figure 22 Data table for sample calculation of wind power generation

Year Day	Year Hour	Day Hour	Average Wind Speed	Average Generation (in MWh)	Capacity factor
1	1	1	6.00	801.26	40%
1	2	2	5.67	771.42	39%
1	3	3	5.38	750.67	38%
1	4	4	5.30	732.25	37%
1	5	5	5.42	713.49	36%
1	6	6	5.61	696.31	35%
1	7	7	5.81	681.92	34%
1	8	8	5.80	590.80	30%
1	9	9	5.78	574.08	29%
1	10	10	6.39	782.35	39%
1	11	11	6.75	884.07	44%
1	12	12	6.85	921.45	46%
1	13	13	6.81	933.76	47%
1	14	14	6.63	926.98	46%
1	15	15	6.24	893.43	45%
1	16	16	5.79	847.23	42%
1	17	17	5.24	776.54	39%
1	18	18	5.08	763.35	38%
1	19	19	5.34	824.87	41%
1	20	20	5.60	880.71	44%
1	21	21	5.85	950.20	48%
1	22	22	5.98	1001.72	50%
1	23	23	6.02	1018.51	51%
1	24	24	6.08	1010.49	51%

Capacity Value calculation

Capacity Value for wind power plants has been computed using the following formulae:

$$CapacityValue = \frac{\sum_{i=1}^n (HD_i * CF_i)}{HD_{max} * n}$$

where:

HD _i	Average Demand of i th critical hour of a financial year, based on 3 year historical hourly demand data
n	Number of critical hours in a financial year for particular state/region/Country.
HD _{max}	Maximum of (HD ₁ , HD ₂ ,....., HD _n)
CF _i	Average Capacity factor of wind plant in i th critical hour of a financial year, based on 3 year historical hourly generation data

Note:

- i. Definition of critical hour changes from one scenario to other. In scenario 1, 3 and 4, critical hour is dependent on peak hour for state defined in its ToD tariff; in scenario 2, its top 10% hours of LDC curve. Therefore value of 'n' changes from one scenario to another as per the change in definition of critical hours'. It takes different value for each state, depending on the corresponding definition of peak hours in ToD tariff regulation.
- ii. For computation of HD_i and CF_i, hourly historical data for FY10, FY11 and FY12 has been used.

The table below shows sample calculation of capacity value using one day data for scenario 1, 2, 3 and 4. Capacity value, in the study, has been computed based on 365 days (1 year) data points.

Figure 23 Data table for sample calculation of capacity value

Year Day	Year Hour	Day Hour	Critical Hour Y/N	Average Demand for KT state	Site Average CF (Chitradurg)
1 st Jan	1	1	N	5338	0.40
1 st Jan	2	2	N	5166	0.39
1 st Jan	3	3	N	4990	0.38
1 st Jan	4	4	N	4895	0.37
1 st Jan	5	5	N	4997	0.36
1 st Jan	6	6	N	5313	0.35
1 st Jan	7	7	N	5338	0.34
1 st Jan	8	8	N	5958	0.30
1 st Jan	9	9	N	6281	0.29
1 st Jan	10	10	N	6151	0.39
1 st Jan	11	11	N	6098	0.44
1 st Jan	12	12	N	6091	0.46
1 st Jan	13	13	N	6004	0.47
1 st Jan	14	14	N	5902	0.46
1 st Jan	15	15	N	5818	0.45
1 st Jan	16	16	N	5744	0.42
1 st Jan	17	17	N	5644	0.39
1 st Jan	18	18	N	5520	0.38
1 st Jan	19	19	Y	5697	0.41
1 st Jan	20	20	Y	6165	0.44
1 st Jan	21	21	Y	6178	0.48
1 st Jan	22	22	Y	5978	0.50
1 st Jan	23	23	N	5817	0.51
1 st Jan	24	24	N	5433	0.51

As per the table above,

n = 4 (ie 19th hour to 22nd hours)

HD1 = 5697; HD2 = 6165; HD3 = 6178; HD4 = 5978

HD_{max} = 6178

Thus, Capacity Value of the renewable plant under consideration would be:

$$\text{Capacity Value} = (5697 * 0.41 + 6165 * 0.44 + 6178 * 0.48 + 5978 * 0.50) / (6178 * 4)$$

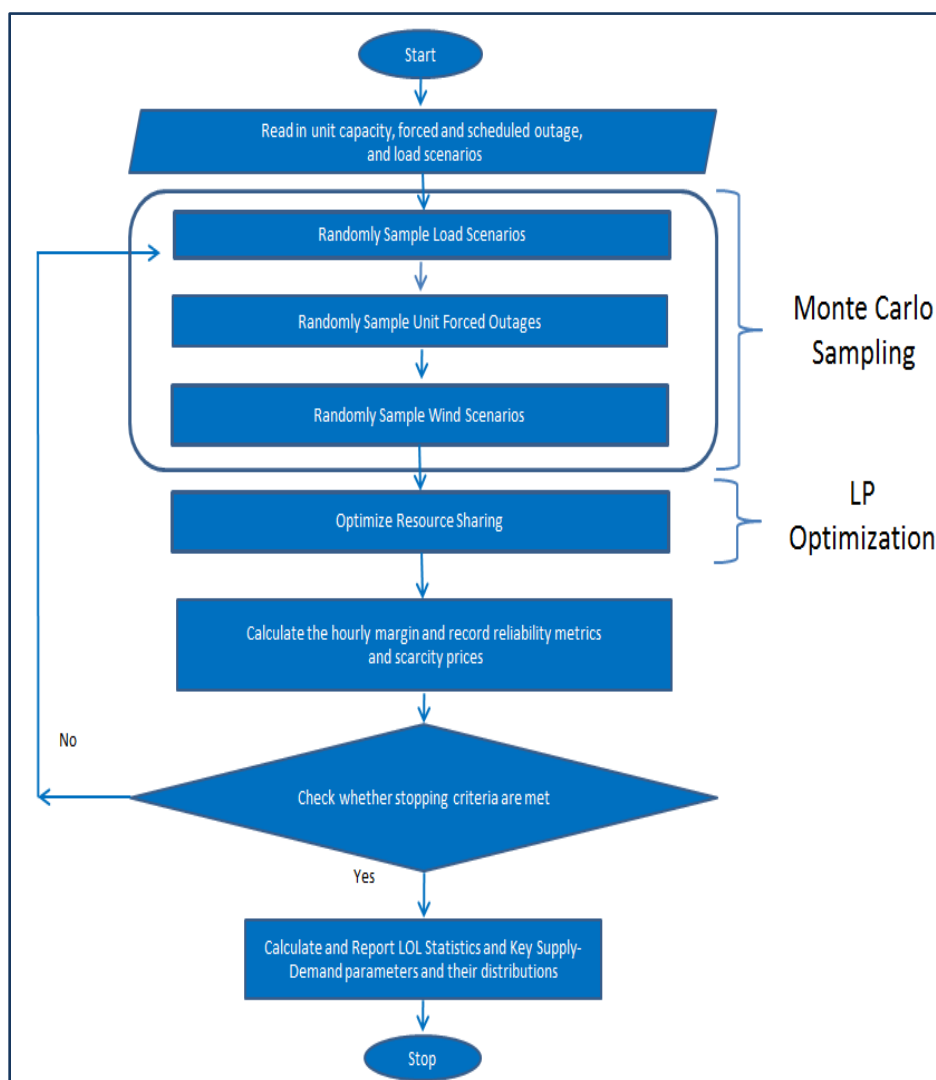
Or 44.48%

10 Annexure 2 – Stochastic Resource Adequacy Model

SRAM is a probabilistic resource adequacy model developed to analyze the impact of uncertainties in load forecasts, generator forced outages and variable energy resources on system reliability and wholesale power prices. SRAM is capable of:

- Probabilistic Multi-Regional Resource Adequacy Analysis (LOLP, LOLH etc.)
- Scarcity Pricing Analysis
- Calculating Effective Load Carrying Capability of Intermittent Resources

Figure 24 SRAM Process



SRAM employs sequential Monte Carlo approach to quantify the risks associated with supply and demand related uncertainties. The random variables accounted for in the model include

forced outage rate of generators, wind turbine dispatch profiles, load uncertainty. In analyzing scarcity prices SRAM works in tandem with our other modeling tools (e.g. IPM, GEMAPS, PSLF).

SRAM Process

- The model simulates hourly load and wind generation profiles based on pre-defined stochastic process.
- Next, the model for each sequential hour within a year under consideration, randomly determines individual generation unit online status based on that unit's historical mean time to failure (MTTF) and mean time to repair (MTTR) statistics.
- After sufficient number of iterations, the model calculates and reports information about the main parameters of sampling distribution of the reliability indices along with indices of the key drivers such as load, supply and wind output.
- SRAM database includes detailed information on forced and scheduled outages, unit capacities, wind profiles and hourly demand profiles.

