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Macro Scale Modelling of Wind Plants in Long Term Planning Studies – A Sri Lankan Case Study

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Abstract: Harnessing Non Conventional Renewable Energy (NCRE) sources as small-scale embedded generation is rapidly increasing around the world. Modelling most NCRE based generation becomes an arduous task owing to their extremely volatile nature of resource availability along with present day economic, technical, social and environmental constraints. In this context, Sri Lanka is no exception. According to the energy policy-2006, energy share from NCRE is targeted to reach 10% of total electricity generation by 2015. According to National Renewable Energy Laboratory (NREL) report [1], wind energy potential in Sri Lanka is high compared with other technologies; mini hydro and biomass. Recent commissioning of about 30 MW of wind plants in Kalpitiya peninsula is an indication of investor interest in wind energy development for power generation. Therefore, modelling of wind power plants in long term planning can no longer be simple, such as representation as a lumped equivalent thermal plant with high Forced Outage Rate (FOR). Preparation of a macro scale wind plant model for Sri Lanka has not been undertaken before using the economic optimisation tool Wien Automatic System Planning (WASP) package. This gap is addressed in this paper. Two models were initially prepared to be compatible with WASP. An in-depth study using (i) Modified Load Duration Curve method and (ii) Run of River (ROR) type hydro equivalent wind model based on five state probabilistic distributions, were investigated. Compatibility of new models was tested with WASP for dispatching as embedded generators. Considering the model simplicity, requirement of time & effort for sensitivity analyses and modifications, the later approach was concluded as the most appropriate for long term planning studies.

Keywords: Wind plants, NCRE, WASP, Run of river, Modelling, load duration curve, Embedded generations.

1. Introduction

Wind power plants have a highly variable pattern of electricity generation, compared with mini hydro power plants located mostly in the central part of the country. According to the findings of "Wind Energy Resource Atlas of Sri Lanka and Maldives" [1], extractable wind power generation including moderate wind potential (without lagoons) is over 50,000 MW of installed capacity. However, this is limited to 24,000 MW if only good to excellent wind potential is considered (without lagoons 20,000 MW).

The 3 MW (5 x600 kW) pilot wind power plant at Hambantota commissioned in 1999 is the only grid connected wind power plant with considerable historical generation records. During the first phase of this study, generation records of about 10 years available with Hambantota wind power plant were analysed. As of 1st September 2010, three new wind plants were in operation in Kalpitiya Peninsula, namely Mampuri (10 MW), Seguwantivu (10 MW) and Vidatamunai (10 MW). All these are Small Power Producers (SPPs) and the generated power is supplied to the national grid under the Standard Power Purchase Agreement (SPPA) signed with Ceylon Electricity Board (CEB). All three power plants have operated for less than three months at the time of this analysis. Owing to non-availability of adequate past data, generation statistics of these power plants have not been considered.

2. Hambantota Pilot Wind Plant

The Hambantota pilot wind project consists of five 600 kW *Vestas* wind turbines situated in close proximity to new Hambantota harbour. Electricity generation in each month for the recorded history did not imply any significant regular pattern of generation but a random behaviour. The only significant finding was the

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monthly plant factor variation, summarised in Figure 1. As expected, the monthly plant factor of every year was high during the South-West monsoon period because the wind speeds are higher.

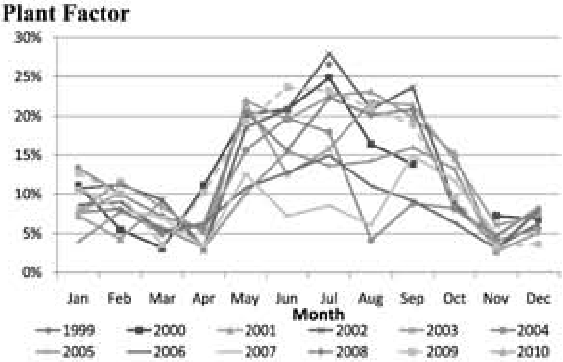


Figure 1 - Monthly Plant Factor Variation of Hambantota Wind Power Plant (1999-2010)

Results showed considerable variations in generation from year to year and a fairly low annual plant factor, as shown in Figure 2. It was also observed that the realistic picture of actual electricity generation potential was not represented by the generation records. Some of the reasons are given below.

1) Most of the time one or more turbines were out of order due to long drawn maintenance problems, absence of spare parts, etc.
2) Although a recording software was available to keep records of generation and operating hours, owing to low resolution of data (i.e. large time steps) a detailed analysis could not be conducted.
3) During the past 10 years, the wind turbine designs and their performance have undergone sharp and dramatic improvements, especially for operation under low wind regimes, so that new turbine units now in the market are expected to have improved wind to electric energy conversion characteristics. (i.e. improved power curves)
4) There are some arguments about the existence of sites with superior wind potential elsewhere in the southern part of the country. Hence it may be an injustice to use wind electric energy data of Hambantota wind plant to represent a typical wind farm in the southern area.

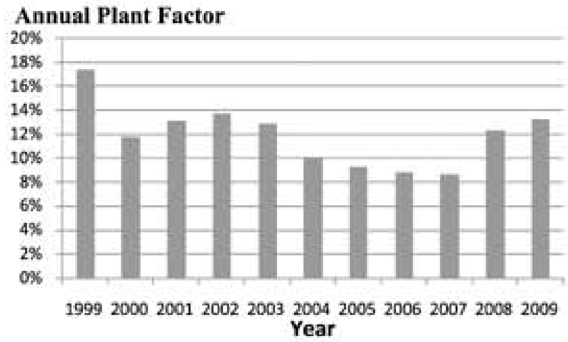


Figure 2 - Annual Plant Factor Variation of Hambantota Wind Power Plant

3. Preliminary Study

In preparing the wind plant model to be used for long-term planning, it was decided to use measured wind data recorded at wind speed measuring stations. Several wind measuring stations are scattered in different locations of Sri Lanka (for the purpose of developing wind power potential) owned and operated by CEB or Sustainable Energy Authority (SEA). Wind measuring stations with a minimum of one full year of continuous readings were only considered for the study. Some of the key aspects in selecting a wind measuring station for its data to be used in the analysis are summarised below.

1) Availability of continuous data for a minimum of one year
2) Data availability with a minimum number of missing values
3) Maximum coverage of the high wind potential areas in NREL study findings
4) Consent of CEB and SEA to release expensive wind data sets
5) All practically viable up-country sites need to be considered as their characteristics are highly site specific

Some details of the data sets used for the assessment is tabulated in Table 1.

Table 1 - Measuring Stations and Resolution of Wind Data Used for the Analysis

Location	Pilot Wind Tower	Year	Data Resolution
Ambewela	Ambewela	2001	10 min
Hambantota	Mirijjawila	1998	1 hr
Mannar	Mannar	2002/ 2003	1 hr
Puttalum	Narakkalliya	2001	1 hr
Puttalum	Mullipurama	2007/ 2008	10 min
Balangoda	Rathinda	2001	10 min

According to NREL study findings, the West coast from Mannar to Jaffna peninsula and the entire northern part of the island have excellent to good wind potential [1]. However, at the time of the study, no reliable wind measuring station was available to assess the wind regime of the northern area, mainly due to civil unrest that prevailed in the area for the last two decades. Owing to many reasons associated with reliability, data available at the Jaffna meteorological station situated within the city limits, the only station operated during the past few years had to be excluded from this analysis.

4. Data Analysis

A few data sets were found to have missing values. All such missing values were rectified with appropriate averaging out by using adjacent data. Data sets with a considerable number of missing values for a given year were removed. However, if missing values could be recovered using another year's records of the same period, then such modified data sets were considered. The resolutions of all selected data sets were transferred to 30 minute (hereafter referred to as "min") intervals, which was the maximum resolution of demand data available with the system control centre of CEB. To identify the missing values, abnormal readings and wind variations over time, each data set was analysed under three bases as,

1) Daily wind variation
2) Monthly wind variation
3) Wind speed frequency distribution

Based on the findings, it was concluded that monthly wind variation of each site was highly influenced during the monsoon period (as clearly observed from Hambantota wind plant analysis) where it goes apparently high compared with inter monsoon periods. On the other hand, daily wind variation over the time in each site did not follow the same pattern. This implied that using one or two sites to represent the macro picture of wind behaviour in Sri Lanka will generate many errors. One extreme way to eliminate this problem is to model all individual sites which are eligible for implementation. But this is an impractical argument in which none can forecast the trending beyond three four years from now. The only approach to eliminate this obstacle is to provide the facility within the model to accommodate practically viable selected sites (which represent specific wind regimes) but not all the sites. Based on this argument, the model was prepared to facilitate up to any number of such data sets but only six were used for the present work, mainly due to lack of quality data.

Wind turbines convert kinetic energy of wind to electrical energy. Wind power generation basically affect by the type of wind regime, roughness of the terrain, type of wind turbine, unit size, hub elevation from the sea level, design tower height and the characteristics of the power curve, etc. Gross wind energy was calculated using wind speed data (30 min resolution) by treating them with key parameters mentioned above. Mainly due the wastage, the total generated energy is not available at the grid point to cater the system. Therefore the gross energy is modified with several correction factors and calculated the net generation; the practically available energy for system feeding. Some typical correction factors along with the assumed figures are given in Table 2. Firstly, two simple techniques were used to calculate the total wind energy extraction potential of each site.

(1) The frequency distribution was multiplied by values corresponding to the relevant power curve at different wind speeds

$$E = \sum_{n=1}^{15} T_n P_n \qquad \text{......(1)}$$

Where

E= Energy output

T= Hourly interval of wind speed frequency

P= Respective power taken from the power curve

(2) Direct calculation of energy in each 30 min. time interval

$$E = \sum_{n=1}^{17520} \frac{1}{2} P_n \qquad \text{......(2)}$$

Net energy injection at grid point was calculated by allowing appropriate losses and uncertainties as given in Table 2.

Table 2 - Correction Factors Used for the Analysis

Topic	Assumed figures
Transformer loss	2%
Transmission loss up to 33 kV level	4%
Machine availability	2%
Grid availability	5%
Power Curve uncertainty	5%

This calculation was done for all possible sites. The aggregate wind energy profile with 30 min resolution for a year was prepared as the summation of all selected sites. The model itself has regular cross checking points to eliminate any impractical figures and human errors in feeding large sets of data. (See Appendix A3) Processed data was then used for modelling.

5. Modelling Techniques

Two modelling approaches were initially considered. Although the two methods use the same data sets, the principles behind each have distinct differences. The two methods/models used are given below.

Method – 1; Modified Load Duration Curve (MLDC) model

Method – 2: Equivalent Run of River (ROR) hydro model

Both can accommodate the variation of generation potential over a given period of time. Method 2 uses de-rated capacity contribution, unlike the first. A detailed comparison between the two methods is available in reference 5. A concise graphical representation of the working algorithm of the model is given in Appendix A3.

5.1 Modified LDC (MLDC) Method

The basic concept is explained in Figure 3 using a hypothetical demand profile and the simulated wind data of large wind farm.

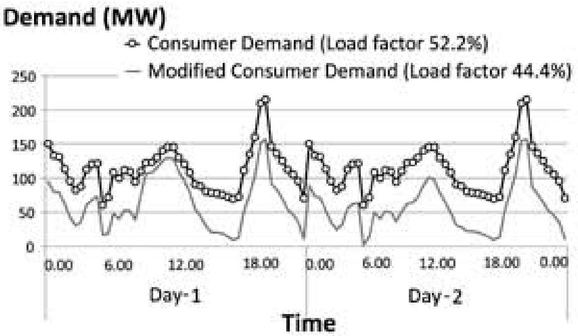


Figure 3 - Concept of Modified LDC Method

A hypothetical demand curve is given as the demand line. After deducting the wind power generation (in 30min intervals), the modified demand curve was developed. Owing to the variation in wind power generation over time, the modified demand is not merely a downward shift of the demand line but a distorted pattern, thereby with a different load factor. This type of approach in wind power modelling is referred to as the MLDC method.

In this particular study, system demand data for each 30 min interval for year 2009 was used for the analysis. The highest accuracy level available with WASP optimisation tool is the monthly load duration curve defined by either a 100 point per unit (pu) value sets or a 5th order polynomial mathematical function. A special effort has been taken to prepare monthly load duration curves for year 2009 based on demand records available from the System Control Centre of CEB.

To ensure a high precision level, different monthly load duration curves were used for the study. Those monthly load factors were calculated based on the expected annual load factors prepared by the generation planning and design (GP & D) branch of CEB. Each year probable generation from wind plants with 30 min resolution was deducted from the actual expected demand curve and the modified monthly load duration curves for each month of the 20 year period was prepared. This method has several drawbacks given below.

1) Highly time consuming & laborious work
2) Conducting corrections and modifications are not convenient
3) Difficulties in automating the process by using simple techniques such as macros in spreadsheets
4) Since Sri Lanka does not experience seasonality (eg. Summer vs. Winter) a more detailed study on monthly LDC does not provide any significant improvement
5) Extremely difficult and time consuming in preparing the input file "LODSY" for the WASP optimisation tool
6) The plant model represents zero capacity energy injection and only the LDC is modified by virtually adding negative demand
7) Dispatch of energy and capacity is not directly available in output files of the WASP optimisation tool.
8) Practical difficulties in conducting sensitivity studies

A typical set of power-duration curves of a wind power plant is given in Appendix A2. Basic model development procedure is given below.

Let, D*i* be the system demand data at grid point having 30 min resolution and G*i* be the net power generation of total wind plants. Then (D*i* - G*i*) was prepared for the total period. This was amounted a manipulation of 350,400 data values. Then all the time and demand values were normalised and load duration curves for each month of the total study period was prepared by using a frequency distribution analysis. All monthly load duration curves were split out to 100 vertical sections and the corresponding mid points of both demand and duration figures of each section was calculated directly used in LOADSY module of the WASP software in optimisation studies [3], [4].

5.2 ROR Type Hydro Equivalent Wind Plant Model

In this modelling approach, the power plants generate electricity only when the energy source is available, thereby lesser control over plant dispatch. A probabilistic distribution was prepared for five possible wind conditions. The defined conditions along with their respective weighing factors used for the analysis are given in Table 3.

Table 3 - Five Wind Conditions and Respective Weighing Factors

Wind Condition	Weighing Factor
Very high speed	0.1
High speed	0.2
Moderate	0.4
Low Speed	0.2
Very low speed	0.1

Based on the energy availability under different conditions defined above, the respective average capacities were also calculated. This method provides a more convenient approach to model the wind power plants compared with the modified monthly load duration curve method. Some more reasons are outlined below.

1) Less time consuming
2) The de-rated capacities in each month can be obtained
3) Modifications take less time
4) Simplicity and easy to handle

Basic model development procedure is given below.

Gi data figures were used to calculate the energy. Each monthly data set was ordered and divided in to five sections. Average values of capacity and energy for each section were used as input value for the optimisation study. This model was directly used under FIXSYS (for committed environment) and in VARSYS (for candidate environment) modules of the WASP software tool [3], [4].

$$E_{month} = \sum_{i=1}^{2\times per\,month} \frac{G_i}{2} \qquad .....(3)$$

$$E_{Avg.,State(n)} = Avg.\left[\sum_{i=1}^{2\times per\,state} \frac{G_i}{2}\right] \qquad .....(4)$$

$$C_{Avg.,State(n)} = \frac{\sum 0.5\times G_i}{hours\ per\ month} \leq C_p \qquad ......(5)$$

Where,

E stands for energy, *C* stands for capacity, *Avg.* for average value, *p* for installed value and *i* is in no. of hours. Also n=1 to 5.

6. Model Selection

Owing to the higher resolution, MLDC method was found to be more precise than ROR type hydro equivalent wind model.

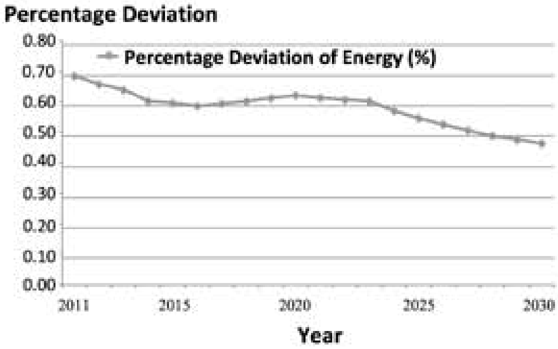


Figure 4 - Error in ROR Hydro Equivalent Wind Model Compared with the MLDC Method

In contrast, the MLDC method has drawbacks stated earlier. An additional analysis was conducted to examine the error or deviation in the ROR hydro equivalent model compared with the MLDC method and the results are given in Figure 4.

As clearly seen in Figure 4, ROR hydro equivalent wind model generated much less deviation of energy compared with the MLDC model and it was concluded that the ROR hydro equivalent wind model can be used without much error in long term planning studies. This model is similar to that of a typical Run-of-River (ROR) hydro plant which operates only when the energy resource is available. Although the WASP software version 4.0.1 cannot model NCRE plants separately, an effort has been taken to model wind plants as equivalent ROR hydro power plants, with certain limitations. Minimising the complexity in modelling due to commissioning and decommissioning of plants each year, a special approach was considered as illustrated in Figure 5. Here, only the plant addition is considered on top of the previous year capacity of the same plant category. Also WASP has a limitation of using hydro plants to a maximum of 30 plants in each category, Hydro A and Hydro B [3], [4].

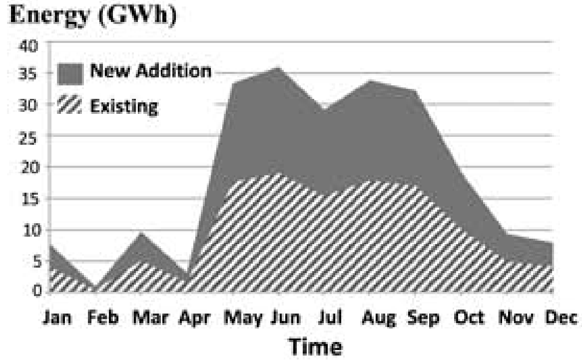


Figure 5 - Concept of Plant Addition

6.1 Adaptability in WASP Software

The model compatibility in optimisation software WASP was also verified. Any ROR type models (inherently, non-dispatchable embedded generation), never operates intentionally to cater to the peak demand. To verify this fact, the model was run with WASP optimisation. After inspecting the output files, it was confirmed that the plant operates as a must run base load plant. Hence the plant is expected to be delivering energy in the base portion but never contribute to displace capacity in peak portion of the load curve. Furthermore, the annual energy balance given as an output of WASP for the whole study period was cross-checked with the expected energy dispatch, so that accurate and complete energy dispatch was confirmed.

6.2 Model Compatibility and Limitations

The model compatibility with the optimisation tool WASP was conducted through three scenario studies.

(i) Energy policy scenario (10% of share of NCRE by 2015)
(ii) NCRE trend scenario (based on latest forecasted NCRE breakdown prepared by GP & D branch of CEB)
(iii) Least cost scenario

Possible impacts on conventional practices of result interpretations such as energy balance, capacity balance, fuel requirements, etc. were also conducted. Not only all scenario studies were conducted successfully but also no hindrance in result interpretation as well. Thereby it was concluded that wind models (both MLDC and ROR hydro equivalent wind) can be used effectively in WASP both under committed plant criteria and economic plant selection criteria. Since WASP facilitates for only two types of hydro categories [3] [4], only two Operation & Maintenance (O & M) costs can be assigned for all types of hydro plants. Hence, this model is not suitable to assess the characteristics and performance of individual plants.

7. Application of Software

Two models considered here were developed on basic principles and no reliance on specific software package in the subject area. But the original data base was created in spread sheet in MS Excel of MS Office package. Macro programming were extensively use in model preparation. Using macros enabled automate the model preparation process by minimising errors in repetitive calculations and saving the processing time. Additionally cross checking and double checking techniques were introduced in several stages of the whole process by using macro programming. The block diagram of the basic algorithm of how the model is prepared is given in Appendix A3.

8. WASP Optimisation

The practical use of new models (MLDC method and ROR type hydro equivalent wind plant model) was testified under three scenarios mentioned in section 6.2. The basic input parameters for relevant input files of the WASP software and assumptions used for the analysis are outlined in the first part of this section. The later part explains the output results obtained and new study areas exposed under least cost scenario incorporating wind plants as candidate option which was not possible in the past.

Demand data for year 2009 in 30 minute intervals was collected from the CEB System Control Centre. Data was refined by removing abnormal readings. Processed data was then used to prepare the basic load duration curve. The latest demand forecast of energy, peak demand and the variation of load factors prepared by CEB were directly used for the studies. All existing, committed and candidate power plants identified by CEB were used for the study with a single exception; the inclusion of a pumped storage hydro power plant as a candidate. However, the pumped storage capacity was limited to 500 MW and the earliest commissioning date was fixed at 2020. All other relevant data such as fuel costs, operation and maintenance costs of plants (Fixed and variable components), pure capital costs (Foreign and local components), cost of energy not served

(ENS), etc were updated and appropriately escalated (both local and foreign components) as applicable. Technical and other relevant data such as rated unit capacities, minimum operating levels, economic plant life, construction period of power plants, reserve margin, Loss Of Load Probability (LOLP) constraints, spinning reserve, Interest During Construction (IDC), Forced Outage Rates (FOR), planned outages of plants, heat rates applicable to thermal plants, heat values of fuels, etc were selected in line with the CEB general practice of data preparation. All studies used a 10% discount rate. No fuel escalation rates were applied, and all studies were conducted in real terms only. A least cost generation expansion study was conducted under a constrained environment by imposing maximum permissible NCRE commissioning level to limit impractical plant selection, as follows.
Mini hydro - 15 MW/year
Biomass - 10 MW/year
Wind - 36 MW/year
The capital cost data of NCRE plants were based on the consultation document used for the calculation of tariffs published by the Public Utilities Commission of Sri Lanka (PUCSL). Economic cost was calculated by multiplying the financial cost by a factor of 0.9. A lower annual O & M cost was used due to limitations in the optimisation software.
According to study results, a wind power addition of 36 MW was picked up in each year from 2012 to 2015. As a result of conducting WASP optimisation studies, the capacity expansion of new research and development (R&D) areas such as,

1. Macro scale modelling of wind plants as candidate plants in long term generation expansion planning studies
2. Finding of breakeven capital investment of wind plants based on economic plant selection
3. Effect of wind plant selection under different discount rates
4. Sensitivity studies in economic wind plant penetration vs. wind farm capacity, etc

9. Conclusion

The practise of deducting total wind energy generation from the total expected consumer demand in annual basis will no longer be precise in long term planning studies. Also it hinders the analytical opportunities (as mentioned in section 8.0) in wind plant absorption and unable to track the volatile nature of wind power generation with time. Therefore it is recommended to improve the present practise by the ROR type hydro equivalent wind plant model which found to be the most suitable option that can directly use in WASP optimisation studies. The concept of modelling wind plants as equivalent ROR hydropower plants with five state probabilistic distributions was found to be the most appropriate approach to be used in long term generation expansion studies. The study also filled a gap in modelling wind power plants of Sri Lanka in long-term generation planning, and enhanced the current practice of generation planning using the software tool WASP.

References

1. Elliott D., Schwartz M., Scott G., Haymes S., Heimiller D. and George R., *Wind Resource Atlas of Sri Lanka and the Maldives*, National Renewable Energy Laboratory, August 2003.

2. Generation Planning & Design Branch, *Long Term Generation Expansion Plan 2009 - 2022*, Ceylon Electricity Board, December 2008.

3. Planning & Economic Studies Section, Division of Nuclear Power, International Atomic Energy Agency, *WASP; A Computer Code for Power Generating System Expansion Planning, Version WASP-III plus*, user's manual, Vienna, 1994.

4. Planning & Economic Studies Section, Division of Nuclear Power, International Atomic Energy Agency, *Wien Automatic System Planning (WASP) Package; A Computer Code for Power Generating System Expansion Planning*, Version WASP-IV, user's manual, 2000.

5. Mudannayake N. A., *Modelling of Renewable Energy Based Embedded Generation in Long Term Planning*, Master of Science Dissertation, Department of Electrical Engineering, University of Moratuwa, Sri Lanka, February 2011.

Appendix A1 - Software Tool WASP

WASP is a widely-used generation expansion optimisation tool distributed by International Atomic Energy Authority (IAEA) among its member countries and member institutions. The program utilizes probabilistic estimation of system production costs, cost of energy not served (ENS) and reliability, linear programming technique for determining the dispatch policy satisfying constraints like environmental emissions, fuel availability and optimal electricity generation by some plants and the dynamic programming technique to optimise the cost of alternative system expansion policies. WASP permits finding the cost of optimal expansion plan for a power generating system over a user defined period (maximum up to 30 years), within the constraints provided by the planner. Every possible sequence of power plant units added to the system (including committed and candidate plants along with the retirement schedule of the existing plants) meeting the constraints defined, is evaluated in terms of economic costs. The objective function (cost function) used for the optimisation is given below.

$$B_j = \sum_{t=1}^{T}\left[\bar{I}_{j,t} - \bar{S}_{j,t} + \bar{F}_{j,t} + \bar{L}_{j,t} + \bar{M}_{j,t} + \bar{O}_{j,t}\right]$$

Where,

Bj is the objective (cost) function for expansion plan j

t is the time in years (1,2,3,……,T)

T is the length of the study period in years

Bar over the symbols represents the discounted values to a reference date at a given discount rate i

I stands for capital investment

S stands for salvage value of investment cost

F stands for fuel costs

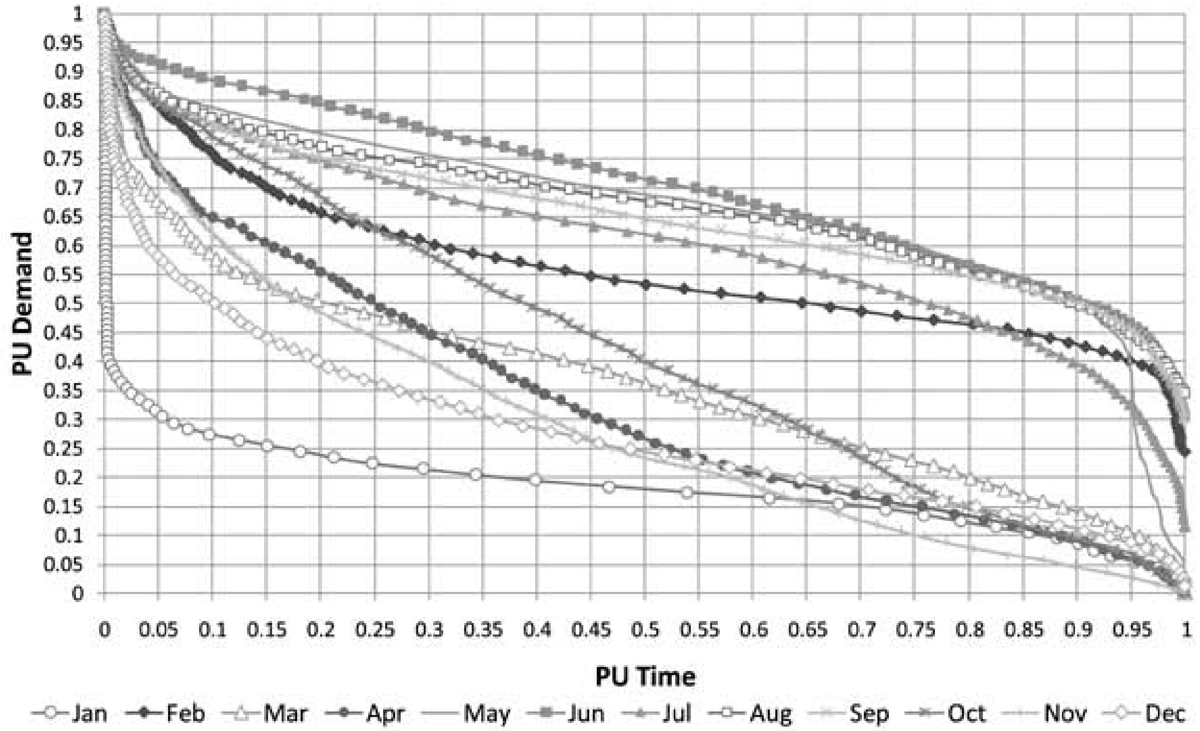
L stands for fuel inventory costs

M stands for non-fuel operation and maintenance costs

O stands for cost of energy not served

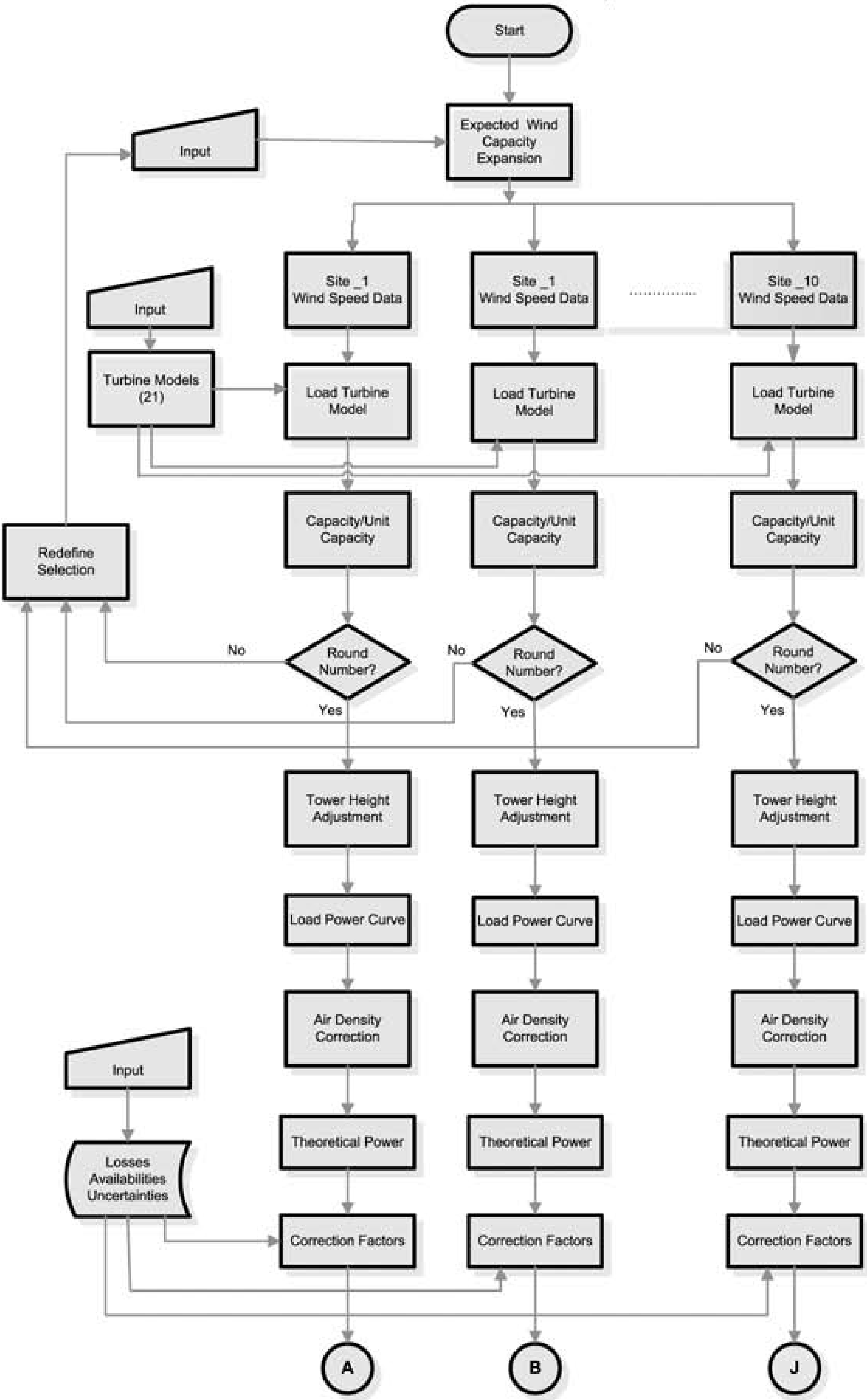
Appendix A2: Typical Wind Power Duration Curve

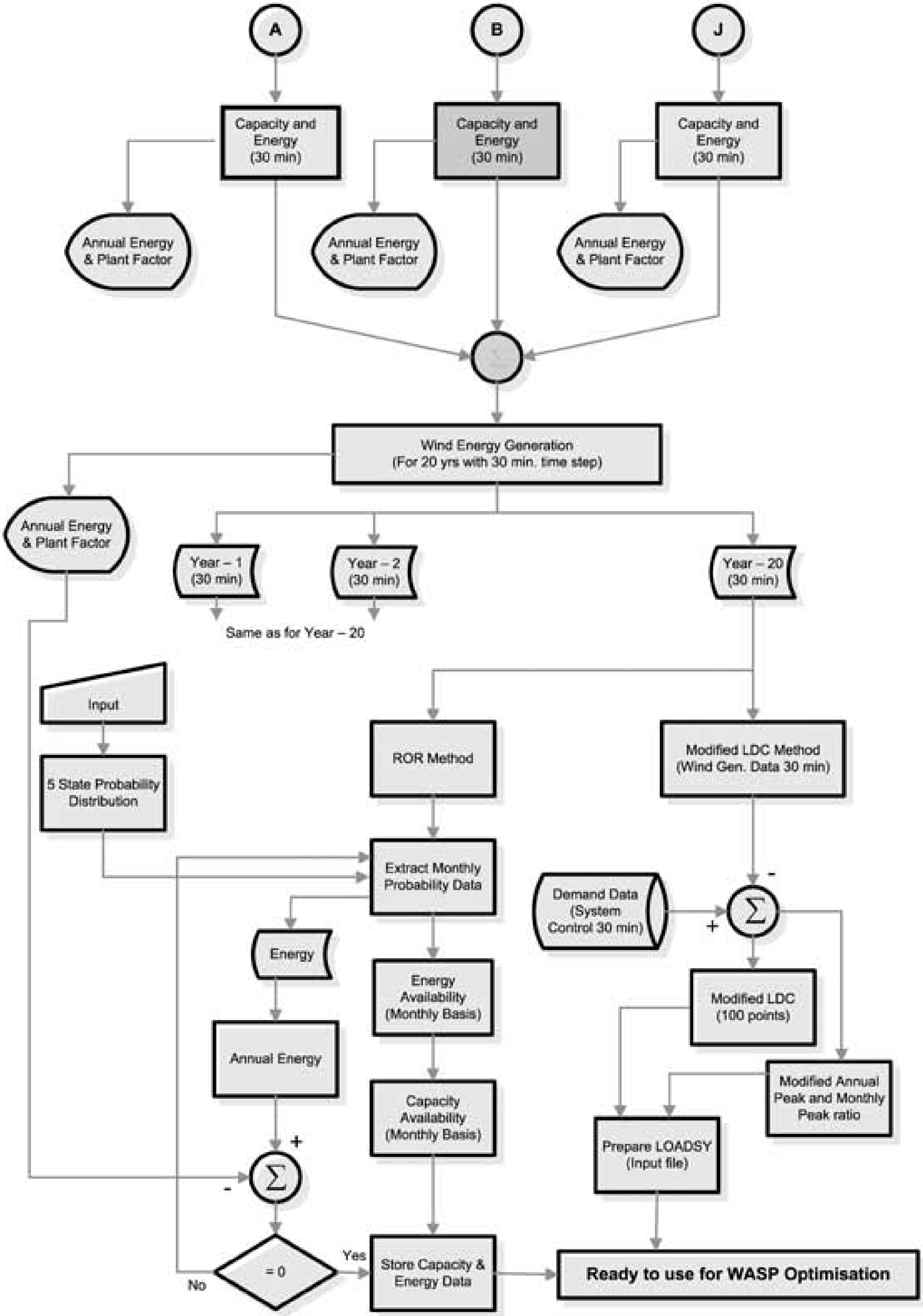
(This illustrates the highly volatile nature of wind power generation)



Appendix A3: Summarised Flow Chart of the Wind Plant Modelling Approach

(This prototype model is prepared for facilitating 10 sites and 21 wind turbine models for the illustration purpose only. But the concept has no such limitation on maximum number of sites and wind turbines to be used.)




A
B
J
Capacity and Energy (30 min)
Capacity and Energy (30 min)
Capacity and Energy (30 min)
Annual Energy & Plant Factor
Annual Energy & Plant Factor
Annual Energy & Plant Factor
Wind Energy Generation (For 20 yrs with 30 min. time step)
Annual Energy & Plant Factor
Year – 1 (30 min)
Year – 2 (30 min)
Year – 20 (30 min)
Same as for Year – 20
Input
5 State Probability Distribution
ROR Method
Modified LDC Method (Wind Gen. Data 30 min)
Extract Monthly Probability Data
Demand Data (System Control 30 min)
Energy
Energy Availability (Monthly Basis)
Modified LDC (100 points)
Annual Energy
Capacity Availability (Monthly Basis)
Modified Annual Peak and Monthly Peak ratio
Prepare LOADSY (Input file)
= 0
Yes
No
Store Capacity & Energy Data
Ready to use for WASP Optimisation