EVALUATING THE CAPACITY VALUE OF WIND GENERATION IN SYSTEMS WITH HYDRO GENERATION

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Abstract – Wind generation is envisaged to be a major contributor for meeting the targets for renewable energy and environment in various countries. However, the limited contribution of this generation source to system reliability requires increased capacity margins (generation capacity above system's maximum demand). This paper investigates the potential impact on the capacity value of wind generation due to the presence of hydro generation in systems. In order to quantify the adequacy of the overall generation capacity and capacity credit of wind generation in wind-hydro-thermal systems a new methodology based on loss of load expectation (LOLE) is developed. Various studies performed through implementing the new methodology establish that the capacity credit of wind generation can increase by up to 10% due to the support of hydro generation.

Keywords: Capacity credit, capacity value, wind integration, wind generation, hydro generation

1 INTRODUCTION

The rapid increase of wind generation in many power systems raises potential concerns regarding the reliability of future systems due to the intermittent nature and limited capacity value of this source. The capacity value of wind generation assessed from its ability to displace conventional (thermal) generation, while maintaining reliable supply of electricity, is termed as the capacity credit of this source. Evaluation of the capacity credit of wind generation is necessary for wind farm developers, utility planners, system operators as well as other decision makers in order to plan future power systems that are economically efficient and meet the desired reliability standards. This evaluation involves assessment of the adequacy of the overall generation capacity of a system with- and without wind generation to serve a given demand system with a set reliability target.

Capacity credit of wind generation varies across different regions due to the difference in the characteristics of the wind output as well as due to the different compositions of the incumbent generation systems. The presence of other flexible generation sources in the system such as hydro power (with reservoir/storage capability) can mitigate the variability of wind generation. This will lead to retain reduced thermal capacity in the system to maintain system security and thus enhances the capacity value of wind generation. However, the presence of such generation sources besides wind generation in a system further complicates the determination of the capacity adequacy and capacity credit of wind generation.

There has been some useful previous work in this area [1], [2] which applies equivalent load duration curve for reliability assessment of the system while minimizing the production costs. Wind generation is expressed as a multistate unit characterized by the probability density function of wind power output. The wind capacity credit is calculated using three different indices; effective load carrying capability, equivalent firm capacity and equivalent conventional capacity. Wind representation in this approach loses the chronological behaviour of wind as well as any correlations that may exist among wind, demand and hydro generation. Furthermore, the multistate wind representation of wind results in specific levels of wind output being available all the time with certain probability which differs from actual wind behaviour. Also due to a focus on production costing, these approaches do not fully utilize the flexibility potential of hydro to mitigate variability of wind power in order to minimize thermal capacity requirements.

In order to quantify the impact of the presence of a flexible generation source such as hydro power, on the capacity value of wind generation a new developed methodology based on loss of load expectation (LOLE) is presented in this paper. A linear programming (LP) based optimization model for generation dispatch is developed. It optimally allocates wind, hydro and thermal generation during each time period (half-hour) of weekly simulations time steps throughout a year to meet demand such that the thermal capacity requirements are minimized within the given constraints. This approach is different from peak-shaving based approaches [3], [4] and equivalent load duration curve methods [5], [6]. It preserves the chronological behavior of hydro energy which may have correlation with wind and demand.

An analytical technique based on Markov model is also employed to determine the probability or long-term availability of the various possible capacity states of total thermal capacity considered in the system. The amount of thermal dispatch required in each time period (assessed by the optimization model) is applied to the analytical model to determine the LOLP in the corresponding period. These periodical LOLP values are aggregated to determine the annual LOLE. Subsequently, thermal capacity is added or removed iteratively from the system as required to match the computed LOLE with the target LOLE set as system's reliability level.

The developed methodology is applied on New Zealand's (NZ) generation system which presently has about 60% hydro generation and is expecting a rapid growth of wind power. The expected large deployment of wind generation in the NZ's system poses several challenges to the system security. One of the key issues is the capacity contribution of intermittent wind power in NZ system that is a hydro dominated system.

The work presented in this paper demonstrates that the contribution of hydro to compensate low/no availability of wind power, in particular during peak demand periods, significantly augments the capacity value of wind generation. The additional (benefit) capacity credit of wind generation due to the support of hydro generation is observed to increase with the rise in wind penetration and reaches to about 10% at its 30% wind penetration. Impact of various key factors on the overall capacity adequacy and capacity credit of wind generation is also assessed. These factors include diversity of wind resource, wind load factor and penetration levels of wind and hydro generation in the system.

Section 2 of the paper describes the details of the developed methodology. Section 3 presents the various case studies performed by implementing the new methodology. Sensitivity studies performed for key factors affecting the capacity value of wind power in a wind-hydro-thermal system are also provided in this section. Conclusions are given in section 4.

2 METHODOLOGY

A methodology developed to evaluate the overall adequacy of generation capacity in systems having wind, hydro and thermal generation is elaborated in the following sub-sections. The same methodology with few additional steps is applied to determine the capacity credit of wind generation.

2.1 Capacity Adequacy Assessment of Thermal Systems

The thermal capacity model is based on a conventional approach [7] that employs the Markov model to compute the probability or long-term availability of various generation capacity states of the system.

Each unit in the system is characterized by its maximum rated capacity and its operating capacity states with associated probabilities. Generating units were added to the capacity model one by one and an array of the possible capacity states of the system with their associated probabilities is prepared. Such an array when represents capacity outage states of the system is termed as capacity outage probability table (COPT). The cumulative probability *P(X)* of a particular capacity outage state of the system, say '*X*' MW on addition of a unit of capacity '*C*' MW, is given by expression (1).

$$P(X)=\sum_{i=1}^{n} p'(X-C_i)p_i \tag{1}$$

Where n represents the number of capacity states of the thermal generator added to the capacity model, p_i is the probability of the unit's state *i and* $p'(X-C_i)$ is the probability of system's capacity state of $(X-C_i)$ size before addition of the unit.

The load model constitutes a time series of half-hourly peak loads (L_t) over a one year time horizon (*T*). A loss of load situation occurs when the load exceeds the available generation. For each half hour time slot '*t*' the probability of all the capacity states of the system that lead to insufficient available generation in meeting concurrent demand is added to determine the loss of load probability during that period, as given by (2).

$$LOLP_t=\sum_{i=1}^{N} p(X_i<L_t) \tag{2}$$

Where *N* represents the number of the capacity states X of the system. The annual loss of load expectation (LOLE in hours/year) is then determined by summing the LOLP values of each half hour period of the year as given by expression (3).

$$LOLE=\frac{1}{2}\sum_{t=1}^{T} LOLP_t \tag{3}$$

The adequacy of the capacity present in the system is determined through computation of the annual LOLE. If the computed LOLE matches the benchmark reliability level set for the system, the amount of capacity present in the system is considered adequate. Otherwise capacity is iteratively added (or removed) until the computed LOLE level matches the target LOLE level.

2.2 Capacity Adequacy Assessment of Wind-Hydro-Thermal Systems

For system having wind, hydro and thermal generation a linear programming (LP) based optimization model for generation dispatch is developed which can be implemented using an optimization software like Dash Xpress optimization tools [9]. The optimization formulation optimally allocates the wind, hydro and thermal generation during each time slot (half hour) of analysis such that the requirements of total thermal capacity in the system are minimized for given levels of wind and hydro generation in the system.

The objective is to optimally dispatch all generators in the system (wind, hydro and thermal generators) over '*T*' periods such that the utilization of wind and hydro energy is maximized and the cumulative output from thermal generators is minimized. This leads to the following objective function:

$$\text{Minimize } Z=MaxP^{th} \tag{4}$$

where $MaxP^{th}$ is the maximum of the cumulative power outputs from all thermal generators across all time periods of the simulation horizon determined by expression (5): $\forall t\in T$

$$MaxP^{th}\geq\sum_{i=1}^{I} P_i^{th}(t) \tag{5}$$

Where $P_i^{th}(t)$ is the power output of thermal generator '*i*' in period '*t*'; '*I*' is the number of thermal generators.

$MaxP^{th}$ is minimized subject to a number of constraints in order to satisfy electricity demand in each period while maintaining the specific characteristics of each power plant.

2.2.1 Modeled Constraints

In order to balance demand and supply in each time period, the power output from all generators in each time period equals the demand in the same time period as represented by expression (6): $\forall t \in T$

$$\left(\sum_{i=1}^{I} P_i^{th}(t)\right)+\left(\sum_{h=1}^{H} P_h^{hd}(t)\right)+\left(\sum_{w=1}^{W} P_w^{wd}(t)\right)=d(t) \qquad (6)$$

Where $P_h^{hd}(t)$ is the power output of hydro generator '*h*'; '*H*' is the total number of hydro generators. $P_w^{wd}(t)$ is the power output of wind generator '*w*' in period '*t*'; '*W*' is the number of hydro generators.

The optimization also includes operational constraints specific to wind, hydro and thermal power plants. The generation output level of each thermal power plant is constrained in each time period by the minimum stable generation level $P_{\min_i}^{th}$ and the maximum (rated) capacity $P_{\max_i}^{th}$ of the generator '*i*', according to expression (7). $\forall i \in I, \forall t \in T$

$$P_{\min_i}^{th}(t) \le P_i^{th}(t) \le P_{\max_i}^{th} \qquad (7)$$

Wind power is modeled as a non-dispatchable energy source. The model attempts to maximize its use unless it is restricted by low load and/or excess available energy conditions. Therefore, all wind power available $W_w(t)$ in each time period (obtained from historical wind data) is used towards meeting demand unless its curtailment is necessary. This is expressed by expression (8). $\forall w \in W, \forall t \in T$

$$P_w^{wd}(t) \le W_w(t) \qquad (8)$$

where $P_w^{wd}(t)$ is the wind power output of wind generator in period '*t*'.

All hydro generators are aggregated in the form of a single plant. The available energy within a simulation horizon (one week) is aggregated by type i.e., run-of-river (ROR) or reservoir. The run-of-river hydro component is treated as a must-run part of the aggregated hydro plant. It therefore, determines the minimum hydro generation level according to expression (9) which must be supplied to meet demand in each time period (*t*). $\forall h \in H, \forall t \in T$

$$P_{\min_h}^{hd}(t) = \frac{ror_h \cdot E_h(t)}{\tau} \qquad (9)$$

$P_{\min_h}^{hd}(t)$ is the minimum power output limit of the hydro generator in period '*t*'; ror_h is the ROR percentage of total available hydro energy $E_h(t)$ during the same period and τ is the duration of the time period i.e., half-hour as considered in this paper.

The hydro output level in each time period is also constrained by the total rated capacity of the hydro plants $P_{\max_h}^{hd}(t)$ in the system. Expression (10) defines the power output limits of the hydro generators: $\forall h \in H, \forall t \in T$

$$P_{\min_h}^{hd}(t) \le P_h^{hd}(t) \le P_{\max_h}^{hd}(t) \qquad (10)$$

An energy balance constraint, expression (11), is also applied to the hydro generation such that the total energy produced by hydro power plants does not exceed the available hydro energy during the simulation horizon (one week). $\forall h \in H, \forall t \in T$

$$\sum_{t=1}^{T}\left(\eta_h \cdot P_h^{hd}(t)\right)\cdot \tau \le \sum_{t=1}^{T} E_h(t) \qquad (11)$$

Where η_h is the efficiency of the hydro generator.

Energy balance during each time period (*t*) in the hydro reservoir is modeled through two constraints. Expression (12) gives the energy level of the reservoir at the end of first time interval (*t* = 1). $\forall h \in H, \forall t \in T$

$$E_h^{hd}(t) = res_{InSt} \cdot E_{\max}^{hd} - \eta_h \cdot P_h^{hd}(t) \cdot \tau + E_h(t) \qquad (12)$$

Where $E_h^{hd}(t)$ is the stored energy in the reservoir of the hydro generator at period '*t*'; res_{InSt} is the initial condition of the hydro reservoir (expressed as percentage of maximum energy storage level $E_{\max}^{hd}$ of the reservoir).

Expression (13) represents the energy balance in the reservoir for all other time periods (i.e. for all *t* > 1). At the end of a period (*t*), the stored energy in the reservoir is the stored energy at the end of previous period $E_h^{hd}(t-1)$, minus the energy produced by the plant in period (*t*), plus the inflow energy during the same period.

$$E_h^{hd}(t) = E_h^{hd}(t-1) - \eta_h \cdot P_h^{hd}(t) \cdot \tau + E_h(t) \qquad (13)$$

In order to ascertain that the reservoir energy in all time period (*t*) is within the limits, expression (14) is applied: $\forall h \in H, \forall t \in T$

$$E_{\min_h}^{hd}(t) \le E_h^{hd}(t) \le E_{\max_h}^{hd} \qquad (14)$$

Where $E_{\min_h}^{hd}(t)$ and $E_{\min_h}^{hd}(t)$ are respectively the cumulative minimum and cumulative maximum energy storage limits of the reservoir representing the aggregated hydro generator.

2.2.2 Procedure to determine the overall capacity requirement in wind-hydro-thermal systems

First, the thermal capacity requirement to meet a given demand considering only a thermal based system using its COPT and annual LOLE requirements is determined by applying the approach mentioned in section 2.1.

Subsequently, given quantities of wind and hydro power are added to the same system and thermal power output in each time period is assessed by applying the LP dispatch model explained in the previous sections. The half-hourly thermal power output obtained from the model is then combined with the COPT of the thermal capacity considered in the system and annual value of LOLE is computed. This generally results in significantly low level of LOLE. Therefore, thermal capacity is gradually reduced from the system, new COPT tables are prepared and LOLE is computed again. This process is repeated unless the amount of thermal capacity in the system in combination with given wind and hydro capacities provides the required level of LOLE.

A schematic representation of the capacity adequacy assessment model is shown in Figure 1.

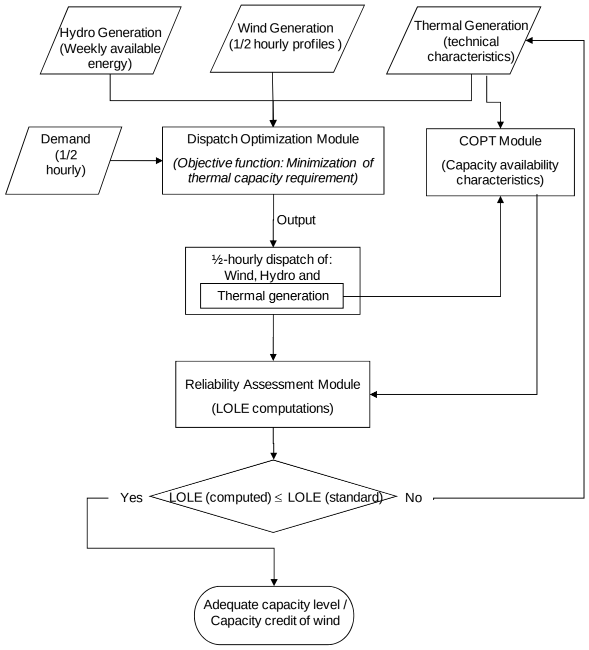

Figure 1: Schematic of developed model for capacity adequacy assessment in wind-hydro-thermal systems

2.3 Evaluation of Capacity Credit of Wind Generation

The capacity credit of wind generation is generally defined as “The reduction in the capacity of thermal plant due to the introduction of wind generation, while maintaining the system reliability”. The capacity credit of wind generation in a wind-thermal or in a wind-hydro-thermal system can be evaluated by first assessing the adequate capacity levels in these systems.

The starting point is to determine the amount of thermal generation capacity that is adequate to supply a given demand with a desired level of LOLE. Wind generation is then added to the system and the generation adequacy evaluation model is re-run for the same demand. This provides the new thermal capacity in the wind-thermal system that provides the same level of LOLE as in the only thermal based system. The difference in the total amount of thermal capacity between the thermal alone and wind-thermal systems represents the capacity credit of wind generation in the wind-thermal system which is generally expressed as the percentage of wind capacity in the system.

Similarly Wind capacity credit in wind-hydro-thermal systems represents the difference in the thermal capacity requirements between hydro-thermal and wind-hydro-thermal systems. Using the dispatch model and COPT the amount of thermal capacity necessary to supply a given demand with desired level of LOLE in both hydro-thermal and wind-hydro-thermal systems is determined. The difference in the thermal capacity requirement between the two systems is the capacity credit of wind generation in the wind-hydro-thermal system.

2.3.1 Additional capacity credit of wind due to hydro generation

The energy storage capability of hydro generation can be used to manage the variability in wind generation output. Previous work by the authors [8] indicates that low or no availability of wind power during peak demand days significantly reduces the capacity credit of wind power, reducing it to more than half the annual value if no wind power is available for about five days during peak demand. During periods of high wind power output, hydro output levels can be reduced and hydro energy stored for later use during periods of low/no wind output or during peak demand. Therefore, the presence of hydro generation enhances the capacity value of wind generation and therefore, reduces the amount of thermal capacity that would be required to maintain system security.

In order to quantify the benefit of the presence of the hydro generation in the system, the capacity credit of wind generation is determined in both the wind-thermal and wind-hydro-thermal systems. The difference of the two indicates the overall capacity benefit (added value) due to the presence of hydro generation in the system. For the purposes of simplicity, in this work the overall advantage of wind, hydro and thermal coordination has been attributed to wind power.

3 CASE STUDIES

The developed methodology is applied to a system equivalent to New Zealand as it represents a good combination of thermal and hydro generation with an expected rapid deployment of wind power in near future. The system description and the range of various parameters studied are given in Table 1.

System Demand: Peak demand: 8,400MW Electricity demand: 51TWh
Thermal Generation(generic plants): Unit size: 100MW Unit availability: 85% (FOR = 15%)
Hydro Generation: Penetration level (% energy demand): 30% to 60% Load factor (%): 60%
Wind Generation: Penetration level (% energy demand): 5% to 30% Load factor (%): 30% to 50%
System Reliability Level: LOLE ≤ 8 hours/year

Table 1: System Description

The system demand is modeled as a half-hourly annual load profile based on historical demand data. Thermal generation is represented as generic plants. A standard two state operation mode (fully up and fully down) of these units is applied. All generating units are assumed to operate independently. For example, it is assumed that an outage of one generator would not directly affect the operation of the other units in the system.

Hydro generators are considered to be fully reliable i.e. these are assumed to be available all the time and constrained only by their rated capacities and available hydro energy. The hydro inflow energy available per week is obtained from historical data for average hydrology conditions in NZ.

Half-hourly aggregated wind power output profiles representative of various levels of wind penetration in the system are prepared from historical wind data that represent a 40% load factor of wind generation.

3.1 *Thermal System*

The developed methodology is employed to calculate the amount of thermal capacity necessary to meet the load system (shown in Table 1) with a loss of load expectation (LOLE) of 8 hours/year. Starting with an initial estimate of thermal capacity requirement (higher than the system peak demand) the optimization model developed for generation dispatch optimally allocates the thermal generation during each time period of analysis to meet demand. In an only thermal generation based system this equals the load requirement in each period. This thermal dispatch in each time period is then combined with the COPT of the thermal capacity considered in the system to determine the LOLP in the corresponding period. Yearly distribution of LOLP for this system is shown in Figure 2. The LOLP is observed to be significant during winter (high demand) season.

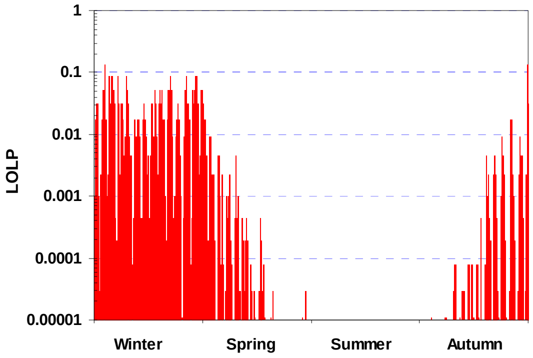

Figure 2: Yearly distribution of LOLP (thermal system)

The LOLP of all periods is added to determine the annual LOLE. This computed LOLE value was compared with the standard (8 hours/year) level and the thermal capacity was increased (or removed) unless it matches the standard LOLE requirement. This resulted in an overall thermal capacity requirement of 10,300MW.

3.2 *Hydro-Thermal System*

Hydro generation is introduced to the above thermal system as an aggregated hydro plant with an energy penetration level of 60% (31TWh) representing 6,500MW hydro capacity. The share of the run-of-river energy in the total available annual energy is considered to be 40% and is assumed constant in each week of the year. Also at the beginning of the simulation it was assumed that the reservoir level is at 50% of its total storage capacity. The reservoir capacity of the aggregated hydro plant (in terms of number of days of hydro generator's full output) is assumed to be 7 days.

The optimization model now allocates hydro and thermal generation during each period (half hour) in weekly simulations, such that the requirements of thermal capacity in the system are minimized. Such a dispatch for the peak demand week is depicted in Figure 3. During daily peak load periods hydro power can be seen to supply demand. While, during daily off-peak periods the power output from hydro generator reduces to conserve energy for subsequent peak periods while demand is met by thermal generation. However, even during the off-peak conditions hydro output is not reduced below a certain levels due to the (must-run) run-of-river constraint.

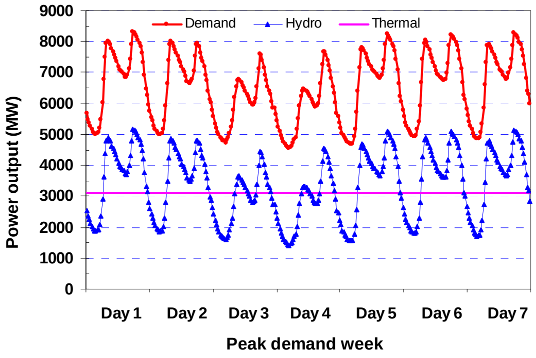

Figure 3: Optimal output of hydro and thermal generation during the peak demand week.

It can also be observed that during this peak demand week the total power output of thermal plants remains constant (3,100MW) as a result of the capacity minimization process. However, during other weeks, thermal power output within a week as well as across different weeks varies. In this study, the amount of thermal generation required in the system to serve demand with 8 hours/year LOLE is determined to be 4,400MW.

The presence of hydro generation in the system reduces the risk of loss load during peak demand season as shown in Figure 4.

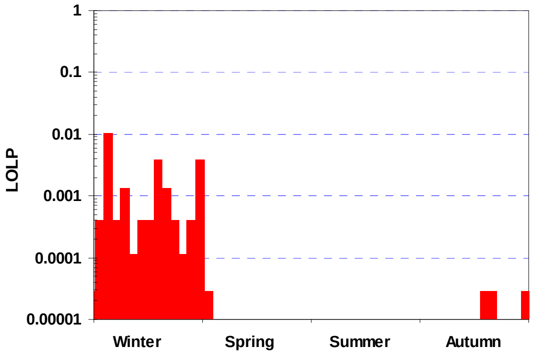

Figure 4: Yearly distribution of LOLP (hydro-thermal system)

3.3 Wind-Hydro-Thermal Systems

A wind energy penetration level of 20% (wind capacity of 2,900MW) was considered in the hydro-thermal system examined in section 3.2. To assess the adequate level of total capacity, thermal generation is gradually reduced from the system in order to match the computed LOLE with the target LOLE level (8hours/year). This results in a thermal capacity requirement of 3,500MW to securely meet the demand in the wind-hydro-thermal system.

A snapshot of the optimal wind-hydro-thermal output for a week is shown in Figure 5. It can be observed that during periods of relatively high wind power output (day 3 and 5), hydro output is reduced to conserve hydro energy for use during periods of low/no wind output (day 2 and 7) coinciding with high demand periods. It can also be observed in that during periods when high wind power output coincides with low demand conditions (start of the day 3 and 5), the power output from thermal generators can be further reduced.

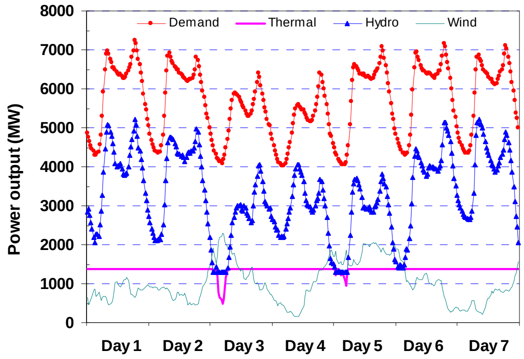

Figure 5: Optimal output of wind, hydro and thermal generation (one week period).

The optimal coordination between wind, hydro and thermal generation also flattens the LOLP distribution across the year as presented in Figure 6. (Due to very small values of LOLP and its wide spread in different periods of the year it is not clearly visible in the figure)

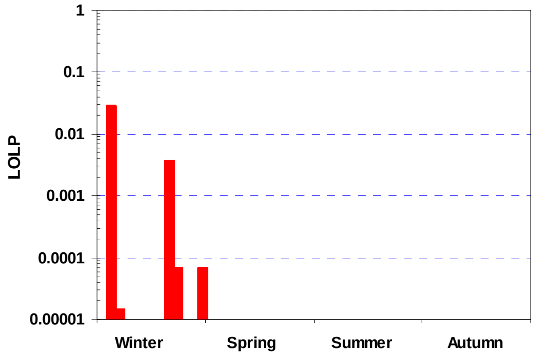

Figure 6: Yearly distribution of LOLP (wind-hydro-thermal system)

As a result of the above described wind, hydro and thermal output optimization, overall thermal capacity requirements are decreased resulting in enhancing the capacity value of wind generation.

3.4 Capacity Credit of Wind Generation

Studies were performed to evaluate the capacity adequacy and capacity credit of wind power for various levels of wind penetration in the system. Figure 7 shows the capacity credit evaluations for both wind-thermal system and wind-hydro-thermal systems.

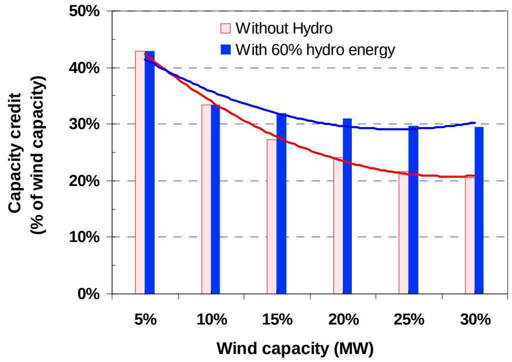

Figure 7: Capacity credit of wind at various wind penetrations levels

For both the wind-thermal and wind-hydro-thermal systems at small levels of wind penetration the capacity credit of wind is close to its load factor. But as the wind penetration in the system increases its capacity credit tends to decline and saturates at about 20% wind penetration. However, a clear difference can be noted in the wind capacity credit in both systems. This difference in the capacity credit of wind in wind-hydro-thermal and wind-thermal systems indicates the capacity credit benefit due to the presence of hydro generation in the system as given in Figure 8. This capacity credit gain due to hydro presence is more significant at higher penetration levels of wind and is primarily driven by the supporting wind during periods of peak demand and low/no available wind.

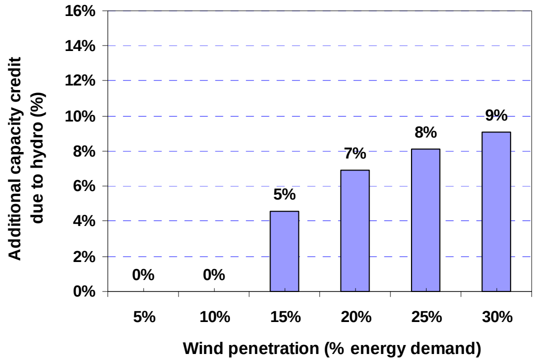

Figure 8: Additional capacity credit of wind due to hydro generation in the system

3.5 Effect of Key Factors on Capacity Contribution of Wind Generation

The developed methodology is also applied to quantify the impact of various key factors influencing the capacity value of wind generation. The factors studied include wind resource diversity, wind load factor, wind penetration level and hydro penetration level in the system and are investigated for the same demand system as given in Table 1.

3.5.1 *Effect of wind resource diversity*

In order to study the effect of wind resource diversity on the capacity credit of wind generation two different wind profiles for various penetration levels of wind in the system were prepared. For the diverse wind profile, data is used from wind sites spread across both islands of NZ while for the non-diverse case data from only one island is used that is linearly scaled to represent various levels of wind penetration. In both cases 60% of hydro energy penetration was considered.

The capacity credit of wind determined for the diverse case at various penetration levels of wind is presented in Figure 9 while the results for the non-diverse wind are displayed in Figure 10. Clearly diverse wind resource contributes significantly higher than the non-diverse case to save thermal capacity.

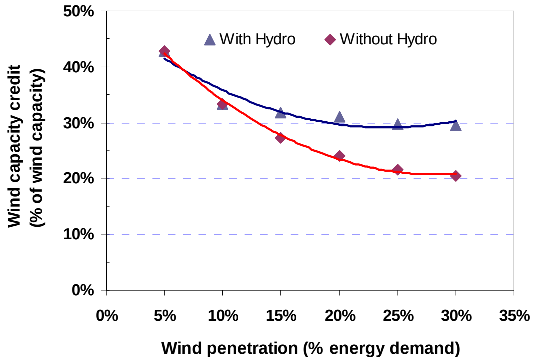

Figure 9: Capacity credit of diverse wind resource.

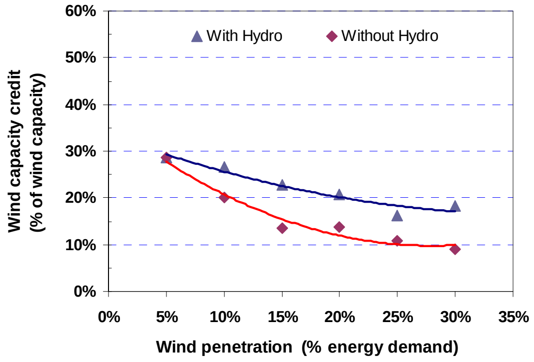

Figure 10: Capacity credit of non-diverse wind resource.

In all subsequent sensitivity studies, wind output profiles of a diverse wind resource were used, which is considered a better representative of the generation system under investigation.

3.5.2 *Effect of load factor of wind generation*

The load factor of wind generation represents the average output of all wind farms. In order to analyse the impact of various achievable load factors of wind generation on the capacity credit of wind, studies were performed considering 30% to 50% range of wind load factor. Half-hourly wind output profiles representing these load factors for different levels of wind penetration in the system are prepared.

Figure 11 presents the capacity credit of wind obtained for different wind load factors and for various levels of wind penetration in the wind-thermal system. It shows that at lower levels of wind penetration the capacity credit of wind generation equals the corresponding load factor. However, as the level of wind penetration rises, the capacity credit begins to decline and this trend exists for all for the entire load factor range. It was noted that the capacity credit reduces to about half for an increase of wind penetration from 5% to 30% in the wind-thermal system.

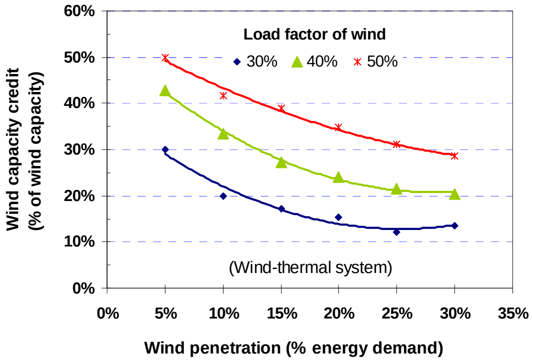

Figure 11: Effect of wind load factors on capacity credit of wind generation in wind-thermal system.

The same wind load factor range (30% to 50%) is tested for wind capacity credit evaluation in the wind-hydro-thermal system. It can be seen in Figure 12 that at lower levels of wind penetration the presence of hydro generation in the system does not influence the capacity credit for any level of wind load factor. However, at higher wind penetration levels the wind capacity credit is increased by 5 to 10 percentage points for all wind load factors considered. This clearly indicates the effectiveness of the role of hydro generation in enhancing capacity contribution of wind power even in those systems where achievable load factor of wind generation are relatively low.

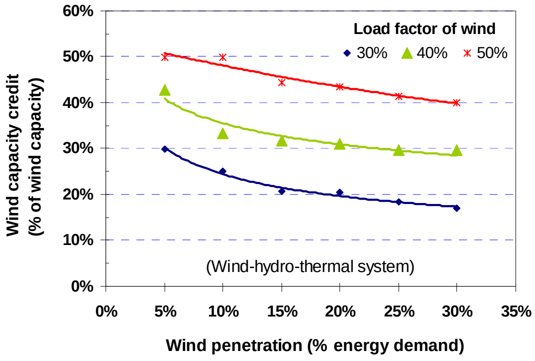

Figure 12: Effect of wind load factors on capacity credit of wind generation in wind-hydro-thermal system.

3.5.3 *Effect of the amount of hydro generation in the system*

In order to analyse the impact of the relative size of hydro and wind generation in the system on capacity credit of wind, different levels of hydro generation in the system are also investigated. For 5% to 30% wind penetration levels, a range of 40% to 60% hydro penetration in the system is examined.

The application of the developed methodology reveals that at lower levels of wind penetration i.e., below 10%, even changing the amount of hydro generation in the system does not significantly affect the capacity credit of wind generation. However, as the amount of wind in the system increases the level of hydro presence in the system becomes more important. Increasing hydro penetration from 40% to 60% at 30% penetration of wind will increase in the capacity credit of wind by 5%. In general, presence of greater amount of hydro generation in the system results in larger additional capacity credit benefit for wind generation.

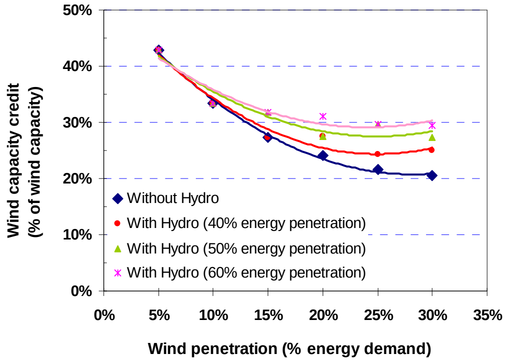

Figure 13: Effect of magnitude of hydro generation in the system on capacity credit of wind generation.

4 CONCLUSIONS

This paper described a methodology to evaluate the capacity value of wind generation in systems with hydro generation. The methodology respects the chronological behavior of wind as well as any correlations that may exist among wind, demand and hydro generation. The robustness of the methodology has been tested through a set of studies on the NZ generation system.

The results demonstrate that the contribution of hydro to compensate the negative effects of intermittent wind power, in particular during peak demand periods, considerably augments the capacity value of wind generation. The additional (benefit) capacity credit of wind generation due to the support of hydro generation can reach about 10% for high wind penetration. Assessment of the impact of various key factors on the overall capacity adequacy and capacity credit of wind generation has also been carried out and described. The key factors include diversity of wind resource, wind load factor, wind penetration level, installed capacity of hydro generation in the system and the availability of wind power during peak demand periods. Although the studies are carried out on a specific system, generic understanding on the effects of various key factors on the capacity value of wind generation can be derived.

The developed methodology is being extended to add transmission network and respective constraints. This will enable the quantification of the impact of transmission network on adequacy of the generation capacity in the interconnected wind-hydro-thermal systems for various levels and locations of wind generation. Furthermore, analysis of the effect of uncertainty in wind and hydro output will be carried out. Also the developed model will be applied to assess the impact of the optimal use of wind, hydro and thermal generation on emissions.

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