Development of Models and Methodology for the Reliability Evaluation of Two Interconnected Power Systems

Elvin D. Dulce
Department of Electrical Engineering
College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños

Rowaldo D. del Mundo
Electrical and Electronics Engineering Institute
College of Engineering, University of the Philippines Diliman

Abstract – *This study developed analytical and probabilistic models and methodology that simultaneously take into account the intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty, in evaluating the reliability of two interconnected power systems. The intermittency of wind power was incorporated by using a sliding window approach with a 7-hour period while the seasonal variation in hydropower was incorporated by considering the hourly generation. A seven-step approximation of the normal distribution was used for the load forecast uncertainty considerations. The Loss-of-Load Expectation (LOLE) in the Luzon Grid in 2014, when assisted by the Visayas Grid, increased from 53 hours/year to 95 hours/year when the intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty were considered. On the other hand, when the Luzon Grid is the assisting system, the LOLE in the Visayas Grid increased from 12 hours/year to 32 hours/year. A significant improvement was observed in the accuracy of the calculated LOLE in the two interconnected power systems when the intermittency and the seasonal variation in the generation, and the load forecast uncertainty were simultaneously considered.*

Keywords—Reliability, Loss-of-Load Expectation, Intermittency, Seasonal Variation, Load Forecast Uncertainty

Nomenclature:

C	is the capacity outage of state i for the TCEAU being added (MW)
D_k	is the actual demand (MW)
F_k	is the forecast demand (MW)
n	is the number of data points
p_i	is the probability of the existence of the TCEAU capacity outage state i
$P(X)$	is the probability that X MW will be on outage in the assisted system defined by Eq. 1
$P'(X\text{-}C_i)$	is the probability of $X\text{-}C_i$ MW or more on outage in the assisted system
%S.D.	is the percentage standard deviation of forecast error defined by Eq. 2
X	is the capacity outage level one step higher than the Reserve level in the final COPT (MW)

Subscripts, Superscripts, and Abbreviations:

HVDC	High Voltage Direct Current
i	pertains to capacity outage state of the TCEAU model
j	pertains to each step in the seven-step approximation of the normal distribution
LFU	Load Forecast Uncertainty
LOLE	Loss-of-Load Expectation
NERC-GADS	North American Electric Reliability Corporation - Electronic Generator Availability Data System
NGCP	National Grid Corporation of the Philippines
SA	System Assistance (MW)
SD	Standard Deviation
TCEAU	Tie-Line Constrained Equivalent Assisting Unit

I. INTRODUCTION

Power systems should be able to supply electrical energy while satisfying economic constraints and acceptable levels of reliability and service quality. However, uncertainties in energy supply, which are brought about by several factors such as random system component failures, seasonal variation, intermittency of resource, and fluctuation of load, affect the operation of the power system, which may cause interruption to load customers [1]. To prevent this from happening, the reliability of a power system must be studied.

Interconnected power systems are composed of several individual power systems connected by tie-lines. Interconnecting a power system to other power systems generally improves the adequacy of the generating capacity since the capacity deficiency may be accommodated by available assistance from other systems [2].

The Philippine power system is composed of three main grids: the Luzon Grid, the Visayas Grid, and the Mindanao Grid. As of the moment, only the Luzon and the Visayas Grids are interconnected by a 440 MW HVDC link [3] but the construction of the $500-million Leyte-Mindanao Interconnection Project is underway. This project involves linking the Visayas and Mindanao Grids into a unified Philippine National Grid – the “One Grid, One Nation” goal [4].

The models and methodologies available do not comprehensively and accurately evaluate the reliability of interconnected power systems, such as the Luzon-Visayas interconnected power system, since several factors that affect the reliable operation of power systems such as the intermittency and the seasonal variation in the generation, and the load forecast uncertainty are not simultaneously taken into account. Several simplifying assumptions are made in the models and methodologies available for evaluating the reliability of interconnected power systems which include a constant level of generation and a negligible deviation between forecast and actual load values. As shown in Table 1, only a few studies considered the intermittency and the seasonal variation in the generation, and the load forecast uncertainty. Evidently, not much attention is given to considering the factors simultaneously.

Table 1. Reliability Evaluation Methodologies for Interconnected Power Systems

Reference	Year of Publication	Evaluation Method/Technique	Considered the Intermittency and the Seasonal Variation in the Generation	Considered the Load Forecast Uncertainty
V.M. Cook *et al.* [5]	1963	Analytical	NO	NO
G.Samorodov *et al.* [6]	2006	Analytical	NO	NO
S.M. Shahidehpour [7]	1986	Analytical	NO	NO
F.F. Wu *et al.* [8]	1988	Analytical	NO	NO
M.Cepeda *et al.* [9]	2008	Analytical	NO	NO
A.S. Cook *et al.* [10]	1993	Monte-Carlo	NO	NO
T.C. Justino *et al.* [11]	2012	Monte-Carlo	NO	NO
B. Bagen *et al.* [12]	2010	Monte-Carlo	YES	YES
A.K. Mehta *et al.* [13]	2007	Enumeration	NO	NO
M.A.H. El-Sayed [14]	1996	Hybrid Enumeration And Monte-Carlo	NO	NO
M.F. Firuzabad and R. Billinton [15]	2001	Hybrid Probabilistic And Deterministic	NO	YES
F.A. El-Sheikhi and R. Billinton [16]	1984	Gram-Charlier Expansion	NO	NO
N. S. Rau *et al.* [17]	1982	Bivariate Gram-Charlier Expansion	NO	NO
C.K. Yin and M.Mazumdar [18]	1989	Large Deviation Method	NO	NO
G.M. Chintaluri and C. Singh [19]	1995	Multi-Parameter Gamma Distribution Method	NO	NO
A.K. Azad and R.B. Misra [20]	1996	Robust Convolution	NO	NO
J.Mitra and C.Singh [21]	1996	Decomposition	NO	NO
A.Lago-Gonzalez and C.Singh [22]	1989	Extended Decomposition Simulation	NO	NO
Z.Deng, and C.Singh [23]	1992	Simultaneous Decomposition Simulation	NO	NO
N.Gubbala *et al.* [24]	1994	Preferential Simultaneous Decomposition Simulation	NO	NO
X. Wand and X. Wang [25]	1993	Equivalent Energy Function Approach	NO	NO
J.S. Choi *et al.* [26]	2004	Tie-Line Constrained Equivalent Assistance Approach	NO	NO
Q. Ahsan [27]	1995	Segmentation Method	NO	NO
K.R. Khan *et al.* [28]	2004	Segmentation Method	NO	NO

Based on the different studies presented in Table 1, several tasks can be done in evaluating the reliability of interconnected power systems. One of the common tasks, although executed differently depending on the approach used, is calculating the Reliability Indices such as the Loss-of-Load Expectation (LOLE) and the Reserve Margin. LOLE is the expected number of days in the specified period in which the daily peak load will exceed the available capacity [2]. On the other hand, the Reserve Margin is a measure of available capacity above the capacity needed to meet normal peak demand levels [29].

This study aims to develop models and methodology that simultaneously take into account factors which affect the reliable operation of power systems to accurately evaluate the reliability of interconnected power systems. Specifically, it aims to:

a. Develop the generation, the load, the Tie-Line Constrained Equivalent Assisting Unit (TCEAU), and the overall reliability models for two interconnected power systems simultaneously considering the following factors:

i. Intermittency of wind power;
ii. Seasonal variation in hydropower; and
iii. Load forecast uncertainty;

b. Develop a methodology that will calculate the Reserve Margin and the Loss-of-Load Expectation (LOLE) in two interconnected power systems incorporating the intermittency and the seasonal variation in the generation, and the load forecast uncertainty; and

c. Apply the models and methodology developed to evaluate the reliability of the Luzon-Visayas interconnected power system and investigate the effects of interconnection to the individual systems.

II. MATERIALS AND METHODS

To incorporate the effects of the intermittency in wind power, a sliding window approach [30] with a 7-hour period was used for the generation model of the wind power generating unit. To incorporate the effects of the seasonal variation in hydropower, the hourly generation profile purchased from the Philippine Electricity Spot Market (PEMC) was used for the generation models of the hydropower generating units. For conventional generating plants and renewable energy plants like geothermal and biomass plants, the power outputs of which are not affected by seasonal variation, the Dependable Capacity in MW obtained from the Department of Energy (DOE) was used as the hourly generating unit capacity. The Forced Outage Rates (FOR) of the generating units were obtained from the North American Electric Reliability Corporation - Electronic Generator Availability Data System (NERC-GADS). Using the data and models developed, the hourly COPT, which is an array of capacity levels and the associated probabilities of existence, was obtained using a recursive algorithm [2, 31] - a total of 8,760 COPTs for each grid arising from 8,760 generation capacity levels in one year.

For the load models, this study used forecast hourly system demand for the year 2014 based on the historical hourly system demand for the year 2013 purchased from PEMC and the 2014 forecast annual system peak demand from the 2013 Transmission Development Plan [4]. The load forecast uncertainty (LFU) was incorporated using a seven-step approximation of the normal distribution [2, 12].

The Tie-Line Constrained Equivalent Assisting Unit (TCEAU) models, which represent the available assistance from the assisting system constrained by the tie-line capacity, were derived from the hourly COPTs and load models using the Equivalent Assisting Unit approach [2]. Seven TCEAU models were derived for each hour based on the seven-step normal distribution.

The overall reliability models of the two interconnected power systems were obtained by convolving the generation model of the assisted system, the load model of the assisted system, and the TCEAU model of the assisting system. The resulting convolution calculated the Reserve levels, the hourly LOLE, and the annual LOLE in the two interconnected power systems, as shown in Table 2.

Since there are seven TCEAU models ($TCEAU_{hour\text{-}j}$) for each hour, seven System Capacity levels of the assisted system were obtained by adding the System Capacity (C_{hour}) of the assisted system without assistance and the available assistance ($SA_{hour\text{-}j}$) from the assisting system as shown in column two of Table 2. For each System Capacity level, seven Load levels in the assisted system based on the seven-step normal distribution were used to determine seven corresponding Reserve levels as shown in columns five and six of Table 2, respectively. The standard deviation level (SD) in column five was calculated by multiplying the %S.D. value to the Load level (L_{hour}) in the current hour.

The LOLE at a certain Reserve level, shown in column seven of Table 2, was calculated by convolving the TCEAU model of the assisting system and the generation model of the assisted system using Equation 1 [2].

$$P(X)=\sum_{i=0}^{n} p_i P'(X-C_i) \qquad \textit{(Equation 1)}$$

Since each of the seven TCEAU models from the assisting system exists only with the existence of a Load level in the assisting system based on the seven-step normal distribution, the probability of the existence of each TCEAU model, shown in column eight of Table 2, was used to get the weighted LOLE for each Reserve level shown in column nine of Table 2. The sum of the seven weighted LOLE values was obtained producing a total of seven preliminary LOLE values for the hour - LOLE_{hour} $[\text{TCEAU}_{hour\text{-}j}]$.

Table 2. Calculation of the Reserve Margin and the LOLE

hour	System Capacity (MW)	Standard Deviation	Probability of Existence of the Load Level	Load (MW)	Reserve (MW)	LOLE	Probability of Existence of the TCEAU	Weighted LOLE
1	$C_1 + SA_{1-1}$	-3	0.006	L_1 - 3SD	$(C_1 + SA_{1-1}) - (L_1 - 3SD)$	$P((C_1 + SA_{1-1}) - (L_1 - 3SD))$	0.006	$(0.006)(0.006)*P((C_1 + SA_{1-1}) - (L_1 - 3SD))$
		-2	0.061	L_1 - 2SD	$(C_1 + SA_{1-1}) - (L_1 - 2SD)$	$P((C_1 + SA_{1-1}) - (L_1 - 2SD))$	0.006	$(0.061)(0.006)*P((C_1 + SA_{1-1}) - (L_1 - 2SD))$
		-1	0.242	L_1 - 1SD	$(C_1 + SA_{1-1}) - (L_1 - 1SD)$	$P((C_1 + SA_{1-1}) - (L_1 - 1SD))$	0.006	$(0.242)(0.006)*P((C_1 + SA_{1-1}) - (L_1 - 1SD))$
		0	0.382	L_1	$(C_1 + SA_{1-1}) - L_1$	$P((C_1 + SA_{1-1}) - L_1)$	0.006	$(0.382)(0.006)*P((C_1 + SA_{1-1}) - L_1)$
		1	0.242	L_1 + 1SD	$(C_1 + SA_{1-1}) - (L_1 + 1SD)$	$P((C_1 + SA_{1-1}) - (L_1 + 1SD))$	0.006	$(0.242)(0.006)*P((C_1 + SA_{1-1}) - (L_1 + 1SD))$
		2	0.061	L_1 + 2SD	$(C_1 + SA_{1-1}) - (L_1 + 2SD)$	$P((C_1 + SA_{1-1}) - (L_1 + 2SD))$	0.006	$(0.061)(0.006)*P((C_1 + SA_{1-1}) - (L_1 + 2SD))$
		3	0.006	L_1 + 3SD	$(C_1 + SA_{1-1}) - (L_1 + 3SD)$	$P((C_1 + SA_{1-1}) - (L_1 + 3SD))$	0.006	$(0.006)(0.006)*P((C_1 + SA_{1-1}) - (L_1 + 3SD))$
							LOLE_1 $[\text{TCEAU}_{1-1}]$	$\sum$ Weighted LOLE
1	$C_1 + SA_{1-2}$	-3	0.006	L_1 - 3SD	$(C_1 + SA_{1-2}) - (L_1 - 3SD)$	$P((C_1 + SA_{1-2}) - (L_1 - 3SD))$	0.061	$(0.006)(0.061)*P((C_1 + SA_{1-2}) - (L_1 - 3SD))$
		-2	0.061	L_1 - 2SD	$(C_1 + SA_{1-2}) - (L_1 - 2SD)$	$P((C_1 + SA_{1-2}) - (L_1 - 2SD))$	0.061	$(0.061)(0.061)*P((C_1 + SA_{1-2}) - (L_1 - 2SD))$
		-1	0.242	L_1 - 1SD	$(C_1 + SA_{1-2}) - (L_1 - 1SD)$	$P((C_1 + SA_{1-2}) - (L_1 - 1SD))$	0.061	$(0.242)(0.061)*P((C_1 + SA_{1-2}) - (L_1 - 1SD))$
		0	0.382	L_1	$(C_1 + SA_{1-2}) - L_1$	$P((C_1 + SA_{1-2}) - L_1)$	0.061	$(0.382)(0.061)*P((C_1 + SA_{1-2}) - L_1)$
		1	0.242	L_1 + 1SD	$(C_1 + SA_{1-2}) - (L_1 + 1SD)$	$P((C_1 + SA_{1-2}) - (L_1 + 1SD))$	0.061	$(0.242)(0.061)*P((C_1 + SA_{1-2}) - (L_1 + 1SD))$
		2	0.061	L_1 + 2SD	$(C_1 + SA_{1-2}) - (L_1 + 2SD)$	$P((C_1 + SA_{1-2}) - (L_1 + 2SD))$	0.061	$(0.061)(0.061)*P((C_1 + SA_{1-2}) - (L_1 + 2SD))$
		3	0.006	L_1 + 3SD	$(C_1 + SA_{1-2}) - (L_1 + 3SD)$	$P((C_1 + SA_{1-2}) - (L_1 + 3SD))$	0.061	$(0.006)(0.061)*P((C_1 + SA_{1-2}) - (L_1 + 3SD))$
							LOLE_1 $[\text{TCEAU}_{1-2}]$	$\sum$ Weighted LOLE

Table 2. Calculation of the Reserve Margin and the LOLE *(continued)*

hour	System Capacity (MW)	Standard Deviation	Probability of Existence of the Load Level	Load (MW)	Reserve (MW)	LOLE	Probability of Existence of the TCEAU	Weighted LOLE
		-3	0.006	$L_1 - 3SD$	$(C_1 + SA_{1-3}) - (L_1 - 3SD)$	$P((C_1 + SA_{1-3}) - (L_1 - 3SD))$	0.242	$(0.006)(0.242)*P((C_1 + SA_{1-3}) - (L_1 - 3SD))$
		-2	0.061	$L_1 - 2SD$	$(C_1 + SA_{1-3}) - (L_1 - 2SD)$	$P((C_1 + SA_{1-3}) - (L_1 - 2SD))$	0.242	$(0.061)(0.242)*P((C_1 + SA_{1-3}) - (L_1 - 2SD))$
		-1	0.242	$L_1 - 1SD$	$(C_1 + SA_{1-3}) - (L_1 - 1SD)$	$P((C_1 + SA_{1-3}) - (L_1 - 1SD))$	0.242	$(0.242)(0.242)*P((C_1 + SA_{1-3}) - (L_1 - 1SD))$
1	$C_1 + SA_{1-3}$	0	0.382	L_1	$(C_1 + SA_{1-3}) - L_1$	$P((C_1 + SA_{1-3}) - L_1)$	0.242	$(0.382)(0.242)*P((C_1 + SA_{1-3}) - L_1)$
		1	0.242	$L_1 + 1SD$	$(C_1 + SA_{1-3}) - (L_1 + 1SD)$	$P((C_1 + SA_{1-3}) - (L_1 + 1SD))$	0.242	$(0.242)(0.242)*P((C_1 + SA_{1-3}) - (L_1 + 1SD))$
		2	0.061	$L_1 + 2SD$	$(C_1 + SA_{1-3}) - (L_1 + 2SD)$	$P((C_1 + SA_{1-3}) - (L_1 + 2SD))$	0.242	$(0.061)(0.242)*P((C_1 + SA_{1-3}) - (L_1 + 2SD))$
		3	0.006	$L_1 + 3SD$	$(C_1 + SA_{1-3}) - (L_1 + 3SD)$	$P((C_1 + SA_{1-3}) - (L_1 + 3SD))$	0.242	$(0.006)(0.242)*P((C_1 + SA_{1-3}) - (L_1 + 3SD))$
							$LOLE_1$ [$TCEAU_{1-3}$]	$\sum$ Weighted LOLE
		-3	0.006	$L_1 - 3SD$	$(C_1 + SA_{1-4}) - (L_1 - 3SD)$	$P((C_1 + SA_{1-4}) - (L_1 - 3SD))$	0.382	$(0.006)(0.382)*P((C_1 + SA_{1-4}) - (L_1 - 3SD))$
		-2	0.061	$L_1 - 2SD$	$(C_1 + SA_{1-4}) - (L_1 - 2SD)$	$P((C_1 + SA_{1-4}) - (L_1 - 2SD))$	0.382	$(0.061)(0.382)*P((C_1 + SA_{1-4}) - (L_1 - 2SD))$
		-1	0.242	$L_1 - 1SD$	$(C_1 + SA_{1-4}) - (L_1 - 1SD)$	$P((C_1 + SA_{1-4}) - (L_1 - 1SD))$	0.382	$(0.242)(0.382)*P((C_1 + SA_{1-4}) - (L_1 - 1SD))$
1	$C_1 + SA_{1-4}$	0	0.382	L_1	$(C_1 + SA_{1-4}) - L_1$	$P((C_1 + SA_{1-4}) - L_1)$	0.382	$(0.382)(0.382)*P((C_1 + SA_{1-4}) - L_1)$
		1	0.242	$L_1 + 1SD$	$(C_1 + SA_{1-4}) - (L_1 + 1SD)$	$P((C_1 + SA_{1-4}) - (L_1 + 1SD))$	0.382	$(0.242)(0.382)*P((C_1 + SA_{1-4}) - (L_1 + 1SD))$
		2	0.061	$L_1 + 2SD$	$(C_1 + SA_{1-4}) - (L_1 + 2SD)$	$P((C_1 + SA_{1-4}) - (L_1 + 2SD))$	0.382	$(0.061)(0.382)*P((C_1 + SA_{1-4}) - (L_1 + 2SD))$
		3	0.006	$L_1 + 3SD$	$(C_1 + SA_{1-4}) - (L_1 + 3SD)$	$P((C_1 + SA_{1-4}) - (L_1 + 3SD))$	0.382	$(0.006)(0.382)*P((C_1 + SA_{1-4}) - (L_1 + 3SD))$
							$LOLE_1$ [$TCEAU_{1-4}$]	$\sum$ Weighted LOLE
		-3	0.006	$L_1 - 3SD$	$(C_1 + SA_{1-5}) - (L_1 - 3SD)$	$P((C_1 + SA_{1-5}) - (L_1 - 3SD))$	0.242	$(0.006)(0.242)*P((C_1 + SA_{1-5}) - (L_1 - 3SD))$
		-2	0.061	$L_1 - 2SD$	$(C_1 + SA_{1-5}) - (L_1 - 2SD)$	$P((C_1 + SA_{1-5}) - (L_1 - 2SD))$	0.242	$(0.061)(0.242)*P((C_1 + SA_{1-5}) - (L_1 - 2SD))$
		-1	0.242	$L_1 - 1SD$	$(C_1 + SA_{1-5}) - (L_1 - 1SD)$	$P((C_1 + SA_{1-5}) - (L_1 - 1SD))$	0.242	$(0.242)(0.242)*P((C_1 + SA_{1-5}) - (L_1 - 1SD))$
1	$C_1 + SA_{1-5}$	0	0.382	L_1	$(C_1 + SA_{1-5}) - L_1$	$P((C_1 + SA_{1-5}) - L_1)$	0.242	$(0.382)(0.242)*P((C_1 + SA_{1-5}) - L_1)$
		1	0.242	$L_1 + 1SD$	$(C_1 + SA_{1-5}) - (L_1 + 1SD)$	$P((C_1 + SA_{1-5}) - (L_1 + 1SD))$	0.242	$(0.242)(0.242)*P((C_1 + SA_{1-5}) - (L_1 + 1SD))$
		2	0.061	$L_1 + 2SD$	$(C_1 + SA_{1-5}) - (L_1 + 2SD)$	$P((C_1 + SA_{1-5}) - (L_1 + 2SD))$	0.242	$(0.061)(0.242)*P((C_1 + SA_{1-5}) - (L_1 + 2SD))$
		3	0.006	$L_1 + 3SD$	$(C_1 + SA_{1-5}) - (L_1 + 3SD)$	$P((C_1 + SA_{1-5}) - (L_1 + 3SD))$	0.242	$(0.006)(0.242)*P((C_1 + SA_{1-5}) - (L_1 + 3SD))$
							$LOLE_1$ [$TCEAU_{1-5}$]	$\sum$ Weighted LOLE

Table 2. Calculation of the Reserve Margin and the LOLE *(continued)*

hour	System Capacity (MW)	Standard Deviation	Probability of Existence of the Load Level	Load (MW)	Reserve (MW)	LOLE	Probability of Existence of the TCEAU	Weighted LOLE
		-3	0.006	$L_1 - 3SD$	$(C_1 + SA_{1\text{-}6}) - (L_1 - 3SD)$	$P((C_1 + SA_{1\text{-}6}) - (L_1 - 3SD))$	0.061	$(0.006)(0.061)*P((C_1 + SA_{1\text{-}6}) - (L_1 - 3SD))$
		-2	0.061	$L_1 - 2SD$	$(C_1 + SA_{1\text{-}6}) - (L_1 - 2SD)$	$P((C_1 + SA_{1\text{-}6}) - (L_1 - 2SD))$	0.061	$(0.061)(0.061)*P((C_1 + SA_{1\text{-}6}) - (L_1 - 2SD))$
		-1	0.242	$L_1 - 1SD$	$(C_1 + SA_{1\text{-}6}) - (L_1 - 1SD)$	$P((C_1 + SA_{1\text{-}6}) - (L_1 - 1SD))$	0.061	$(0.242)(0.061)*P((C_1 + SA_{1\text{-}6}) - (L_1 - 1SD))$
1	$C_1 + SA_{1\text{-}6}$	0	0.382	L_1	$(C_1 + SA_{1\text{-}6}) - L_1$	$P((C_1 + SA_{1\text{-}6}) - L_1)$	0.061	$(0.382)(0.061)*P((C_1 + SA_{1\text{-}6}) - L_1)$
		1	0.242	$L_1 + 1SD$	$(C_1 + SA_{1\text{-}6}) - (L_1 + 1SD)$	$P((C_1 + SA_{1\text{-}6}) - (L_1 + 1SD))$	0.061	$(0.242)(0.061)*P((C_1 + SA_{1\text{-}6}) - (L_1 + 1SD))$
		2	0.061	$L_1 + 2SD$	$(C_1 + SA_{1\text{-}6}) - (L_1 + 2SD)$	$P((C_1 + SA_{1\text{-}6}) - (L_1 + 2SD))$	0.061	$(0.061)(0.061)*P((C_1 + SA_{1\text{-}6}) - (L_1 + 2SD))$
		3	0.006	$L_1 + 3SD$	$(C_1 + SA_{1\text{-}6}) - (L_1 + 3SD)$	$P((C_1 + SA_{1\text{-}6}) - (L_1 + 3SD))$	0.061	$(0.006)(0.061)*P((C_1 + SA_{1\text{-}6}) - (L_1 + 3SD))$
							$LOLE_1$ [$TCEAU_{1\text{-}6}$]	$\sum$ Weighted LOLE
		-3	0.006	$L_1 - 3SD$	$(C_1 + SA_{1\text{-}7}) - (L_1 - 3SD)$	$P((C_1 + SA_{1\text{-}7}) - (L_1 - 3SD))$	0.006	$(0.006)(0.006)*P((C_1 + SA_{1\text{-}7}) - (L_1 - 3SD))$
		-2	0.061	$L_1 - 2SD$	$(C_1 + SA_{1\text{-}7}) - (L_1 - 2SD)$	$P((C_1 + SA_{1\text{-}7}) - (L_1 - 2SD))$	0.006	$(0.061)(0.006)*P((C_1 + SA_{1\text{-}7}) - (L_1 - 2SD))$
		-1	0.242	$L_1 - 1SD$	$(C_1 + SA_{1\text{-}7}) - (L_1 - 1SD)$	$P((C_1 + SA_{1\text{-}7}) - (L_1 - 1SD))$	0.006	$(0.242)(0.006)*P((C_1 + SA_{1\text{-}7}) - (L_1 - 1SD))$
1	$C_1 + SA_{1\text{-}7}$	0	0.382	L_1	$(C_1 + SA_{1\text{-}7}) - L_1$	$P((C_1 + SA_{1\text{-}7}) - L_1)$	0.006	$(0.382)(0.006)*P((C_1 + SA_{1\text{-}7}) - L_1)$
		1	0.242	$L_1 + 1SD$	$(C_1 + SA_{1\text{-}7}) - (L_1 + 1SD)$	$P((C_1 + SA_{1\text{-}7}) - (L_1 + 1SD))$	0.006	$(0.242)(0.006)*P((C_1 + SA_{1\text{-}7}) - (L_1 + 1SD))$
		2	0.061	$L_1 + 2SD$	$(C_1 + SA_{1\text{-}7}) - (L_1 + 2SD)$	$P((C_1 + SA_{1\text{-}7}) - (L_1 + 2SD))$	0.006	$(0.061)(0.006)*P((C_1 + SA_{1\text{-}7}) - (L_1 + 2SD))$
		3	0.006	$L_1 + 3SD$	$(C_1 + SA_{1\text{-}7}) - (L_1 + 3SD)$	$P((C_1 + SA_{1\text{-}7}) - (L_1 + 3SD))$	0.006	$(0.006)(0.006)*P((C_1 + SA_{1\text{-}7}) - (L_1 + 3SD))$
							$LOLE_1$ [$TCEAU_{1\text{-}7}$]	$\sum$ Weighted LOLE
							$LOLE_1$	$\sum_{j=1}^{7} LOLE_1 [TCEAU_{1-j}]$
:	:	:	:	:		:		:
							Annual LOLE in the Assisted System	$\sum_{hour=1}^{8760} LOLE_{hour}$

The LOLE for the hour ($LOLE_{hour}$) was then obtained by getting the sum of the seven preliminary LOLE values. Finally, the annual LOLE was obtained from the summation of the 8,760 hourly LOLE values in the assisted system.

In this study, the Luzon-Visayas interconnected power system was used as the test system. Different scenarios and cases, shown in Figure 1, were considered in the simulation to examine the effects of interconnecting the two grids and the impact on the reliability risks when the intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty are simultaneously considered.

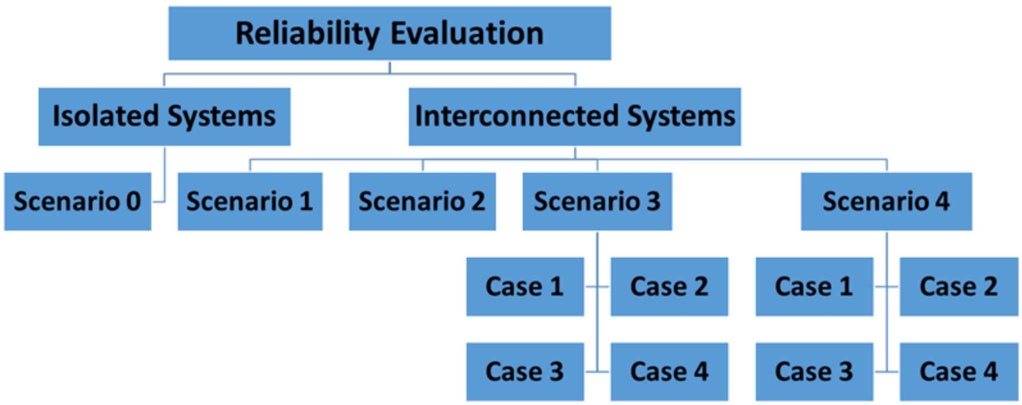

Figure 1. Different Scenarios and Cases for the Reliability Evaluation.

The conditions for the scenarios and cases are shown in Tables 3 and 4, respectively. The conditions for the scenarios were varied depending on the factors considered namely the intermittency of wind power, the seasonal variation in hydropower, and load forecast uncertainty.

Table 3. Conditions for the Scenarios used in the Study

Scenario	with the intermittency of wind power and the seasonal variation in hydropower	with the load forecast uncertainty
0 - Isolated	YES	YES
1 - IPS	NO	NO
2- IPS	YES	NO
3- IPS	NO	YES
4- IPS	YES	YES

Table 4. Conditions for the Cases used in the Study

Model	Case 1	Case 2	Case 3	Case 4
TCEAU	Low %S.D.	High %S.D.	Low %S.D.	High %S.D.
Assisted System	Low %S.D.	Low %S.D.	High %S.D.	High %S.D.

For scenarios that considered load forecast uncertainty (Scenario 3 and Scenario 4), the simulation was done using four cases summarized in Table 4, depending on the load forecast accuracy used in obtaining the TCEAU model from the assisting system and the load forecast accuracy in the assisted system. The percentage standard deviation (%S.D.) of forecast error represents the variability between the forecast and the actual demand, which was calculated using Equation 2 [2, 32] based on historical and forecast demands from various Philippine power, energy, and development plans [33, 34, 35, 36, 37, 38].

$$\%S.D. = 1.25\left(\sum_{k=1}^{n}|D_k\text{-}F_k|/n \Big/ \sum_{k=1}^{n}F_k/n\right)\times 100\% \qquad \textit{(Equation 2)}$$

For High %S.D., forecast demands until the year 2013 from all available published sources were considered. For Low %S.D., forecast demands with high forecast error exceeding 1000 MW were omitted. Both values were considered in this study together with the seven-step load forecast probability distribution to examine the effects of forecast accuracy and load forecast uncertainty on the reliability of two interconnected power systems. A MATLAB® program was developed to obtain the results.

III. RESULTS AND DISCUSSION

3.1 Luzon Grid Assisted by the Visayas Grid

This section presents the analyses of reliability evaluation results when the Luzon Grid is the assisted system and the Visayas Grid is the assisting system. The Luzon grid has 77 generating units of different fuel types, a total of 11,431 MW of dependable capacity in 2013. There are 21 hydropower generating units and one wind power generating unit which contribute about 19% to the total generation in the Luzon Grid. The Visayas Grid, on the other hand, has 80 generating units of different fuel types (Appendix B), a total of 1,972 MW of dependable capacity in 2013. There are three hydro generating units which contribute less than 1% to the total generation in the Visayas Grid.

Table 5 shows the summary of LOLE values in the Luzon Grid when operating as an isolated system and when it is assisted by the Visayas Grid for the different scenarios and cases described in Tables 3 and 4. Table 6 shows a sample calculation of the hourly LOLE when the Luzon Grid is the assisted system.

Table 5. Summary of LOLE values in the Luzon Grid

Scenario 0		**Scenario 1**	**Scenario 2**	**Scenario 3**		**Scenario 4**	
%S.D.	LOLE (hrs/ yr)	LOLE (hrs/ yr)	LOLE (hrs/ yr)	Case	LOLE (hrs/ yr)	Case	LOLE (hrs/ yr)
4.51%	158.5302	0.5994	52.9745	1	1.9724	1	95.1310
				2	2.0027	2	95.3449
25.94%	1443.8457			3	407.9573	3	1197.2561
				4	408.4365	4	1204.0294

Table 6. Sample calculation of the LOLE when the Luzon Grid is assisted by the Visayas Grid (Scenario 4, Case 1)

hour	System Capacity (MW)	S.D. Level	Probability of the Existence of the Load Level	Load (MW)	Reserve (MW)	LOLE	Probability of the Existence of the TCEAU	Weighted LOLE
14	10271	-3	0.006	7496.86	2774.14	0.000103	0.006	3.71E-09
14	10271	-2	0.061	7888.24	2382.76	0.000758	0.006	2.77E-07
14	10271	-1	0.242	8279.62	1991.38	0.004522	0.006	6.57E-06
14	10271	0	0.382	8671	1600	0.021976	0.006	5.04E-05
14	10271	1	0.242	9062.38	1208.62	0.085799	0.006	0.00012458
14	10271	2	0.061	9453.76	817.24	0.259900	0.006	9.51E-05
14	10271	3	0.006	9845.14	425.86	0.589899	0.006	2.12E-05
LOLE from TCEAU (S.D. Level = -3)								0.000298156
14	10271	-3	0.006	7496.86	2774.14	0.000156	0.061	5.72E-08
14	10271	-2	0.061	7888.24	2382.76	0.001098	0.061	4.08E-06
14	10271	-1	0.242	8279.62	1991.38	0.006261	0.061	9.24E-05
14	10271	0	0.382	8671	1600	0.029003	0.061	0.000675835
14	10271	1	0.242	9062.38	1208.62	0.107493	0.061	0.00158681
14	10271	2	0.061	9453.76	817.24	0.309058	0.061	0.001150004
14	10271	3	0.006	9845.14	425.86	0.665295	0.061	0.000243498
LOLE from TCEAU (S.D. Level = -2)								0.003752709
14	10216	-3	0.006	7496.86	2719.14	0.000275	0.242	4.00E-07
14	10216	-2	0.061	7888.24	2327.76	0.001826	0.242	2.70E-05
14	10216	-1	0.242	8279.62	1936.38	0.009830	0.242	0.000575706
14	10216	0	0.382	8671	1545	0.042752	0.242	0.003952205
14	10216	1	0.242	9062.38	1153.62	0.148520	0.242	0.008697904
14	10216	2	0.061	9453.76	762.24	0.395424	0.242	0.005837247
14	10216	3	0.006	9845.14	370.86	0.780219	0.242	0.001132877
LOLE from TCEAU (S.D. Level = -1)								0.0202233
14	10103	-3	0.006	7496.86	2606.14	0.000467	0.382	1.07E-06
14	10103	-2	0.061	7888.24	2214.76	0.002937	0.382	6.84E-05
14	10103	-1	0.242	8279.62	1823.38	0.014980	0.382	0.001384827
14	10103	0	0.382	8671	1432	0.061569	0.382	0.008984411
14	10103	1	0.242	9062.38	1040.62	0.200593	0.382	0.018543576
14	10103	2	0.061	9453.76	649.24	0.489988	0.382	0.011417697
14	10103	3	0.006	9845.14	257.86	0.881819	0.382	0.002021129
LOLE from TCEAU (S.D. Level = 0)								0.04242114
14	9989	-3	0.006	7496.86	2492.14	0.000695	0.242	1.01E-06
14	9989	-2	0.061	7888.24	2100.76	0.004208	0.242	6.21E-05
14	9989	-1	0.242	8279.62	1709.38	0.020685	0.242	0.001211387
14	9989	0	0.382	8671	1318	0.081308	0.242	0.007516391
14	9989	1	0.242	9062.38	926.62	0.249756	0.242	0.014626729
14	9989	2	0.061	9453.76	535.24	0.572964	0.242	0.008458097
14	9989	3	0.006	9845.14	143.86	0.965445	0.242	0.001401826
LOLE from TCEAU (S.D. Level = 1)								0.033277552
14	9876	-3	0.006	7496.86	2379.14	0.000818	0.061	3.00E-07
14	9876	-2	0.061	7888.24	1987.76	0.004885	0.061	1.82E-05
14	9876	-1	0.242	8279.62	1596.38	0.023673	0.061	0.000349457
14	9876	0	0.382	8671	1205	0.091096	0.061	0.002122714
14	9876	1	0.242	9062.38	813.62	0.272456	0.061	0.004022
14	9876	2	0.061	9453.76	422.24	0.611726	0.061	0.002276233
14	9876	3	0.006	9845.14	30.86	0.998767	0.061	0.000365549
LOLE from TCEAU (S.D. Level = 2)								0.009154429
14	9831	-3	0.006	7496.86	2334.14	0.000827	0.006	2.98E-08
14	9831	-2	0.061	7888.24	1942.76	0.004932	0.006	1.80E-06
14	9831	-1	0.242	8279.62	1551.38	0.023874	0.006	3.47E-05
14	9831	0	0.382	8671	1160	0.091735	0.006	0.000210257
14	9831	1	0.242	9062.38	768.62	0.273917	0.006	0.000397727
14	9831	2	0.061	9453.76	377.24	0.614303	0.006	0.000224835
14	9831	3	0.006	9845.14	-14.14	1.000000	0.006	3.60E-05
LOLE from TCEAU (S.D. Level = 3)								0.000905319
LOLE (hour = 14)								**0.110033**

3.1.1 Impact Assessment on the Reliability Risks in the Luzon Grid

As shown in Figure 2, the LOLE values in the Luzon Grid when assisted by the Visayas Grid are higher in Scenario 4 (Cases 1 to 4), which means that when the intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty are all present, the LOLE values become higher.

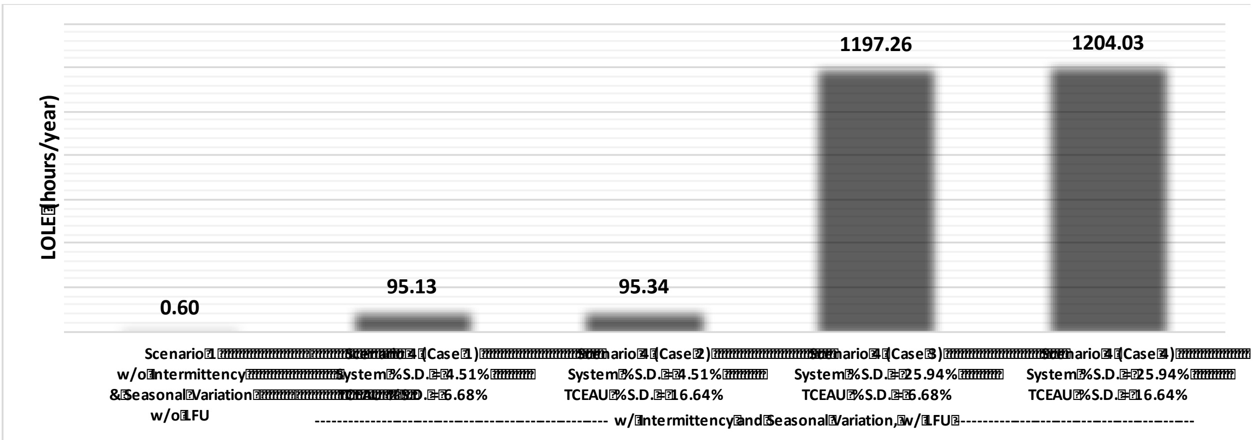

Figure 2. Comparison of LOLE values in the Luzon Grid when assisted by the Visayas Grid - with and without the Intermittency and the Seasonal Variation in the Generation, and LFU considerations.

In Figure 3, it can be observed that the LOLE values in Scenario 3 (Cases 1 and 2) are lower than the LOLE in Scenario 2. This means that when the %S.D. level in the Luzon Grid (4.51%) is low, the intermittency of wind power and the seasonal variation in hydropower have a greater impact than the load forecast uncertainty on the LOLE in the Luzon Grid when assisted by the Visayas Grid. Recall that about 19% of the total generation in the Luzon Grid comes from wind and hydropower and only about 1% of the total generation in the Visayas Grid comes from hydropower. This means that the increase in the LOLE in Scenario 3 can be highly attributed to the intermittency of wind power and the seasonal variation in hydropower in the Luzon Grid (assisted system) and not to that of the Visayas Grid (assisting system). Also, out the 19% of the total generation in the Luzon Grid that comes from wind and hydropower, only 0.015% comes from wind power. This means that the impact on the LOLE can be highly attributed to the seasonal variation in hydropower. However, when the penetration level of wind power is increased to 20%, the intermittency of wind power alone can have a significant impact on the LOLE, as shown in Figure 3. In increasing the capacity of wind to 20% of the total system capacity in the Luzon Grid, the capacity of each coal power generating unit is reduced by 65%.

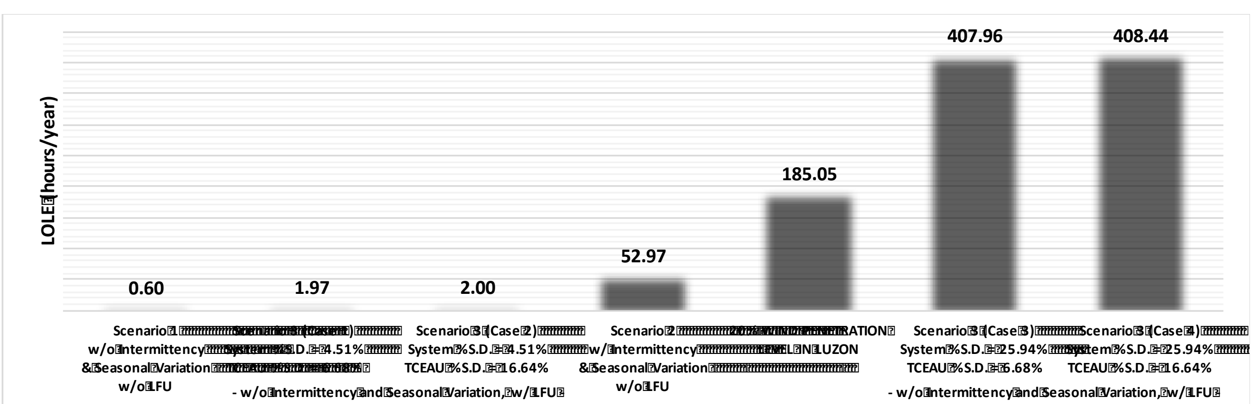

Figure 3. Comparison of LOLE values in the Luzon Grid when assisted by the Visayas Grid for different *Scenarios.*

On the other hand, it can be observed that the LOLE values in Scenario 3 (Cases 3 and 4) are higher than LOLE in Scenario 2. This means that when the %S.D. level in Luzon is high (25.94%), the load forecast uncertainty has a greater impact than the intermittency of wind power and the seasonal variation in hydropower on the LOLE in the Luzon Grid when assisted by the Visayas Grid.

From Table 7, it can be observed that the annual average reserve levels are higher when the % S.D. of the TCEAU is low (Cases 1 and 3) since the available assistance levels from the assisting system are higher. When the %S.D. of the TCEAU is high (Cases 2 and 4), the Reserve levels are lower since the available assistance levels from the assisting system are lower. This means that the average reserve level in the assisted system decreases as the load forecast accuracy in the assisting system decreases.

Table 7. %Reserve and LOLE values when the Luzon Grid is assisted by the Visayas Grid

Scenario 4 (Luzon Grid Assisted by the Visayas Grid)				
Case	%S.D.		%Reserve	LOLE (hours/year)
	System	TCEAU		
1	4.51%	6.68%	30.78%	95.131
2		16.64%	30.45%	95.3449
3	25.94%	6.68%	30.78%	1197.2561
4		16.64%	30.45%	1204.0294

Also, although the annual average reserve levels are the same in Cases 1 and 3 and in Cases 2 and 4, the LOLE values are higher when the %S.D. value of the assisted system is high (Case 3 and 4). This means that the impact of the load forecast uncertainty on the LOLE increases when the load forecast accuracy decreases.

3.1.2 Improvement in the Accuracy of the Calculated LOLE in the Luzon Grid

As discussed in the previous section, each factor considered in this study - the intermittency and the seasonal variation in the generation, and the load forecast uncertainty, has a significant impact on the LOLE of the assisted system when considered independently. When all the factors are present, the impact on the LOLE becomes even greater, although the impact of the factors when considered independently are not simply additive. Therefore, a significant improvement in the accuracy of the calculated LOLE can be achieved by considering all the factors simultaneously since each factor significantly affects the reliability of the interconnected power system.

In Figure 4, it can be observed that the improvement in the accuracy of the calculated LOLE in the Luzon Grid when assisted by the Visayas Grid is highest when the intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty are taken into account simultaneously (Scenario 4 – Case 1). The percentage improvement decreases when the intermittency and the seasonal variation in the generation and the load forecast uncertainty are considered independently, with the load forecast uncertainty considerations providing the lowest improvement (Scenario 3 – Case 1).

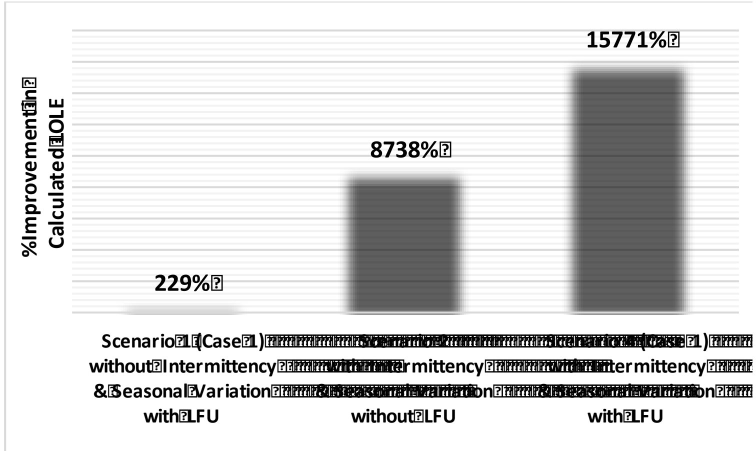

Figure 4. Percentage Improvement in the Accuracy of the Calculated LOLE in the Luzon Grid (Base Case: no factors considered).

However, nowadays, considering the seasonal variation in hydro in the reliability evaluation of generation systems has become a common practice. In Figure 5, considering the seasonal variation in the generation to be present in the base case, the improvement in the accuracy of the calculated LOLE in the Luzon Grid is highest when both the intermittency of wind power and the load forecast uncertainty are considered simultaneously. The percentage improvement decreases when the intermittency of wind power and the load forecast uncertainty are considered independently, with the intermittency of wind power consideration providing the lowest improvement.

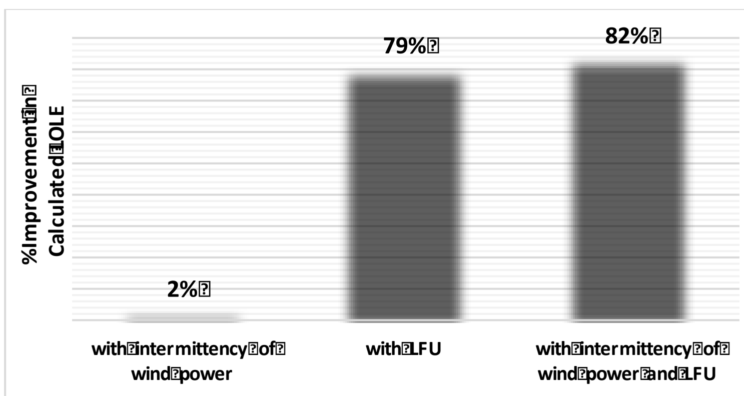

Figure 5. Percentage Improvement in the Accuracy of the Calculated LOLE in the Luzon Grid (Base Case: with seasonal variation in hydropower).

In the impact assessment of the load forecast accuracy on the LOLE in the Luzon Grid for load forecast uncertainty considerations, as the load forecast accuracy decreases, the impact on the LOLE increases but this does not mean that the accuracy of the LOLE also increases. High level of load forecast accuracy, meaning low levels of %S.D. in both the assisted and the assisting systems, is desired to improve the calculated LOLE. Therefore, in both Scenario 3 and Scenario 4, the level of accuracy is highest in Case 1 (low system %S.D., low TCEAU %S.D.) and lowest in Case 4 (high system %S.D., high TCEAU %S.D.).

3.1.3 Benefits of Interconnection to the Luzon Grid

As shown in Figures 6a and 6b, the LOLE values in the Luzon Grid when assisted by the Visayas Grid are lower than the LOLE when it is operating as an isolated system. This means that higher reliability is achieved when the system is assisted by the Visayas Grid. Generally, the decrease in the LOLE values can be attributed to the higher reserve levels when the Luzon Grid is assisted by the Visayas Grid as shown in Figures 7a and 7b (Scenario 4, Case 1).

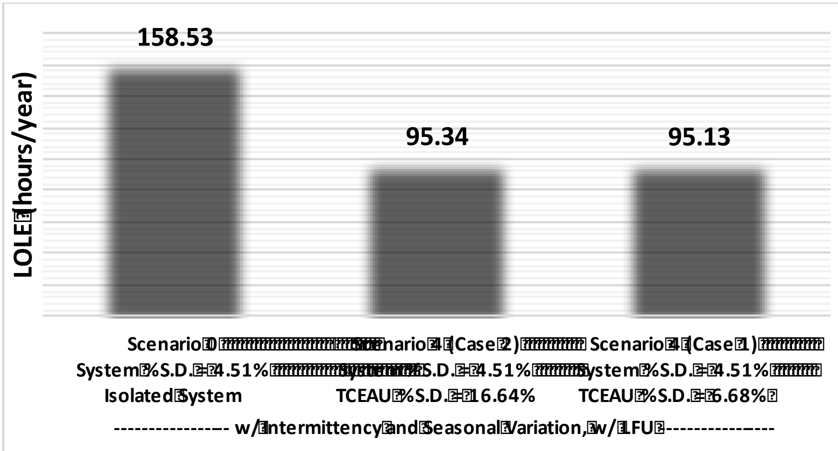

Figure 6a. Isolated System vs. Interconnected System when the %S.D. in the Luzon Grid is low (4.51%) - with the Intermittency and the Seasonal variation in the Generation, and LFU considerations.

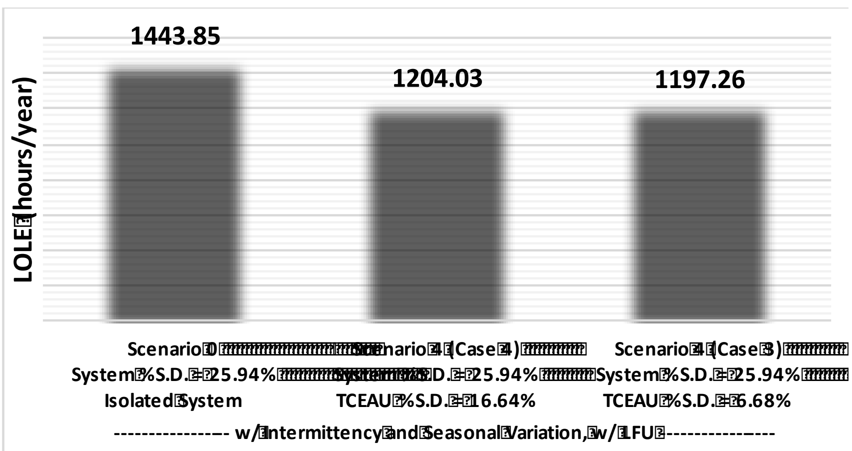

Figure 6b. Isolated System vs. Interconnected System when the %S.D. in the Luzon Grid (25.94%) is high - with the Intermittency and the Seasonal variation in the Generation, and LFU considerations.

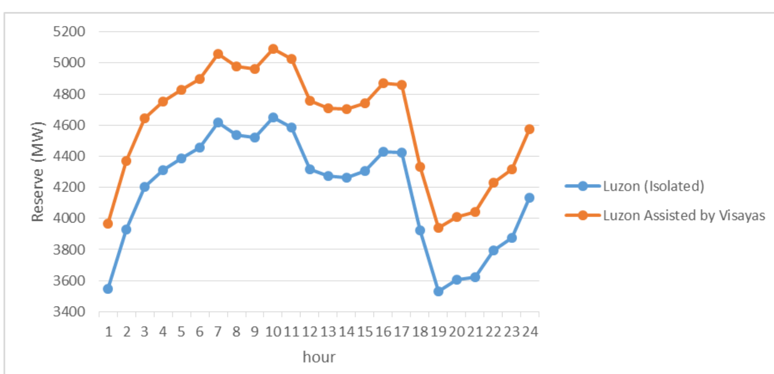

Figure 7a. Comparison of hourly Reserve levels in the Luzon Grid with and without assistance (January 1, 2014).

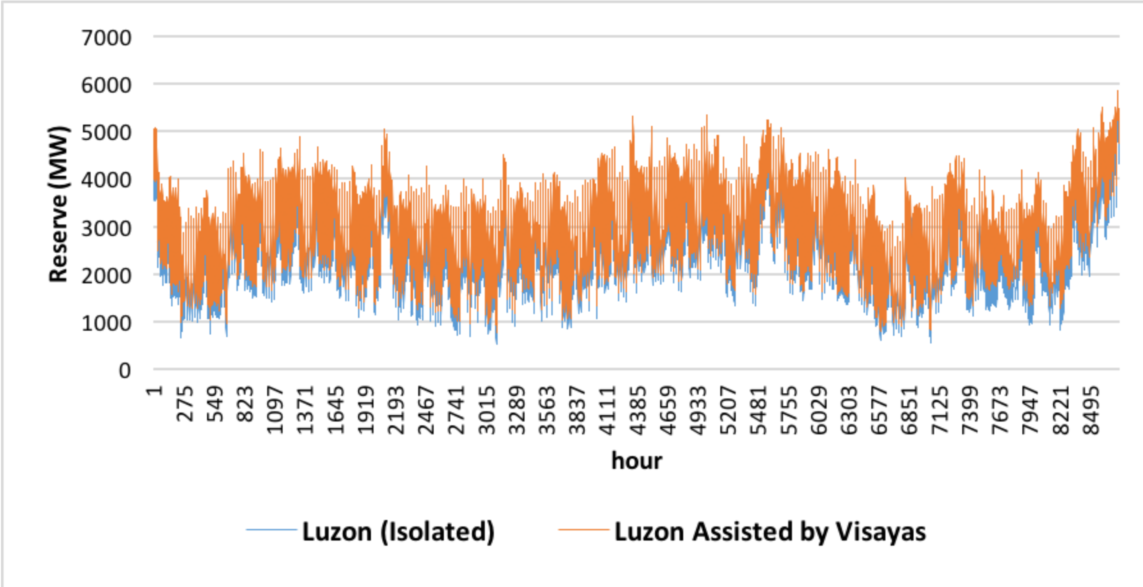

Figure 7b. Comparison of hourly Reserve levels in the Luzon Grid with and without assistance, 2014.

3.2 Visayas Grid Assisted by the Luzon Grid

This section presents the analyses of reliability evaluation results when the Visayas Grid is the assisted system and the Luzon Grid is the assisting system. Table 8 shows the summary of LOLE values in the Visayas Grid when operating as an isolated system and when assisted by the Luzon Grid for different scenarios and cases described in Tables 3 and 4. Table 9 shows a sample calculation of the hourly LOLE when the Visayas Grid is the assisted system.

Table 8. Summary of LOLE values in the Visayas Grid

Scenario 0		**Scenario 1**	**Scenario 2**	**Scenario 3**		**Scenario 4**	
%S.D.	LOLE (hrs/ yr)	LOLE (hrs/ yr)	LOLE (hrs/ yr)	Case	LOLE (hrs/ yr)	Case	LOLE (hrs/ yr)
6.68%	506.5986	0.2387	12.2513	1	1.7481	1	32.4615
				2	69.2292	2	150.0385
16.64%	1016.2290			3	67.4766	3	128.9632
				4	185.5587	4	337.3417

3.2.1 Impact Assessment on the Reliability Risks in the Visayas Grid

As shown in Figure 8, the LOLE values in the Visayas Grid when assisted by the Luzon Grid are higher in Scenario 4 (Cases 1 to 4). This means that when the intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty are all present, the LOLE becomes higher. Also, it can be observed that the LOLE in Scenario 4 (Case 2) is higher than the LOLE in Scenario 4 (Case 3) even though the %S.D. level in the Visayas Grid is higher in Scenario 4 (Case 3). This shows that the load forecast accuracy of the assisting system can also significantly affect the LOLE in the assisted system.

Table 9. Sample calculation of the LOLE when the Visayas Grid is assisted by the Luzon Grid (Scenario 4, Case 1)

hour	System Capacity (MW)	S.D. Level	Probability of the Existence of the Load	Load (MW)	Reserve (MW)	LOLE	Probability of the Existence of the TCEAU	Weighted LOLE
11	2406	-3	0.006	1395.980	1010.020	2.62E-07	0.006	9.42E-12
11	2406	-2	0.061	1512.654	893.346	7.19E-06	0.006	2.63E-09
11	2406	-1	0.242	1629.327	776.673	1.10E-04	0.006	1.60E-07
11	2406	0	0.382	1746	660	8.85E-04	0.006	2.03E-06
11	2406	1	0.242	1862.67	543.33	3.74E-03	0.006	5.43E-06
11	2406	2	0.061	1979.35	426.65	0.010809	0.006	3.96E-06
11	2406	3	0.006	2096.02	309.98	0.052889	0.006	1.90E-06
LOLE from TCEAU (S.D. Level = -3)								1.35E-05
11	2406	-3	0.006	1395.98	1010.02	1.27E-06	0.061	4.64E-10
11	2406	-2	0.061	1512.65	893.35	3.47E-05	0.061	1.29E-07
11	2406	-1	0.242	1629.33	776.67	5.27E-04	0.061	7.78E-06
11	2406	0	0.382	1746	660	4.19E-03	0.061	9.76E-05
11	2406	1	0.242	1862.67	543.33	0.016866	0.061	2.49E-04
11	2406	2	0.061	1979.35	426.65	0.036614	0.061	1.36E-04
11	2406	3	0.006	2096.02	309.98	0.088292	0.061	3.23E-05
LOLE from TCEAU (S.D. Level = -2)								5.23E-04
11	2406	-3	0.006	1395.98	1010.02	4.93E-06	0.242	7.16E-09
11	2406	-2	0.061	1512.65	893.35	1.34E-04	0.242	1.98E-06
11	2406	-1	0.242	1629.33	776.67	2.03E-03	0.242	1.19E-04
11	2406	0	0.382	1746	660	0.015914	0.242	1.47E-03
11	2406	1	0.242	1862.67	543.33	0.062357	0.242	0.003651897
11	2406	2	0.061	1979.35	426.65	0.121760	0.242	1.80E-03
11	2406	3	0.006	2096.02	309.98	0.197994	0.242	2.87E-04
LOLE from TCEAU (S.D. Level = -1)								0.007328646
11	2406	-3	0.006	1395.98	1010.02	1.50E-05	0.382	3.44E-08
11	2406	-2	0.061	1512.65	893.35	4.08E-04	0.382	9.50E-06
11	2406	-1	0.242	1629.33	776.67	0.006109	0.382	5.65E-04
11	2406	0	0.382	1746	660	0.047484	0.382	0.006929049
11	2406	1	0.242	1862.67	543.33	0.182012	0.382	0.016825951
11	2406	2	0.061	1979.35	426.65	0.333277	0.382	0.007766017
11	2406	3	0.006	2096.02	309.98	0.444023	0.382	0.001017701
LOLE from TCEAU (S.D. Level = 0)								0.033113014
11	2406	-3	0.006	1395.98	1010.02	3.46E-05	0.242	5.02E-08
11	2406	-2	0.061	1512.65	893.35	9.35E-04	0.242	1.38E-05
11	2406	-1	0.242	1629.33	776.67	0.013934	0.242	8.16E-04
11	2406	0	0.382	1746	660	0.107267	0.242	0.009916204
11	2406	1	0.242	1862.67	543.33	0.402360	0.242	0.023563799
11	2406	2	0.061	1979.35	426.65	0.694538	0.242	0.010252766
11	2406	3	0.006	2096.02	309.98	0.813360	0.242	0.001180999
LOLE from TCEAU (S.D. Level = 1)								0.045743661
11	2029	-3	0.006	1395.98	633.02	6.00E-05	0.061	2.20E-08
11	2029	-2	0.061	1512.65	516.35	1.61E-03	0.061	6.00E-06
11	2029	-1	0.242	1629.33	399.67	0.023757	0.061	3.51E-04
11	2029	0	0.382	1746	283	0.179270	0.061	0.004177344
11	2029	1	0.242	1862.67	166.33	0.643270	0.061	0.009495955
11	2029	2	0.061	1979.35	49.65	0.996288	0.061	0.003707188
11	2029	3	0.006	2096.02	-67.02	1	0.061	0.000366
LOLE from TCEAU (S.D. Level = 2)								0.018103212
11	1966	-3	0.006	1395.98	570.02	6.27E-05	0.006	2.26E-09
11	1966	-2	0.061	1512.65	453.35	0.001679	0.006	6.14E-07
11	1966	-1	0.242	1629.33	336.67	0.024612	0.006	3.57E-05
11	1966	0	0.382	1746	220	0.184448	0.006	4.23E-04
11	1966	1	0.242	1862.67	103.33	0.654983	0.006	0.000951035
11	1966	2	0.061	1979.35	-13.35	1	0.006	3.66E-04
11	1966	3	0.006	2096.02	-130.02	1	0.006	3.60E-05
LOLE from TCEAU (S.D. Level = 3)								0.001812141
LOLE (hour = 11)								**0.106637**

In Figure 9, it can be observed that the LOLE in Scenario 3 (Case 1) is lower than the LOLE in Scenario 2. This means that when both the %S.D. level in the Visayas Grid (assisted system, 6.68%) and the %S.D. level in the Luzon Grid (assisting system, 4.51%) are low, the intermittency of wind power and the seasonal variation in hydropower have greater impact than the load forecast uncertainty on the LOLE in the Visayas Grid when assisted by the Luzon Grid. Recall that only about 1% of the total generation in the Visayas Grid comes from hydropower and about 19% of the total generation in the Luzon Grid comes from wind and hydropower. This means that the increase in the LOLE in Scenario 3 can be highly attributed to the intermittency of wind power and the seasonal variation in hydropower in the Luzon Grid (assisting system) and not to that of the Visayas Grid (assisted system). Also, as discussed previously, only 0.015% of the total generation in the Luzon Grid comes from wind power which means that the increase on the LOLE can be highly attributed to the seasonal variation in hydropower. However, when the penetration level of the wind power in the Luzon Grid is increased to 20%, the intermittency of wind power alone can have a significant impact on the LOLE of the Visayas Grid, as shown in Figure 9.

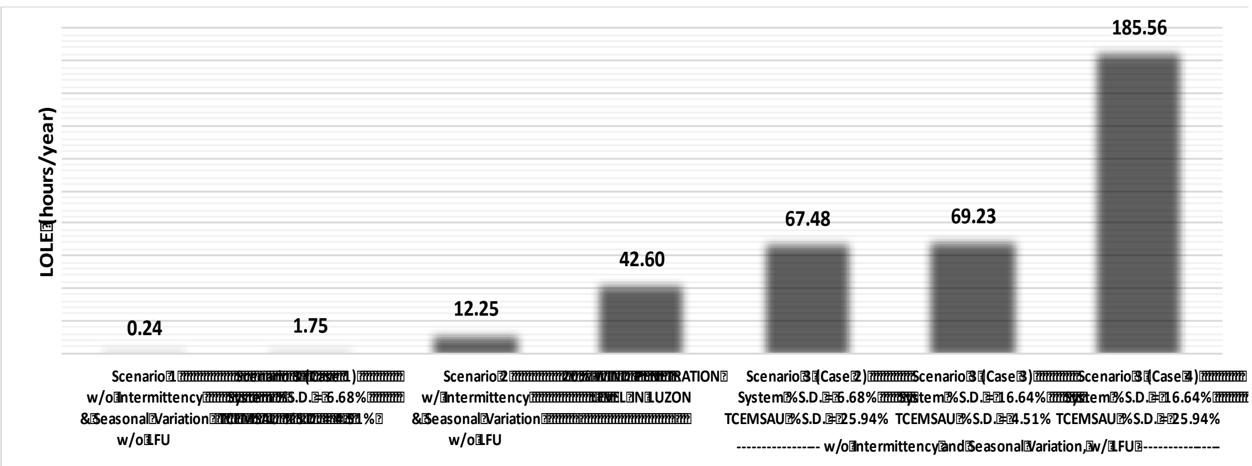

Figure 9. Comparison of LOLE values in the Visayas Grid when assisted by the Luzon Grid for different Scenarios.

On the other hand, it can be observed that the LOLE values in Scenario 3 (Cases 2, 3 and 4) are higher than the LOLE in Scenario 2. This means that when either the %S.D. level in the Visayas Grid (the assisted system, 16.64%) or the %S.D. level in the Luzon Grid (the assisting system, 25.94%) is high, the load forecast uncertainty has greater impact than the intermittency of wind power and the seasonal variation in hydropower on the LOLE in the Visayas Grid when assisted by the Luzon Grid.

From Table 10, it can be observed that the annual average reserve levels are higher when the % S.D. of the TCEAU is low (Cases 1 and 3) since the available assistance levels from the assisting system are higher. When the %S.D. of the TCEAU is high (Cases 2 and 4), the Reserve levels are lower since the available assistance levels from the assisting system are lower. This means that the average reserve level in the assisted system decreases as the load forecast accuracy in the assisting system decreases.

Table 10. %Reserve and LOLE values when the Visayas Grid is assisted by the Luzon Grid

Scenario 4 (Luzon Grid Assisted by the Visayas Grid)				
Case	%S.D.		%Reserve	LOLE (hours/year)
	System	TCEAU		
1	6.68%	4.51%	43.86%	32.4615
2		25.94%	40.59%	150.0385
3	16.64%	4.51%	43.86%	128.9632
4		25.94%	40.59%	337.3417

Also, although the annual average reserve levels are the same in Cases 1 and 3 and in Cases 2 and 4, the LOLE values are higher when the %S.D. value of the assisted system is high (Case 3 and 4). This means that the impact of the load forecast uncertainty on the LOLE increases when the load forecast accuracy decreases.

3.2.2. Improvement in the Accuracy of the Calculated LOLE in the Visayas Grid

As discussed in the previous section, each factor considered in this study, the intermittency and the seasonal variation in the generation, and the load forecast uncertainty, has a significant impact on the LOLE of the assisted system when considered independently. When all the factors are present, the impact on the LOLE becomes even greater, although the impact of the factors when considered independently are not simply additive. Therefore, a significant improvement in the accuracy of the calculated LOLE can be achieved by considering all the factors simultaneously since each factor significantly affects the reliability of the interconnected power system.

In the same way, it can be observed that the improvement in the accuracy of the calculated LOLE in the Visayas Grid when assisted by the Luzon Grid is highest when the intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty are taken into account simultaneously (Scenario 4 – Case 1) as shown in Figure 10. The percentage improvement decreases when the intermittency and the seasonal variation in the generation, and the load forecast uncertainty, are considered independently, with the load forecast uncertainty providing the lowest improvement (Scenario 3 – Case 1).

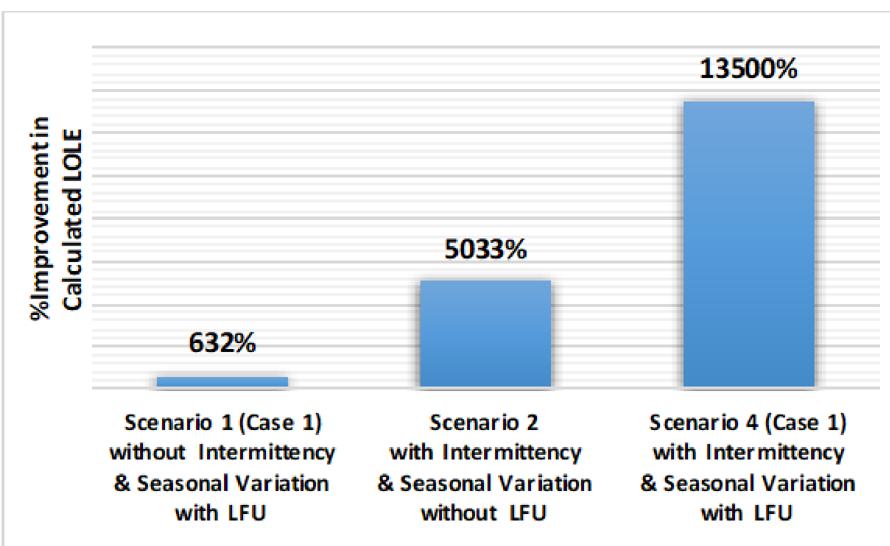

Figure 10. Percentage Improvement in the Accuracy of the Calculated LOLE in the Visayas Grid (Base case: no factors considered).

In Figure 11, considering the seasonal variation in the generation to be present in the base case, the improvement in the accuracy of the calculated LOLE in the Visayas Grid is highest when both the intermittency of wind power and the load forecast uncertainty are considered simultaneously. The percentage improvement decreases when the intermittency of wind power and the load forecast uncertainty are considered independently, with the intermittency of wind power consideration providing the lowest improvement. Recall that the wind power is only present in the Luzon Grid, the assisting system in this case, which means that the 3% improvement in the accuracy of the calculated LOLE is mainly due to the due to the intermittency of wind power considerations in the Luzon Grid.

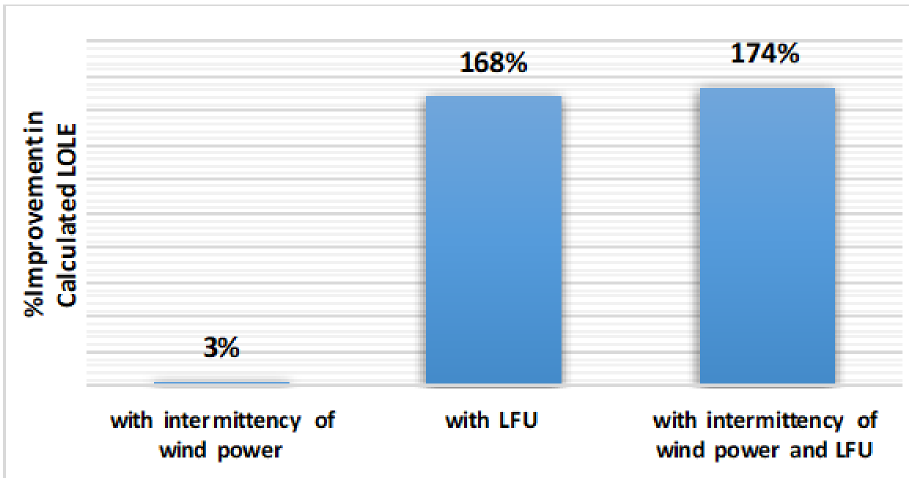

Figure 11. Percentage Improvement in the Accuracy of the Calculated LOLE in the Visayas Grid (Base case: with the seasonal variation in the generation).

In the impact assessment of the load forecast accuracy on the LOLE in the Visayas Grid for load forecast uncertainty considerations, as the load forecast accuracy decreases, the impact on the LOLE increases but this does not mean that the accuracy of the LOLE also increases. High level of load forecast accuracy, meaning low levels of %S.D. in both the assisted and the assisting systems, is desired to improve the calculated LOLE. Therefore, in both Scenario 3 and Scenario 4, the level of accuracy is highest in Case 1 (low system %S.D., low TCEAU %S.D.) and lowest in Case 4 (high system %S.D., high TCEAU %S.D.).

3.2.3. Benefits of Interconnection to the Visayas Grid

As shown in Figures 12a and 12b, the LOLE values in the Visayas Grid when assisted by the Luzon Grid are lower than the LOLE when it is operating as an isolated system. This means that higher reliability is achieved when the system is assisted by the Luzon Grid. Generally, this can be attributed to the higher reserve levels when the Visayas Grid is assisted by the Luzon Grid as shown in Figures 13a and 13b (Scenario 4, Case 1).

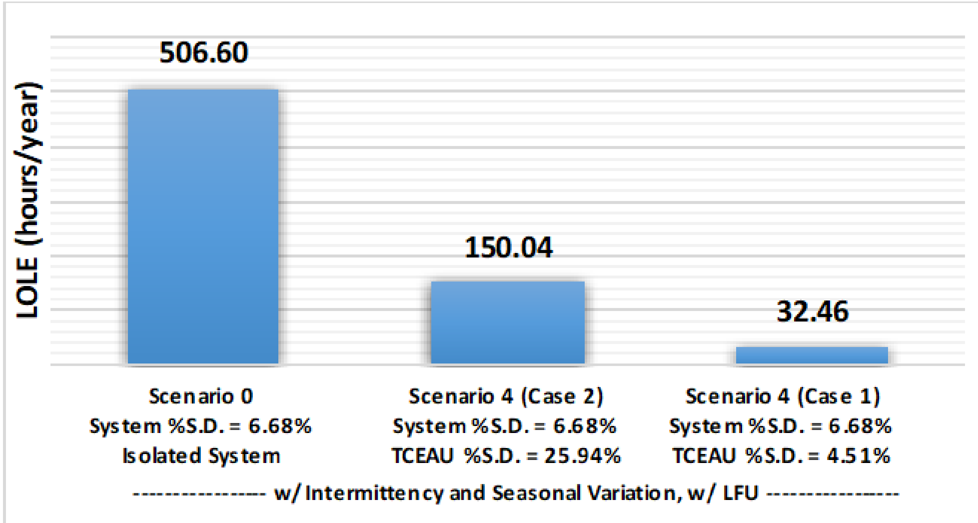

Figure 12a. Isolated System vs. Interconnected System when the %S.D. in the Visayas Grid is low (6.68%).

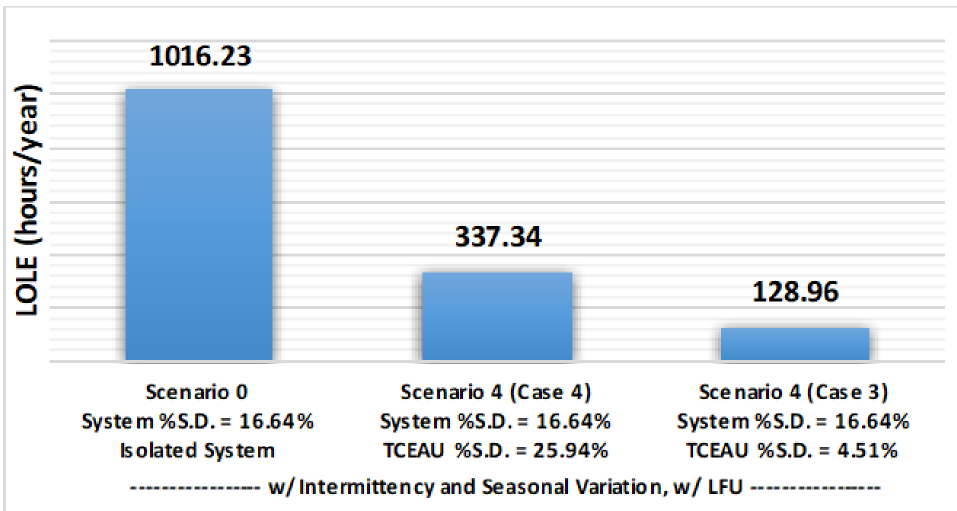

Figure 12b. Isolated System vs. Interconnected System when the %S.D. in the Visayas Grid (16.64%) is high.

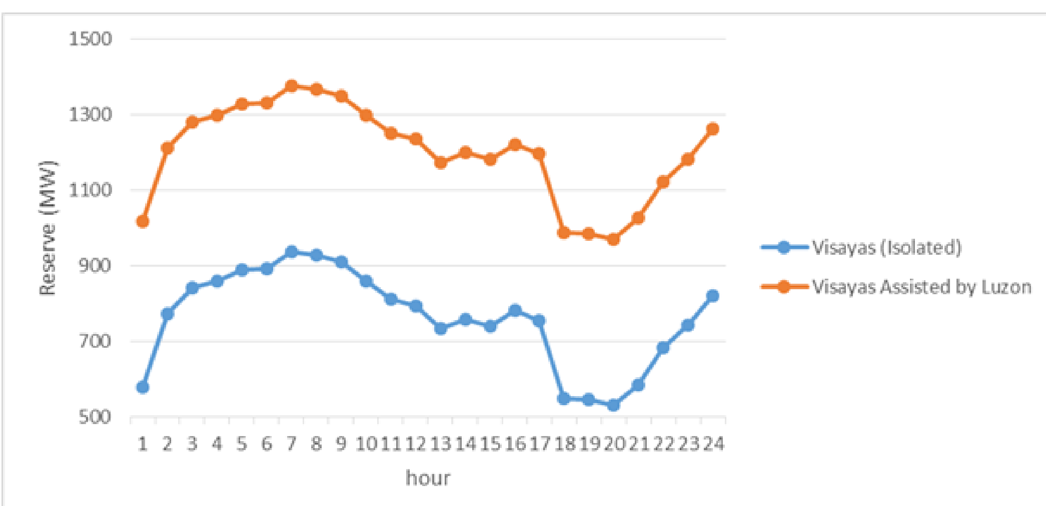

Figure 13a. Comparison of hourly Reserve levels in the Visayas Grid with and without assistance, 2014.

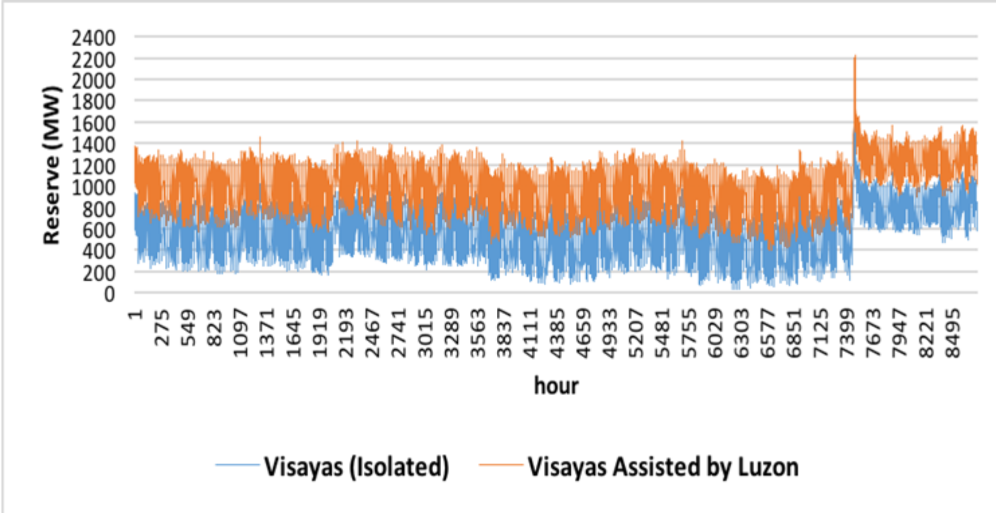

Figure 13b. Comparison of hourly Reserve levels in the Visayas Grid with and without assistance (year 2014).

3.3 Assessment of the Benefits of Interconnection

As shown in Figure 14, the percentage decrease in the LOLE in the Visayas Grid when assisted by the Luzon Grid is higher than the percentage decrease in the LOLE in the Luzon Grid when assisted by the Visayas Grid, in all cases. This means that the Luzon Grid does not benefit from the interconnection as much as the Visayas Grid, which can be attributed to the higher reserve levels in the Luzon Grid.

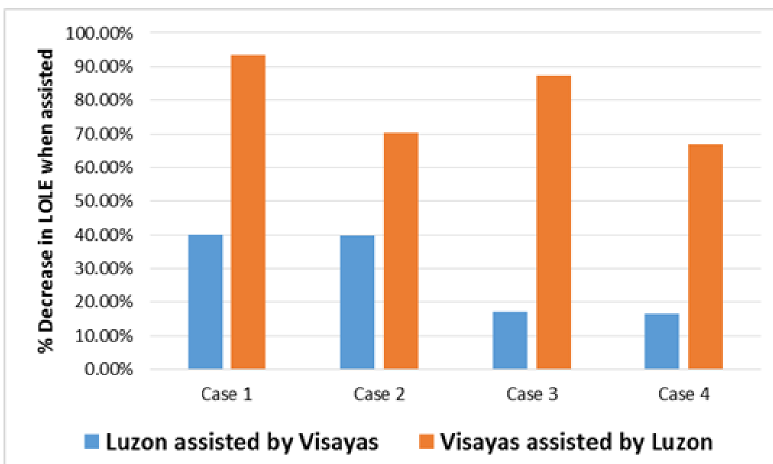

Figure 14. Comparison of the benefits of interconnection to Luzon and Visayas.

IV. CONCLUSIONS

This study developed models and methodology that take into account the intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty in evaluating the reliability of two interconnected power systems. The models and methodology developed were used to evaluate the reliability of the Luzon-Visayas interconnected power system.

This study further concludes the following:

The reliability of a power system improves when it is assisted by other power systems. The annual LOLE in the Luzon Grid is lower when it is operating with assistance from the Visayas Grid than when it is operating as an isolated system. In the same way, the annual LOLE in the Visayas Grid is lower when it is operating with assistance from the Luzon Grid than when it is operating as an isolated system. The decrease in the annual LOLE can be attributed to the higher reserve levels when the systems are operating as an interconnected power system.

The intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty have a significant impact on the reliability risks of two interconnected power systems. The LOLE in the Luzon Grid in 2014, when assisted by the Visayas Grid, increased from 53 hours/year to 95 hours/year when all the factors are present. When the Luzon Grid is the assisting system, the LOLE in the Visayas Grid increased from 12 hours/year to 32 hours/year.

The impact of the intermittency and the seasonal variation in the generation, and the load forecast uncertainty on the LOLE varies depending on the generation mix and the accuracy of load forecast, respectively. Knowing the weight of impact of the factors on the reliability of interconnected power systems is important in determining the policies needed to be developed to achieve higher reliability at low cost.

The intermittency and the seasonal variation in the generation of the assisting system affect the reliability of its assisted system. The generation mix of both the assisting and the assisted systems should, therefore, be carefully considered in reliability planning for interconnected power systems. Similarly, for the load forecast uncertainty considerations, the load forecast accuracy in the assisting system affects the reliability of the assisted system. High load forecast accuracy, which can be achieved by using an effective load forecasting methodology, is desired to avoid overestimation of the reliability risks.

The improvement in the accuracy of the calculated LOLE in two interconnected power systems significantly increases when the intermittency of wind power, the seasonal variation in hydropower, and the load forecast uncertainty are all considered simultaneously. The calculated LOLE significantly improves when these factors are considered as compared to assuming a constant level of generation throughout the year and negligible deviation between the forecast and the actual load values. Therefore, there is a definite and imperative need to consider the factors simultaneously to avoid considerable underestimation of the reliability risks.

The interconnection between two power systems may not equally benefit both systems. In this study, the Luzon Grid does not benefit from the interconnection as much as the Visayas Grid as shown by the lower improvement in the expected loss-of-load of the Luzon Grid when assisted by the Visayas Grid, as compared to that of the Visayas Grid when assisted by the Luzon Grid.

Future research work may consider the tie-line outages, the scheduled quantity and the direction of power flow in the tie-lines, and the trading of ancillary services in the electricity spot market to further improve the accuracy of the calculated LOLE in the two interconnected power systems. The study can also be extended to develop models and methodologies for three or more interconnected power systems.

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