CHAPTER 6

Results and Discussion

6.1 Introduction

Increasing of renewable energy unit in the power system influences the reliability of the system due to the intermittent characteristics of renewable energy resources. So, there are three main issues which are presented. The first issue is the impacts of renewable generation on electricity demand characteristic. These impacts are assessed by using the concept of net load. The investigating time frames are annual basis and seasonal basis. The second issue is the effective capacity for generation reliability evaluation of renewable power plant in order to correlate between conventional capacity and renewable capacity. There are two definitions of the effective capacity to evaluate the contribution of renewable energy unit. The third issue is the reliability evaluation by using proposed reliability modeling.

This chapter is organized as follow: Section 6.2 presents the impacts of renewable generation on electricity demand characteristic. Section 6.3 presents test results and discussion of the effective capacity of renewable power plant. Section 6.4 and Section 6.5 present the test results and discussion of reliability evaluation using conventional approach and modified approach respectively. Finally, the chapter summary is described in Section 6.7.

6.2 Impact of Renewable Generation on Electricity Demand Characteristics

The impacts of renewable generation on electricity demand characteristic are investigated with a time frame from seasonal basis to annual basis. Electricity demand characteristics are expressed in terms of peak demand, energy demand, load factor, and load groups. Numerical model is taken from hourly load data and generation data of

Thailand during 2009 to 2011. The main interest is on the changes of peak and energy demands as well as load factor. In addition, the impacts on load and plant groups as well as cycling operation are also subject to investigation in order to fully assess the impact of renewable generation [Chaiamarit and Nuchprayoon, 2014b].

6.2.1 Annual Impact

The power duration curves of five renewable energy resources are shown in Figure 6.1. On one hand, electricity generation of wind, hydro, and biomass powers is available throughout the year. On the other hand, electricity generation of photovoltaic and biogas powers is available from time to time. The power output of biogas power is constant whenever it is available. When all sources were considered aggregately, it can be estimated that renewable generation is available more than 40% of generation capacity for one-fourth of the time and is available less than 40% of generation capacity for three-fourth of the time. Thus, it may be stated that renewable generation fluctuates from time to time. Numerically, the plant factor of renewable generation is 0.35 which is approximately half of the average plant factor of conventional generation. The plant factor of biomass power is the highest (0.73), while the plant factor of wind power is the lowest (0.08) so that biomass power is relatively steady and wind power highly varies. Comparatively, photovoltaic and biomass highly affect the load duration curve given that their generation capacities are much higher than other resources.

When hourly renewable generation was subtracted from hourly load, it can be seen from Figure 6.2(a) that the coincident net load is less than the gross load by 10%. However, the renewable generation at the peak-load hour is higher than other hours so that the peak hour of the net load has shifted from the original hour. The peak hour has shifted from April 24th at 2 PM to April 24th at 4 PM. The minimum load has also shifted from January 1st at 4 AM to January 1st at 12 noon. As seen from the top 100 maximum-demand hours, it is obvious that conventional power plant is required to vary their generation to cope with fluctuating demand (net load). Variable operation of conventional generation would cause high cycling costs. Figure 6.2(b) shows the gross load duration curve and net load duration curve which are similar to each other. As shown in Table 6.1, it was found that the annual load factor has slightly changed from 0.74 to 0.75. As a result, change in demand characteristics on an annual basis is not substantial.

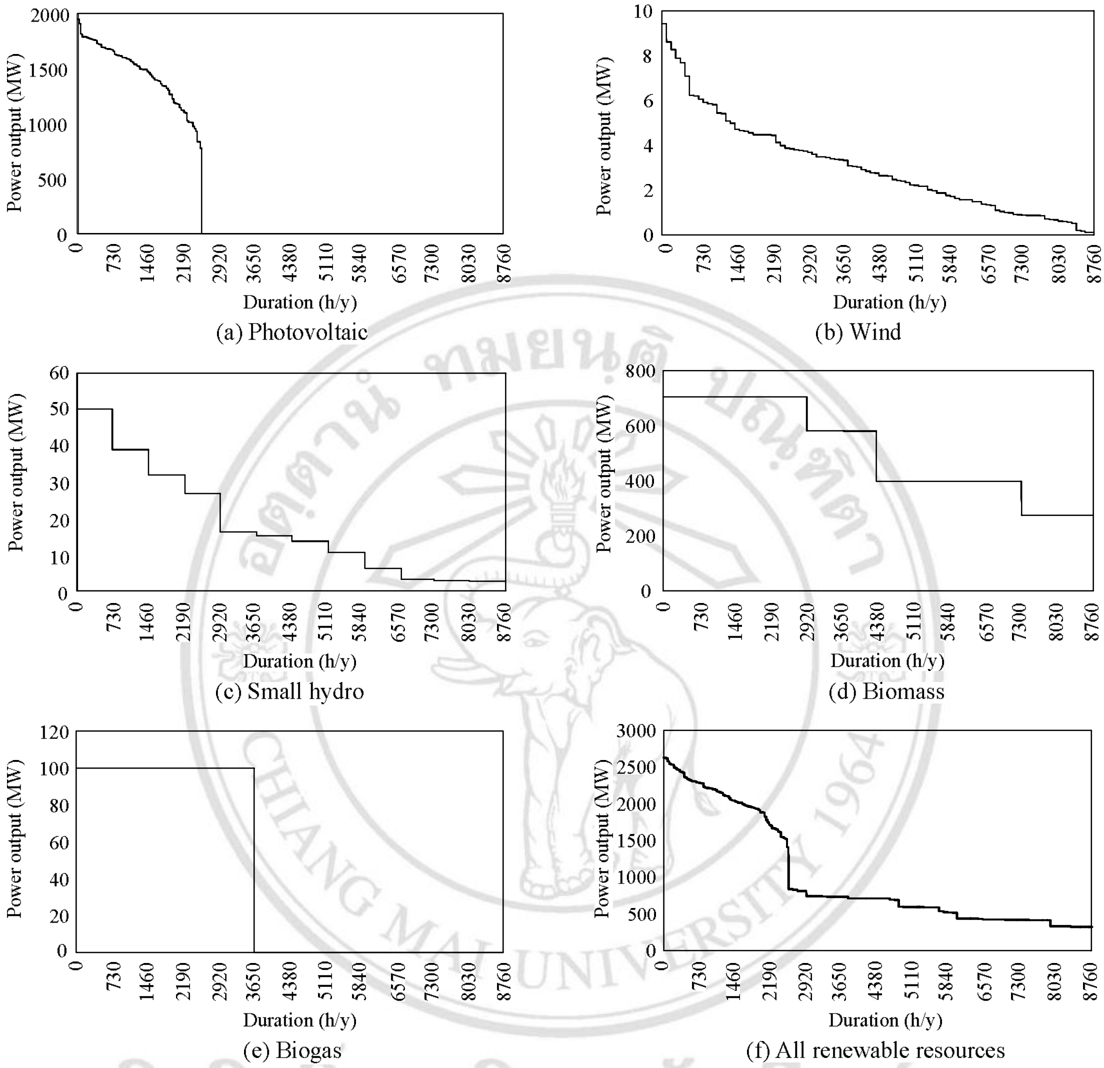


Figure 6.1 Comparison of annual power duration curves of renewable energy resources.

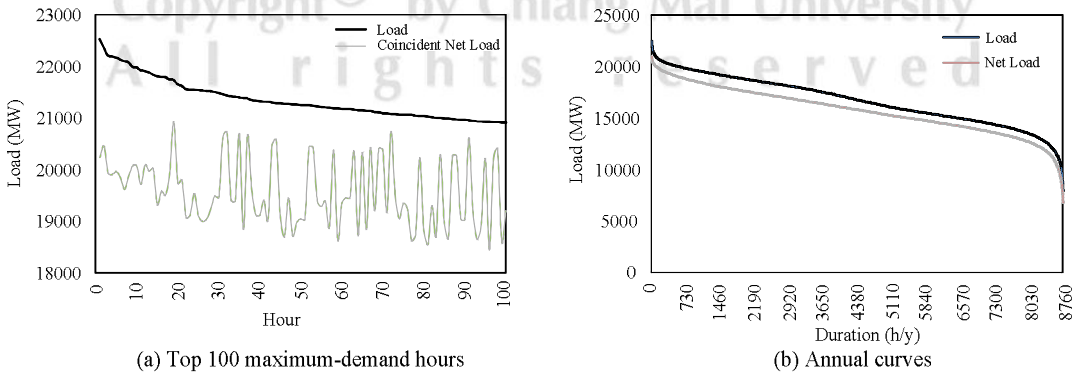


Figure 6.2 Comparison of annual load duration curve and annual net-load duration curve.

Table 6.1 Comparison of load factors.

	w/o renewable	w/ renewable
Nov-Feb	0.76	0.73
Mar-Jun	0.77	0.78
Jul-Oct	0.80	0.78
Annual	0.74	0.75

6.2.3 Seasonal Impact

The power duration curves of all renewable energy resources, except that of biogas, on a seasonal basis are shown in Figure 6.3. Based on a seasonal comparison, wind power is relatively low during March-June. Photovoltaic power is relatively constant over all seasons. Hydro power varies by season and is relatively high in the rainy season (July-October). On the contrary, biomass is relatively low during July-October because this period is a cultivation season. As a consequence, renewable generation is relatively low during July-October because biomass has the highest generation proportion. Numerically, maximum renewable output is approximately 91% and 81% of total renewable energy output during November-June and July-October respectively.

Table 6.2 compares plant (capacity) factors of renewable energy resources which vary by seasons, except those of biogas. The plant factors of all renewable energy resources reduce from 0.37-0.38 in November-June to 0.30 in July-October. Variations of plant factors are quite significant, especially the variation of biomass. The variation of small hydro power is the highest but its generation capacity is low so that its impact is not significant. Given variations of plant factors, it is implied that conventional power or energy storage to accommodate unavailability of photovoltaic and wind power is essential. Thus, additional reserve capacity would be required in July-October. Meanwhile, secondary fuel would be a good option for improving biomass power to compete with conventional power.

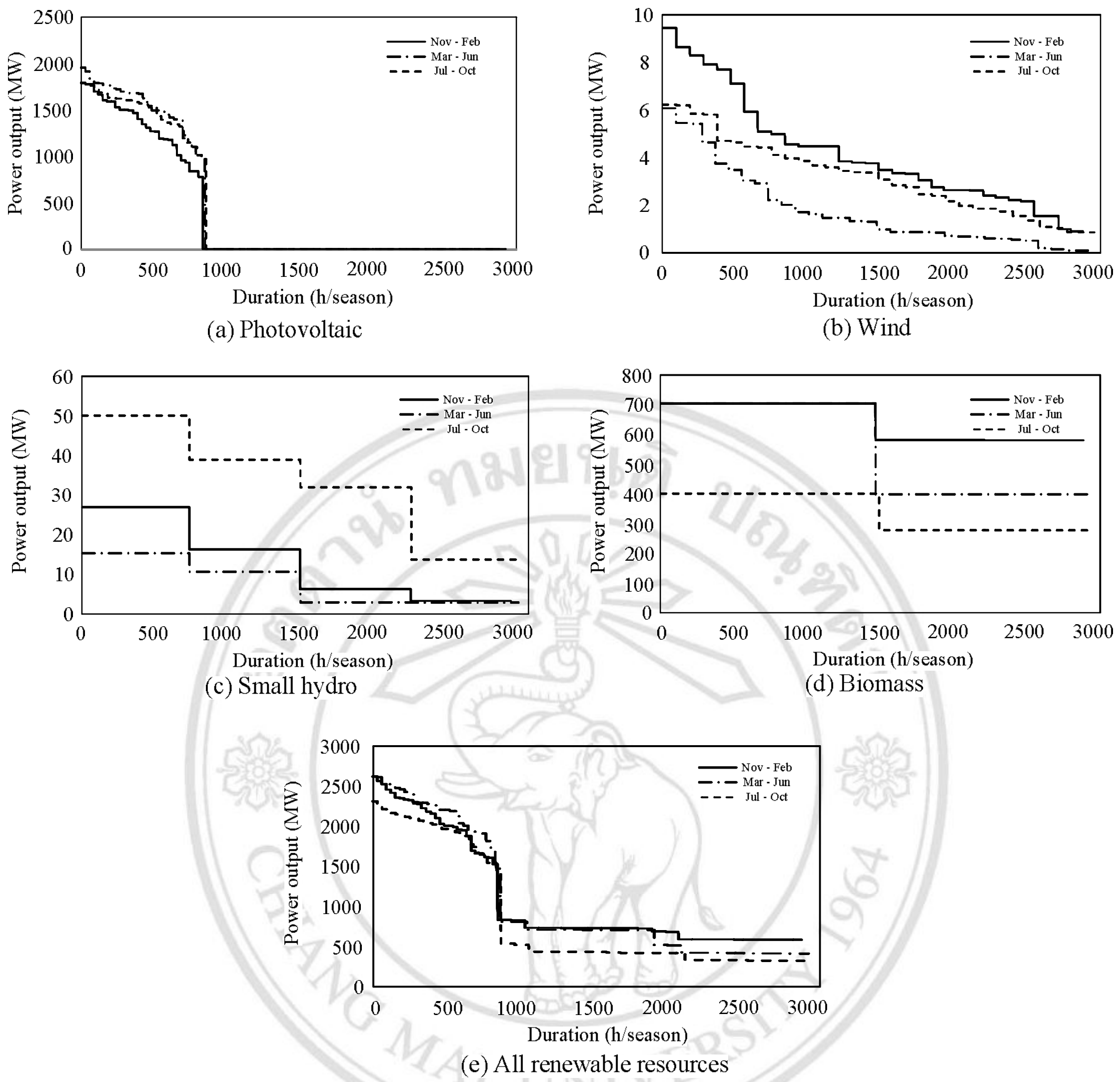
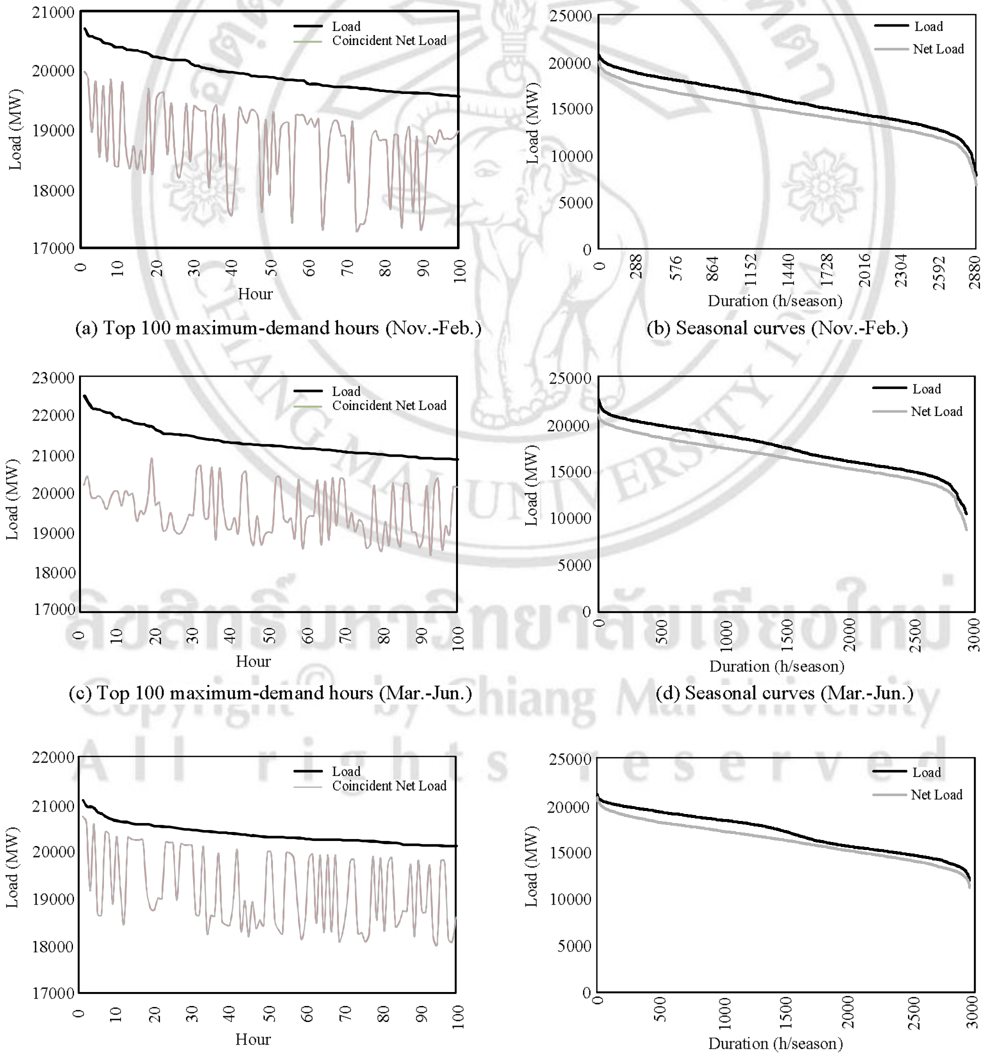


Figure 6.3 Comparison of seasonal power duration curves of renewable energy resources.

Table 6.2 Plant factors of renewable energy resources on a seasonal basis.

Resource	Nov-Feb	Mar-Jun	Jul-Oct
PV	0.13	0.15	0.14
Wind	0.10	0.04	0.08
Small hydro	0.27	0.16	0.67
Biomass	0.92	0.79	0.48
Biogas	0.42	0.42	0.42
All resources	0.38	0.37	0.30

Figure 6.4 shows the gross loads and net loads on a seasonal basis. The net-load duration curves seem to be flatter. By considering only top 100 hours of each season, renewable power could reduce electricity demand between 1000 and 3000 MW during November-June, but could reduce electricity demand between 500 and 2000 MW during July-October. Renewable power reduces peak demand in the range of 3-7% in November-June and in the range of 1-2% in July-October. Similarly, renewable power reduces minimum demand by 14-16% during November-June and by 6-7% during July-October. As a result, the gross and net load duration curves during July-October are so closed, implying that renewable generation has little impact on demand characteristics during July-October.



(a) Top 100 maximum-demand hours (Nov.-Feb.)
(b) Seasonal curves (Nov.-Feb.)
(c) Top 100 maximum-demand hours (Mar.-Jun.)
(d) Seasonal curves (Mar.-Jun.)
(e) Top 100 maximum-demand hours (Jul.-Oct.)
(f) Seasonal curves (Jul.-Oct.)

Figure 6.4 Comparison of seasonal load duration curve and seasonal net-load duration curve.

But it has significant impact on demand characteristics during November-June. In all seasons, renewable generation contributes to base load or low-demand hours more than peak load or high-demand hours. Thus, reduction of generation of base-load power plants could cause excess generation and higher cycling costs, which negatively affect the operating costs. On the other hand, reduction of generation of peak-load power plants positively affects the operating costs.

6.2.3 Impact on Load and Plant Groups

The load was divided into three groups, i.e. peak, intermediate, and base. By applying the K-mean clustering technique [Salimi-beni *et al*., 2006] to the hourly generation data of Thailand, the base, intermediate, and peak ranges are set as 0-35, 35-80, and 80-100% of the peak demand, respectively. When renewable generation is integrated, it can be seen from Table 6.3 that the penetration level of renewable energy resources is less than 7% in the intermediate-load and base-load groups and less than 4% in the peak-load group. This can be explained by the photovoltaic and biomass have small generation in the peak-load period. So, renewable generation has more impact on the base-load and intermediate-load groups than the peak-load group.

The impact of renewable generation on annual energy generation and duration of each load group is shown in Table 6.4. Both energy generation and duration of the intermediate-load group are constant. While energy generation and duration of the peak-load group are significantly decreasing; consequently, energy generation and duration of the base-load group are increasing.

The annual load duration is flatter, resulting in higher (better) load factor. It can then be concluded that renewable generation improves demand characteristics by decreasing the peak-load group and increasing the base-load group. As such, the average operating costs would be lower because the peaking plants have lower generation and the base plants have higher generation.

When considering the impact of renewable generation on a seasonal basis, it is shown in Table 6.5 that the seasonal impact during November-June is consistent with the annual impact, while the seasonal impact during July-October is different from the annual impact. Note that the seasonal impact is dominated by the generation variations of photovoltaic and biomass given that the generations of other renewable energy resources were slightly varied with season. Actually, hydro generation was also varied with season but the generation capacity is too small to cause changes. Renewable generation has less impact on the peak-load and base-load groups during July-October, compared with the period of November-February. In other words, the shape of load duration curve during July-October would be slightly changed after integrating renewable generation.

Table 6.3 Annual generations sorted by fuel type (unit: %).

Load group	Fossil	PV	Wind	Small hydro	Biomass	Biogas
Peak	96.71	0.64	0.01	0.09	2.39	0.15
Intermediate	93.88	3.00	0.02	0.11	2.69	0.31
Base	93.77	2.20	0.02	0.12	3.70	0.18

Table 6.4 Annual energy and duration of each load group (unit: % per annum).

Load group	Energy		Duration	
	w/o renewable	w/ renewable	w/o renewable	w/ renewable
Peak	20.69	6.39	17.34	5.11
Intermediate	53.64	55.81	51.84	51.32
Base	25.67	37.80	30.82	43.57

Table 6.5 Seasonal generations sorted by fuel type (unit: %).

Season	Load group	Fossil	PV	Wind	Small hydro	Biomass	Biogas
Nov-Feb	Peak	96.72	0.01	0.02	0.05	3.17	0.03
	Intermediate	93.55	2.43	0.02	0.08	3.59	0.33
	Base	92.57	2.58	0.03	0.09	4.50	0.22
Mar-Jun	Peak	96.04	0.99	0.01	0.04	2.75	0.18
	Intermediate	93.64	3.06	0.01	0.04	2.96	0.28
	Base	93.84	2.12	0.01	0.05	3.80	0.17
Jul-Oct	Peak	98.20	0.01	0.02	0.21	1.49	0.08
	Intermediate	94.49	3.15	0.02	0.19	1.85	0.31
	Base	95.58	1.68	0.02	0.22	2.35	0.14

Renewable generation could reduce fossil-fuel generation by 2-4% in the peak-load group, 5-7% in the intermediate-load and base-load groups. Thus, renewable generation contributes to fossil-fuel reduction in the peak-load group less than the intermediate-load and base-load groups. However, the impact on fuel cost is inconclusive unless the fuel mix of each load group is quantified.

Similar to Table 6.4, the impact of renewable generation on seasonal energy generation and duration of each load group is shown in Table 6.6. The seasonal impact is also similar to the annual impact. In the period of November-February, renewable generation reduced energy generation and duration in the peak-load and intermediate-load periods by 2-3%. On the contrary, energy generation and duration in the base-load period was increased by approximately 5%. In the period of March-June, renewable generation reduced energy generation and duration in the peak-load period by approximately 6%, while energy generations and durations in the intermediate-load and base-load periods were increased by approximately 3% and 4%, respectively. In the period of July-October, renewable generation reduced energy generation and duration in the peak-load period by 4-5%, while energy generations and durations in the intermediate-load and base-load periods were increased by approximately 2% and 3%, respectively.

Table 6.6 Seasonal energy and duration of each load group (unit: % per annum).

Season	Load group	Energy		Duration	
		w/o renewable	w/ renewable	w/o renewable	w/ renewable
Nov-Feb	Peak	2.72	0.44	2.32	0.35
	Intermediate	16.76	13.52	16.27	12.60
	Base	11.56	16.77	14.29	19.92
Mar-Jun	Peak	10.96	3.91	9.10	3.12
	Intermediate	17.83	20.80	17.29	19.01
	Base	5.94	9.98	7.03	11.30
Jul-Oct	Peak	7.01	2.04	5.92	1.63
	Intermediate	19.04	21.50	18.28	19.71
	Base	8.18	11.04	9.50	12.35

In all seasons, renewable energy reduces energy generation and duration in the peak-load period and increases energy generation and duration in the base-load period. This seasonal impact is consistent with the annual impact mentioned earlier. But, the seasonal impact on the intermediate-load period varies with season. Energy generation and duration are decreased in November-February, but increased in March-October. Hence, it is observed that the impacts of renewable generation in March-June and July-October are consistent with the annual impact, while the impact in November-February is different from the annual impact. This difference may be caused by temperature. Given that the period of November-February has lower average temperature than other months, the intermediate-load group is larger by means of energy and duration so that renewable generation contributes to lower energy and duration. But, when the average temperature is higher, the intermediate-load group would be smaller and the peak-load group would be larger. In summary, renewable generation has positive impact on the distribution of load groups because the peak-load is decreased and the base-load group is increased so that time-varying characteristic of electricity demand is smaller. In addition, lower operating costs can be expected because peaking plants would have less operation while base plants would have more operation.

Power plants may also be classified into peak, intermediate, and base groups. Peak plants have relatively low capital costs and high operating costs, while base plants have relatively high capital costs but and low operating costs. As a result, peak plants have low plant factor and would operate only during peak periods. On the other hand, base plants have high plant factor because they are supposed to operate most of the time at almost full capacity. Peak plants can take a rapid start up or shut down so that cycling operation can be made frequent. Thus, they are promptly responsive to load variation. Intermediate and base plants need longer time to start up and shut down. They are less responsive to changes of load. Base plants are designed to operate continuously and may start up/shut down only a few times a year. Intermediate plants are more flexible for cycling operation than base plants but the number of start-up and shut-down is still limited.

In response to changes of load groups, plant groups are also affected by renewable generation. Given that renewable generation covers peak load slightly but covers intermediate and base loads significantly, it can be said that renewable generation could reduce fuel costs of all plant groups. Nonetheless, the impact on operating is not conclusive, depending on plant groups. The operating costs of peak plants would definitely be lower because they are capable of working cyclically. Reduction of fuel costs would directly force operating costs to be lower. In case of intermediate and peak plants, although renewable generation helps reducing fuel costs but cycling costs may increase. Variable generation of renewable energy resources causes intermediate and base plants to operate cyclically so that those plants are subject to ageing problem and may require more maintenance. Otherwise, they may be forced to be in spinning mode. Hence, the operating costs of intermediate and base plants would be either lower or higher, depending on plant types. If they are gas-fired power plants, which are more flexible for cycling operation, the operating costs could be lower. But, if they are coal-fired power plants, cycling operation is strictly limited so that the operating costs could be higher. By the way, the impact on revenue is interesting and subject to further investigation. For instance, if gas-fired power plants are more flexible for cycling operation than coal-fired power plants, then gas-fired power plants would have been forced to respond to variable generation. As a result, their revenue would decrease in such scenario.

6.3 Effective Capacity of Renewable Power Plant

The equivalency between renewable and conventional capacities and their contribution on generation reliability are investigated by using the concept of effective capacity, which has two definitions as mentioned in Section 4.3. The effective capacity can be computed from generation capacities of renewable and conventional power plants as well as the ELCC [Chaiamarit and Nuchprayoon, 2014a]. FOR, generation capacity, and number of renewable units are varied to reflect operation behavior of renewable power plant. The LOLP is considered as generation reliability index.

6.3.1 Test Model

The load duration curve is assumed to be linearly downward sloping from 500 to 250 MW. The peak demand is initially at 500 MW and increases by 50-MW increment to 800 MW. The growth of load is assumed in such a way that the load factor is constant as shown in Figure 6.5.

The generation system consists of three conventional units and one renewable unit. Each conventional unit has generation capacity of 250 MW with 6% FOR. The renewable unit has maximum capacity of 250 MW and its capacity can be varied from 25, 50, 75, and 95% of maximum capacity. The FOR of the renewable unit can be varied from 5, 25, 50, and 75%.

Figure 6.6 compares the LOLP of the model under various renewable capacities and peak-demand conditions. The LOLP is proportional to renewable capacity and peak demand. The LOLP is suddenly increasing when either no renewable unit or peak demand reaches 750 MW, which is the total capacity of three conventional units.

Figure 6.7 compares the LOLP of the model under various FORs of the renewable unit and peak-demand conditions. The LOLP is increasing with the rise of FOR of the renewable unit.

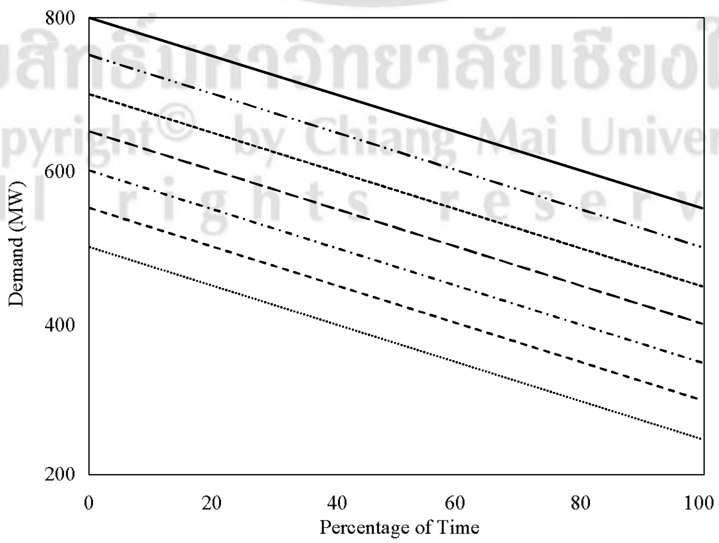


Figure 6.5 Normalized load duration curves.

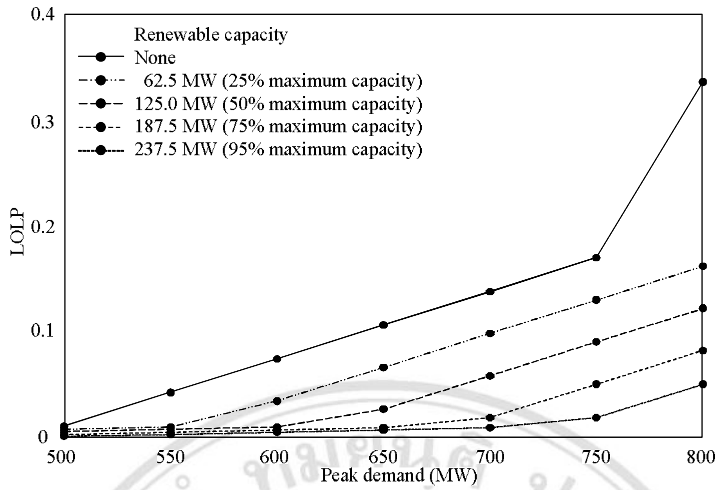


Figure 6.6 Comparison of loss of load probabilities under various generation capacities and peak-demand conditions.

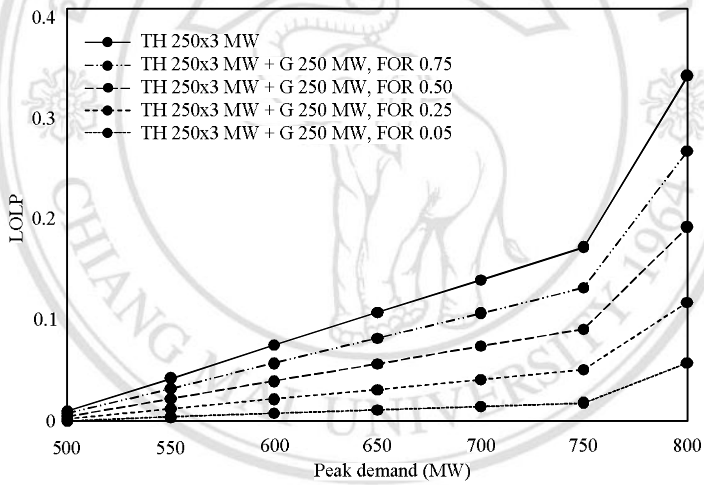


Figure 6.7 Comparison of loss of load probabilities under various forced outage rates of the renewable unit and peak-demand conditions.

If the maximum capacity of the renewable unit increases, the generation reliability would be better off, by means of lower LOLP. Figure 6.8 compares the LOLP of the model when the maximum capacity of renewable unit is varied from 250 to 850 MW. The peak demand is 800 MW. It is found that the LOLP slightly decreases when the maximum capacity increases because the LOLP is highly dependent of the FOR of the renewable unit.

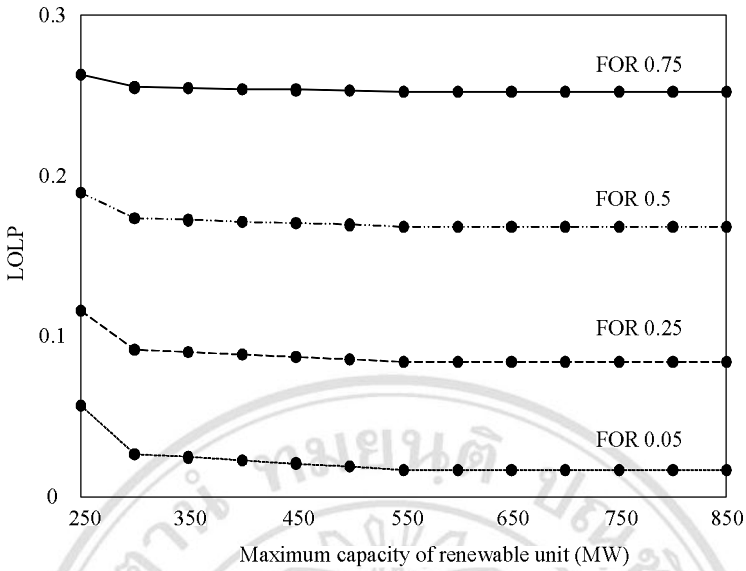


Figure 6.8 Comparison of loss of load probabilities under various maximum capacities and forced outage rates of the renewable unit.

Figure 6.9 compares the LOLP of the model when the renewable unit is broken into multiple units, i.e. 250x1, 125x2, 50x5, and 25x10 MW. The peak demand is 800 MW. It is obvious that generation reliability improves when the model is supplied by multiple units. However, the FOR still has significant effect on the LOLP.

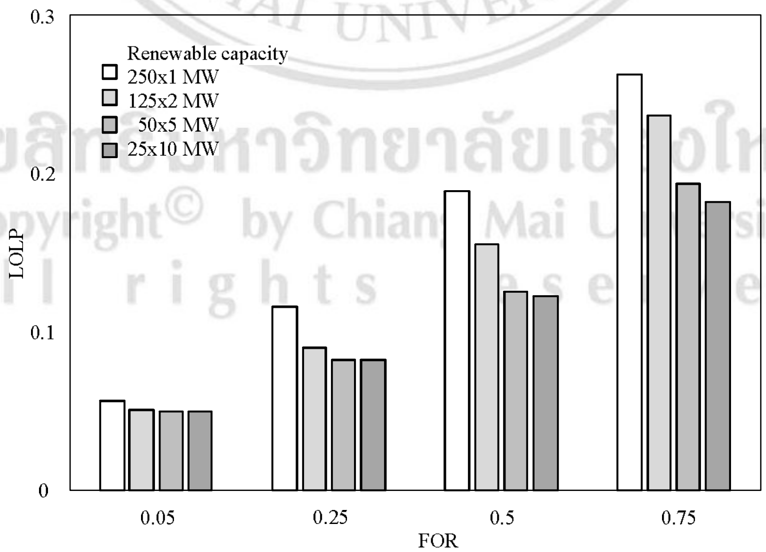


Figure 6.9 Comparison of loss of load probabilities under various capacity sizes and forced outage rates of the renewable unit.

To compute the effective capacity of the test model, the normalized load duration curve in Figure 6.5 is used with 800-MW peak demand. The generation system comprises three conventional units. The generation capacity and FOR of each unit are 250 MW and 6%, respectively. A conventional unit with generation capacity of 50 MW and 5% FOR is then added as a benchmark unit. The reliability criterion is set by limiting the LOLP to be less than 0.2.

It is divided into three cases for simulation as follow:

- The first case assumes that the renewable unit replaces the benchmark unit with 25-MW increment. The FOR of the renewable unit is assumed to be 5, 25, 50, and 75%.

- The second case is identical to the first case, except that the capacity increment of the renewable unit is 50 MW.

- The third case assumes that the renewable unit has zero FOR. Instead of using the generation capacity, the average power is taken to compute the LOLP. It is assumed that the average power of the renewable unit is 25, 50, 75, and 95% of its installed capacity (50MW).

In all cases, renewable capacity is added into the generation system until satisfying the LOLP limit.

6.3.2 Effective Capacity Results

Table 6.7 shows LOLP and ELCC after adding renewable unit with 25-MW increment under different FORs. When the FOR of the renewable unit increases, higher renewable capacity is required to satisfy the LOLP limit. For instance, when the FOR of the renewable unit is 75%, it requires 225-MW (25x9 MW) renewable capacity, while 50-MW conventional capacity with 5% FOR could also satisfy the LOLP limit. Meanwhile, the ELCC is inversely varies with the LOLP. The higher LOLP, the lower ELCC. As a result, the higher value of LOLP and the lower value of ELCC indicate that the generation system is less reliable. Because the ELCC is less than conventional capacity of the benchmark unit (50 MW), it is implied that the EC using the first definition would be less than that of the second definition.

Figure 6.10 illustrates the ECs using the two definitions under different FORs, as a result of Table 6.7. It can be seen that the EC decreases as the FOR increases. The two definitions yield different values of EC. For instance, when the FOR of the renewable unit is 75%, the EC is approximately 20%. Simply speaking, 5-MW renewable capacity is equivalent to 1-MW conventional capacity, considered at the same level of generation reliability. Renewable power plant with lower FOR contributes to more reliable generation system.

Table 6.8 shows LOLP and ELCC after adding renewable unit with 50-MW increment under different FORs. The result is similar to the first case (Table 6.7). To satisfy the LOLP limit, it requires higher renewable capacity than conventional capacity. For example, at 75% FOR, the first case requires 225-MW renewable capacity but the second case requires 250-MW renewable capacity. The LOLP is then much lower than its limit because of using larger increment. Consequently, the ELCC is higher and closed to conventional capacity of the benchmark unit, compared to the first case.

In the second case, the ECs using the two definitions are so closed as shown in Figure 6.11.

Table 6.7 LOLP and ELCC after adding renewable unit with 25-MW increment.

	FOR			
	0.05	0.25	0.50	0.75
RK (MW)	25x2	25x3	25x4	25x9
LOLP	0.178	0.177	0.195	0.191
ELCC (MW)	47.42	47.65	42.34	43.53

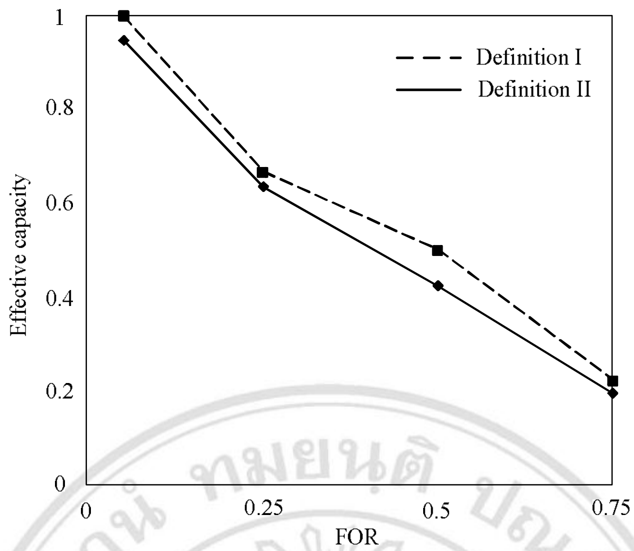


Figure 6.10 Effective capacity of renewable unit with 25-MW increment.

Table 6.8 LOLP and ELCC after adding renewable unit with 50-MW increment.

	FOR			
	0.05	0.25	0.50	0.75
RK (MW)	50x1	50x2	50x3	50x5
LOLP	0.178	0.162	0.170	0.193
ELCC (MW)	47.42	52.18	49.66	42.72

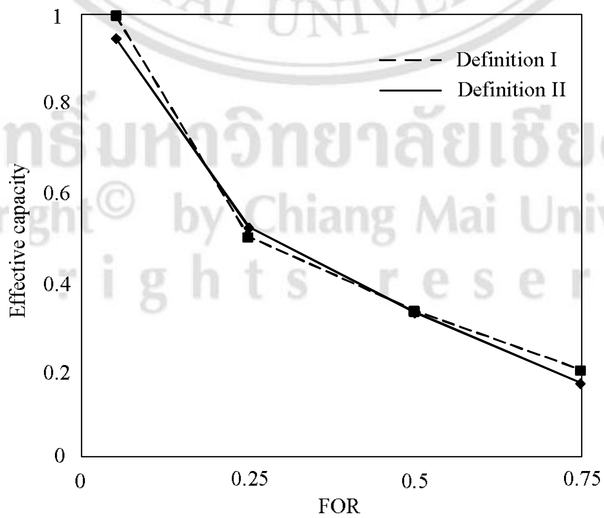


Figure 6.11 Effective capacity of renewable unit with 50-MW increment.

From Figure 6.11, given that the ELCC is closed to conventional capacity of the benchmark unit. It is found that the EC in the first case (Figure 6.10) is not less than the EC in the second case (Figure 6.11). Thus, the addition of small renewable capacity yields higher EC than the addition of large renewable capacity.

In the third case, the ECs using the two definitions are almost identical as shown in Table 6.9. The EC increases with the average power. It can be said that the EC is equivalent to its average power when the renewable unit has zero FOR. So, the higher the average power of renewable unit, the higher contribution to generation reliability.

For example, when the average power is 25% of installed capacity, 4-MW renewable capacity is equivalent to 1-MW conventional capacity considered at the same level of generation reliability. But, when the average power is 50%, 2-MW renewable capacity is equivalent to 1-MW conventional capacity. Thus, renewable power plant with higher average power contributes to more reliable generation system.

Table 6.9 Effective capacity of renewable unit with zero FOR.

	Average power (% installed capacity)			
	25	50	75	95
RK (MW)	200.0	100.0	66.7	52.6
EC (Definition I)	0.250	0.500	0.750	0.950
EC (Definition II)	0.250	0.499	0.749	0.949

6.4 Reliability Evaluation Using Conventional Approach

This research considers the LOLP as the reliability index and the ELCC as the reliability contribution.

To investigate the impact of renewable energy generation on reliability; it is needed to set up two generation systems, one with only conventional capacity and another with both conventional and renewable capacities. The simulation steps are as follows:

- Compare the LOLPs of both generation systems, given that system capacity and load profile are identical.
- Observe change of the LOLPs after varying the penetration levels of renewable capacity.
- Observe change of the LOLPs after varying the penetration levels of renewable capacity and removing conventional capacity in such a way that the system capacity remains constant.

When renewable capacity exists, it is required to determine the ELCC of each renewable energy resource to evaluate reliability contribution. The ELCC is dependent of reserve capacity so that various loading conditions should be assumed.

6.4.1 Test Model

A small-scale generation system comprises two conventional units and five renewable units. They are 750-MW thermal (coal-fired) unit, 250-MW gas-turbine unit, 5-MW wind-turbine unit, 10-MW PV unit, 15-MW hydro unit, 210-MW biomass unit, and 10-MW biogas unit. As a result, the sum of renewable capacities is 250 MW, which is equals to generation capacity of the gas turbine. Note that the generation capacity of each unit was scaled down from the generation capacity portfolio of Thailand. Generation characteristics are taken from the actual data available from the Electricity Generating Authority of Thailand and the Energy Policy and Planning Office, Ministry of Energy.

The load duration curve is assumed to be linearly downward as shown in Figure 6.12. The peak demand is 800 MW. The growth of load is assumed in such a way that the load factor is constant.

Numerical simulations were divided into 2 cases with the system capacity of 1000 MW. The reserve margin of both cases is 20%.

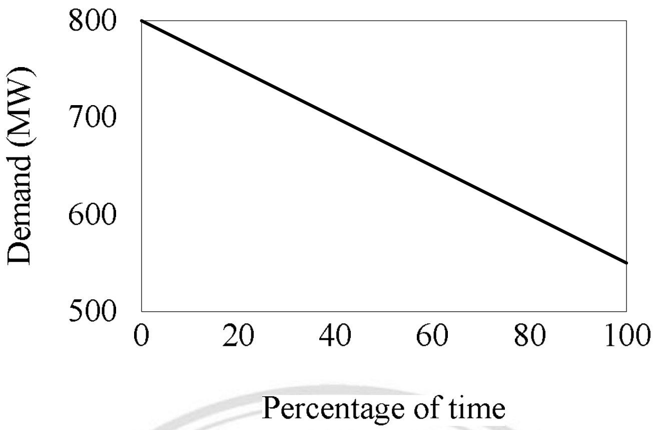


Figure 6.12 Load duration curve of the test system.

- Case I assumes that the generation system has only two conventional units which are 750-MW thermal (coal-fired) unit and 250-MW gas-turbine unit.
- Case II assumes that the gas-turbine unit is replaced by five renewable units. Those are 5-MW wind-turbine unit, 10-MW PV unit, 15-MW hydro unit, 210-MW biomass unit, and 10-MW biogas unit. As a result, renewable capacity in Case II is 25% of the system capacity.

6.4.2 Reliability Evaluation Results

Based on the daily generation data and generation characteristics of both conventional and renewable units in Thailand, the FOR and EFOR are shown in Table 6.10. The FORs of thermal, gas-turbine, and small hydro plants were simply taken from typical data. The EFORs of wind-turbine and PV units are high due to their intermittent nature, while the EFOR of biogas unit is relatively high due to gas availability. On the contrary, the EFOR of biomass unit is quite low under the assumption that fuel supply is abundant [Chaiamarit and Nuchprayoon, 2013].

The LOLPs of both cases are compared in Figure 6.13. It can be seen that the LOLPs of Case II are always higher than those of Case I, meaning that Case II is less reliable than Case I. As a result, the presence of renewable energy resources has negative impact on generation reliability. This conclusion is intuitive because the EFORs of the renewable units are much higher than the FORs of the conventional units.

Table 6.10 FOR and EFOR of generating units based on daily generation data in Thailand.

Plant	Capacity (kW)	Max. power (kW)	Operation (h/d)	Energy (kWh/d)	CF	FOR/EFOR
Thermal						0.060
Gas turbine						0.050
Wind	600	228	21	1,843.32	0.128	0.872
PV	34	27	14	183.60	0.225	0.775
Small hydro						0.020
Biomass	600	470	24	11,280.00	0.783	0.217
Biogas	37	23	14	318.73	0.359	0.641

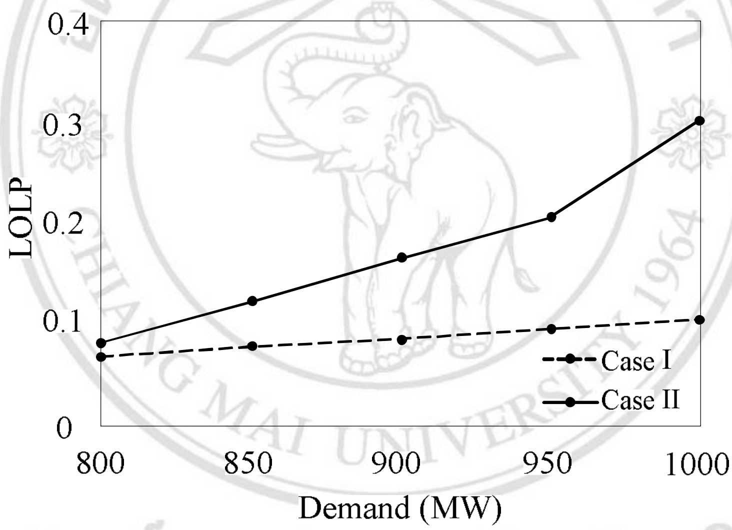


Figure 6.13 Comparison of LOLPs under various loading conditions.

When the load is growing, the LOLP of Case I is slightly higher, while the LOLP of Case II is spiking. This implies that renewable energy resources would have a severe impact when the generation reserve is low, and vice versa.

To illustrate the impact of penetration levels of renewable energy resources, Case II was modified by keeping the 750-MW thermal unit but increasing the renewable capacity from 250 MW to be 300, 400, and 500 MW. The system capacity was varied from 1000 MW to be 1050, 1150, and 1250 MW so that the renewable capacity accounts for 25-40% of the system capacity accordingly. Note that the generation capacity of each renewable unit was adjusted proportionally. If the generation reserve were neglected, the generation system could serve the peak demand up to 1250 MW. The impact of penetration levels of renewable energy resources in case of increasing the capacity of renewable energy units at 800-MW peak demand is shown in Table 6.11.

It is shown in Figure 6.14 that the LOLP varies directly with the peak demand but the relationship is nonlinear. It is noticeable that when the peak demand is more than 1000 MW and the renewable capacity is either 400 or 500 MW, the LOLP was constant over a certain range of load because the step size of load is less than the capacity outage state. When the peak demand reaches the system capacity, the LOLP is increasing rapidly. By adding more capacity into the generation system, the generation reliability would be better (lower LOLP), regardless of adding conventional or renewable capacity.

Then, it is assumed that the increasing capacity of renewable energy resource should be matched by removing the conventional capacity so that the system capacity remains unchanged. In so doing, the renewable capacity was increased from 250 to 500 MW and the conventional capacity was decreased from 750 to 500 MW so that the system capacity is constant at 1000 MW.

Table 6.11 Impact of penetration levels of renewable energy resources at 800-MW peak demand.

Conventional capacity (MW)	Renewable capacity (MW)	System capacity (MW)	Renewable capacity (%)	LOLP	EENS (MWh/d)
750	250	1000	25.000	0.084	713.328
750	300	1050	28.571	0.080	657.864
750	400	1150	34.783	0.074	548.040
750	500	1250	40.000	0.068	439.464

Note: For Case I, the LOLP is 0.069 and EENS is 635.64 MWh/d

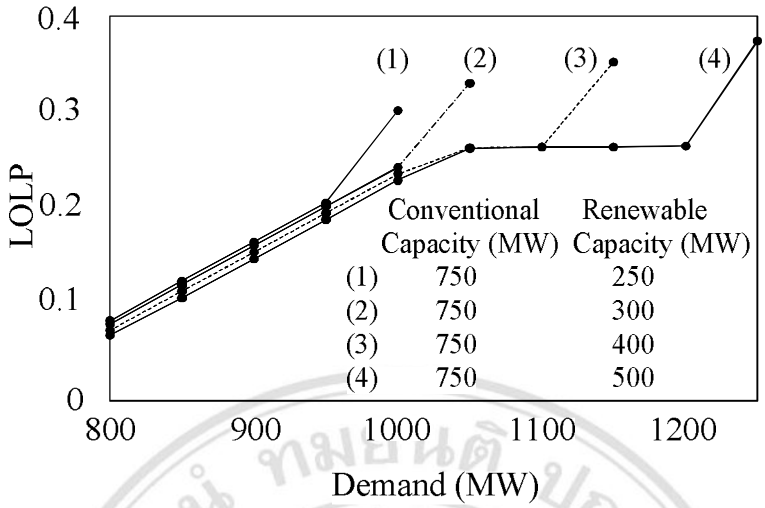


Figure 6.14 Comparison of LOLPs under various penetration levels of renewable energy resources.

As a result, the renewable capacity was increased from 25% to 50% of the system capacity. Again, the generation capacity of each renewable plant was adjusted proportionally. The impact of penetration levels of renewable energy resources with reduction of conventional resource (Increasing the capacity of renewable energy units without changing system capacity) at 800-MW peak demand is shown in Table 6.12. Figure 6.15 shows the comparison of LOLPs under various penetration levels of renewable energy resources with reduction of conventional resource at different peak demand.

Table 6.12 Impact of penetration levels of renewable energy resources with reduction of conventional resource at 800-MW peak demand.

Conventional capacity (MW)	Renewable capacity (MW)	System capacity (MW)	Renewable capacity (%)	LOLP	EENS (MWh/d)
750	250	1000	25	0.084	713.328
700	300	1000	30	0.121	706.392
600	400	1000	40	0.196	815.712
500	500	1000	50	0.262	1087.200

Note: Peak demand is 800 MW. For Case I, the LOLP is 0.069 and EENS is 635.64 MWh/d

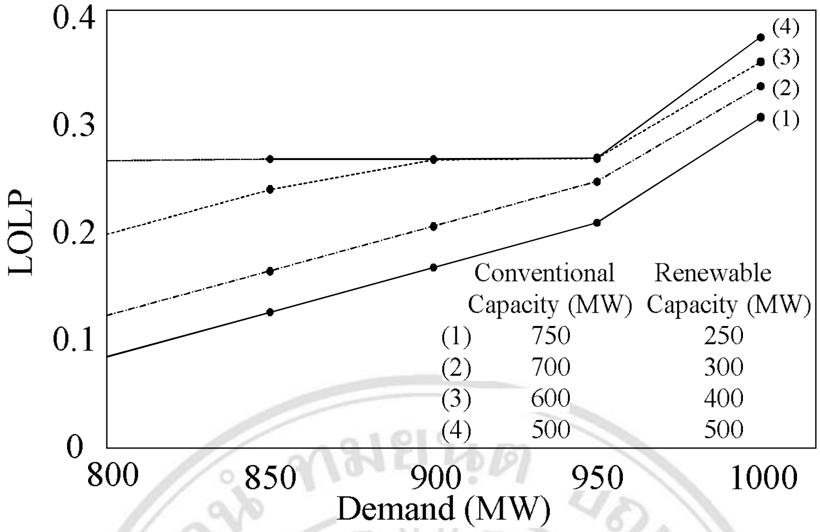


Figure 6.15 Comparison of LOLPs under various penetration levels of renewable energy resources with reduction of conventional resource.

When the renewable capacity has higher penetration into the generation system and keeping the system capacity constant, it is shown in Figure 6.15 that the generation reliability drops dramatically. The difference in LOLPs at various penetration levels is so obvious when the generation reserve is high (e.g. at 800-MW peak demand). Thus, it must be careful when the renewable capacity has higher proportion in generation capacity.

The relationship between the generation reliability (in terms of LOLP) and the penetration level is signified in Figure 6.16. Given the desirable level of reliability, the maximum penetration of renewable energy resources may be determined accordingly. For instance, if the LOLP is bounded at 0.2, the maximum capacity of renewable energy resources would be up to 40% of the system capacity.

Next, the ELCC of each generating unit is evaluated and the result is shown in Table 6.13. The thermal unit is considered as a standing unit (always exist) of the generation system so that its ELCC was not computed. But, if the ELCC of the thermal unit were needed, the value would be 100% meaning that every unit of capacity contributes to generation reliability.

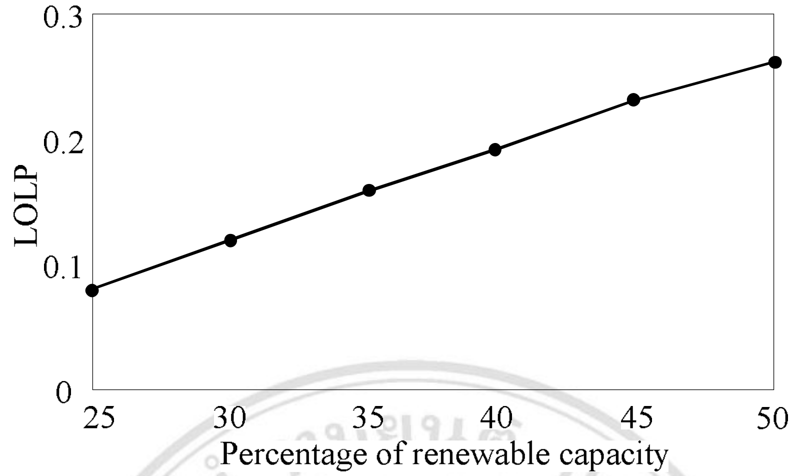


Figure 6.16 Impact of penetration level of renewable energy resources on LOLP.

Refer to Case I, there are only thermal and gas-turbine units. It was found that the ELCC of the gas-turbine unit is almost equal to its capacity. Thus, it may be able to state that almost every unit of capacity is essential for maintaining generation reliability. When the peak demand is 1000 MW which is equal to the system capacity, it is clear that the ELCC of the gas-turbine unit is 100% (i.e., every unit of capacity must be accounted for).

Refer to Case II, the gas-turbine unit was replaced by a group of five renewable units with the total capacity of 250 MW. The ELCCs of renewable units may be separated into two groups based on capacity. For large unit (biomass), the ELCC is proportional to the peak demand. As the load increases, renewable capacity of large unit becomes more essential for generation reliability. In contrast, the ELCCs of small units (PV, wind, small hydro, and biogas) are relatively constant and independent of loading condition. Empirically, it was found that the ELCC of small unit can be approximated as 1 – EFOR.

If all five renewable units were considered as an aggregated unit, the ELCC is similar to that of biomass unit, i.e. renewable capacity has more contribution to generation reliability as the load increases. But, the ELCC of the gas-turbine unit is more than the ELCC of 250-MW aggregated renewable unit, compared at the same loading condition.

Table 6.13 ELCC of generating units given three loading conditions (unit: percent of capacity).

Plant	Capacity (MW)	Peak demand (MW)		
		800	900	1,000
Gas turbine	250	95.67	97.89	100.00
Wind	5	12.88	12.82	12.80
PV	10	22.49	22.47	22.55
Small hydro	15	98.01	97.99	98.25
Biomass	210	49.52	84.01	97.20
Biogas	10	35.85	35.95	35.95
Renewable*	250	73.83	81.39	100.00

* *All renewable units are considered all together*

This is due to the fact that the aggregated renewable unit consists of five units so that the renewable capacity is less essential than that of the gas-turbine unit. Hence, it is concluded that the contribution on generation reliability of large renewable unit depends on loading condition, while that of small renewable unit is relatively constant.

6.5 Reliability Evaluation Using Modified Approach

6.5.1 Test Model

The test model is divided into three cases which are shown as follow:

- Case I: assumes that the generation system has four conventional units which are three units of 250-MW thermal (coal-fired) unit with FOR 0.06 and a unit of 250-MW gas-turbine unit with FOR 0.05.

- Case II: assumes that the 250-MW gas-turbine unit is replaced by a 250-MW renewable energy unit with FOR 0.05. The intermittent characteristics of the renewable energy unit are represented in the form of six different generation profiles. The six different generation profiles of the renewable energy unit are divided into two groups: 1) three generation profiles by varying the capacity factors as 0.75, 0.5

and 0.25 and changing the maximum power output as shown in Figure 6.17 and 2) three generation profiles by varying the capacity factors as 0.75, 0.5 and 0.25 and changing the operation duration as shown in Figure 6.18.

- Case III: assumes that the 250-MW gas-turbine unit is replaced by a 250-MW photovoltaic (PV), 250-MW wind, 250-MW biomass, or 250-MW biogas unit respectively. The simplified generation profile of each renewable energy resource is shown in Figure 6.19.

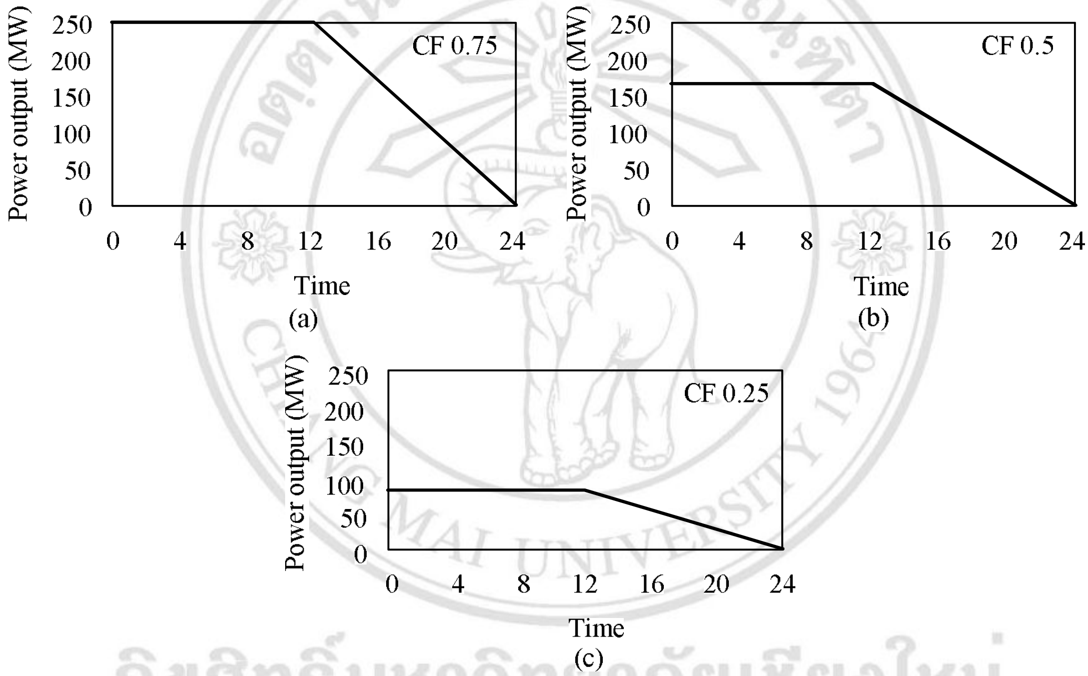


Figure 6.17 Generation profiles of the renewable energy unit with changing maximum power output.

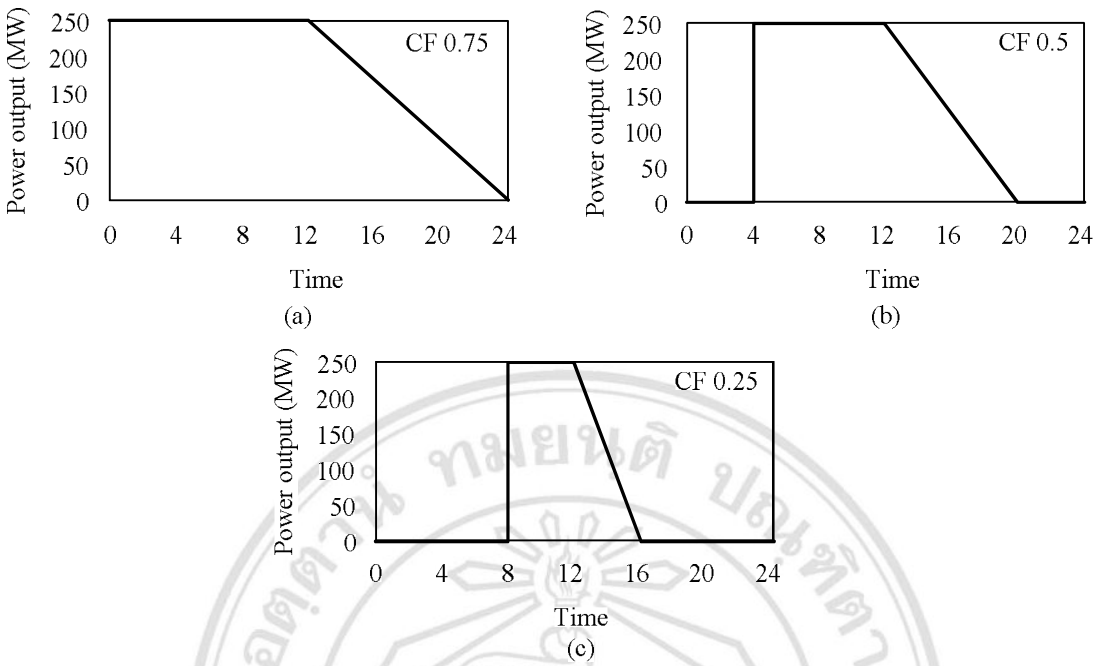


Figure 6.18 Generation profiles of the renewable energy unit with changing operation duration.

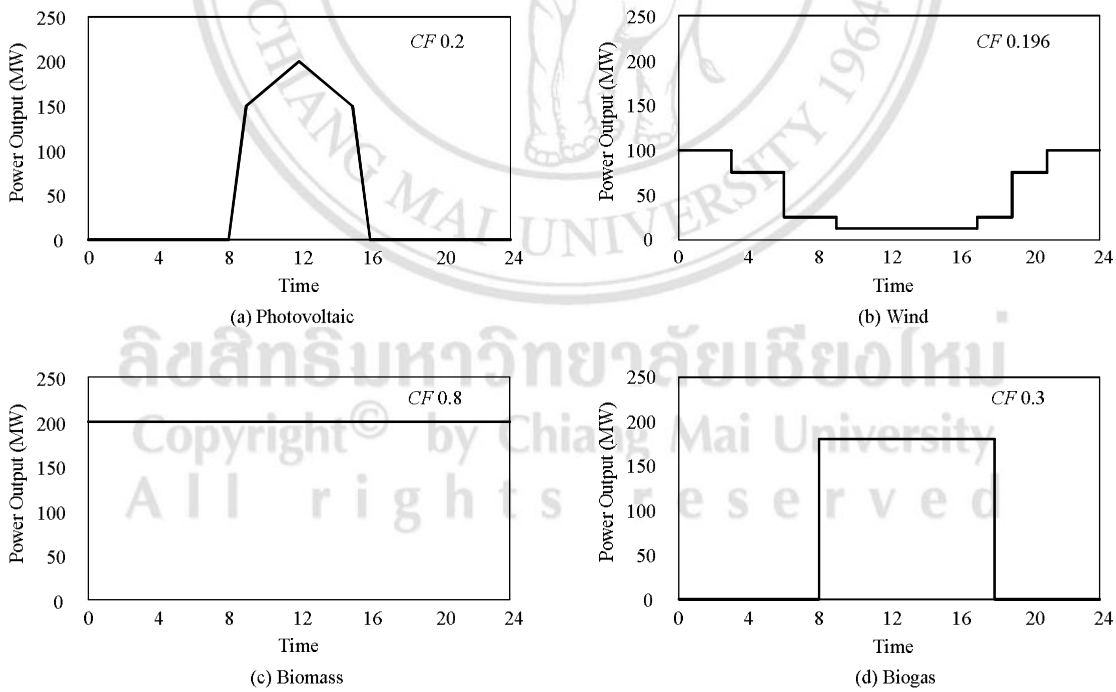


Figure 6.19 Simplified generation profiles of each renewable energy resource.

The load duration curve is assumed to be linearly downward as shown in Figure 6.12. The peak demand is 800 MW. The growth of load is assumed in such a way that the load factor is constant.

6.5.2 Reliability Evaluation Results

In Case I, the LOLPs of four-conventional unit system are 0.008 at 600 MW peak demand, 0.015 at 700 MW peak demand and 0.057 at 800 MW peak demand. In Case II, the LOLPs of Case II (the gas-turbine was replaced by the renewable energy unit with six different generation profiles) are shown in Table 6.14.

The LOLPs of Case II are always higher than that of Case I. It is implied that Case II is less reliable than Case I. In all approaches, as the peak demand increases, the LOLP increases. The LOLPs from the approach IIA and IIIA are always equal. That is because the modified generation capacity and modified FOR which are used to calculate LOLP are the same.

Table 6.14 Case II: LOLP evaluation in each approach.

	Direction of change	Ref. no.	CF	Approach									
				IA	IB	IC	ID	IIA	IIB	IIC	IIIA	IIIB	IIIC
Peak demand 600 MW	Maximum power output	1	0.75	0.022	0.022	0.022	0.022	0.010	0.010	0.010	0.010	0.010	0.010
		2	0.50	0.039	0.022	0.039	0.022	0.013	0.013	0.013	0.013	0.013	0.013
		3	0.25	0.057	0.021	0.057	0.021	0.036	0.036	0.037	0.036	0.036	0.037
	Duration	4	0.75	0.022	0.022	0.022	0.022	0.010	0.010	0.010	0.010	0.010	0.010
		5	0.50	0.039	0.039	0.022	0.022	0.013	0.010	0.010	0.013	0.031	0.031
		6	0.25	0.057	0.057	0.022	0.022	0.036	0.010	0.010	0.036	0.053	0.053
Peak demand 700 MW	Maximum power output	7	0.75	0.041	0.041	0.041	0.041	0.024	0.024	0.038	0.024	0.024	0.024
		8	0.50	0.073	0.041	0.073	0.041	0.062	0.062	0.062	0.062	0.062	0.062
		9	0.25	0.105	0.040	0.105	0.040	0.100	0.100	0.100	0.100	0.100	0.100
	Duration	10	0.75	0.041	0.041	0.041	0.041	0.024	0.024	0.038	0.024	0.024	0.024
		11	0.50	0.073	0.073	0.041	0.041	0.062	0.024	0.038	0.062	0.062	0.071
		12	0.25	0.105	0.105	0.041	0.041	0.100	0.024	0.038	0.100	0.100	0.105
Peak demand 800 MW	Maximum power output	13	0.75	0.116	0.116	0.116	0.116	0.095	0.095	0.095	0.095	0.095	0.095
		14	0.50	0.189	0.116	0.189	0.116	0.132	0.132	0.132	0.132	0.132	0.132
		15	0.25	0.262	0.115	0.262	0.115	0.170	0.170	0.182	0.170	0.170	0.182
	Duration	16	0.75	0.116	0.116	0.116	0.116	0.095	0.095	0.095	0.095	0.095	0.095
		17	0.50	0.189	0.189	0.116	0.116	0.132	0.095	0.095	0.132	0.175	0.175
		18	0.25	0.262	0.262	0.116	0.116	0.170	0.095	0.095	0.170	0.255	0.255

At different CFs by changing maximum power output of the renewable generation profile, the LOLP should be increased when the CF decreases because the generation capability of the unit decreases. As same as at different CFs by changing operation duration of the renewable generation profile, the LOLP should be increased when the CF decreases because the generation capability of the unit decreases.

From Table 6.14, when the CF decreases by decreasing maximum power output, the LOLPs from approach IA, IC, IIA, IIB, IIC, IIIA, IIIB and IIIC increase but the LOLPs from approach IB and ID are constant. When the CF decreases by decreasing operation duration, the LOLPs from approach IA, IB, IIA, IIIA, IIIB and IIIC increase but the LOLPs from approach IC, ID, IIB and IIC are constant.

Figure 6.20 shows the variation of LOLPs with different renewable energy unit's generation profiles and peak demand in each approach. It is shown that the LOLPs from approach IA, IIA, IIIA, IIIB and IIIC are varied by generation profiles and peak demand. On the other hand, the LOLPs from approach IB are not changed although the maximum power generation of the generation profile is changed. The LOLPs from approach IC, IIB and IIC are not changed although the operation duration of the generation profile is changed. And the LOLPs from approach ID are not changed although the maximum power generation or the duration of the generation profile is changed.

From the results, the approaches which are proper to use to calculate LOLPs are IA, IIA, IIIA, IIIB and IIIC. The approaches IB, IC, ID, IIA and IIB are neglected.

If the LOLPs from approach IA, IIA, IIIA, IIIB and IIIC are considered only, the LOLPs ranges and the LOLPs statistic values of all possible LOLPs ranges are shown in Figure 6.21 and Table 6.15 respectively.

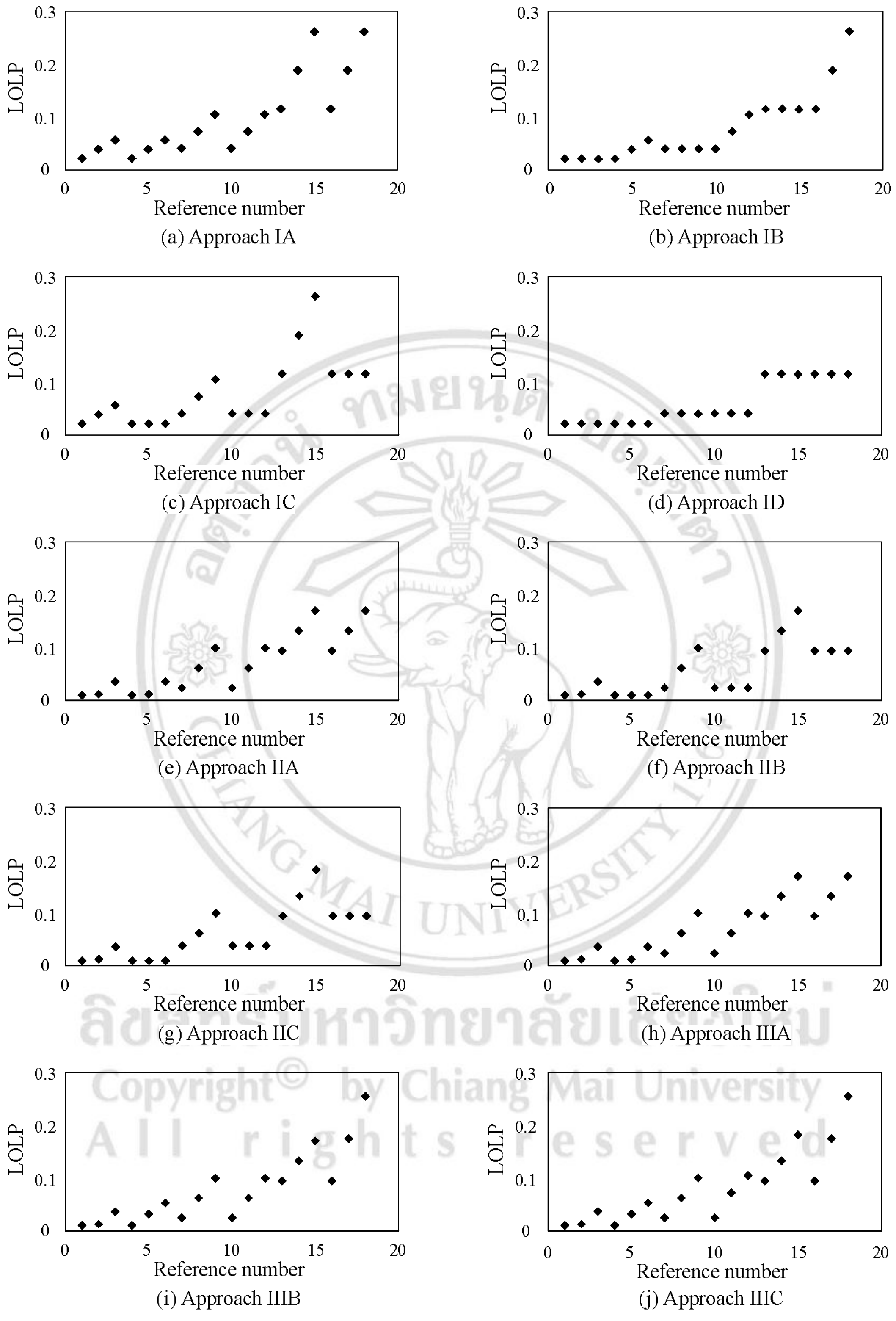


Figure 6.20 Variation of LOLPs with different renewable energy unit’s generation profiles and peak demand in each approach.

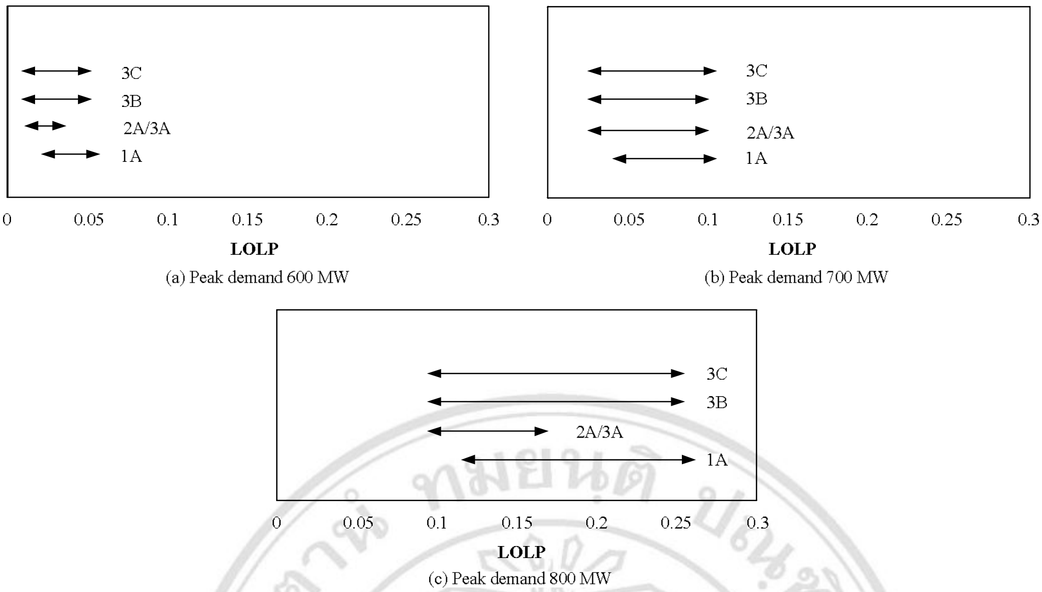


Figure 6.21 All possible LOLP Ranges.

Table 6.15 All possible LOLPs statistic values.

	Direction of change	CF	Min	Max	Avg.	Median
Peak demand 600 MW	Maximum power output	0.75	0.010	0.022	0.012	0.010
		0.50	0.013	0.039	0.018	0.013
		0.25	0.036	0.057	0.040	0.036
	Duration	0.75	0.010	0.022	0.012	0.010
		0.50	0.013	0.039	0.025	0.031
		0.25	0.036	0.057	0.047	0.053
Peak demand 700 MW	Maximum power output	0.75	0.024	0.041	0.028	0.024
		0.50	0.062	0.073	0.064	0.062
		0.25	0.100	0.105	0.101	0.100
	Duration	0.75	0.024	0.041	0.028	0.024
		0.50	0.062	0.073	0.066	0.062
		0.25	0.100	0.105	0.102	0.100
Peak demand 800 MW	Maximum power output	0.75	0.095	0.116	0.099	0.095
		0.50	0.132	0.189	0.144	0.132
		0.25	0.170	0.262	0.191	0.170
	Duration	0.75	0.095	0.116	0.099	0.095
		0.50	0.132	0.189	0.161	0.175
		0.25	0.170	0.262	0.223	0.255

From Table 6.15, with different generation profiles of renewable energy unit, the average LOLPs and the median of LOLPs are not much different. The LOLPs range increases as the peak demand increases. While the CF of the renewable energy unit decreases, the LOLP increases. That means as the CF of the renewable energy unit decreases, the reliability of the system decreases. As the peak demand increases, the LOLP increases. It is concluded that the reliability of the system decreases when the peak demand increases. Table 6.16 presents the impact of maximum power generation changing on LOLPs in each approach. The approach IA gives the highest LOLP whereas the approach IIA, IIIA and IIIB give the lowest LOLP. The LOLPs from the approach IIA, IIIA, IIIB and IIIC are similar. In case of the renewable energy unit generates power output over 24 hours, although the maximum power generation is changed, the LOLPs in the approach IIA, IIIA and IIIB are similar. That is because the modified generation capacity and modified FOR which are used to calculate LOLP are the same.

The impact of generation duration changing on LOLPs in each approach is shown in Table 6.17. The approach IA gives the highest LOLP whereas the approach IIA and IIIA give the lowest LOLP.

Table 6.16 Impact of maximum power generation changing on LOLPs in each approach.

Renewable energy unit	GC	FOR	Approach	Peak demand 600 MW		Peak demand 700 MW		Peak demand 800 MW	
				LOLP	Rank	LOLP	Rank	LOLP	Rank
CF 0.75	×	✓	IA	0.022	5	0.041	5	0.116	5
	✓	×	IIA	0.010	1	0.024	1	0.095	1
	✓	✓	IIIA	0.010	1	0.024	1	0.095	1
	✓	✓	IIIB	0.010	1	0.024	1	0.095	1
	✓	✓	IIIC	0.010	1	0.024	1	0.095	1
CF 0.5	×	✓	IA	0.039	5	0.073	5	0.189	5
	✓	×	IIA	0.013	1	0.062	1	0.132	1
	✓	✓	IIIA	0.013	1	0.062	1	0.132	1
	✓	✓	IIIB	0.013	1	0.062	1	0.132	1
	✓	✓	IIIC	0.013	1	0.062	1	0.132	1
CF 0.25	×	✓	IA	0.057	5	0.105	5	0.262	5
	✓	×	IIA	0.036	1	0.100	1	0.170	1
	✓	✓	IIIA	0.036	1	0.100	1	0.170	1
	✓	✓	IIIB	0.036	1	0.100	1	0.170	1
	✓	✓	IIIC	0.037	4	0.100	1	0.182	4

Note: ✓ is a modified value, × is an unmodified value, Rank 1 is the lowest LOLPs and Rank 5 is the highest LOLPs.

Table 6.17 Impact of generation duration changing on LOLPs in each approach.

Renewable energy unit	GC	FOR	Approach	Peak demand 600 MW		Peak demand 700 MW		Peak demand 800 MW	
				LOLP	Rank	LOLP	Rank	LOLP	Rank
CF 0.75	×	✓	IA	0.0217	5	0.0407	5	0.1155	5
	✓	×	IIA	0.0102	1	0.0243	1	0.0946	1
	✓	✓	IIIA	0.0102	1	0.0243	1	0.0946	1
	✓	✓	IIIB	0.0102	1	0.0243	1	0.0946	1
	✓	✓	IIIC	0.0102	1	0.0243	1	0.0946	1
CF 0.5	×	✓	IA	0.0391	5	0.0730	5	0.1889	5
	✓	×	IIA	0.0126	1	0.0621	1	0.1324	1
	✓	✓	IIIA	0.0126	1	0.0621	1	0.1324	1
	✓	✓	IIIB	0.0314	3	0.0621	1	0.1749	3
	✓	✓	IIIC	0.0314	3	0.0715	4	0.1749	3
CF 0.25	×	✓	IA	0.0566	5	0.1053	5	0.2622	5
	✓	×	IIA	0.0362	1	0.0998	1	0.1702	1
	✓	✓	IIIA	0.0362	1	0.0998	1	0.1702	1
	✓	✓	IIIB	0.0527	3	0.0998	1	0.2551	3
	✓	✓	IIIC	0.0527	3	0.1045	4	0.2552	3

Note: ✓ is a modified value, × is an unmodified value, Rank 1 is the lowest LOLPs and Rank 5 is the highest LOLPs.

In case III, the gas turbine unit is replaced by a photovoltaic, wind, biomass and biogas unit respectively. The LOLPs of Case III with different peak demands are shown in Table 6.18.

The results of Case III are corresponding with the results of Case II. The LOLP increases as the peak demand increases. The LOLPs are in the range of the LOLP from the approach IIA/IIIA to the LOLP from the approach IA. By the LOLP from the approach IIA and IIIA is the lowest LOLP whereas the LOLP from the approach IA is the highest LOLP.

From all test cases, the proper approaches which are used to calculate LOLP are approach IA, IIA, IIIA, IIIB and IIIC. The approach IA gives the highest LOLP whereas the approach IIA and IIIA give the lowest LOLP. The LOLP from approach IIA and IIIA are always similar because the modified generation capacity and modified FOR are the same.

Table 6.18 Case III: LOLPs of each approach.

Renewable unit	Peak demand (MW)	Approach			
		IA	IIA/IIIA	IIIB	IIIC
PV	600	0.060	0.044	0.053	0.053
	700	0.112	0.107	0.107	0.107
	800	0.277	0.178	0.263	0.263
Wind	600	0.060	0.044	0.044	0.044
	700	0.112	0.108	0.108	0.108
	800	0.278	0.181	0.181	0.213
Biomass	600	0.018	0.010	0.010	0.010
	700	0.034	0.017	0.017	0.017
	800	0.101	0.087	0.087	0.087
Biogas	600	0.053	0.029	0.048	0.048
	700	0.099	0.092	0.092	0.092
	800	0.248	0.163	0.237	0.237

Practically, the modification of generation capacity is more difficult to calculate LOLP than the modification of the FOR because the capacity outage state may be changed. So it is suggested that the approach which is simple and intuitive to use in LOLP calculation is the approach IA. From the approach IA, the generation capacity remains as its own and the FOR is modified as EFOR. The EFOR depends on the capacity factor and equals to 1-CF. Meanwhile, the approach which has the equivalent generation profile like the actual generation profile the most is the approach IIIC.

6.6 Chapter Summary

This chapter presents the results and discussion of all contributions in this research which are:

- The impacts of renewable generation on electricity demand characteristic are investigated with a time frame from seasonal basis to annual basis. It is proposed to treat renewable generation as negative load. Electricity demand is characterized by using peak demand, energy demand, and load factor as well as it is divided into three groups: peak, intermediate, and base. Variation of renewable generation is expressed through a concept of net load. Changes of demand characteristics can be analyzed from annual and seasonal changes of load duration curves after integrating renewable energy resources. The impacts on demand characteristics and load groups have meaningful implication on operating costs.

- The effective capacity of renewable power plant for generation reliability evaluation is proposed with two definitions. The effective capacity can be computed from generation capacities of renewable and conventional power plants as well as effective load carrying capability. FOR, generation capacity, and number of renewable units are varied to reflect operation behavior of renewable power plant. It can be observed that renewable power plant with either lower FOR or higher average power contributed to better generation reliability. Given identical renewable capacity; more renewable units (smaller in capacity size) yields better generation reliability.

- The reliability evaluation using conventional approach, the modeling of various renewable energy resources is proposed by considering daily operation profile. The FOR of renewable unit can be obtained by using the EFOR. Generation reliability is then evaluated under the presence of renewable energy resources by using the LOLP and EENS as reliability index and the ELCC as capacity contribution. It is obvious that the penetration of renewable energy resources would have negative impact on generation reliability. The impact of renewable energy resources on generation reliability depends on generation capacity and loading condition. The contribution of renewable energy resources is important and deserves attention when they replace conventional (fossil-fuelled) resources.

- The reliability evaluation using modified approach is proposed into three approaches which are modification of FOR, modification of generation capacity, and modification of both FOR and generation capacity. The proper approaches which are used to calculate LOLP are approach IA, IIA, IIIA, IIIB and IIIC. The approximated LOLP is in the range of the LOLP from the approach IIA and IIIA to the LOLP from the approach IA. It is concluded that the simplified approach which is easiest and proper approach to use in LOLP calculation is the approach IA. From the approach IA, the generation capacity remains as its own and the FOR is modified as EFOR. The EFOR depends on the capacity factor and equals to 1-CF. Meanwhile, the approach which has the equivalent generation profile like the actual generation profile the most is the approach IIIC. From the approach IIIC, the actual generation profile of the renewable energy unit is represented as an equivalent generation profile which is a three-state model with the ON-state power generation is a maximum power generation and the de-rated state power generation is an average power generation in a de-rated hour. The modified FOR is a probability at OFF state.