Investigation of System Reserve Margins based on Probabilistic and Deterministic Methods

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Abstract

Generation system reliability can be measured through its reserve margin, which is generally defined based on either deterministic or probabilistic method. Thailand's generation reserve margin has been planned based on deterministic method for several years, i.e. not less than 15% of peak demand. This paper attempts to relate reserve margin used in Thailand's power development plan to the one based on probabilistic criteria. The developed algorithm has been tested with a modified Thailand's generation system. Results obtained from both criteria are compared, the proposed algorithm may be used to review and adjust Thailand's reserve margin criteria in the future.

Keywords: Reliability index, Reserve margin

1. Introduction

Generation system reliability is one of the important issues to support country development. It generally concerns adequacy level of the supply capacity compared to the demand. The generation reserve margin is well recognised as an index to measure system adequacy or reliability. System adequacy generally relates with investment, especially on the supply side. In general, the system adequacy or reserve margin can be increased through investment in constructing new power plants. On the other hand, the reserve margin can be decreased if the new invested supply capacity is less than the demand growth.

Generation System reliability can be divided into two basic approaches, deterministic and probabilistic. The reserve margin based on the deterministic approach is generally defined as a fixed percentage of the expected peak demand, e.g. 15% for Thailand, whereas the probabilistic approach generally uses a reliability index, e.g. Loss of load expectation (LOLE), as criteria to evaluate adequacy of electrical supply capacity. However, defining appropriate level of reserve margin is a difficult task. Too high reserve margin causes over-investment to the utility, resulting in high electricity price, whereas too low reserve margin causes high risk of electricity shortage to customers. The reserve margin based on deterministic criteria can be found in a straight forward method, which generally focuses on peak demand and is convenient to communicate with public. However it does not take into account generation failure and demand forecast uncertainties. The probabilistic based method, even though found to be more difficult to understand by the public, can cope with these uncertainties. This paper attempts to relate the probabilistically required generation capacity, based on LOLE of 0.1,1 and 2 day/year, which will then be translated into the well familiar percentage reserve margin. An algorithm has been developed and tested with a modified Thailand's generation system. Detailed procedures of the methodology, developed algorithm and results are presented in the following sections.

2. Generation System and Load Modeling

2.1 Generating unit unavailability

One of the basic parameters used in developing generation capacity model is the probability of finding a generating unit on forced outage at some time in the future.

In this paper, a two-state model is used to present generating unit operating status, as shown in Figure 1, where λ is expected failure and μ is expected repair rate.

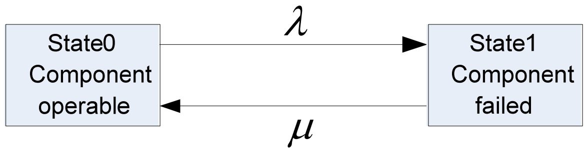

Figure 1 Two-state model for base load unit

With a two state model, we can calculate unit's Force Outage Rate (FOR) as shown in (1).

$$FOR = \frac{\lambda}{\lambda + \mu} \qquad (1)$$

The FOR is referred as unavailability (U) in this paper.

2.2 Generation system model

The generation system model can be presented as a Capacity Outage Probability Table (COPT), which is a simple array of capacity levels and the associated probabilities of their existence. The formula to obtain the cumulative probability of the X MW outage in the system can be demonstrated by equation (2).

$$P(X) = (1-U)P'(X) + (U)P'(X-C) \qquad (2)$$

where

$P(X)$ is cumulative probability of the capacity outage state of X MW after the generating unit is added ,

$P'(X)$ is cumulative probability of the capacity outage state of X MW before the generating unit is added,

U is the unavailability of the added unit,

C is the added unit's capacity in MW.

Equation (2) is illustrated using a simple generation system shown in Table 1. Each unit has U of 0.02. The above expression is initialized by setting $P'(X)=1.0$ for $X \leq 0$ and $P'(X)=0$ otherwise.

Table 1 Generation system information

Capacity(MW)	Number of unit	FOR
25	2	0.02
50	1	0.02

The system capacity outage probability is created as shown in Table 2.

Table 2 COPT

Capacity outage (MW)	Cumulative probability
0	1
25	0.058808
50	0.020392
75	0.000792
100	0.000008

A more detailed process can be founded in [1].

2.3 Load model

Information of annual hourly load curve comprising 8,760 hours, load data, as shown in Figure 2 should be firstly collected. Then the hourly load duration curve as shown in Figure 3, or the daily peak load duration curve can be developed and used in conjunction with the system's COPT to obtain reliability indices, e.g. LOLE, Expected energy not supplied (EENS) etc.

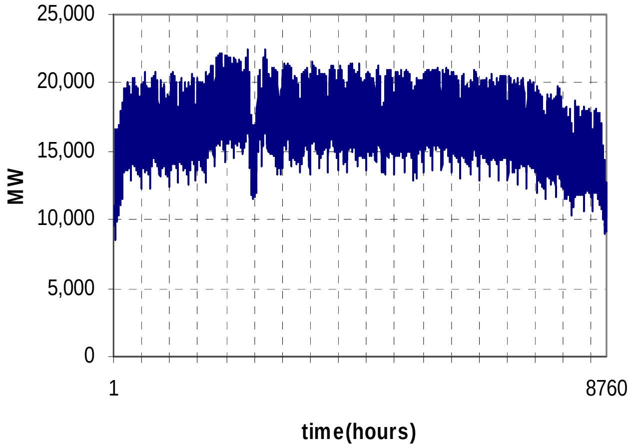

Figure 2 Hourly load curve

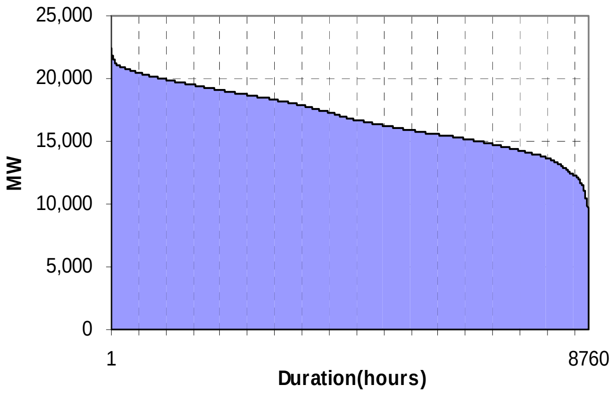

Figure 3 Hourly load duration curve

2.4 Energy-limited generation

In general, each generating unit is assumed to be able to generate power with sufficient fuel supply for all the considering time. However some units, e.g. hydro units, is of energy-limited type in nature since the amount of water in the reservoir, which can be discharged to generate electric energy, is varied along the considering time. Therefore these units are generally dispatched as peak-shaving unit, leaving the rest of the demand to be supplied by other generating units. In this paper, the characteristic of the limited amount of energy presented as probability distribution shown in Table 3 will be considered.

The "peak-shaving" technique [2] will be firstly applied to modify the original load duration curve using a conditional probability which can be illustrated by Equations (3).

$$D(L)=\sum_{i=1}^{N} d_i(L)*P_i(C_i) \qquad (3)$$

where

D (L) is the duration of load L on the capacity modified curve,

$d_i(L)$ is the duration reduction of load L on the original load duration curve by C_i MW,

C_i is output capacity of i th capacity state of the peak-shaving unit,

N is number of capacity states of peak-shaving unit, and

$P_i(C_i)$ is probability of unit's capacity of C_i.

$$D(L)=d_c(L)*P(E(L))+d_o(L)*[1-P(E(L))] \qquad (4)$$

where

D(L) is the duration of the final peak-shaved curve corresponding to load of L MW,

$d_c(L)$ is the duration of capacity modified curve corresponding to load of L MW,

$d_o(L)$ is the duration on original load duration curve corresponding to load of L MW, and

E (L) is expected energy output of the unit.

*P(E(L))*is probability of energy equaling or exceeding *E(L)*.

Table 3 Energy distribution

Unit size (MW)	Energy (MWh)	Cumulative probability
72	258,838	1
	448,886	0.81
	630,720	0.24
300	888,534	1
	1,348,678	0.71
	1,808,822	0.21

Then the energy distribution of the unit as shown in Table 3, formulated by Equation (4) will be considered. The result of the modified LDC can be obtained as shown in Figure 4.

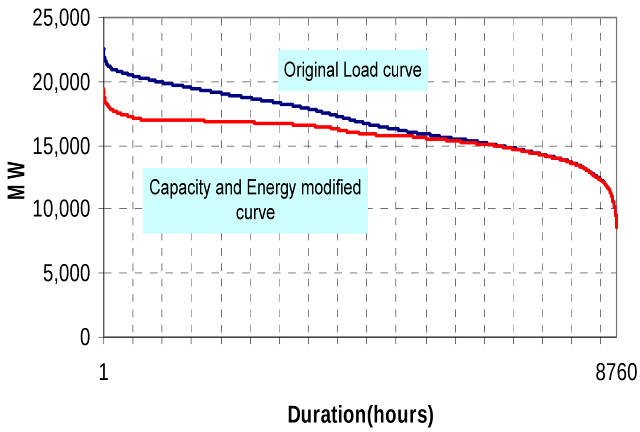

Figure 4 Original and energy modified load duration curve

3. Reliability Index Calculation

In this part, two types of generation system reliability indices [1, 4] used in this paper will be presented, i.e. LOLE and EENS.

3.1 Loss of load expectation index

The LOLE is the average number of days in which the daily peak load is expected to exceed the available generation capacity. It indicates the expected number of day in which a load loss or generation deficiency will occur. As illustrated in Figure 5, The LOLE index can be obtained using the daily peak load variation curve expressed by equation (5).

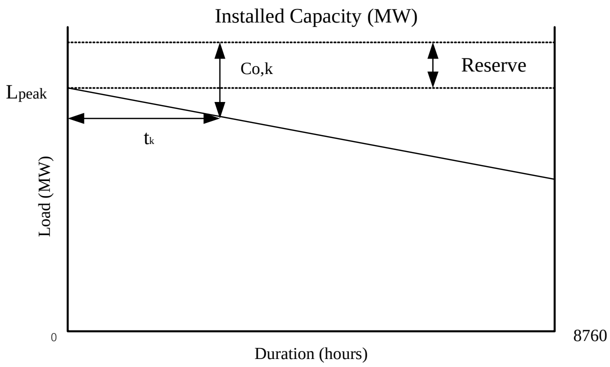

Figure 5 LOLE calculation

$$LOLE = \sum_{k=1}^{N} p_k t_k \qquad (5)$$

where

$C_{o,k}$ is capacity outage or $p_k t_k$ time unit,

p_k is the individual probability,

t_k is the duration of the load loss due to the outage of $C_{o,k}$, resulting in loss of load, and

N is number of states of the COPT.

3.2 Expected energy not supplied index

EENS [1] is the expected energy not supplied by the generation system due to the energy demand exceeding the available generating capacity. EENS index can be obtained using the hourly peak load variation curve as shown in Figure 6, and can be expressed mathematically by equations (6) and (7). The expected energy produced by each unit can be calculated by equation (8).

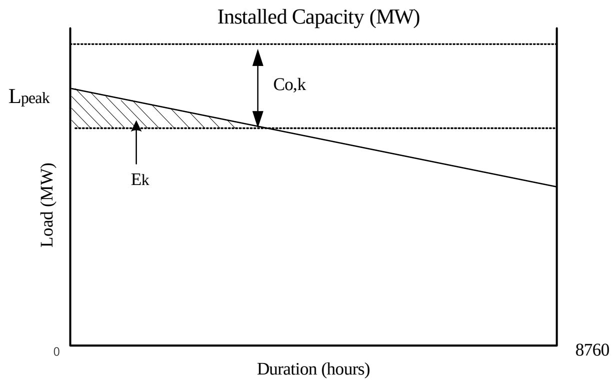

Figure 6 EENS calculation

$$EENS_0 = t * \sum_{i=1}^{n} L_i \qquad (6)$$

$$EENS_q = \sum_{k=1}^{N} p_k E_k \qquad (7)$$

$$EEP_q = EENS_{q-1} - EENS_q \qquad (8)$$

where

t is the during time period being considered,

L_i is actual load at hour i,

$EENS_0$ is the total energy demand,

$EENS_q$ is expected energy not supply of unit q,

p_k is individual probability of state k,

E_k is expected energy curtailed of state k and

EEP_q is expected energy produced by unit q.

4. Reserve Margin Determination

An algorithm is developed to evaluate and compare the reserve capacity between the deterministic criteria, i.e. the percentage, reserve margin and the probabilistic criteria, i.e. LOLE. The developed algorithm is shown in Figure 7.

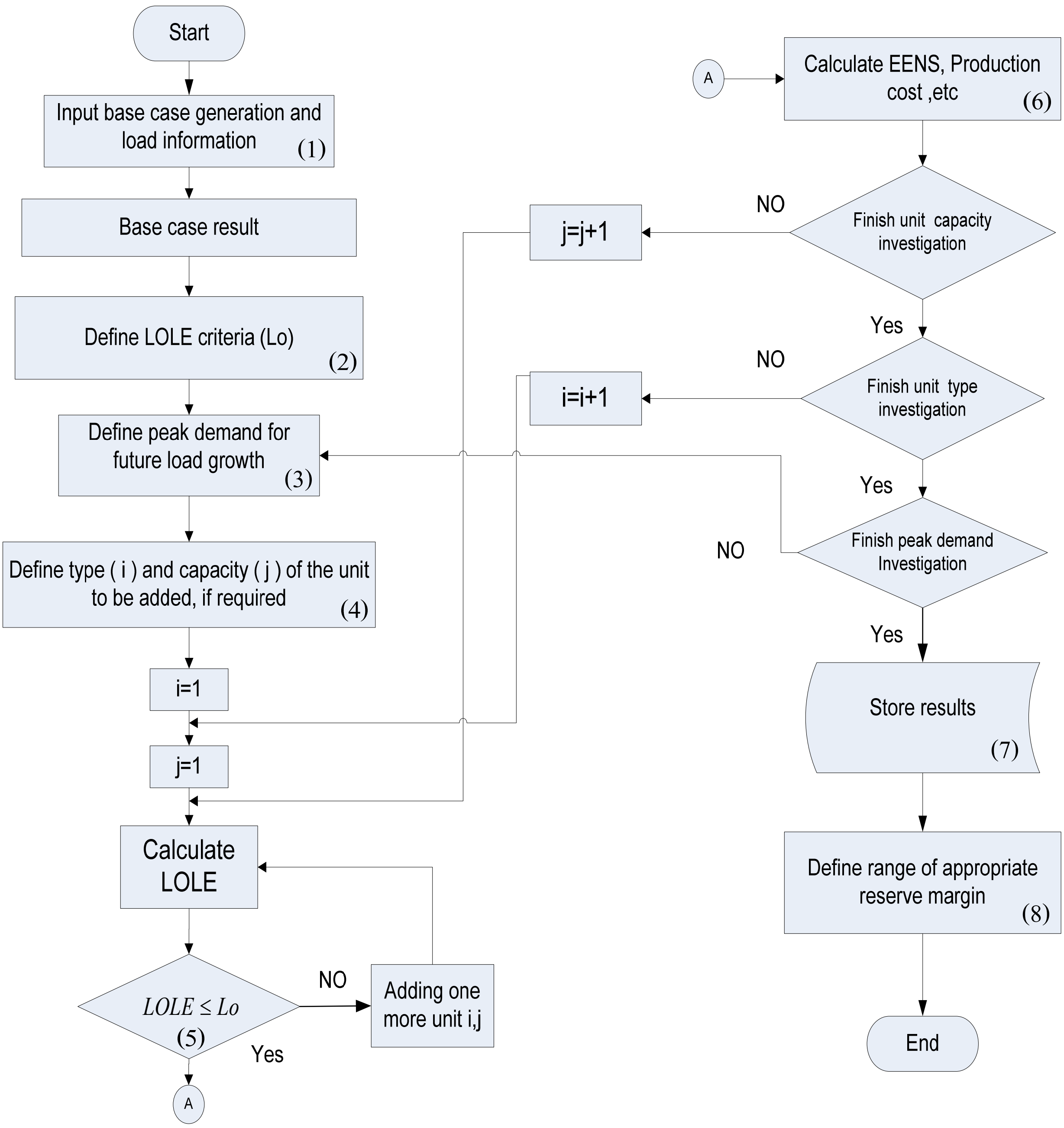

Figure 7 Reserve margin determination based on probabilistic and deterministic methods

The developed algorithm is tested with a modified Thailand's system, of which the data is shown in Appendix A. Details of the 8-step procedure, with the number of the referred step shown in each box of Figure 7, are presented below.

Step 1 Input base case generation and load information, then calculate reliability indices and reserve margin.

Step 2 Define LOLE criteria, e.g. 0.1, 1 and 2 day/year.

Step 3 Consider peak demand and assume the increase of peak demand in the future as 5,10,..,100% of peak demand.

Step 4 Define type and capacity of the units to be added.

Step 5 Evaluate LOLE of each modified load with added unit. If the obtained LOLE is less than the required LOLE, then add a unit defined in step 4.

Step 6 Recalculate LOLE, EENS, and production cost etc.

Step 7 Store results.

Step 8 Plot all results and then evaluate range of reserve margin according to each defined LOLE level.

5. Result

A modified Thailand's system is used as base case for testing with the peak demand of 22,500 MW, and installed generation capacity of 30,508MW. The reserve margin for the base case is 35.59%, which results in the LOLE of 0.00005 day/year and EENS of 0.1 MWh. In case of an additional generating unit is required to meet the defined LOLE, only the 250 MW steam power plant fossil coal type, with FOR of 6.29%, will be considered in this paper. The obtained results for the LOLE of 1 day/year criteria are shown for example in Table 4, with the increased peak demand of 20, 30,…, 100% from the base case.

Table 4 The reliability indices, LOLE $\leq$ 1 day/year

Load demand increased (%)	%Reserve margin	LOLE (day/yr)	EENS (MWh)	Required additional power	
				Unit capacity (MW)	Number
20%	13.0	0.9	8784.9	-	-
30%	12.0	1.0	8913.4	250	9
40%	11.2	1.0	9228.5	250	18
50%	10.4	1.0	9874.6	250	27
75%	9.2	1.0	9988.1	250	50
100%	8.4	1.0	10611.5	250	73

Results of the investment cost, production cost, and outage cost are also shown in Table 5 [7]. The outage cost is obtained based on the Interrupted Energy Assessment Rate of 60.34 Baht/kWh.

Table 5 Cost, LOLE $\leq$ 1 day/year

Load demand increased (%)	Investment cost (M.Baht)	Production cost (M.Baht)	Outage cost (M.Baht)
20%	-	310,405	530.1
30%	94,500	316,943	537.8
40%	189,000	323,889	556.8
50%	283,500	331,139	595.8
75%	525,000	348,232	602.7
100%	766,500	366,716	640.3

Based on the obtained results, we can evaluate the relationship between the percentage reserve and the required LOLE with the increased peak demand as shown in Figure 8.

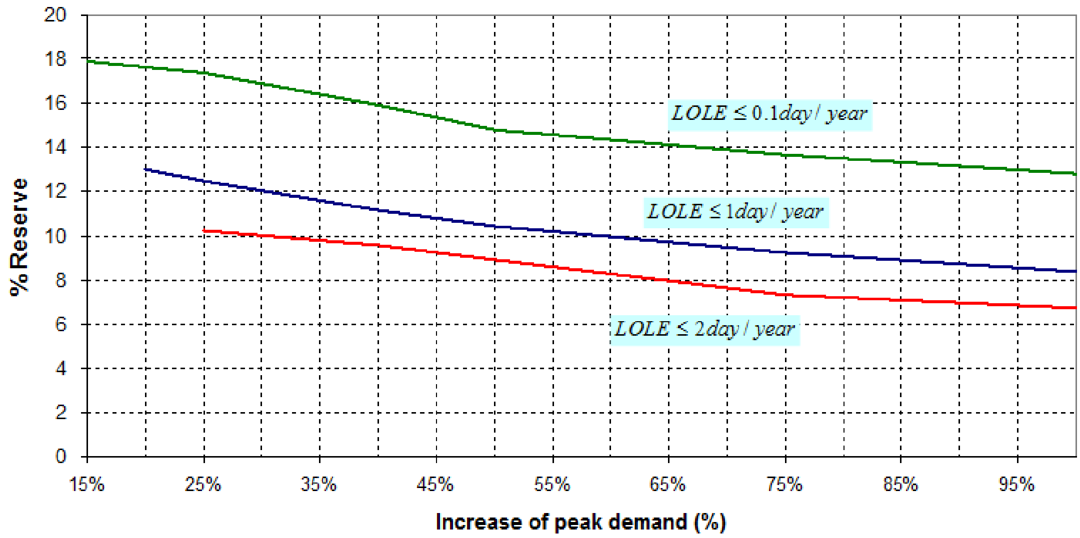

Figure 8 Relation of reserve margin and LOLE

In Figure 8, it shows the relation of the reserve margin and the LOLE with peak demand for the cases of LOLE 0.1, 1 and 2 day /year. It can be found that if the peak demand increases by 35%, the reserve margin should be at least 10, 11, and 16.5% for the case of LOLE 2, 1 and 0.1 day/year respectively. In general, it can be noticed that the higher the percentage increase of peak demand, the lower reserve margin (%) tends to be required to meet a defined LOLE.

6. Conclusions

This paper presents the developed process to relate the required capacity reserve based on the probabilistic and deterministic planning methods. It is found that results obtained from the probabilistic based generation planning method can be mapped to the deterministic based method, i.e. percentage reserve margin, which is more convenient to communicate with public.

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Appendix

The modified Thailand's system information [3, 8] is shown in Table's 6 and 7.

Table 6: Hydro units

Plant No.	Number of unit(s) x (MW)	Total capacity (MW)	FOR (%)
1	[6 x 82.2] + [1 x 115] + [1 x 171]	779.2	3.58
2	4 x 125	500	3.58
3	3 x 8.4	25.2	6.76
4	3 x 12	36	3.58
5	2 x 20	40	3.58
6	2 x 3	6	6.76
7	[3 x 120] + [2 x 180]	720	3.58
8	3 x 100	300	3.58
9	2 x 19.5	39	3.58
10	1 x 19	19	6.76
11	3 x 24	72	3.58
12	1 x 1.275	1.275	6.76
13	2 x 4.5	9	6.76
14	1 x 1.06	1.06	6.76
15	3 x 80	240	3.58
16	4 x 34	136	3.58
17	2 x 250	500	3.58
18	[2x115]	214	3.58
19	[2x75]	126	3.58
Total		3763.735	

Table 7 Thermal units

Plant No.	Number of unit(s) x (MW)	Total capacity	FOR(%)
1	[2 x 310]	620	5.3
2	[2 x 550] + [2 x 600]	2,300	7.0
3	[4 x 150] + [6 x 300]	2,400	5.8
4	1 x 340	340	3.9
5	[1 x 69.9] + [1 x 70.2]	140.1	8.4
6	2 x 720	1,440	11.3
7	2 x 673.3	1,346.5	6.3
8	[2x368.3]+[2*328.5]	1429.7	6.1
9	[2 x 110] + [1 x 115] + [2 x 200] + [1 x 218]	953	6.1
10	[1x120.7]+[2*121.9]+[1x124]+ [1x125]	737.2	6.1
11	[2x205.4]+[4x223.4]+[2x233]+ [1x256.7]	2027.1	6.1
12	[2x230]+[1x250]	710	6.1
13	[1x678]	678.0	6.1
14	[1x294.6]+[1x287.6]+[1x289.8]+ [1x302.9]	1174.9	6.1
15	[1x685]+[1x675]+[1x681]	2041	6.1
16	[2 x 230] + [1 x 240]	700	6.1
17	[2 x 230] + [1 x 240]	700	6.1
18	[2 x 356.5]	712	6.1
19	[1 x 350]	350	6.1
20	[2x 734]	1,468	6.1
21	[2x700]	1,400	6.1
22	[2 x 14] + [1 x 13] + [2 x 16] + [2 x 22] + [1 x 120]	237	8.4
23	3 x 122	366	10.5
24	2 x 122	244	10.5
Total		24,515	

Biography

Yod Nitikitpaoboon received the B.Eng, degree in Electrical Engineering from Khon Kaen University, Thailand, in 2006. He is currently a master degree student in Electrical Engineering, Chulalongkorn University, Thailand.