LEAST COST DISPATCH SCHEDULING MODEL

v2.0

Single Buyer

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List of Abbreviations

Abbreviation	Unit
kJ	kilo-joule. Can also be represented as J, MJ, GJ, TJ
kWh	kilo-watt-hour. Can also be represented as MWh, GWh
W	Watt

Terms and Definitions

Term	Definition
Generator	A person who is licensed under the Electricity Supply Act 1990 to generate electricity in Peninsular Malaysia
Generator Contract	An agreement for the sale and purchase of electricity between the Grid Owner and a Generator, including, but not limited to Service Level Agreement or Power Purchase Agreement (SLA/PPA) of a Generator
PPA	Power Purchase Agreement
SLA	Service Level Agreement

1. Least Cost Dispatch Scheduling Methodology

1.1 Merit Order List (MOL)

Traditionally, a "Merit Order List" (MOL) is used as a tool for unit commitment and dispatch. An MOL is a ranking list of power plants from the lowest to the highest energy cost per unit in RM/kWh or sen/kWh at the maximum generation capacity. A sample is shown in Table 1 below.

Plant	Max Capacity (MW)	Energy Cost (sen/kWh)	Cumulative MW
A1	50	15.07	50
A2	40	17.58	90
B2	40	18.21	130
B1	35	20.23	165
D2	10	26.22	175
C2	15	27.22	190
C1	15	29.64	205
D1	15	30.63	220
D3	12	30.88	232

Table 1: Sample of Merit Order List

Plants will be dispatched in sequence starting from the cheapest unit until the total generation output matches system demand. Using Table 1 as an example, in order to meet system demand of 175MW, Plants A1 up to D2 will be dispatched first. If demand increases to 176MW, Plant C2 will be next to run.

Dispatch based on MOL is quick and easy but may not necessarily result in the optimized solution that gives the lowest total system cost. There are a few disadvantages of MOL, such that it only shows:

- the cost at its most optimum operation. In reality, generator's efficiency is lower at lower output, hence the energy cost is higher;
- the maximum generation capacity without information on the minimum generation capability.

Going back to the example above, Plant C2 may not be the optimized solution to serve the additional 1MW demand if its minimum generation capability is higher than 1MW or its energy cost of generating 1MW is higher than other plants with lower ranking in the MOL.

In a real power system, there are hundreds of plants, varying range of minimum and maximum capacity and efficiency. It is evident that a robust tool is essential to perform the optimization of production costing, taking into consideration various inputs, to finally produce a least cost unit commitment schedule and dispatch for a power system operation.

1.2 Unit Commitment and Economic Dispatch (UCED)

With advancement in computing technology, robust tools in the form of simulation software are now available for solving the unit commitment and dispatching problem. The main objective is to minimize total system cost within various limitations and constraints. In other words, the aim is to choose the cheapest possible combination of generating units to serve the demand at all times.

Generally, the principle of any unit commitment and economic dispatch program is that the lowest cost plant will be scheduled first to meet demand followed by the next lowest cost plant until all demand is met. The optimization is to minimize total system cost which consist of the following components:

Total system cost:

$$\begin{aligned} System\ Cost = {} & Fuel + Variable\ operations\ and\ maintenance + Startup + Contract\ Purchase \\ & + (-Contract\ Sale) + Transmission\ Wheeling \\ & + Energy/Ancilliary\ /capacity\ market\ cost \\ & - Energy/Ancilliary\ /capacity\ market\ sale \end{aligned}$$

The above equation is to be solved subject to:

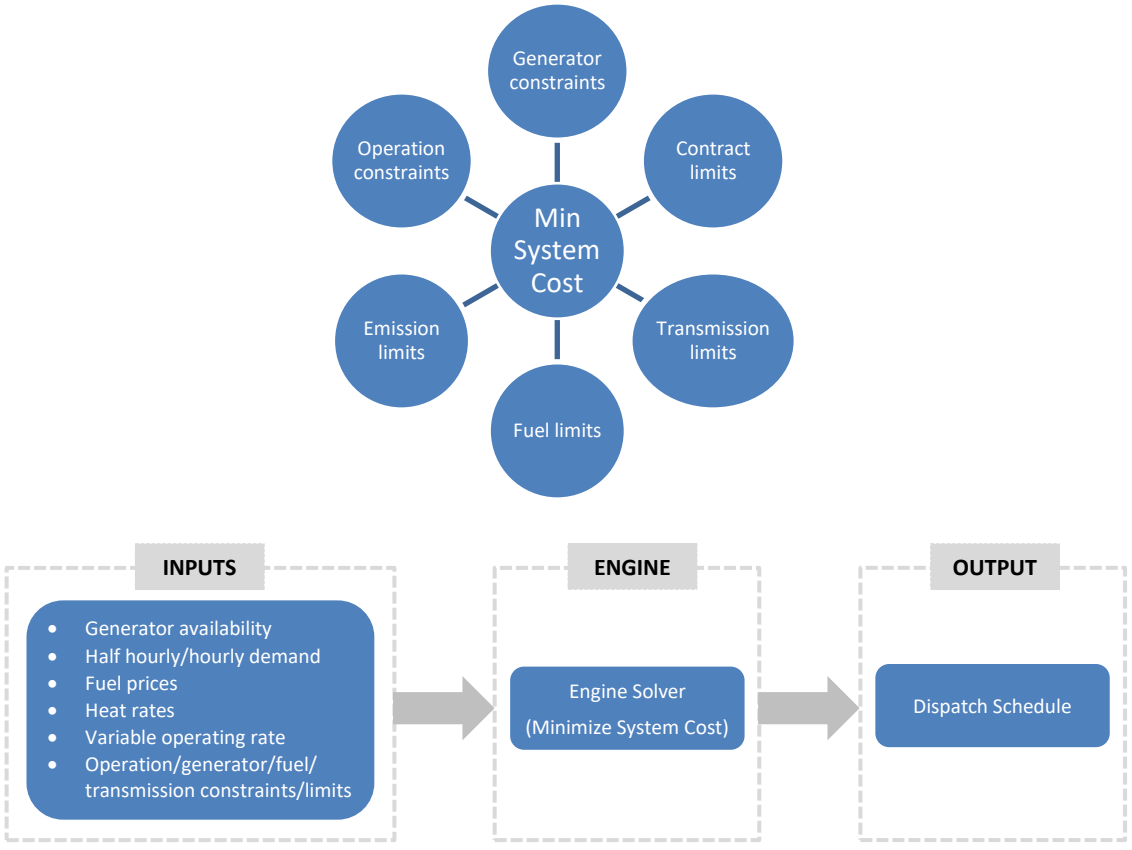

Figure 1: Schematic of the least cost dispatch scheduling model

This methodology involves more mathematical equations and intensive calculation. To put in perspective, for a small system with 2 generators and 2 heat rate points, number of possible combination for each hour is 2^4, i.e. 16 possible solutions. For a one-day horizon of 24-hour period, no of calculations required to find the best combination is 16 x 24 = 384.

Hence for a bigger system in Peninsular Malaysia with hundred over generators with hundreds of heat rate points solving for a 30-min interval period in a 24-hour horizon, the problem size is too big to be done by manual calculation and simple algorithm.

For reference, an example is provided in Appendix 1 to illustrate the comparison between the two methods described here.

1.3 Optimization Tool

The bigger the system is, the more complicated and time-consuming calculation is required, particularly if it is done manually using a simple algorithm. An optimization tool is essential to facilitate the calculation and analysis of least cost unit commitment and economic dispatch.

PLEXOS® is one of the leading optimization tools that uses cutting-edge data handling, mathematical programming, and stochastic optimization techniques to provide a robust analytical framework for power market analysis. The software is developed by an Australian-based company Energy Exemplar Pty. Ltd and currently being used in many countries worldwide[1]. Single Buyer has been using this software since 2011 for long-term capacity planning, looking at capacity adequacy and reliability over a 20-year ahead horizon period. In 2013, its usage was expanded for short-term generation planning to perform least cost unit commitment and economic dispatch for 1-day horizon up to 5-year ahead period. Currently, PLEXOS® is used by Single Buyer and Grid System Operator for all generation-related simulation and analysis.

[1] Please refer to Energy Exemplar's website http://www.energyexemplar.com/ for more details on PLEXOS software.

2. Heat Rate

2.1 Overview

One of the key inputs in any optimization tool for least cost dispatch is generator's heat rates. Generator heat rates consist of generation levels in MW ranging from the minimum up to its maximum generation, and their corresponding heat rate value typically in kJ/kWh. For example, a generator with capacity between 110 – 150 MW is represented by its heat rate table in Table 2 below.

Generation (MW)	Heat Rate (kJ/kWh)
110	10,005
120	9,800
130	9,750
140	9,700
150	9,670

Table 2: Sample of generator heat rate

Heat rate is important as it represents the generator efficiency at each generation level. Efficiency of a generator can be calculated from the heat rate value using Equation 1 shown below. Based on Equation 1, it can be seen that heat rate is inversely proportional to efficiency which means the lower the heat rate, the higher the efficiency of the machine:

$$Efficiency = \frac{3{,}600(\frac{kJ}{kWh})}{HeatRate} x\ 100\%$$

Equation 1: Efficiency Formula based on Average Heat Rate

Using the heat rate example in Table 2, the generator's efficiency ranges between 36% and 37.2% from its minimum up to maximum generation of 150MW. In other words at maximum level, only 37 units of energy will be produced at the generator output for every 100 units of input energy.

$$Efficiency\ @\ 110MW = \frac{3{,}600}{10{,}005} x\ 100\% = 36\%$$

Generator heat rate input can be presented in three main forms; "average heat rate", "input-output" or "heat input" and "marginal heat rate" or also known as "incremental heat rate". All forms can be used interchangeably in the sense that each type can be converted into one form or another. However, the most common forms are the "average heat rate" and "marginal heat rate". In the context of generators in the Peninsular Malaysia system, all heat rate data provided are in the form of average heat rate. As such, this document will describe in detail how the heat rate data (represented as average heat rate) is used as an input for the least cost dispatch scheduling model.

2.2 Heat Rate Data Characteristic

Another sample of a heat rate table and heat rate curve for a 170MW generating unit is shown in Table 3 and Figure 2 respectively. As discussed in the previous section, since heat rate is inversely proportional to efficiency, the curve indirectly shows that this generator's efficiency increases from 110MW up to 170MW. This is an important characteristic to ensure a "properly" modeled heat rate function in any production costing optimization program.

Generation (MW)	Heat Rate (kJ/kWh)
110	10,027
115	9,847
120	9,681
125	9,529
130	9,390
135	9,265
140	9,154
145	9,057
150	8,974
155	8,904
160	8,848
165	8,806
170	8,790

Table 3: Heat rate table of a 170MW generator

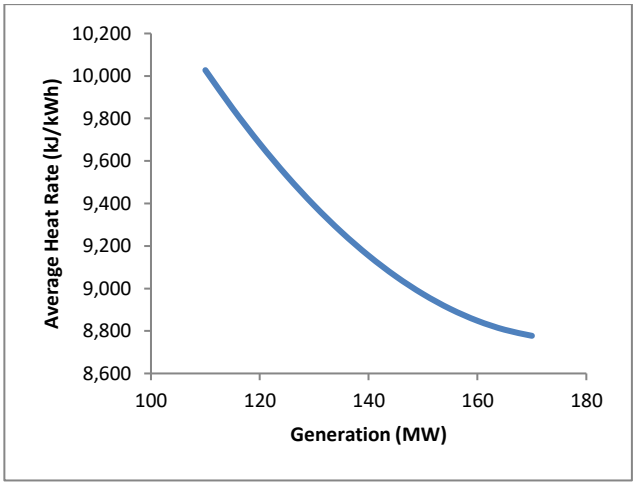

Figure 2: Heat rate curve of a 170MW generator

For comparison, samples of curves which do not conform to the expected heat rate characteristic are illustrated in Figure 3. Both curves seem illogical since the curve on the left symbolizes that generator efficiency remains constant beyond 325MW while the curve on the right shows a reduced efficiency as generator out is 325MW and higher. These types of curves may lead to inaccurate modeling of the generator subsequently leading to non-optimized solution for the production costing problem.

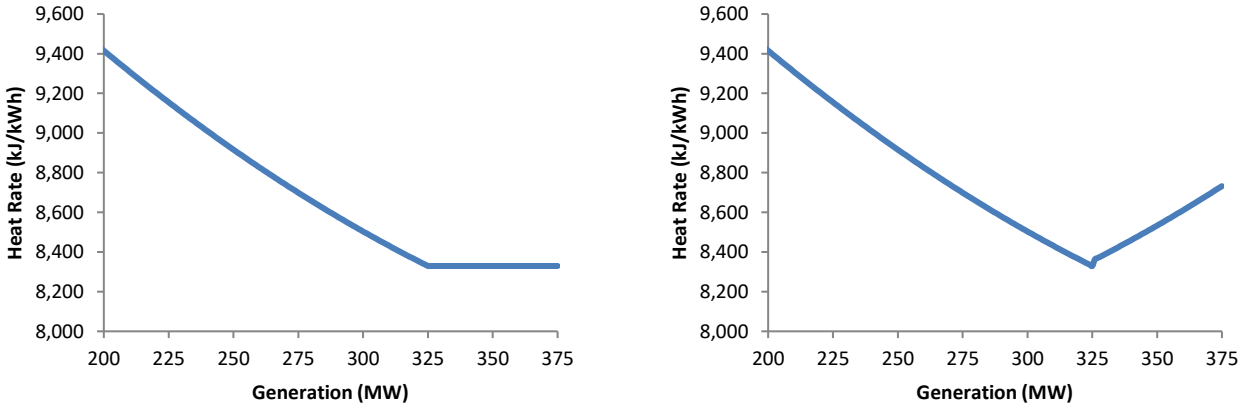

Figure 3: Samples unacceptable heat rate curve

A good average heat rate curve will normally translate to a good marginal heat rate curve. Most production costing program requires the marginal heat rate curve to be monotonically non-decreasing or also known as "convex". Marginal heat rates sometimes are provided in steps or blocks and samples of a convex and non-

convex curve are shown in Figure 4 below. More explanation on this will be discussed in the following section.

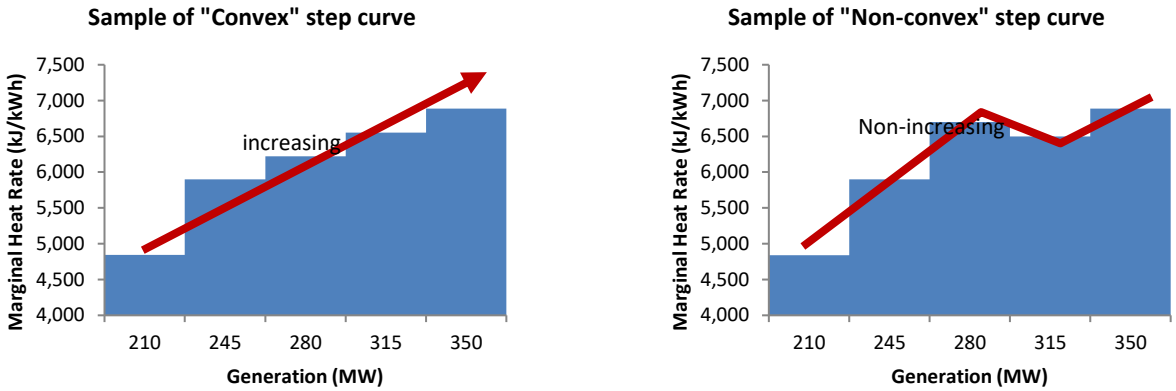

Figure 4: Samples of convex and non-convex marginal heat rate step curve

2.3 Heat Rate Modeling

Previously, only marginal heat rate data is accepted by the software used for UCED. One of the reasons for this is optimization program essentially performs all calculations based on marginal values rather than the average. However with better computing capability, other forms are now acceptable where the process of conversion to the marginal heat rate format is performed internally by the program itself. This section describes the process of heat rate modeling performed by PLEXOS based on average heat rate as the input data, generally shown by Figure 5. In each step of the process, internal calculation performed by PLEXOS is verified using external calculation which is used for illustration in this section.

In calculating the marginal heat rate internally, most optimization program will also perform some estimation on the input data. For PLEXOS®, the heat input will be re-estimated by piece-wise linear segments where the number of segments (or tranches) are specified by the user. The higher the number of tranches, the better the heat input curve will be estimated. Mathematically, marginal heat rate can be calculated for each MW value as specified by user (sometimes as detailed as in 1MW interval). However, PLEXOS® provides an option for users to make best estimation of the detailed heat rate data into segments to achieve better computation efficiency. The processes involved are discussed in detail in the following section.

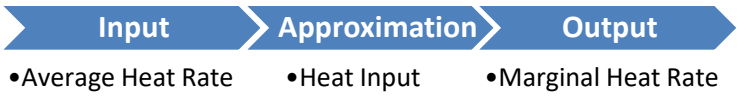

Figure 5: Process flow of heat rate modeling based on average heat rate input data

The step-by-step process is as follow:

i. Use average heat rate data as the input.
ii. Calculate the heat input data by multiplying each average heat rate point by its corresponding MW value. Note that the heat input data's unit is in kJ/h.
iii. Plot the heat input data against the MW values and best fit the heat input curve to a 3rd order of polynomial function[2] ($y = dx^3 + cx^2 + bx + a$).
iv. Determine the polynomial coefficients of a, b, c, d and verify against PLEXOS results.
v. Once verified, the next step is to re-estimate the heat input curve based on the number of tranches specified by user.
vi. Calculate the marginal heat rate by taking the slope ($\frac{dy}{dx}$) of the re-estimated heat input curve. The resulting values represent the marginal heat rate steps with SI unit of kJ/kWh.
vii. Check the tranche estimation error by comparing the fuel offtake results between estimated curve and the polynomial equation.

The following sections provide examples for each of the steps above using the data in Table 3.

Step ii: Calculate the heat input data by multiplying each average heat rate point by its corresponding MW value. Note that the heat input data unit in this example is in GJ/h.

Generation (MW)	Average Heat Rate (kJ/kWh)	Heat Input (GJ/h)
110	10,027	1,103
115	9,847	1,132
120	9,681	1,162
125	9,529	1,191
130	9,390	1,221
135	9,265	1,251
140	9,154	1,282
145	9,057	1,313
150	8,974	1,346
155	8,904	1,380
160	8,848	1,416
165	8,806	1,453
170	8,790	1,494

Table 4: Calculated heat input data for each MW point

Step iii: Plot the heat input data against the MW values and best fit the heat input curve to a 3rd order polynomial function $y = dx^3 + cx^2 + bx + a$ **.**

Figure 6 shows the plot of heat input data calculated in step ii (in blue) as an X-Y scatter chart[3] and its corresponding best fit to a 3rd order polynomial trendline (in black) with an R^2 value[4] of 1.

[2] For optimization process occurs in the software, PLEXOS will do the mathematical analysis up to 3rd order of polynomial function. Therefore, it is best to keep the same order of polynomial for external manual calculation for comparison.
[3] X-Y scatter graph differs from line graph in terms of data distribution. For more information, go to Microsoft Office Support: https://support.office.com/en-us/article/Present-your-data-in-a-scatter-chart-or-a-line-chart-4570a80f-599a-4d6b-a155-104a9018b86e
[4] If R^2 equals 1, it means that all points in the trendline will lie exactly on the original data points without scattering. This will help to predict Y values perfectly by knowing the value of X.

Important: If the R^2 value is poor, the heat rate input data must be reviewed and checked before proceeding to the next step.

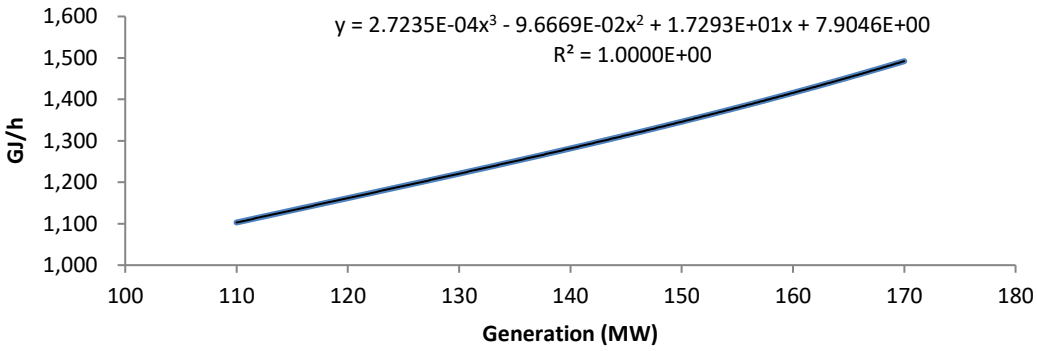

Figure 6: Plot of the heat input data and its 3rd order polynomial curve fit

Step iv: Determine the polynomial coefficients of $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}, \boldsymbol{d}$ and verify against PLEXOS results.

Based on the curve fit trendline equation shown in Figure 6, the polynomial coefficients of $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}, \boldsymbol{d}$ are: $d = 2.7235 \times 10^{-4}, c = -9.6669 \times 10^{-2}, b = 17.293, a = 7.9046$

The estimated polynomial coefficients based on curve fitting should be very close to the polynomial terms calculated by PLEXOS®. The figures are to be compared with the polynomial terms determined by PLEXOS, as shown in Table 5 below:

Polynomial Terms								
Name	Step	Pmin	Pmax	a	b	c	d	Point
Gen A	1	110	170	7.904615599	17.29337096	-0.096668931	0.000272354	4

Table 5: Coefficients from PLEXOS

Important: Be cautious in ensuring consistency of input data especially number of decimal points used in checking the model. Insufficient or inconsistent decimal points may result in different coefficients.

Step v: Once verified, the next step is to re-estimate the heat input curve based on the number of tranches specified by user.

For this example, the number of tranches is 4. The heat input curve will be re-estimated in steps from 0MW up to 170MW, with the first interval is between 0MW to minimum generation level and the remaining 3 intervals are equally spaced between the minimum and maximum generation level. This process will essentially reduce the generator model from 13 data points to only 4 points. Hence, as expected, some of the points in between will be approximated and may differ from the input data. This can be checked in the final step.

Important: Note that there is a point called "no-load heat input" which signifies the fuel requirement to keep the generator spinning without producing any electricity output. The value should not be zero or less than zero because a negative value means that the generator is actually "producing" fuel to run.

x	x_n	$y(x_n)$
0	X_0	7.9046
110	X_1	1102.98495
130	X_2	1220.70033
150	X_3	1346.05511
170	X_4	1492.12231

Table 6: Calculate corresponding heat input value based on 4 tranches

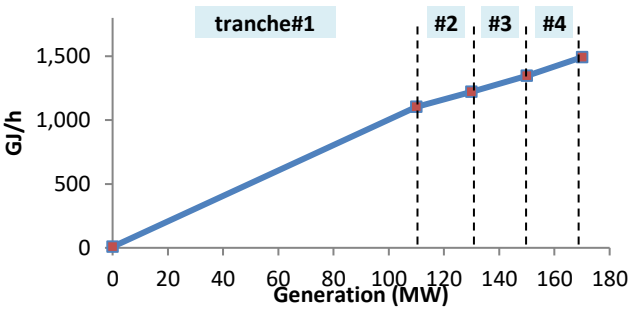

Figure 7: Plot of the re-estimated heat input data and its 3rd order polynomial curve fit

Step vi: Calculate the marginal heat rate by taking the slope ($\frac{dy}{dx}$) of each tranche in the re-estimated heat input curve. The resulting values represent the marginal heat rate steps with SI unit of kJ/kWh or GJ/kWh.

For this example, the number of tranches is 4. The slope between the intervals of x values are calculated and tabulated in Table 7. The corresponding values are shown in a chart form in Figure 8.

Important: As stated previously, an important characteristic of a good marginal heat rate is such that the points are monotonically increasing.

x	x_n	$y(x_n)$	$\frac{y(x_{n+1}) - y(x_n)}{x_{n+1}-x_n}$
0	X_0	7.9046	
110	X_1	1102.98495	9.95528
130	X_2	1220.70033	5.88577
150	X_3	1346.05511	6.26774
170	X_4	1492.12231	7.30336

Table 7: Calculated marginal heat rate steps based on 4 tranches

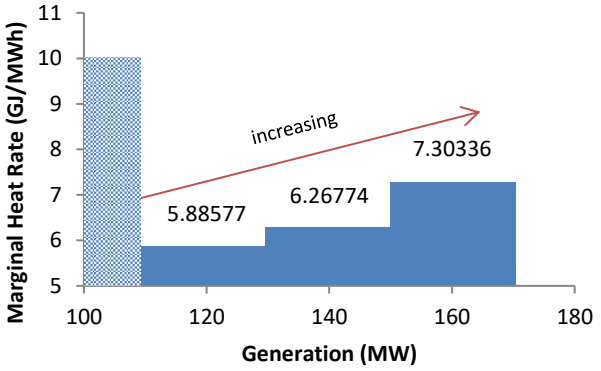

Figure 8: Plot of the marginal heat rate steps with 4 tranches

To confirm, the calculated values in Table 7 can be compared against PLEXOS® values in Table 8 below.

Stepwise Functions						
Name	Step	Sample	Point	Load (MW)	Avg. Incr.	Incr.
Gen A	1	1	1	110	9.955275722	9.955275722
Gen A	1	1	2	130	5.885769231	5.885769231
Gen A	1	1	3	150	6.267739261	6.267739261
Gen A	1	1	4	170	7.30335964	7.30335964

Table 8: PLEXOS marginal heat rate steps based on 4 tranches

Step vii: Check the tranche estimation error by comparing the fuel offtake results between estimated curve and the polynomial equation.

It is expected that re-estimation with lesser number of points (tranches) may lead to some inaccuracy from the input data. Hence, it is important to check that the tranche estimation is within reasonable deviation tolerance.

The fuel offtake for different generation levels can be calculated using the heat input estimation by PLEXOS and heat input from the 3rd order polynomial equation. Calculation example for generator output of 125MWh is shown below.

Calculation from polynomial equation:

$$y(x) = dx^3 + cx^2 + bx + a$$

Equation 2: 3rd order heat input polynomial equation

$$\begin{aligned} Fuel Offtake@125MW, y(x) &= dx^3 + cx^2 + bx + c \\ &= (2.7235 \times 10^{-4})\, x^3 + (-9.6669 \times 10^{-2})\, x^2 + 17.293x + 7.9046 \\ &= (2.7235 \times 10^{-4})(125)^3 + (-9.6669 \times 10^{-2})(125)^2 + 17.293(125) + 7.9046 \\ &= 1{,}191.01 GJ/h \end{aligned}$$

Estimation by PLEXOS:

$$PLEXOS estimation for XMW = NoLoad + MHR1(Tranche1 - 0) + MHR2(MW - Tranche1)$$

Equation 3: 3rd order heat input polynomial equation

$$\begin{aligned} Fuel Offtake@125MW &= NoLoad + MHR1 \times (110 - 0) + MHR2 \times (125 - 110) \\ &= 7.905 + 9.9553 \times (110) + 5.8858 \times (15) \\ &= 1{,}191.275 GJ/h \end{aligned}$$

Estimation error:

$$\%Error = \frac{(1{,}191.275 - 1{,}191.01)}{1{,}191.01} = 0.02\%$$

From the above example, we can see that the estimation with 4 tranches resulted in an error in fuel offtake by 0.02%.

Important: This check must be performed at various MW points of the curve.

- End of Section -

3. Appendix

3.1 Appendix 1: Economic dispatch example

The following example illustrates an economic dispatch problem to achieve an optimized, least cost dispatch to meet demand.

Demand: A small system demand profile is shown below. Demand at 1300hrs is selected to perform all calculations here.

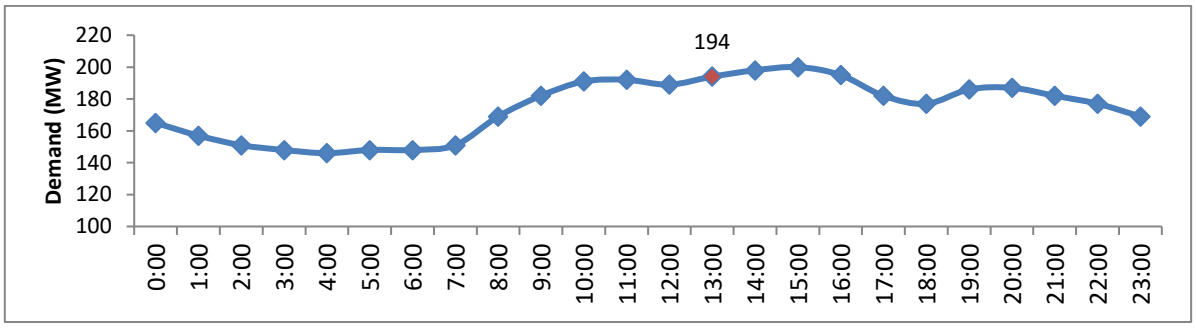

Figure 9: 24-hour demand profile for test system

Generation Capacity: The system consists of 9 generators with total capacity of 232MW. Detail data for each generator, i.e. heat rates, Variable Operating Rate (VOR), fuel type and fuel prices are shown in table below.

Plant	Capacity	Heat Rate (kJ/kWh)				VOR	Fuel	
	MW	100%	75%	50%	25%	sen/kWh	Type	RM/GJ
A1	50	10,100	10,500	11,200	NA	1.30	Coal	13.63
A2	40	10,700	11,200	11,700	NA	1.35	Coal	15.17
B1	35	7,700	8,100	8,600	NA	1.98	Gas	23.70
B2	40	7,000	7,500	8,000	8,200	1.62	Gas	23.70
C1	15	12,000	12,360	12,731	15,000	1.20	Gas	23.70
C2	15	11,000	11,330	11,670	13,800	1.15	Gas	23.70
D1	15	12,500	12,875	13,261	14,600	1.00	Gas	23.70
D2	10	10,600	10,918	11,246	11,583	1.10	Gas	23.70
D3	12	12,500	12,875	13,,261	14,600	1.25	Gas	23.70
Total Capacity	**232**							

Energy Cost: To achieve a least cost solution to meet demand of 194MW, the generator data above is to be converted to energy cost. The full cost data are tabulated below for all plants at all generation levels. Sample calculation of fuel cost and energy cost for Plant A1 at 100% generation level are shown here.

$$FuelCost@100\% = HeatRate@100\% \times Fuel\ Price$$
$$= 10{,}100\frac{kJ}{kWh} \times \frac{GJ}{10^6 kJ} \times 13.63\frac{RM}{GJ} \times \frac{100\ sen}{RM}$$
$$= 13.77 sen/kWh$$

$$Energy\ Cost@100\% = FuelCost@100\% + VOR\ Cost$$
$$= 13.77 + 1.30$$
$$= 15.07 sen/kWh$$

Plant	Capacity	VOR	Fuel Price	Fuel Cost (sen/kWh)				Energy Cost (sen/kWh)			
	MW	sen/kWh	RM/GJ	100%	75%	50%	25%	100%	75%	50%	25%
A1	50	1.30	13.63	13.77	14.31	15.27	NA	15.07	15.61	16.57	NA
A2	40	1.35	15.17	16.23	16.99	17.75	NA	17.58	18.34	19.10	NA
B1	35	1.98	23.70	18.25	19.20	20.38	NA	20.23	21.18	22.36	NA
B2	40	1.62	23.70	16.59	17.78	18.96	19.43	18.21	19.40	20.58	21.05
C1	15	1.20	23.70	28.44	29.29	30.17	35.55	29.64	30.49	31.37	36.75
C2	15	1.15	23.70	26.07	26.85	27.66	32.71	27.22	28.00	28.81	33.86
D1	15	1.00	23.70	29.63	30.51	31.43	34.60	30.63	31.51	32.43	35.60
D2	10	1.10	23.70	25.12	25.88	26.65	27.45	26.22	26.98	27.75	28.55
D3	12	1.25	23.70	29.63	30.51	31.43	34.60	30.88	31.76	32.68	35.85

Table 9: Fuel cost and energy cost for all plants

Merit Order List: As decribed in section 1.1, the MOL for the 9-generator system is as listed in the table below. To meet demand at 194MW, the generating units that will be committed is from Plant A1 up to Plant C2.

Plant	Capacity (MW)	Energy Cost (sen/kWh)	Cumulative MW
A1	50	15.07	50
A2	40	17.58	90
B2	40	18.21	130
B1	35	20.23	165
D2	10	26.22	175
C2	15	27.22	190
C1	15	29.64	205
D1	15	30.63	220
D3	12	30.88	232

Table 10: Merit Order List for 9-generator system

Least Cost Dispatch: The cheapest unit to meet additional 4MW based on MOL above is Plant C1. To check if this is consistent at all generating levels, the energy cost for Plant C1,D1 and D3 are drawn in the chart below. As the figure shows, C1 is the cheapest unit for generation output beyond 8MW. For 4MW, Plant D3 is the least cost and should be selected to serve the demand.

To further check this solution, total generation cost between the two possible solutions can be calculated accordingly. As expected, the option with Plant D3 gives the lower total generation cost by RM163 or 0.44% as compared to the option of Plant C1.

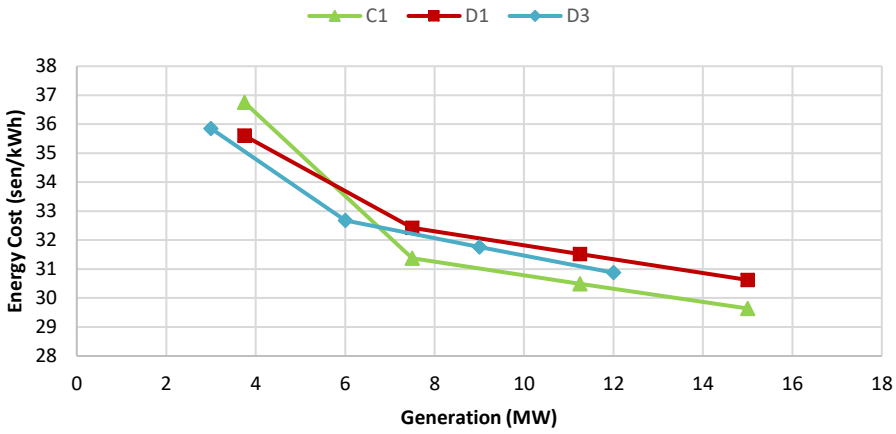

Figure 10: Energy cost for Plants C1, D1 and D3 at corresponding generation level

Based on MOL

Plant	MW Schedule	MW Capacity	Energy Cost (sen/kWh)	Total Cost (RM)
A1	50	50	15.07	7,533
A2	40	40	17.58	7,033
B2	40	40	18.21	7,284
B1	35	35	20.23	7,080
D2	10	10	26.22	2,622
C2	15	15	27.22	4,083
C1	4	15	36.75	1,470
Total	194	205		**37,105**

Based on UCED

Plant	MW Schedule	MW Capacity	Energy Cost (sen/kWh)	Total Cost (RM)
A1	50	50	15.07	7,533
A2	40	40	17.58	7,033
B2	40	40	18.21	7,284
B1	35	35	20.23	7,080
D2	10	10	26.22	2,622
C2	15	15	27.22	4,083
D3	4	12	32.68	1,307
Total	194	202		**36,942**

Table 11: Comparison of generation cost calculation

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