Jurnal Ekonomi Malaysia 47(1) 2013 125 - 130

Modeling of the Malaysian Crude Oil System

(Pemodelan Sistem Minyak Mentah Malaysia)

Ahmad Mohd Yusof
Fakulti Ekonomi dan Pengurusan
Universiti Kebangsaan Malaysia

Maznah Banu Mohamed Habiboo Raman
Zulkifli Mohd Nopiah
Fakulti Kejuruteraan dan Alam Bina
Universiti Kebangsaan Malaysia

ABSTRACT

As a part of energy planning, Malaysia is developing a long term energy model as a tool to manage its natural resources. The purpose of paper is to present the preliminary results obtained from optimizing the initial model. Being a net exporter of crude oil, Malaysia exports its crude oil and compressed natural gas, as well as imports crude oil and coal to satisfy its own energy needs. At the earlier stage of model development, the crude oil system is cast as an energy flow network model tracing its flow from extraction sources or imports; and following the flow through conversion and transformation processes; and, ultimately, distribute its end products to the final demand sectors. The preliminary results of the model indicate that the extraction and the import of several petroleum products show erratic behavior and, thus, such irregularity should be overcome before adding further energy systems to the model.

Keywords: Crude oil; petroleum products; energy; energy planning; linear programming

ABSTRAK

Sebagai sebahagian daripada perancangan tenaga, Malaysia kini sedang membangunkan sebuah model tenaga berjangka masa panjang sebagai satu alat bagi menguruskan sumber-sumber aslinya. Tujuan kertas ini adalah untuk membentangkan keputusan awal yang diperolehi daripada mengoptimumkan model awal. Sebagai pengeksport bersih minyak mentah, Malaysia mengeksport minyak mentah dan gas asli termampat, serta mengimport minyak mentah dan arang batu untuk memenuhi keperluan tenaganya sendiri. Pada peringkat awal pembangunan model ini, sistem minyak mentah diacu sebagai model rangkaian aliran tenaga mengesan aliran dari sumber pengeluaran atau import; dan mengikut aliran melalui penukaran dan perubahan proses; dan akhirnya, mengedar produk akhir kepada sektor permintaan akhir. Keputusan awal model menunjukkan bahawa pengeluaran dan import beberapa produk petroleum menunjukkan satu tingkah laku yang tidak menentu , oleh itu, ketidaktentuan itu harus diatasi sebelum menambah sistem tenaga kepada model yang ada

Kata kunci: Minyak mentah; produk petroleum; tenaga; perancangan tenaga; pengaturcaraan linear

INTRODUCTION

Natural resources are known as assets of a country. Malaysia possesses a considerable amount of crude oil and natural gas reserves that could be readily exploited them in an attempt to move the country to a higher level of development. One of the crude oil blends discussed in the present paper is the Tapis Blend, which Malaysia had been extracting for the past 60 years. Furthermore, Malaysia is currently actively pursuing new crude oil and natural gas reservoirs. Most Malaysian crude oil is extracted from offshore wells and contains low sulfur (Tapis Blend), a mark of the high quality of any type of crude oil. The Tapis blend is primarily exported, while Malaysia imports lower quality crude oil to meet local demand. At present, Malaysia has 6 refineries with a combined capacity of 544,832 barrels per day. Three of the refineries are owned by Petroliam Nasional Berhad (PETRONAS), a company wholly owned by the Malaysian government. PETRONAS had been empowered by the Malaysian government to control all its hydrocarbon resources, in particular the crude oil and natural gas (Annual Report Petronas 2009).

The demand for final commercial energy in Malaysia has increased over the past ten years. In 2000, the final commercial energy demand stood at 1243.7 Peta Joule (PJ), or 29.76 million ton of oil equivalent (MTOE), which increased to 1631 PJ in 2005 (38.9 MTOE) and further increased to 2217PJ (52.98 MTOE) in 2010,following an annual growth rate of 6.3%. The demand sectors for petroleum products in Malaysia are classified as industrial; transportation; residential and commercial; agriculture and forestry; and the non-energy sector. In 2000, the transportation sector consumed 40.6 % of the final commercial demand, followed by the industrial sector (38.4%). The residential and commercial sector consumed 13.0 % of the final commercial energy, while the non-energy sector consumed 7.6% of the final commercial energy in 2000.According to 9th Malaysia Plan, the percentage of energy consumption by sectors did not vary significantly from its 2000 year level in 2010. Accordingly, final demand for commercial energy is still projected higher throughout the 10th Malaysia Plan with an emphasis on green energy (9th Malaysia Plan). Table 1 shows the final commercial energy demand and its annual growth rates by sector.

The objective of the present paper is to report the preliminary results on crude oil extraction behavior and the pattern of imports on petroleum products when the objective function used is the maximization of the sectoral demands for the petroleum products. Thus, a linear programming (LP) algorithm is used as an optimization technique, which allows a 'what if' analysis to be performed. Such analysis is the essence of energy scenario planning studies. Furthermore, the LP model provides the flexibility of adding (deleting) any energy system to (form) the model without undergoing major structural changes to the model. For example, Malaysia desires to acquire nuclear energy by year 2020 and, by using the LP model, that energy subsystem could later be included in the model.

LITERATURE REVIEW

The demand for petroleum and its products is linked to the growth of a country's economy. This is the case in the Gulf Cooperative Council (GCC) countries where the total consumption of petroleum products increased by 97 MTOE over a period of 17 years (Al-Faris 1997). At present, the highest percentage of increase in energy demand stems from China and India (Leder 2008).Leder further predicts that, at the present rate of increase, China will import millions of barrels of oil daily. Li et al. (2010) find that the total energy consumption in Shanghai increased rapidly between 1995 and 2006, identifying the industry and construction sectors as the highest consumers. In India, the annual growth for motor gasoline demand has been over 7 % with the highest consumption being in the form of transport fuel. The growth in demand for petroleum products in Indiasis expected to continue due to the increase in economic activities under economic reforms (Ramanathan 1999). Sharma et al. (2002) further elaborate the high and ever increasing demand for petroleum products has become a crucial issue for energy planners and policy makers. Similarly,in Iran, Jafari (2008) reports that the consumption of motor gasoline in the year of 2005 alone increased by 10.2 % compared with the previous year. Turkey is facing a similar problem with its continuously increasing oil consumption despite the fact it has been importing petroleum to meet its needs for the past few years (Canyurt 2008). South Korea faced high demand for petroleum due to economic growth in the late 1980s and early 1990s, while at present demand is expanding at a slower pace. Still, South Korea is expected to increase its final energy demand from 150.4 MTOE to 314.5 MTOE during the period between 1995 and 2020 (Moon 1997). South Korea has also made plans to increase oil refinery capacity to meet increasing demand in the country for crude oil and petroleum products (Koyama 1997). Abdul Hamid et al. (2008) find a positive correlation between gross domestic product (GDP) growth and energy demand in Malaysia.

The global oil crises of the 1970s and 1980s prompted several countries and energy institutes to develop energy models of varying structures and objectives to fulfill national and regional energy demands. These energy models can be broadly classified into the following categories:

1. Single Fuel Models : World Energy Modeling, World Petroleum Modeling, and Simulation of Future Oil Flow.
2. Multi-Fuel Models : New Zealand's Energy Systems, ENERGETICOS (Mexican Energy System), Energy

TABLE 1. Final Commercial Energy Demands by Sector

Source	PJ			% of Total			Average Annual Growth Rate (%)
	2000	2005	2010	2000	2005	2010	
Industrial	477.6	630.7	859.9	38.4	38.6	38.8	6.4
Transportation	505.5	661.3	911.7	40.6	40.5	41.1	6.6
Residential and Commercial	162.0	213.0	284.9	13.0	13.1	12.8	6.0
Non-Energy	94.2	118.7	144.7	7.6	7.3	6.6	4.0
Agriculture and Forestry	4.4	8.0	16.7	0.4	0.5	0.8	15.9
Total	1,243.7	1,631.7	2,217.9	100.0	100.0	100.0	6.3

Source: 9th Malaysia Plan

Flow Optimization Model (EFOM) and Market Allocation (MARKAL).
3. Multi-Fuel Models with link to Economic Model: US Energy Policy and Economic Growth Model, Energy Technology Assessment Macro Economic Growth (ETA-MACRO) and others.
4. Multi-Fuel Models with link to Economic and Environment Model: Energy Environment Economy Model of Europe (E3ME), World Energy Model-Economic (WEM-ECO) Model and others.

The Malaysian government, during the aftermath of the first world energy crisis in 1973-1974, declared energy to be a major and vital economic commodity and established PETRONAS to enable the government to replace the traditional petroleum concessionary system with a production sharing contract system. The move complemented Malaysia's national energy policy, which gave top priority to domestic hydro carbon resources for satisfying national energy needs. Under the national energy policy, various strategies were developed, including the National Depletion Policy of 1980; the Fuel Diversification Policy of 1981 and 1989; and the Fifth Fuel Policy, which established biomass as an important energy of the country. Such policies were implemented to ensure an adequate energy supply, while promoting efficient energy consumption.

DATA AND METODOLOGY

SCOPE OF THE MODEL

The energy model used in the present study is derived from the market allocation model (MARKAL) which was jointly developed by the Brookhaven National Laboratory (BNL) and Kernforschungsaulage (KFA) (a German Energy institute); and is used in over 50 countries to study and review national and regional energy policies. Figure 1 illustrates the structure of the Malaysian energy model. Primary energy carriers, such as crude oil, natural gas, coal and renewable energy, in the energy supply module are processed (conversion and transformation) in the energy conversion and technology module before being distributed as final products, in the form of electricity and motor gasoline, to the economic and energy demand sectors for final consumption. The extraction, import and export process for all primary energy carriers are included in the energy supply module. Interface modules consist of economic, environmental and energy demand sub-modules; and all of these modules are inter-linked.

At the current phase of the model development, the focus is on one type of energy carrier that is crude oil named as Tapis Blend which is extracted off shore coast of Malaysia. In the conversion and technology module, crude oil is processed through basic refinery activities, known as topping process, to produce a variety of basic petroleum products such as diesel, raw gas, naptha, fuel oil, kerosene and bitumen. Further refinery activity includes the hydro skimming process where product inputs, such as naptha and raw gas, are hydro skimmed to produce motor gasoline and liquefied petroleum gas (LPG), respectively. In this module, the export and import of petroleum products is allowed in order to satisfy energy needs at a given time. Upon entering the interface module, in particular the energy demand sub-module, the products will be distributed according to the demand sectors identified above. By modeling the energy system according to the network flow theory, the model will generate a positive feedback loop among the modules in the model. Specifically, if there is an increase in demand for the motor gasoline in the transportation

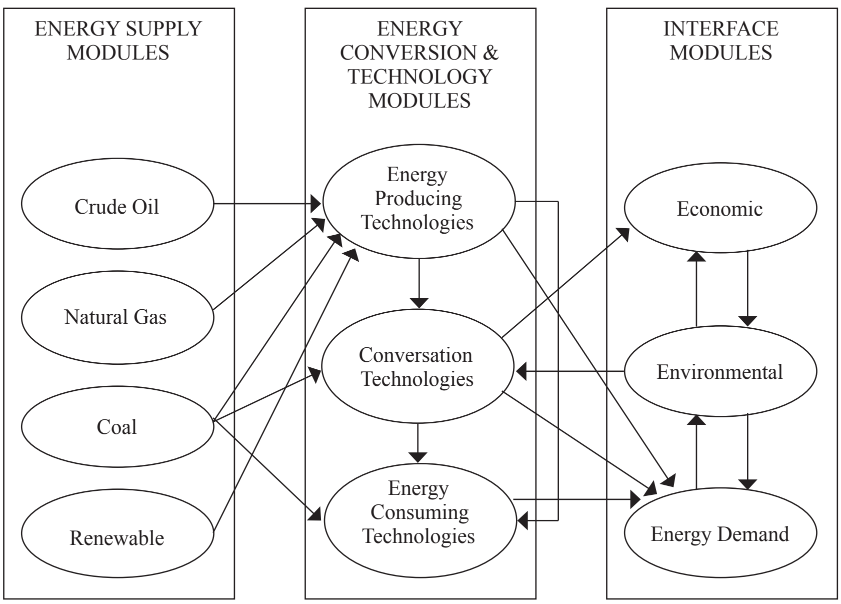

FIGURE 1. The Framework of Malaysia Energy Model

sector, then the system will activate the conversion and technology module to increase the production of naptha or motor gasoline, which, in turn, will activate the energy supply module to extract more crude oil. Alternatively, the conversion and technology module will increase the import of the products if that proved to be optimal.

MATHEMATICAL EQUATIONS OF THE MODEL

The general form of the m (constraints) by *n* (variables) LP model is cast as follows:

$$\text{Max(min)} \sum_j c_j x_j$$
$$\ni$$
$$\sum_i a_{i,j}\, x_j = b_i$$
$$x_j \geq 0$$

Where x_j represents decision variables, while $c_j x_j$ is the linear objective function and $a_{ij} x_j = b_i$ are a set of linear constraints, where $i \in \{1,\ldots m\}$ and $j \in \{1,\ldots n\}$. Thus, in this model, the energy system is formulated as a LP model with a number of constraints and variables dependent on the number of crude oil types, production and conversion processes, the demand sectors; and the optimization time periods. To facilitate the discussion of the equation, variable *R*(, , ,) and process *P*(, , ,) are defined by crude oil type *i*, time *t*, and three abbreviated letter representing a particular process. For example, *R*(*i*,*t*,MIN) represents the flow of crude oil type *i* at time t from the mining operation (MIN). Similarly, the same interpretation is also applied to input coefficient *i*(, , ,) and output coefficient *o*(, , ,)to and from any production and conversion process. Some of the major equations of the model are presented below.

The first component of the model is the mining (extraction) of crude oil from its sources and distribution to refineries for processing. This is represented by the following equation:

$$R(i,t,\ \mathit{MIN}) - R(i,t,\ \mathit{EXP}) \geq i(i,t,\ \mathit{TOP})\ P(i,t,\ \mathit{TOP})\text{----} \qquad (1)$$

Equation (1) represents the amount of crude oil from mining activity, less exports, that undergoes the topping process *P(i,t,TOP)*, which is constrained by the input coefficient *i(i,t,TOP)*. Variables *R(i,t, MIN)* and *R(i,t, EXP)* represent the amount of crude oil mined (MIN) and exports (EXP), respectively.

Two of the products from topping process, namely naphtha and raw gas, must undergo a second process called hydro skimming for the production of motor gasoline and LPG, respectively. This is represented by the following equation:

$$o(i,t,\mathit{TOP})\ P(i,t,\mathit{TOP}) + R(i,t,\mathit{IMP}) \geq i(i,t,\mathit{HYD})\ P(i,t,\mathit{HYD}) + R(i,t,\mathit{EXP})\text{----} \qquad (2)$$

Equation (2) mathematically expresses the hydro skimming process of product *i* naphtha and raw gas. In this model, naphtha can be exported or imported if the need arises, but this is not possible with raw gas obtained from domestic refineries.

The third component is the process of distributing petroleum products *i P(i,t,DEM)* to the demand sectors. For each demand sector, the following equation represents the sale of petroleum products after taking into account of the export and import of the products.

$$o(i,t,\mathit{TOP})P(i,t,\mathit{TOP}) + R(i,t,\mathit{IMP}) \geq i(i,t,\mathit{DEM})\ P(i,t,\mathit{DEM}) + R(i,t,\mathit{EXP})\text{---} \qquad (3)$$

Under the network flow theory, the equations previously discussed fall into the category of material balance equations in the sense that the energy content of a particular energy carrier after undergoing some conversion and technological processes will transform the energy carrier into different energy products with the same energy content. Specifically, the model assumes the conservation of flow to and from any node exists in this energy model. For example, one barrel of crude oil with an energy content of 6.1 Gigajoule will produce six basic products with a combined total energy content of 6.1 Gigajoule after undergoing topping processes. In some cases, processing or technological losses may be accounted for. Other equations of the model include the refinery capacity constraints; crude oil resource availability; demand for petroleum products; and the minimum current crude oil extraction level.

The objective function used in this study is the maximization of the intertemporal sectoral demands for petroleum products. Mathematically, the objective function is written as follows: the maximization of $\sum_t \sum_i R(i,t,\mathit{DEM})$ where *i* represents all petroleum products, *t* time period of 1 year to 5 years and DEM the demand sectors.

FINDINGS AND DISCUSSION

The model is optimized for 3, 5 and 10 time periods. The output coefficients from the refinery are used to calculate the product outputs, which are dependent upon the quality of crude oil. A matrix generator from the LP routine is used to generate the equations and variables of the model. For the three period model, a total of 126 variables and 103 constraints (excluding the non-negativity constraints) are generated, while for the five period the corresponding variables and constraints are 210 and 171 respectively. The data used in this study is obtained from National Energy Balance which was provided annually by the Energy Commission of Malaysia. As the optimization period increases, the number of variables and constraints increases accordingly.

EXTRACTION OF CRUDE OIL

In Malaysia, the extraction of crude oil is performed offshore where a few different blends of crude oil are

TABLE 2. Extraction of Crude Oil (PJ)

Optimization Period	t									
	1	2	3	4	5	6	7	8	9	10
3	1034	1034	1034	-	-	-	-	-	-	-
5	4896	4896	4896	4896	4896	-	-	-	-	-
10	18496	1034	1034	1034	1034	369	369	369	369	369

extracted. However, in this model, only Tapis Blend is selected since it has largest reserve. Table 2 shows the value of the crude oil extracted.

With the three period optimization, the amount of crude oil extracted is at a level of 1034 PJ for $t = 1, 2, 3$. However, when the optimization period increases to five, the extraction level increases to 4896 PJ at $t = 1$ and remains at that level until $t = 5$. When the period increases to ten, erratic behavior in the extraction level is observed with a maximum extraction level of 18496 PJ at $t = 1$ and a drastic drop to 1034 PJ at $t = 2, 3, 4$, and 5.The extraction level drops further to 369 PJ at $t = 6, 7, 8, 9$ and 10. One interesting observation is that when the optimization period equals 10, the model exhausts all its available resources, while at periods three and five there are leftovers in the crude oil reserves.

IMPORTS OF PETROLEUM PRODUCTS

The projections concerning the import of petroleum products indicate no import for three petroleum products, namely naphtha, kerosene and bitumen. Other petroleum products that have some imports projections are shown in Table 3. Motor gasoline and LPG show erratic behavior in import projections, especially at $t = 3, 4, 5$ for the five period model. For the five period model, diesel is imported at $t = 5$ at a level of 9.4 PJ, while the overall import pattern is quite unreasonable for the ten period model.

TABLE 3. Import of Petroleum Products (PJ)

Optimization Period		Petroleum Products			
		Diesel	Fuel Oil	LPG	Mogas
t= 3	t= 1	0	0	0	39.5
	t=2	0	0	0	47.6
	t=3	0	0	0	55.9
t=5	t= 1	0	0	43.9	39.5
	t=2	0	0	4.0	47.6
	t=3	0	0	5.1	55.9
	t= 4	0	0	25.5	156.4
	t=5	9.4	0	7.5	72.5
t=10	t= 1	0	0	43.9	262.3
	t=2	0	0	46.2	278.9
	t=3	0	0	48.5	55.9
	t= 4	0	0	50.9	64.2
	t=5	9.4	0	53.2	72.5
	t=6	0	6.1	80.5	112.3
	t=7	0	6.2	82.5	116.2
	t=8	3.8	6.9	84.8	121.8
	t=9	93.9	7.6	36.7	127.3
	t=10	363.9	8.3	37.9	231.1

CONCLUSION AND IMPLICATIONS

At this stage of model development, the results obtained suffer from a lot of inconsistencies in regards to real data. As expected, the major problem is the erratic behavior of some of the model's variables: common feature in practical linear programming optimization. This is reflected in the results obtained for the extraction of crude oil, as well as for the imports of the petroleum products. Future research on the model should focus on the correction of this erratic behavior, as well as specifying an objective function that truly reflects the national energy policy. As the development of the model proceeds, more energy carriers could be added to the model. It is the modest aim of the researchers to develop an energy model that can be used as a tool for future energy planning in Malaysia.

REFERENCES

Abdul Hamid Jafar, Al-Amin A.Q., Siwar C. 2008. Environmental impact of alternative fuel mix in electricity generation in Malaysia. *Renewable Energy* 33: 2229-2235

Abdul Rahman Mohamed, Keat T. L. 2006. Energy for sustainable development in Malaysia: Energy policy and alternative energy. *Energy Policy* 34: 2388-2397.

Al-Faris Abdul-Razak. 1997. Demand for oil products in the GCC countries. *Energy Policy* 25: 55-61.

*Petronas. 2009. *Annual Report 2009.* http://www.petronas.com.

Bhattacharyya, S., Blake, A. 2009. Domestic demand for petroleum products in MENA countries. *Energy Policy* 37: 1552-1560.

Bhattacharyya, S. C., Timilsina, G. R. 2010. Modelling energy demand of developing countries: Are the specific features adequately captured? *Energy Policy* 38: 1979-1990.

Canyurt O. E., Ozturk H. K. 2008. Application of genetic algorithm (GA) technique on demand estimation of fossil fuel in Turkey. *Energy Policy* 36: 2562-2569.

Ghosh, S. 2006. Future demand of petroleum products in India. *Energy Policy* 34: 2032-2037.

Huntington, H. G. 2010. Short- and long-run adjustments in U.S. petroleum consumption. *Energy Economics* 32: 63-72.

Iwayemi, A., Adenikinju, A., Babatunde, M. A. 2010. Estimating petroleum products demand elasticities in Nigeria: A multivariate cointegration approach. *Energy Economics* 32: 73-85.

Jafari, H. H., Baratimalayeri, A. 2008. The crisis of gasoline consumption in the Iran's transportation sector. *Energy Policy* 36: 2536-2543.

Koh S. L. & Lim Y. S. 2010. Meeting energy demand in a developing economy without damaging the environment – A case study in Sabah, Malaysia, from technical, environmental and economic perspectives. *Energy Policy* 38: 4719-4728.

Koyama, Y. & Ogawa, Y. 1997. Prospects of petroleum products trades by ROK/Taiwan/Singapore: tougher environmental standards and changes in product imports/exports. *Energy Policy* 25: 259-265.

Leahy, E. & Lyons, S. 2010. Energy use and appliance ownership in Ireland. *Energy Policy* 38: 4265-4279.

Leder, F. & Shapiro, J. N. 2008. This time it's different An inevitable decline in world petroleum production will keep oil product prices high, causing military conflicts and shifting wealth and power from democracies to authoritarian regimes. *Energy Policy* 36: 2850-2852.

Lee C. L., Kok T. T., Keat T. L. & Abdul Rahman Mohamed. 2009. An comparative study on the energy policies in Japan and Malaysia in fulfilling their nations' obligations towards the Kyoto Protocol. *Energy Policy* 37: 4771-4778.

Leesombatpiboon, P. & Joutz, F. L. 2010. Sectoral demand for petroleum in Thailand. *Energy Economics* (2010), doi:10.1016/j.eneco.2010.07.006.

Li, L., Chen, C., Xie S., Huang, C., Cheng, Z., Wang, H., Wang, Y., Huang, H., Lu, J. & Dhakal, S. 2010. Energy demand and carbon emissions under different development scenarios for Shanghai, China, *Energy Policy* 38: 4797-4807.

Moon, Y-S. 1997. The outlook of the Korean petroleum industry and its deregulation process. *Energy Policy* 25(12): 983-988

Nava, M., Gasca, J., Gonzales, U. 2006. The energy demand and impact by fossil fuels use in the Mexico City Metropolitan Area, from 1988 to 2000. *Energy* 31: 3381-3390.

Odhiambo, N. M. 2010. Energy consumption, prices and economic growth in three SSA countries: A comparative study. *Energy Policy* 38: 2463-2469.

Ozturk I., Aslan, A. & Kalyoncu, H. 2010. Energy consumption and economic growth relationship: Evidence from panel data for low and middle income countries. *Energy Policy* 38: 4422-4428.

Parikh, J., Purohit, P. & Maitra, P. 2007. Demand projections on petroleum products and natural gas in India. *Energy* 32: 1825-1837.

Parshall, L., Gurney, K., Hammer, S. A., Mendoza, D., Zhou, Y. & Geethakumar, S. 2010. Modelling energy consumption and CO_2 emissions at the urban scale: Methodological challenges and insights from the United States. *Energy Policy* 38: 4765-4782.

Peck, Y.G. & Zhi Dong, L. 2008. An Econometric study on long-term energy outlook and the implications of renewable energy utilization in Malaysia. *Energy Policy* 36: 890-899.

Pedregal, D. J., Dejuan, O., Gomez, N. & Tobarra M. A. 2009. Modelling demand for crude oil products in Spain. *Energy Policy* 37: 4417-4427.

Rancangan Malaysia Kesembilan. 2006-2010. *Unit Perancang Ekonomi*. Putrajaya: Unit Perancangan Ekonomi.

Ramanathan, R. 1999. Short and long-run elasticities of gasoline demand in India: An empirical analysis using cointegration techniques. *Energy Economics* 21: 321-330.

Rao, R. D. 2002. Modeling optimal exploitation of petroleum resources in India. *Resources Policy* 28: 133-144.

Rao, R. & Parikh, J. K. 1996. Forecast and analysis of demand for petroleum products in India. *Energy Policy* 24: 583-592.

Tick, H. O., Shen, Y. P. & Shing, C. C. 2010. Energy policy and alternative energy in Malaysia: Issues and Challenges for sustainable growth. *Renewable and Sustainable Energy Reviews* 14: 1241-1252.

Sharma, D. P., Nair, C. P. S. & Balasubramanian, R. 2002. Demand for commercial energy in the state of Kerala, India: An econometric analysis with medium-range projections *Energy Policy* 30: 781-791.

Zhang, M., Mu, H., Li, G. & Ning, Y. 2009. Forecasting the transport energy demand based on PLSR method in China. *Energy* 34: 1396-1400.

Ahmad Mohd Yusof
Fakulti Ekonomi dan Pengurusan
Universiti Kebangsaan Malaysia
43600 Bangi Selangor
Malaysia
ahmadf@ukm.my

Maznah Banu Mohamed Habiboo Raman
Kejuruteraan Mekanik Bahan
Fakulti Kejuruteraan dan Alam Bina
Universiti Kebangsaan Malaysia
43600 Bangi, Selangor
Malaysia
maznahbanu@yahoo.co.uk

Zulkifli Mohd Nopiah
Unit Pengajian Asas Kejuruteraan
Fakulti Kejuruteraan dan Alam Bina
Universiti Kebangsaan Malaysia
43600 Bangi, Selangor
Malaysia
zmn@vlsi.eng.ukm.my