Multi-Criteria Generation Optimal Mix Planning for Malaysia’s Additional Capacity

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Abstract**—**In August 2010, the Malaysian government announced that an additional 2000MW needs to be constructed to meet the projected electricity demand in Peninsular Malaysia. The proposed generation technology for the 2000MW capacity is coal technology. This paper considers other generation technology options, namely nuclear, solar thermal and biomass. These four technologies, along with coal technology will be compared based on three criteria, economic cost, reliability and socio-environmental cost. The proposed comparison algorithm is the two-phase K-best dynamic programming trade-off method.

Keywords**—** Multi-criteria decision making, nuclear energy power systems, generation optimal mix planning, renewable energy.

I. Introduction

In recent years, the industrialization of developing countries in Asia has resulted in massive growth of electricity demand in the region. Secure and sufficient electricity supply is essential to support socio-economic growth. Yet, increased electricity production adversely affects the environment with problems like waste and air pollution. Consequently, there is a need to find a healthy balance between providing electricity that is affordable but still adequately reliable and socio-environmentally responsible.

Generation optimal mix planning is one aspect of electricity production in which a healthy balance plays an important role. The choice of which technology to include in the generation mix is essential, yet difficult since each technology has its own advantages and disadvantages.

This paper proposes an algorithm for solving the electricity generation mix problem. The algorithm is the two-phase K-best dynamic programming trade-off method, where the three criteria to be met are economic, reliability and socio-environmental.

K-best dynamic programming was developed to be an advanced version of the extended dynamic programming method first introduced by the authors in [1]. Whereas extended dynamic programming provides a single optimal solution to the problem, K-best dynamic programming is capable of supplying a solution set. The solution set consists of the best solution, the next best solution, and the following best solution up to the K-th best solution. A set of solutions is useful in this application to provide a number of profiles to be compared. In this paper, the K-best dynamic programming method is used in Phase I of the algorithm to form least cost solution profiles made up of combinations of candidate generation technologies.

In Phase II, based on the results of Phase I, first the expected energy generated by each unit is evaluated by the effective energy function approach (EEF) presented in [2]. From there, the corresponding values of reliability and socio-environmental costs for each solution profile is calculated.

Finally, the solution profiles available can be ranked on how well the solution profile meets all three objectives and the best profile is chosen.

The case study analyzed in this paper was inspired from the cancellation of the submarine cables from the Bakun Hydroelectric Project. In 1994, to harness the available hydro potential in Sawawak, construction began for a large-scale 1600MW hydro power plant that came to be known as the Bakun Hydroelectric Project. Its original purpose was to supply electricity to the Peninsular Malaysia via two 800 MW submarine cables in the South China Sea.

However, in August 2010, the Malaysian Minister for Energy, Green Technology and Water announced that the transmission cable project has been cancelled. The expected construction of smelting plants in Sarawak and the vulnerabilities of an undersea transmission cable have been cited as the cause. Instead, a different generation plan consisting of a few generation units with a combined capacity of 2000MW will be constructed on Peninsular Malaysia to meet local electricity needs [3].

Therefore, this paper analyses fourteen different generation plans that are capable of generating the 2000MW capacity required. The generation plans consist of different combinations of four type of generation technologies including coal, nuclear, solar thermal and biomass. The objective is to determine the plan that best balances the three criteria of economic cost, reliability and socio-environmental effects.

II. Malaysia Historical and Electrical Background

Malaysia is a developing country in South East Asia with a population of approximately 28 million people. It has a land area of 329,733 km2 with two distinct parts separated by the South China Sea. The western part is known as the

Peninsular Malaysia and the eastern part which is situated on the Borneo Islands. The eastern part consists of two states, Sabah and Sarawak [4]. Malaysia shares its borders with Singapore, Thailand, Indonesia and Brunei.

Fig. 1: Map of Malaysia [4]

Since 2002, Malaysia has been experiencing consistent economic growth with a gross domestic product (GDP) growth of about 5% annually as reflected in Fig. 2. Statistically, every 1% growth in GDP is accompanied by a 1.2-1.5% in electricity consumption growth [5].

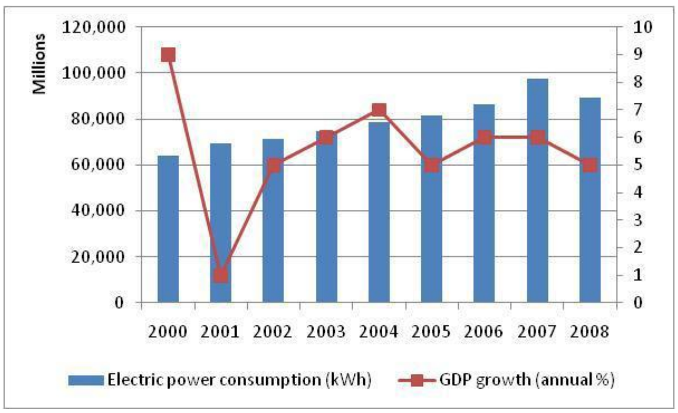

Fig.2 GDP and Electricity Consumption [6]

In order to meet this demand, Malaysia has an installed capacity of 23189 MW, in which 21117 MW is installed in the Peninsular, 835 MW in Sabah and 1237 MW in Sarawak [4]. The current generation mix is shown in Fig. 3.

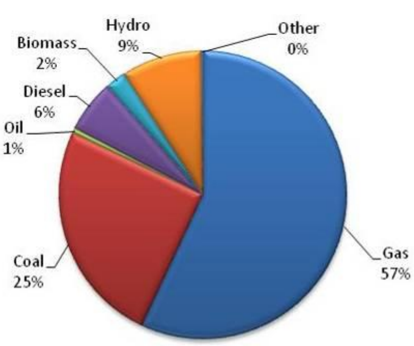

Fig.3 Malaysian Generation Mix by Technology [4]

The current Malaysian generation mix is heavily reliant on fossil fuel thermal technology. Fossil fuels consists of coal, oil and natural gas and are a cheap form of energy. However, many energy experts believe that the fossil fuel reserves around the world are quickly depleting, meaning that this type of generation technology is not sustainable.

Fossil fuel technologies are also known as main contributors to the climate change problem since the burning of fossil fuel causes carbon emissions. Thus, it is imperative that Malaysia takes advantage of its available potential in solar and hydro energy to diversify its generation technology mix.

The progression of the Malaysian generation mix since 1971 is shown in Fig. 4. Please note that this figure does not include small-scale renewable plants since the cumulative capacity is less than 3% of the total capacity.

In accordance to government policies over the years, the generation mix has evolved from two-fuel situation with a heavy reliance on oil into a three-fuel policy in 1978 with the introduction of hydropower into the generation fuel mix and the later the four-fuel policy with the introduction of coal.

Whereas oil was a dominant fuel in the 1970s, oil is now used only for back-up generators while natural gas makes up more than half of the generation mix.

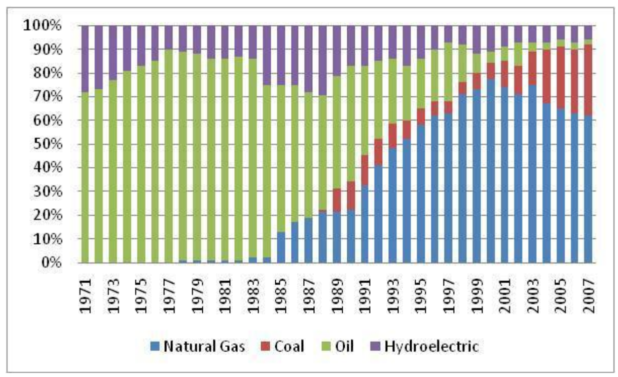

Fig.4 Simplified Malaysian Generation Mix from 1971 to 2007 [6]

In 1999, Malaysia adopted the Five-Fuel Diversification Policy that aims to introduce up to 5% of renewable energy into the total generation mix by 2010 [5]. In line with this policy, the Small Renewable Energy Program (SREP) was launched in 2001 [7] to assist small renewable energy generation plants in selling electricity to the national utility.

Unfortunately, as of 2009, the contribution from renewable energy is still less than 3%. The prohibitively high initial investments as well as the perception that renewable energy is unproven and risky are identified as two of the main reasons for this slow penetration of renewable energy [8]. Also, the Malaysian grid is not equipped to easily accept power from the distribution level. It is postulated in this paper that a large-scale renewable energy technology would be more successful in overcoming these barriers.

III. Generation Technologies for Malaysian Electricity Production

Electrical energy is generated by conversion of energy from one form, such as kinetic energy, chemical energy and nuclear energy, into electrical energy. The conventional method of energy conversion is by using a prime mover, in which a prime-mover is used to drive electrical machines that convert mechanical energy into electrical energy. The non-conventional methods are those not involving a prime-mover, but use other means of energy conversion, such as an electro-chemical conversion in fuel cells, and solar radiation conversion where solar energy is converted directly into electrical energy by photovoltaic panels [9].

The rest of this section introduces the currently available generation technologies, and discusses the suitability of each technology for this case study.

A. Conventional condensing power plants

Conventional condensing power plants are usually fossil fuel fired, and have a typical efficiency of about 40 to 50 percent. Fossil fuel like coal, natural gas or oil is burned, and the heat is used to boil water into super-heated steam that drives a steam turbine, which is interconnected with a generator on a common shaft [10].

For this case study, coal fuel is considered since over sixty percent of the Malaysian generation fuel mix already comes from natural gas, so adding more would only cause further imbalance to generation fuel mix. Coal is abundantly available in Malaysia, and from [7] it can be inferred that Malaysia has plans to continue to introduce more coal fuel into the generation mix to decrease reliance on natural gas.

Combined cycle technology will increase the efficiency of coal generation plants, and clean coal technology will help decrease the negative environmental effects.

B. Nuclear Power Plants

The concept of how nuclear power plants work is essentially similar to the conventional condensing power plants, but instead of burning fuel to create heat, heat energy is produced from the atomic fission process. Thus, the boiler in the conventional condensing power plants is replaced by a nuclear reactor. The overall efficiency of a nuclear power plant is also about 30 to 40 percent [9]-[10].

Since 1982, Malaysia has had an operating nuclear reactor used for research purposes, but none for power generation [11]. Since May 2010, feasibility studies have begun with the aim of identifying suitable sites for nuclear power generation in Malaysia, as well as to further assess its associated risks [12]. As such, nuclear energy will also be included in this analysis.

C. Hydro power plants

Hydroelectric energy is generated by harnessing the kinetic energy of moving water in a waterfall. The waterfall drives a hydraulic turbine that is interconnected to a synchronous generator. The power extracted depends on both the waterfall's height and rate of flow. It is the oldest form of renewable energy extraction and has a high efficiency rate of about 70 to 90 percent [9]-[10].

Although Malaysia has abundance of hydro potential, this generation technology is not considered for this case study since most of the hydropower potential is situated in the Borneo and not on the peninsula.

D. Solar energy

There are two distinct ways of extracting energy from solar radiation. The first technique is by photovoltaic cells, where light is converted into electrical energy by the photoelectric effect. The second is by concentrating solar energy into a small beam that becomes the heat source for a conventional condensing power plant. Due to the intermittent nature of solar energy and the fact that it is only available during the day, complimentary technologies are introduced in conjunction with solar energy to make it stable such as heat storage systems [9]-[10].

Both solar photovoltaic and concentrating solar thermal technologies are fairly new, and the costs are still high, but with depleting fuel sources and as the technologies mature, it is expected that solar energy will play a bigger role in electricity generation in the future.

Malaysia is a tropical, humid country that receives an average solar radiation of 4000 to 5000 Wh/m2 each month about five hours of sunshine each day [13]. Furthermore, T.H. Oh in [5] estimates that there exists potential of 6500 MW capacity by solar energy in Malaysia. Since penetration of small-scale solar photovoltaic has been discouraging, for this case study, the solar technology chosen for consideration is solar thermal technology.

E. Wind energy

When the wind blows, the wind turbine blades are rotated, and this produces electricity in the generator. Wind turbines can be either on-shore or off-shore, and can either operate individually, or as several units in a wind farm. Capacity factor for wind farms are about 20 to 30 percent, depending on the site's wind conditions [10]. In [14], Radhil et al states that wind energy is intermittent and not dispatchable, and proposes three methods to better control wind energy which are transmission line development, wind power prediction and energy accumulation. However, these limitations also mean that wind energy is not recommended for large-scale power production; therefore wind energy is not considered for this case study.

F. Biomass Energy

Energy from biomass can be converted into electricity by two processes. There first is by directly burning bio-waste to produce heat energy that can be converted into electrical energy by the condensing power plant, the second is by converting the bio-waste into a more convenient form such as liquid bio-fuel or combustible bio-gas and ethanol before burning. Biomass waste can come from corn, sugar canes, pellets, wood chips, straws, black liquor, landfill methane, anaerobic digesters and vegetable oils [10].

The Malaysian government, in its Eight Malaysia Plan, has pledged to produce about 500MW of its electricity from biomass [15]. Malaysia has a thriving palm oil industry that produces 70 million tonnes of collected waste per year in the form of empty fruit bunches, fibres, shells and effluents that could be converted into 2500 MW capacity [16]. With these encouraging statistics, biomass energy is also included for consideration in this application.

G. Wave Energy

Wave energy is a promising renewable technology that extracts energy from the surface motion of ocean waves or from pressure fluctuations below the surface. In [17], K. N. Abdul Maulud et al determined that the northern region of Sabah in the Borneo Islands has very high potential for wave energy. However, very large scale projects will have adverse effect on the environment, thus this technology is eliminated from consideration in this paper.

H. Summary

To reiterate, four generation technologies were chosen for consideration in this paper, namely nuclear, coal, biomass and solar thermal. Different combinations of these generation technologies will be formed into profiles that will be analyzed in the simulations section.

IV. K-Best Dynamic Programming Multi-criteria Trade-Off Method

The objective of this problem is to choose a fuel technology, or combination of technologies, that is able to meet electric power demand set at 2000 MW, and best minimizes economic cost and socio-environmental impacts as well as maximizing reliability.

A. Objective Functions

The first objective function is to minimize the total economic cost. This economic cost consists of the fixed cost and variable cost. In this case, the fixed cost is the investment cost of adding new units to the system. Variable costs are the running costs for operating the unit, which includes the operation, maintenance and fuel costs accumulated during the period of the unit in operation.

The reliability objective function here is the minimization of the expected energy not served (EENS) of the power system, calculated using the equivalent energy approach to probabilistic modeling [2]. By minimizing the EENS, reliability is maximized.

The socio-environmental cost objective function should also be minimized, and it is calculated from the socio-environmental cost coefficients and energy output of a generation unit.

B. Problem Formulation

The problem is formulated as follows.

Objective functions:

$$\text{Minimize} \quad z_1 = \sum \{ f_j \, x_j + v_j \, A_j \} \qquad (j=1,\dots,n) \qquad (1)$$

$$\text{Minimize} \quad z_2 = \text{EENS} \qquad (2)$$

$$\text{Minimize} \quad z_3 = \sum e_{1j} \, x_j \, E_j \qquad (j=1,\dots,n) \qquad (3)$$

Constraints:

$$\sum p_j \, x_j \geq q \qquad (j=1,\dots,n) \qquad (4)$$

$$l_j \leq p_j \leq u_j \qquad (j=1,\dots,n) \qquad (5)$$

Here,

$$A_j = \int_{y_{j-1}}^{y_j} LDC(l)dl \qquad (j=1,\dots,n) \qquad (6)$$

$$y_j = \sum p_k \, x_k \qquad (k=1,\dots,j) \qquad (7)$$

where,
n: Number of generation units
f_j: Fixed cost of generation type j [€/unit]
v_j: Variable cost of generation type j [€/MWh]
x_j: Decision variable for generation type j
A_j: Annual power generated by generation type j [MWh]
EENS: Expected Energy Not Served
e_{1j}: The socio-environmental cost co-efficient [€/MWh]
E_j: The energy served by generation type j [MW]
q: Target capacity[MW]
i_j: and u_j: The lower and upper bounds of generation type j
y_j: Cumulative power output [MW] from generation type 1 to generation type j
LDC: Load duration curve

Note that the following assumptions are observed for this formulation.

- LDC is defined as a discrete non-increasing step function.
- All attributes of generation unit such as capacity, fixed and variable unit costs are given.

The first constraint ensures that the combined capacity always fulfill the electric power demand, while the second constraint sets the safe operating range of each generating unit.

C. Solution Method

In the problem formulation, three objectives were defined for the optimal mix problem. This solution method proposes that the three objectives are separated into primary and secondary functions. The economic cost is the primary function, and the socio-environment and reliability objectives are the secondary functions. By this separation, the solution algorithm could now be separated into two phases.

1) Phase I: K-Best DP for Economic Cost Function

In Phase I, the aim is to find the capacity for different combinations of fuel technologies and the solution tool chosen is the K-best dynamic programming (K-best DP) method. K-best DP looks for a set of optimal solutions so that if $K = n$, and solution set $z = \{z_1, z_2, \ldots z_n\}$, then z_1 is the optimal solution, z_2 is the next best solution, and so on until z_n, the n-*th* best solution [18]. The ability to obtain a set of cost efficient solutions is useful in multi-criteria analysis because the most cost-efficient solution may not be as efficient when other criteria are evaluated.

In the K-best DP, the generation supply units are treated as stages in increasing merit order while the cumulative capacity of the generating units is treated as states. At each stage, optimal decisions are decided following the constraints given. At the final stage, the K-best solutions are obtained.

These solutions are used to form a set of profiles. Each profile represents different combinations of generation supply types by capacity. These profiles are next used in Phase II.

2) Phase II: Effective Energy Function Approach for Reliability and Environmental Impact Function

From Phase I, the capacities for different technology combinations were obtained. This has to be processed into expected energy served before reliability and environmental impact can be calculated. Expected energy generated is calculated using the effective energy function approach (EEF) presented in [2].

Further calculations by the same method yields the reliability impact in the form of expected energy not served (EENS). The expected energy not served (EENS) is defined as the expected amount of energy that cannot be met due to capacity deficit.

The energy served by each generating unit calculated from equivalent energy function approach is then used to compute the associated socio-environmental impact by equation (3). The socio-environmental cost co-efficient used in this paper is effectively the negative externalities cost associated with electricity generation given in [8], converted to Euro currency (1 USD= 0.7765 Euros).

Externalities represent the social and environmental impacts of electricity production that is not reflected in the economic cost. Sundqvist T and Soderholm P obtained the values given in Table 1 by analyzing as many as 132 negative and positive externality estimates. This includes air pollution, water pollution, impacts on health, noise, emissions, impacts on local biodiversity, local income benefits, employment benefits, accidents and aesthetics [8],[19].

Table 1: Socio-environmental Impact Costs for e_{j1}

	Coal	Nuclear	Solar	Biomass
e_{j1} (€/KWh)	11.54656	6.701195	0.535785	4.0378

The energy served by each generating unit, expected energy not served and socio-environmental impacts are calculated using a program constructed in MATLAB.

3) Trade-off and Evaluation

In Phase I, the capacity for each generation type in are obtained that minimizes the economic cost objective. In the second phase, for each profile, the expected energy not served (EENS) and socio-environmental impacts costs are calculated.

In this part of the solution algorithm, trade-off plots are first constructed. Trade-off plots are used to screen-out options that are unacceptable. If a clearly dominant profile does not emerge, trade-off plots help to graphically highlight trade-offs that must be made by the decision makers [20].

The next step is only required if no clearly dominant solution emerges. The three criteria are amalgamated so that rank the remaining profiles can be ranked according to how far the amalgamated value is from the target value. Finally, profile that best meets all three criteria can be identified. The goal programming method is the tool selected for the amalgamation process.

The aim of goal programming is to choose a profile p that is closest to a given goal by minimizing the distance measure as in the following formula [20]:

$$\left\{ \sum_{l=1}^{L} \left[\varpi_l \left| G_l - V_l(P_{lp}) \right|^{\varphi} \right] \right\}^{1/\varphi} \tag{8}$$

where,

P_{lp}: Level of criteria-l for profile-p

$V_l(P_{lp})$: Worth of profile-p for criteria-l. For this study, the normalized criteria values are used.

ϖ: Weight for criteria-l

G_l: Goal for criteria-l. Since the aim is to minimize all objectives, this is set to zero for all criteria.

φ: Penalty constant.

Formula (8) is used to calculate the deviations of each profile from the goal. Then, the profiles can be ranked according to the deviation calculations. The profile with the least deviations is the profile that best compromises between the three criteria.

V. Simulation and Results

The solution method is now applied to the Malaysian case and the objective is to minimize economic cost, maximize reliability by reducing EENS and minimizing environmental impact.

A. Case Study Data

The generation type characteristics, namely the fixed cost, variable cost and forced outage rate, were chosen based on the generic power plants characteristics available on GEMIS database [21]. GEMIS is a life-cycle analysis program and database for energy, material, and transport systems that is freely available in the public domain.

The characteristics for the candidate generation plants chosen for this case study are as shown in Table 2.

Table 2: Generation Type Characteristics

Fuel Type	Fixed Cost, f_j (€/MW)	Variable Cost, v_j (€/MWh)	Forced Outage Rate, FOR_j
Coal	1034070	44.69	0.85
Nuclear	2886780	71.44	0.9
Solar	1723310	105.28	0.31
Biomass	1685250	152.91	0.8

The load duration curve was randomly generated between 200MW to the target capacity of 2000MW. The data is tabulated in Table 3.

Table 3: Load Duration Curve

	1	2	3	4	5
1	2000	1925	1850	1775	1700
2	1625	1550	1475	1400	1325
3	1250	1175	1100	1025	950
4	875	800	725	650	575
5	500	425	350	275	200

The profiles to be analyzed were obtained from different combinations of the four candidate generation technologies. The designations ‘C’, ‘S’, ‘N’ and ‘B’ represent coal, solar, nuclear and biomass respectively while ‘All’ represents all four technologies combined. Fourteen profiles were formed for this analysis.

B. Simulation Results

The objective for this case study is to select a policy that minimizes the economic and environmental impact and maximizes reliability. The two-phase K-best dynamic programming multi-criteria trade-off solution method is applied. In the first phase, K-best DP is used to find capacity combination that minimizes total cost. The result is tabulated in Table 4.

From Table 4, it can be seen that the cheapest option is by coal generation technology only. The most expensive profile is Profile B that uses biomass technology only at almost four times the price of the price for Profile C.

It should also be observed that all total capacity for every profile meets the power demand constraint that was set at 2000 MW. This means that any of these solution profiles, if chosen, are capable of supplying the demands of the system.

Table 4: Results from Phase I of Simulation

Profile	Capacity(MW)					Z_1
	Coal	Nuclear	Solar	Bio mass	Total	
C	2000	0	0	0	2000	434768800
C+S	1500	0	600	0	2100	481498000
C+N	1000	1250	0	0	2250	502839700
C+B	1500	0	0	1050	2550	565715900
All	500	1250	150	120	2020	599253200
C+S+B	1000	0	450	1050	2500	687570600
N	0	2500	0	0	2500	694169800
N+S	0	1250	750	0	2000	748812500
N+S+B	0	1250	600	150	2000	759270800
N+B	0	1250	0	990	2240	864654200
S	0	0	2250	0	2250	1038605000
S+B1	0	0	1950	60	2010	1041085000
S+B2	0	0	1650	360	2010	1070347000
B	0	0	0	2010	2010	1586353000

z_1: total economic cost in €

The Phase I results are then used to calculate the expected energy served, reliability and socio-environmental cost for each profile. The results are tabulated in Table 5.

The results are very different when other objectives are included. For instance, even though Profile C is the best option when only considering the economic objective, when the socio-environmental objective is considered, Profile C is the most costly.

Table 5: Results from Phase II of Simulation

Profile	Energy(GWh)				Z_2	Z_3
	Coal	Nuclear	Solar	Bio mass		
C	9645	0	0	0	1446.75	11.55
C+S	8966	0	1298	0	1621.18	10.15
C+N	7123	3372	0	0	554.90	9.99
C+B	8966	0	0	1681	678.88	10.36
All	4117	5762	289	213	699.11	8.40
C+S+B	7123	0	2016	2696	807.34	7.96
N	0	9645	0	0	964.50	6.70
N+S	0	8194	1882	0	1687.01	5.55
N+S+B	0	8194	1714	453	1376.35	5.56
N+B	0	8194	0	2013	659.75	6.18
S	0	0	9645	0	6655.05	0.54
S+B1	0	0	9627	368	6366.03	0.66
S+B2	0	0	9291	2223	4985.45	1.21
B	0	0	0	9645	1929.00	4.04

z_2: EENS in GWh, z_3: socio-environmental cost in € ($x10^6$)

The results from Phase I and Phase II are then plotted in Fig. 5 where Fig. 5 is a three-dimensional plot of all the objective functions.

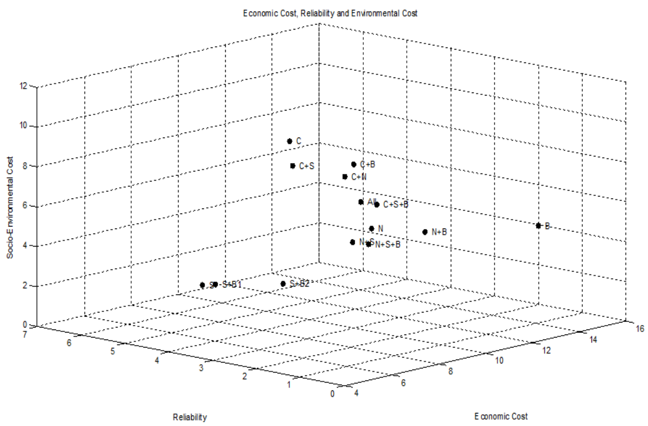

Fig.5 Economic Cost, Reliability and Socio-Environmental Cost

It is difficult to pin-point the acceptable profiles when too many attributes are plotted, so the trade-off plots of only two variables are preferable. Fig. 6, Fig. 7 and Fig. 8 shows the plots of the different pairs of variables.

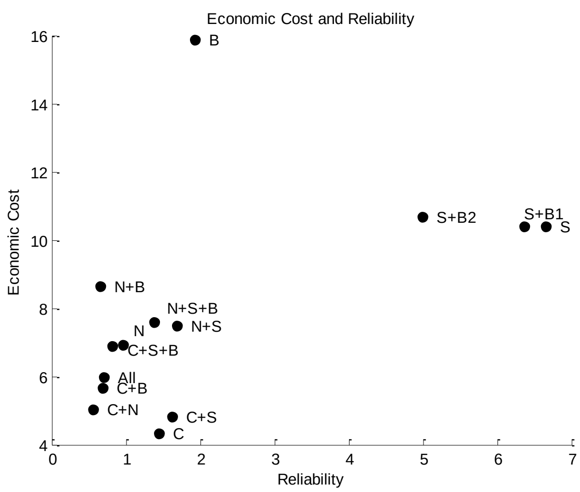

Fig. 6 Economic Cost and Reliability

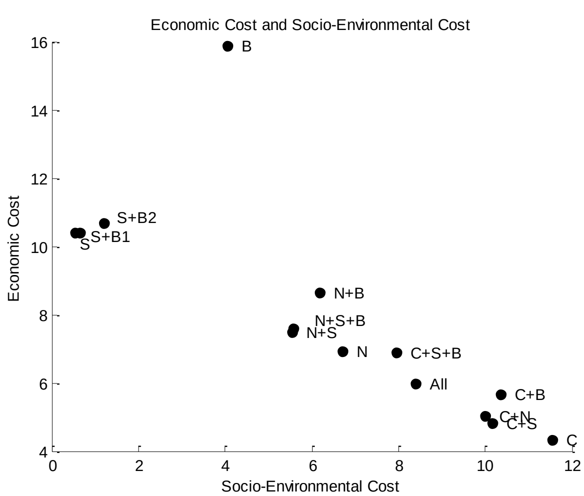

Fig.7 Economic Cost and Socio-Environmental Cost

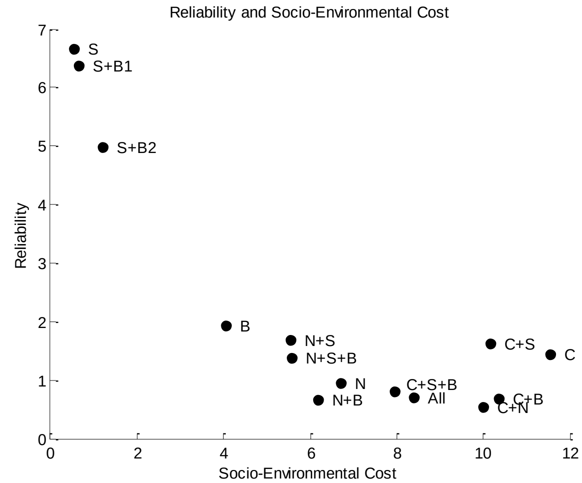

Fig. 8 Reliability and Socio-Environmental Cost

Dominance analysis was carried out for each plot to identify profiles that could be eliminated. It was found that Profile C+B and Profile C+S+B are dominated in all three plots, so these profiles could be safely eliminated from the amalgamation process.

Using formula (8), the profile deviations for the other twelve profiles are calculated. In these calculations, the same weights are used for all criteria, the goal is set to zero for all elements and penalty is 2. Based on the result of goal programming, the remaining twelve profiles can be ranked in order of increasing goal programming value.

Table 6: Profile Rankings

Rank	Profile	Z_1	Z_2	Z_3	GP value
1	N+S+B	0.76	1.38	5.56	0.308
2	N+S	0.75	1.69	5.55	0.314
3	N	0.69	0.96	6.70	0.341
4	N+B	0.86	0.66	6.18	0.345
5	All	0.60	0.70	8.40	0.408
6	S+B2	1.07	4.99	1.21	0.475
7	C+N	0.50	**0.55**	9.99	0.479
8	C+S	0.48	1.62	10.15	0.497
9	B	1.59	1.93	4.04	0.504
10	C	**0.43**	1.45	11.55	0.561
11	S+B1	1.04	6.37	0.66	0.571
12	S	1.04	6.66	**0.54**	0.593

The profile that was found to best minimize all three objectives is the combination of nuclear and renewable. Some other observations that can be made are:

- Profile C is the cheapest, Profile C+N has the best reliability and Profile S the lowest socio-environmental cost.
- All the profiles that best minimizes one of the criteria display low performance when evaluated from other criteria.

- Combinations of technologies tend to fare better than stand-alone technologies

VI. Conclusion

In this paper, the two-phase K-best dynamic programming trade-off method for determining an optimal generation mix has been presented.

The method has been applied for comparing combinations of four technologies as additional capacity for the Malaysian generation mix. The four generation technologies were shortlisted from a variety of technologies based on available potential for success in Malaysia. To this end, only large-scale, centralized technologies are considered since thus far, small-scale generation technologies were subjected to many barriers. Plus, small-scale technologies are not appropriate for the 2000MW required in this case study.

Three criteria considered in this study are economic, reliability and socio-environmental. Based on the simulation results, it was found that a combination of nuclear and renewable best meets all three criteria.

Further work can be done to expand this work into a multi-period planning problem, and include nodal points so that the optimal location of the generation unit could also be determined.

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