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Optimal planning of renewable energy-integrated electricity generation schemes with CO_2 reduction target

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ABSTRACT

This paper presents a Mixed Integer Linear Programming (MILP) model that was developed for the optimal planning of electricity generation schemes for a nation to meet a specified CO_2 emission target. The model was developed and implemented in General Algebraic Modeling System (GAMS) for the fleet of electricity generation in Peninsular Malaysia. In order to reduce the CO_2 emissions by 50% from current CO_2 emission level, the optimizer selected a scheme which includes Integrated Gasification Combined Cycle (IGCC), Natural Gas Combined Cycle (NGCC), nuclear and biomass from landfill gas and palm oil residues. It was predicted that Malaysia has potential to generate up to nine percent of electricity from renewable energy (RE) based on the available sources of RE in Malaysia.

1. Introduction

Rising concentrations of greenhouse gases including carbon dioxide, methane, nitrous oxide (NO_x) and sulfur oxide (SO_x) has increased the average earth surface temperature over time. This has given rise to climate change phenomena such as changes in precipitation patterns, storm severity, and the rise in sea levels.

Carbon dioxide is one of the main greenhouse gases (GHG) that is widely blamed for climate change. Increase in the concentration of carbon dioxide (CO_2) in the atmosphere is primarily attributed to fossil fuel burning. The United Nations Framework Convention on Climate Change (UNFCC) has developed the Kyoto Protocol in 1998 to stabilize the GHG emissions in the atmosphere by having industrialized countries commit to reduce their GHG emissions. The legal binding accord was signed by 165 countries to reduce GHG emissions.

Among the South East Asian countries, Malaysia is the highest emitter of CO_2 [1]. Malaysia, which has rapidly transformed from an agricultural economy to an industrialized one over the last three decades is now the 26th largest greenhouse gas emitter in the world [1]. Total carbon dioxide emissions in Malaysia have increased by 221% from the year 1990–2004. Fossil fuels contribute about more than half of the total increase in CO_2 emissions. Fig. 1 shows a CO_2 emission increase of 153% from 1990 to 2004 [2]. Transportation sector contributes the highest percentage of CO_2 emission at 27% of the total CO_2 emission or 124.3 million metric tonne (MMt) in 2001. This is followed by electricity and energy sectors at 25.7% [2] as shown in Fig. 2.

Electricity in Malaysia is mainly generated by Tenaga Nasional Berhad (TNB) and Independent Power Producers (IPP). Currently, the total installed electricity generation capacity in Peninsular Malaysia is 17,623 MW with TNB share at 48.1%, IPP, including IPP in Sabah, Sarawak, Sabah Electricity Sdn. Bhd. (SESB) and Syarikat SESCO Berhad (SESCO), owning 46.9% and private generation, 5% [3].

In Malaysia, natural gas, coal, diesel, fuel oil (distillate) and hydro are used to generate electricity. The total electricity consumption for Malaysia recorded a growth of 33.4% from 60,492 GWh in 2000 to 80,701 GWh in 2005 [4]. The share of natural gas as energy input in power stations has decreased from 74.9% in 2000 to 66% in 2006. The share of coal, however, increased significantly from 9.7% in 2000 to 23.3% in 2006, with the installed generation capacity shown in Fig. 3.

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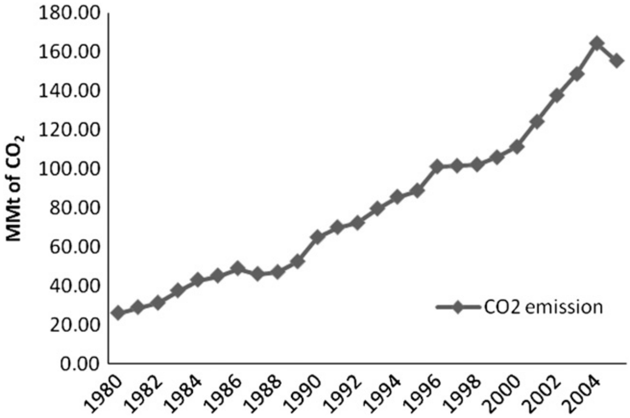

Fig. 1. Carbon dioxide emissions in Malaysia from fossil fuel [2].

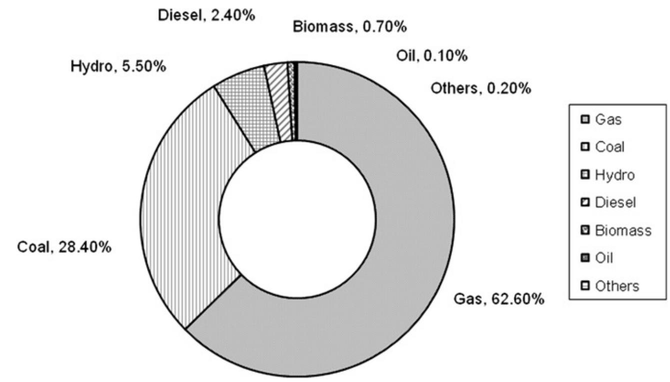

Fig. 3. Malaysia's current installed generation capacity in percentage [4].

In view of the rapid growth in power generation capacity and the corresponding rise in global CO_2 emission in Malaysia, there is a need for the authority to better plan the electricity generation capacity expansion to meet the electricity demand as well as to achieve an overall reduction in CO_2 emissions. Hence, this study aims to develop an optimization model to minimize the cost of electricity generation and simultaneously fulfill the forecasted electricity demand and a specified CO_2 emission reduction targets using a mix of fossil fuel as well as renewable energy. Apart from conventional electricity generation using fuels such as pulverized coal, natural gas and hydroelectricity, current generation technologies such as Pulverized Coal (PC), Integrated Gasification Combined Cycle (IGCC), Natural Gas Combined Cycle (NGCC), solar Photovoltaic (PV), nuclear and biomass from landfill gas, palm oil residues, wood processing residues, rice processing residues and municipal waste were also considered in the model.

2. Literature review

Several researchers have developed energy models for power generation technologies, such as Pulverized Coal (PC), Integrated Gasification Combined Cycle (IGCC) and Natural Gas Combined Cycle (NGCC) in the context of carbon capture and sequestration. Rubin et al. [5], for instance, developed the Integrated Environmental Control Model (IECM) to provide an analytical tool to compare various environmental control options for fossil fuel power plants. The model was built in a modular fashion that allowed new technologies to be easily incorporated into an overall framework. A user can then configure and evaluate a particular environmental control system design. Current environmental control options include a variety of conventional and advanced systems for controlling SO_2, NO_x, CO_2, particulates and mercury emissions for both new and retrofit applications. The IECM framework now is being expanded to incorporate a broader array of power generating systems and carbon management options (multi pollutant).

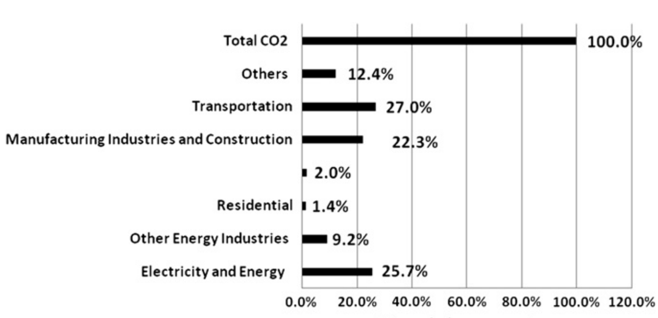

Fig. 2. CO_2 emissions by sectors in Malaysia [2].

A number of studies examined the prospect of incorporating new PC, IGCC and NGCC in the electricity generation sector. Narula et al. [6] considered replacing existing coal plants with new plants such as NGCC, IGCC and PC and studied the impact of the incremental cost of CO_2 reduction on the cost of electricity (COE) by implementing different technology options and compares COE.

Genchi et al. [7] for instance, developed a prototype model for designing regional energy supply systems. Their model calculates a regional energy demand and then recommends the most effective combination of 11 different power supply systems to meet the required CO_2 emission targets at minimum cost. The new energy system to be installed includes co-generation systems, photovoltaic cell system, unused energy in sewage and garbage incineration, and solar energy water supply.

Linares et al. [8] proposed a group decision multi-objective programming model for electricity planning in Spain based upon goal programming (GP). The objective was to minimize the total cost of the electricity generation, CO_2 emission, SO_2, NO_x and radioactive waste. The model is capable of estimating the capacity to be installed for the year 2020 under four different social groups: regulators, academic, electric utilities and environmentalists. The preferences by the groups were expressed as weights in the model that affect the different main criteria in the objective function.

Mavrotas [9] developed a mixed 0–1 Multiple Objective Linear Programming (MOLP) model and applied it to the Greek electricity generation sector for identifying the number and output of each type of power unit needed to satisfy an expected electricity demand. The first objective was to minimize the annual electricity production cost and the second objective dealt with the minimization of the total amount of SO_2 emissions. However, the model did not consider CO_2 mitigation.

Bai and Wei [10] developed a linear programming model to evaluate the effectiveness of possible CO_2 mitigation options for the electricity sector in Taiwan. The strategies they considered included fuel alternatives, reduced peak load, energy conservation, improving power generation efficiency, and CO_2 capture. They found that the combination of reduced peak production and increasing power plant efficiency with CO_2 conservation was an effective strategy to meet significant CO_2 emission reductions.

A study also has been done by Jafar et al. [11] on the environmental impact of fuel mix in electricity generation in Malaysia.

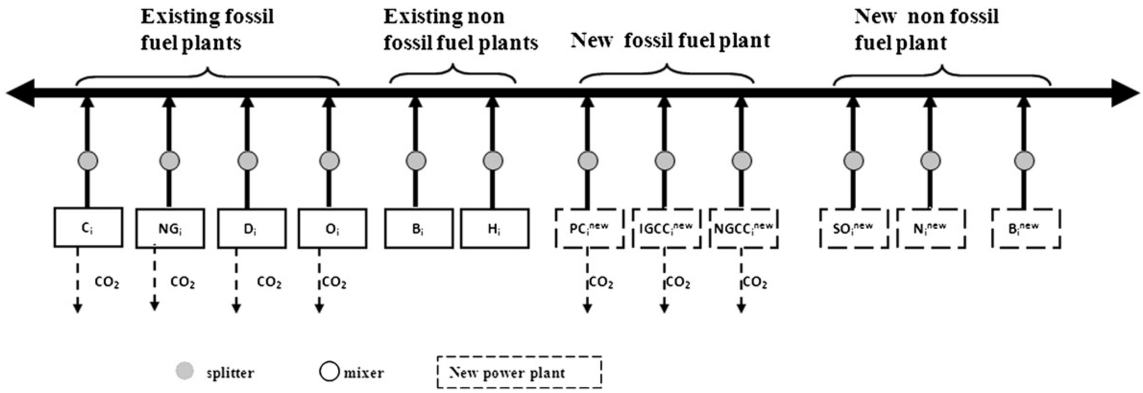

Fig. 4. Superstructure for existing and new technologies.

They estimated the amount of CO_2, SO_2 and NO_x emission using the extended Leontief's input–output (I–O) framework. However, they just consider existing technologies, without biomass.

Seung and Tae [12] investigate the role of nuclear power generation in Korea. They focused on the impact of power supply investment, nuclear power supply shortage effect and the impact of the rise in nuclear power rate on prices of other products.

Utilization of biomass especially palm oil has been investigated through several research [13,14]. Palm oil for example, not only can be used as source of edible oil but also it can be enhanced into an excellent source of renewable energy. Biomass can be converted to electricity through several processes including direct-fired, gasification, anaerobic digestion, pyrolysis and small modular systems [13].

Issues related to renewable energy has been discussed by Urmee et al. [15]. The issues can be divided into three main categories; economics, legal as well as regulatory, and financial as well as institutional. The economic barriers include high capital cost, failure to incorporate future fuel cost risks for fossil fuel and lack of pricing policies that do not take into account the real economic costs of environmental damage. The legal and regulatory barriers include inadequate legal frameworks for renewable energy power sources. Lack of sufficient technical, geographical, and/or commercial information by market participants is one of the barriers for financial and institutional [15].

From the available work, it is clear that greenhouse gas (GHG) emissions must be taken into consideration when evaluating fuel mix for electricity generation. Consideration must be given to meet the rising energy demand in both environmentally and cost-effective manner. In light of all the issues discussed, Malaysia must find a sustainable energy mix in order to realize its future challenges. Therefore, renewable energy such as solar and biomass has been introduced as one of the mitigation strategy to reduce CO_2 emission. The underlining question then becomes "given a CO_2 reduction target, what is the best combination of power plants, fuels, new power plants capacity and retrofit cost for Malaysia to pursue?" This is the question that this paper aims to answer.

3. Methodology

The project methodology includes three key phases, namely data gathering, superstructure development and model development and implementation.

3.1. Phase 1 – data gathering

Phase 1 focuses on gathering of the following key information:

1. Existing plant data i.e. plant capacity, operational costs and CO_2 emission;
2. Capital and operational costs of solar, biomass and nuclear, PC, IGCC and NGCC.
3. Other relevant data such as the current electricity demand.

3.2. Phase 2 – superstructure development

Superstructure representing all possible alternative fuel mix can be very complex indeed. A simplified superstructure is presented to illustrate the concepts. Fig. 4 illustrate the impact of a CO_2 reduction strategy on the structure of energy supply. C_i, NG_i, D_i, O_i, and H_i represents existing coal, natural gas, diesel, oil, and hydroelectric power plants respectively. Hypothetical new power plants are represented by PC_i^{new}, IG_i^{new}, NG_i^{new}, SO_i^{new}, B_i^{new} and N_i^{new} for pulverized coal, Integrated Gasification Combined Cycle (IGCC), Natural Gas Combined Cycle (NGCC), solar, biomass and nuclear respectively.

Three CO_2 mitigations strategies employed included fuel balancing, fuel switching and use of alternative energy as well as advanced technologies.

Fuel balancing involved adjusting the operation of two generation stations to reduce CO_2 emissions. This strategy involves increasing electricity generation by non-fossil fuel plants. Therefore, fossil fuel plants will generate less electricity and hence, less CO_2 emission.

Fuel switching involves changing from carbon-intensive fuels (e.g. coal) to less carbon-intensive fuels (e.g. natural gas). Existing generation stations must be retrofitted in order to use alternative fuel. Energy produced by alternative fuel (e.g. uranium and solar) emits no CO_2, and hence will reduce CO_2 emission.

The third mitigation strategy is to increase the use of renewable energy. The current technology consists of plants using fossil fuel including coal, natural gas, diesel and fuel oil. Non-fossil fuel plants are based on solar and nuclear technology.

3.3. Phase 3 – model development and implementation

The optimization model consists of an objective function and some constraints. The model is formulated using an objective function that minimizes the electricity cost. The objective function consists of operational cost for the existing fossil and non-fossil fuel power plants, retrofit cost due to fuel switching, the annualized capital cost, operational and maintenance cost for a new power plant includes IGCC, NGCC and RE (refer to Eq. (1)).

Objective function

$$\min f(i,j) = \sum_{i\in F}\sum_{j} V_{ij}E_{ij} + \sum_{i\in NF} F_i^{NF}E_i \ \text{Operating and maintenance cost for existing power plants} + \sum_{i\in F^c}\sum_{j} R_{ij}X_{ij} \ \text{Retrofit cost due to fuel switching}$$
$$+ \sum_{i\in P^{new}} S_i^{new}E_i^{new}y_i + \sum_{i\in P^{new}} M_i^{new}E_i^{new} \ \text{Capital and operating and maintenance cost for new power plants (fossil and non fossil plant)} \tag{1}$$

3.4. Constraints

3.4.1. Annual electricity demand

The net electricity generation for the whole fleet must be equal to or greater than the desired total electricity demand. This equation results from the summation of the electricity generation from existing non-fossil power plant, E_i, fossil fuel power plant, E_{ij} either using coal ($j = 1$) or natural gas ($j = 2$) and from the installation of the new power generation plants, E_i^{new}.

$$\left[\sum_{i\in \text{NF}} E_i^{\text{NF}} + \sum_{i\in P^{\text{new}}} E_i^{\text{new}} + \sum_{i\in F}\sum_{j} E_{ij}\right] \geq \text{Demand} \tag{2}$$

3.4.2. Plant capacity constraint

Existing fossil fuel boilers

$$E_{ij} \leq E_{ij}^{\max}X_{ij}, \quad \forall i\in F, \ \forall j \tag{3a}$$

Non-fossil power plants

$$E_i \leq E_i^{\max}, \quad \forall i\in \text{NF} \tag{3b}$$

New power plants

$$E_i \leq E_i^{\max}y_i, \quad \forall i\in P^{\text{new}} \tag{3c}$$

The above constraint set upper bounds on energy produced from the different electricity generating stations. It also ensures that the energy production from fossil fuel plants ($i\in F$) is zero when no fuel is assigned to the plant and a decision of plant shutdown has been made. Capacity of all plants must be less than or equal to its maximum capacity. Two types of binary variables were also introduced in the constraints. These include X_{ij} (the decision variable to represent whether the ith fossil fuel plant runs on coal ($j = 1$) or natural gas ($j = 2$)) and y_i (the decision variable to decide if the ith new plant, e.g. IGCC, NGCC and renewable energy will be chosen to be installed or not).

3.4.3. Upper bound on operational constraint

The electricity generated from the ith unit cannot exceed the current electricity generation for the unit by r_i (the maximum increase in the base load, E_i^{current} due to operational constraints). $E_i^{\max}$ is the maximum installed capacity of ith potential new boiler.

Existing fossil fuel boilers

$$E_{ij} \leq (1+r_i)E_i^{\text{current}}X_{ij}, \quad \forall i\in F, \ \forall j \tag{4a}$$

Non-fossil power plants

$$E_i^{\text{NF}} \leq (1+r_i)E_i^{\text{current}}, \quad \forall i\in NF \tag{4b}$$

New power plants

$$E_i^{\text{new}} \leq E_i^{\max}y_i, \quad \forall i\in P^{\text{new}} \tag{4c}$$

Constraints (4a and 4c), on the other hand include binary decision variables that are essential in the model implementation, especially in the case of plant shutdowns and to indicate existence/nonexistence of new hypothetical plants, e.g. IGCC, NGCC and RE.

3.4.4. Lower bound on operational constraint

The annual capacity factor for each power plant must be greater than some minimum value; otherwise the plants will be shutdown.

Existing fossil fuel boilers

$$f_{ij} \geq l_{ij} \times X_{ij}, \quad \forall i\in F, \forall j \tag{5a}$$

Non-fossil power plants

$$f_i \geq l_i, \quad \forall i\in \text{NF} \tag{5b}$$

New power plants

$$f_i \geq l_i y_i, \quad \forall i\in \text{NF} \tag{5c}$$

where l_{ij} (l_i) is the minimum annual capacity factor for ith fossil fuel boiler (non-fossil fuel plant and hypothetical new boiler). f_{ij} (f_i) is the corresponding annual capacity factor. The relationship between the annual capacity factor and electricity generation is given below:

Existing fossil fuel boilers

$$E_{ij} = f_{ij}E_{ij}^{\max}, \quad \forall i\in F, \ \forall j \tag{5d}$$

Non-fossil power plants

$$E_i = f_iE_i^{\max}, \quad \forall i\in \text{NF} \tag{5e}$$

New power plants

$$E_i = f_iE_i^{\max}y_i, \quad \forall i\in P^{\text{new}} \tag{5f}$$

where $E_{ij}^{\max}$ ($E_i^{\max}$) is the installed capacity of ith fossil (non-fossil power plants/new hypothetical boilers).

3.4.5. CO_2 emission limit

CO_2 emissions from all existing coal-fired boilers and new potential boilers, α_i (million tonne/yr) are defined as below:

$$\sum_{i\in F^C} \mathrm{CO}_2^F ij_{ij}E_{ij}^F + \sum_{i\in P^{\text{new}}} \mathrm{CO}_{2i}^{\text{new}}E_i^{\text{new}} \leq \mathrm{CO}_2\text{lim} \tag{6}$$

where $CO_{2_{ij}}$ is the CO_2 emission for the ith existing fossil fuel boilers using the jth fuel per electricity generated and CO_{2i} is CO_2 emission from new hypothetical boilers (tonne CO_2/MWh).

3.4.6. RE resource limitation

This constraint indicates that the conversion of specific RE to electricity, V_i^{RE} (tonne/Mwh) multiplied by the electricity generation for a particular source of RE, E_i^{RE} (MWh/yr) cannot exceed the RE source availability, Ri. This limitation is shown in Table 3.

Table 1
Actual electricity generation for existing power plant [16].

Power Plant		Generation MWh per year	Operating and maintenance cost (RM per MWh)	
Type	Location		Coal	Natural gas
Coal	Pelabuhan Klang	639,918	69–104	138–208
	Janamanjung	1,254,870		
	Tanjung Bin	1,254,870		
	Pasir Gudang	646,926		
	Prai	1,073,100		
	Jimah	745,000		
Natural gas	Glugor	1,734,480	5.63	
	Pelabuhan Klang	1,734,480		
	Connaught Bridge	6,559,488		
	Serdang	3,740,520		
	Pasir Gudang	3,066,876		
	Paka	8,979,876		
Hydroelectric	Kenyir	1,486,100	1.67	
	Temenggor	823,900		
	Bersia	231,000		
	Kenering	427,000		
	Chenderoh	154,700		
	Jor	280,700		
	Pergau	457,800		
	Woh	429,800		
	Piah & Odak	315,000		

$$V_i^{RE}E_i^{RE} \leq R_i, \quad \forall i \in P^{RE} \tag{7}$$

The above constraint sets the upper bounds on RE generated from the different power stations. The capacity for all RE power plants must be less than or equal to its maximum capacity.

The indices, sets, variables and parameters used in the model are:

Indices
i, power stations
j, fuels

Sets
F, Fossil fueled power plants
NF, non-fossil fueled power plants
new, new power plants

Binary variable

$$x_{ij} = \begin{cases} 1, & \text{if coal} - \text{fired boiler } i \text{ is operational using fuel } j \\ 0, & \text{otherwise} \end{cases}$$

Table 3
Biomass resources potential in Malaysia [19].

Sector	Quantity (ktonne/year)	Potential Annual generation (GWh)	Potential capacity (MW)
Rice mills	424	263	30
Wood industries	2177	598	68
Palm oil mills	17980	3197	365
Bagasse	300	218	25
POME	31500	1587	177
Total	72962	5863	665

$$y_i = \begin{cases} 1, & \text{if new power plant } i \text{ is operational} \\ 0, & \text{otherwise} \end{cases}$$

Parameters
V_{ij}, operating & maintenance (O&M) cost for existing power stations (RM/MWh)
E_{ij}, actual electricity generation from ith fossil fuel using jth fuel type for existing power plant (MWh)
E_i, actual electricity generation from non-fossil fuel (MWh)
E_i^{new}, electricity generation for new power plant (MWh)
R_{ij}, retrofit cost (RM/MW)
S_i^{new}, capital cost for new power plant (RM/MW)
M_i^{new}, operating & maintenance (O&M) cost for new power stations (RM/MWh)

4. Case study

The case study involves electricity generation in Peninsular Malaysia. The case study data was obtained from TNB and from some Independent Power Producers (IPPs). Based on the data from Energy Information Administration (EIA) (2005), carbon dioxide emission from electricity generation in Malaysia is 51,400,000 tonne per year. Since 90% of the electricity share are generated in Peninsular Malaysia, it is estimated about 45,746,000 tonne CO_2 was emitted annually. There are six coal power plants which consist of i identical boilers e.g. Pelabuhan Klang ($i = 1–6$), Janamanjung ($i = 1–3$), Tanjung Bin ($i = 1–3$), Pasir Gudang ($i = 1–2$), Prai ($i = 1–3$) and Jimah ($i = 1–2$). Actual electricity generation and operating and maintenance cost for existing coal, natural gas and hydroelectric power plants was indicated in Table 1. The capital and, operating costs as well as the maintenance cost for new power plants is shown in Table 2. All data was obtained from reference [16–18]. The capital cost and assumed to be amortized over a 30 years period at 15% interest rate.

Table 2
Capital cost and operating and maintenance cost for new power plant [16–18].

Sources		Capital cost ($/MW)	Variable O&M cost ($/MWh)	Fixed O&M cost ($/MW)	Fuel cost ($/tonne)
Landfill gas (LG)		5,005,656	42.42	23.76	–
Municipal solid waste (MSW)		15,271,493	42.42	23.76	–
Palm oil residue (POR)	EFB	4,496,606	42.42	23.76	4.24
	Fibre	4,496,606	42.42	23.76	4.24
	Shell	4,496,606	42.42	23.76	4.24
Wood processing residue (WPR)	Sawn timber (ST)	7,296,380	42.42	23.76	5.66
	Plywood & Venner (PV)	7,296,380	42.42	23.76	5.66
	Moulding Waste (MoW)	7,296,380	42.42	23.76	5.66
Rice processing residue (RPR)	Husk	7,296,380	42.42	23.76	2.83
	Straw	7,296,380	42.42	23.76	2.26
Solar		5,656,109	0.71	–	–
Pulverized coal (PV)		1,578,000	2.87	–	85
Integrated gasification combine cycle (IGCC)		2,121,000	1.24	–	4.77[a]
Natural gas combine cycle (NGCC)		617,000	2.7	–	4.77[a]
Nuclear		2,414,200	5.53	–	–

[a] Unit in USD per mmBTU.

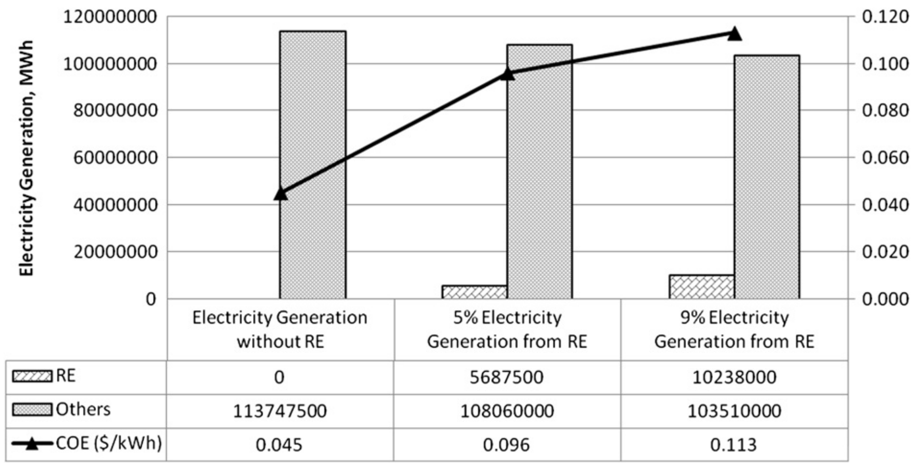

Fig. 5. Electricity generation without RE (base case) and with RE.

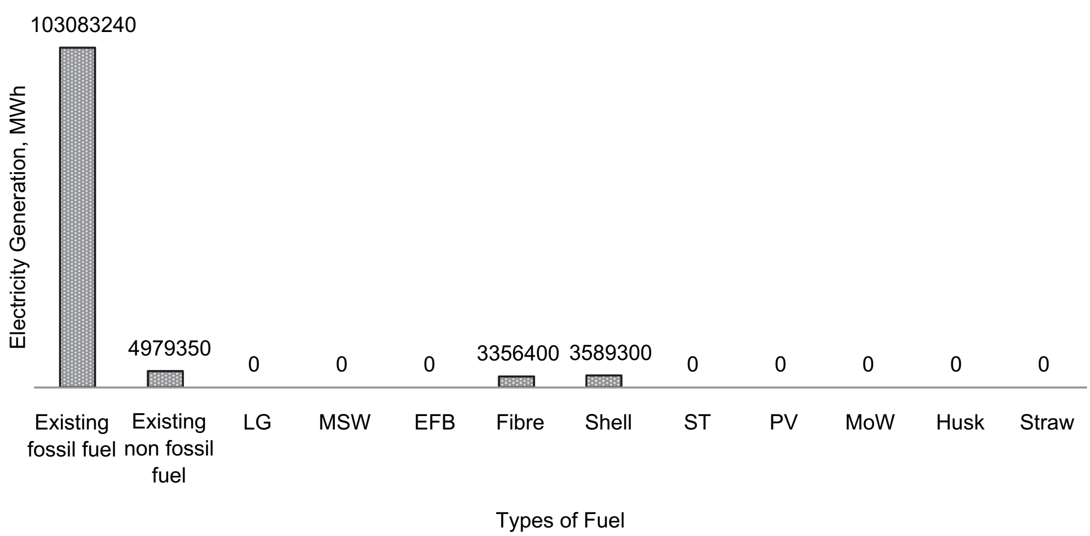

Fig. 6. 5% electricity generation from RE.

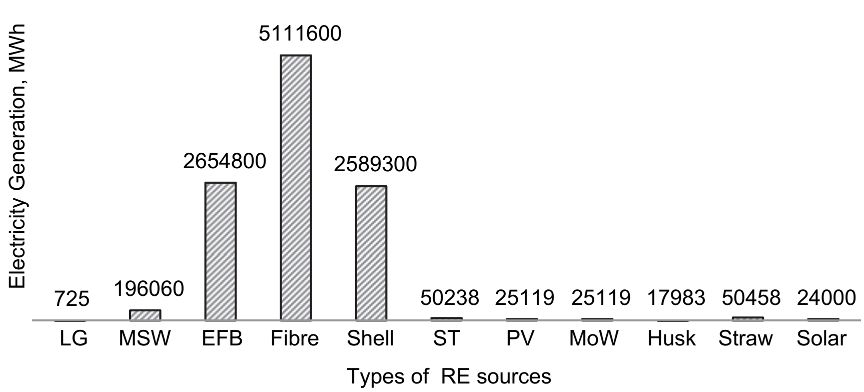

Fig. 7. Maximum potential electricity generation from RE.

5. Results and discussion

This section discusses two main findings from sensitivity analysis conducted on the model. Section 5.1 analyses the effect of RE generation mix on the cost of electricity (COE) while Section 5.2 explores the effect of CO_2 emission reduction on the existing power plants, RE and nuclear.

5.1. Effect of RE generation mix on COE

For this scenario, the model is solved with the aim to meet the current grid electricity demand. In this section, the RE resources available were manipulated to achieve Malaysia's government target without considering the CO_2 emission level. Fig. 5 shows the electricity generation for the base-case scenario which represents the current operational scenario consisting of only 0.21% RE, and 5% and 9% electricity generation mix from RE. As can be seen, increasing RE generation share in the power generation fleet resulted in increased cost of generating electricity. This is expected since RE-based electricity generation is not cost-competitive as compared to fossil-based power plant. The COE is USD0.096/kWh for 5% RE generation mix, which is double the base-case COE. The model output shows that based on the sources of RE currently available in Peninsular Malaysia. This is expected to increase the COE to USD0.113 kWh.

Fig. 6 illustrates the breakdown for electricity generation from RE for 5% RE generation mix. Shell and fibre from palm oil residue are more favorable since it is available in abundance and due to the lower capital investment. On the other hand, solar is included in the model since it is a free resource and due to its lower VOM cost.

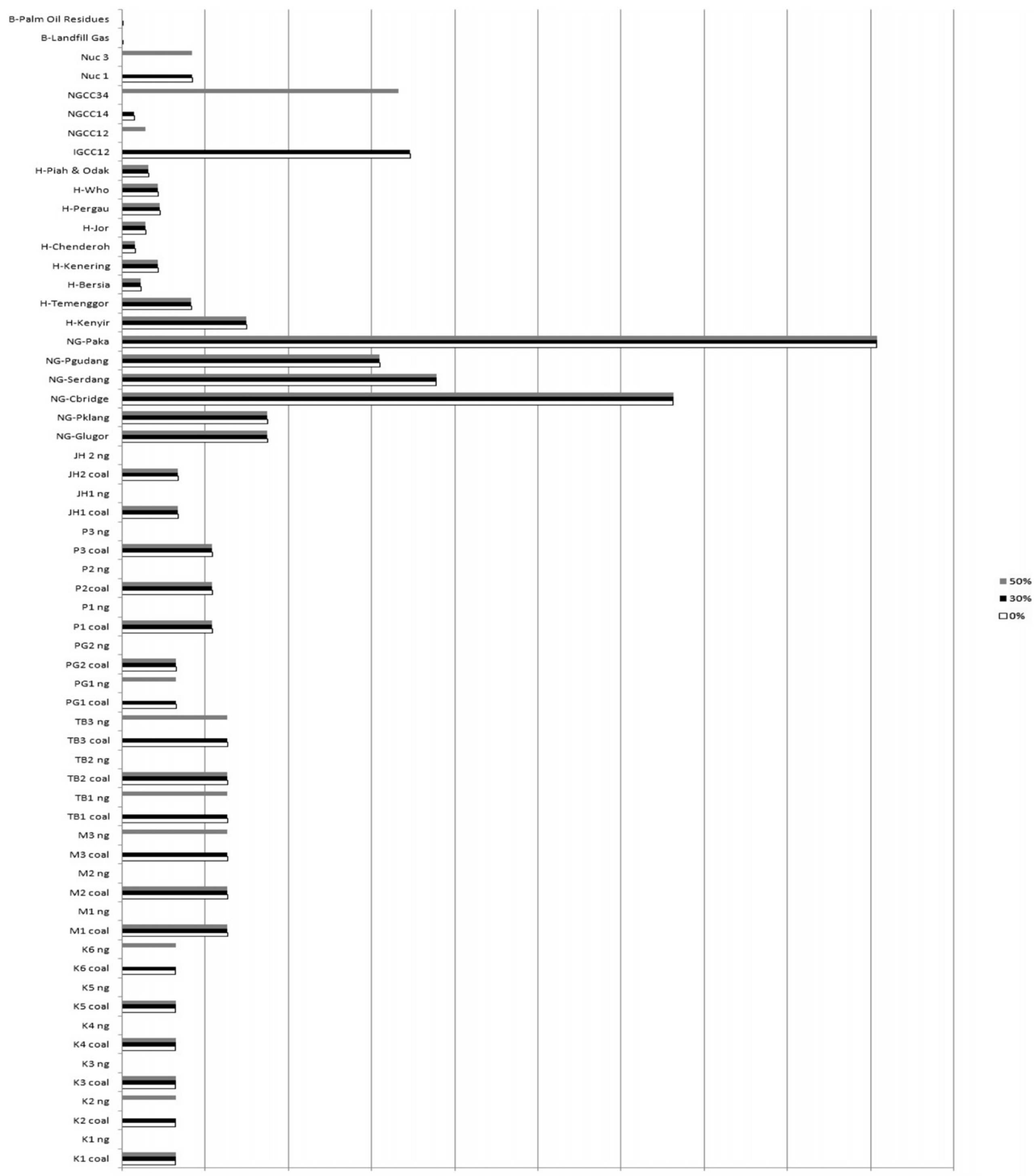

Fig. 8. Optimal electricity generation for base case, 30% and 50% CO_2 reduction.

The target of 9% RE generation mix to meet grid electricity demand can be achieved by selecting 96.4% of RE from palm oil residues which consists of EFB, fibre and shell due to the abundance of these resources from palm oil industry. Another 1.8% should come from municipal solid waste (MSW) and the remaining 1.8% from other types of RE. Fig. 7 shows the breakdown of electricity generation from RE for this scenario.

5.2. CO_2 emission reduction

This section discusses the impact of electricity generation for various CO_2 emission reduction, while satisfing electricity demand at minimum cost. As can be seen in Fig. 8, three mitigation strategies including fuel balancing, fuel switching and installation of new power plants were selected for 0% and 30% and 50% CO_2 emission reduction levels. However, in order to achieve further CO_2 emission reduction target of, for instance 50%, RE tends to become attractive. The existing natural gas plant and hydroelectric plants were fully operational for the base case (0% CO_2 reduction), 30% and 50% CO_2 reduction. Since RE is considered as carbon neutral process, the total optimal value for CO_2 emission are the same for both cases (30% and 50% CO2 reduction), i.e. at 29,143,000 tonne per year. This is due to the constraint in the CO_2 emission reduction, which must be less than the upper limits; 51,400,000 tonne/year for 0% reduction and 35,980,000 for 30% reduction. In order to satisfy the current demand, the solver also selected one IGCC, one NGCC and one nuclear power plant with annual electricity generation of 3,462,400 MWh, 153,170 MWh and 850,000 MWh, respectively to be in place in order to achieve 30% CO_2 reduction.

On the other hand, fuel balancing and fuel switching to less carbon-intensive fuel (e.g. NG and implementation of RE) were chosen to achieve up to 50% CO_2 reduction target. For instance, boilers K2 and K6 in Pelabuhan Klang power station, boiler M3 in Janamanjung power station, boiler TB1 in Tanjung Bin power station and boiler PG1 in Pasir Gudang power station will be switched to natural gas, two NGCC power plants and one nuclear plant were chosen to generate 284,570 MWh electricity per year, 3,331,000 MWh electricity per year and 850,000 MWh electricity per year each respectively. Landfill gas and palm oil residues at 240 MWh capacities were the two biomass power plants chosen for 50% CO_2 reduction cases. Both technologies were chosen due to their low capital investment needs.

The total cost of electricity generation for 0% and 30% CO_2 reduction cases is USD 296,316,383. The total cost of electricity generation for 50% CO_2 reduction is USD 350,388,268. This is 18.2% higher than the total cost for 0% and 30% CO_2 reduction.

6. Conclusion

A Mixed Integer Linear Programming (MILP) model for the optimal planning of electricity generation schemes has been developed for a nation to meet a specified CO_2 emission target. The results indicated that, the selection of type of RE power plant is mainly driven by the capital cost and the availability of RE sources. For 5% RE generation mix, sources of RE from palm oil shell and fibre were found to be the most favorable since it is abundantly available, and requires lower capital investment. On the other hand, solar is also recommended since it is a free renewable source of energy and requires lower variable operating and maintenance costs. The target of 9% RE generation mix to meet grid electricity demand can be achieved by selecting 96.4% RE from palm oil residues which consists of EFB, fibre and shell. Another 1.8% should come from municipal solid waste (MSW) and the remaining 1.8% from other types of RE.

From the results of the case studies, it can be concluded that the biomass, IGCC, NGCC and nuclear power station are among the new technologies that need to be considered to satisfy certain CO_2 emission reduction target. Biomass plant such as landfill gas and palm oil residue tend to become competitive at 50% CO_2 reduction target. However, biomass power plant using municipal waste, rice husk and wood residues are not viable for electricity generation due to their high capital costs. Solar power plant is not favorable due to the high capital cost and low efficiency. For the specified CO_2 emission targets, hydroelectric and natural gas power station was recommended due to the emission free technology and low operating cost.

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Nomenclature
List of symbols

B_i^{new}: New hypothetical biomass boiler
C_i: *i*th boiler running with coal
CO_2: Carbon dioxide
CO_{2ij}^F: Carbon dioxide emission for the *i*th existing coal-fired boilers using the *j*th fuel per electricity generated (tonne/MWh)

$CO_2^{new}{}_i$: Carbon dioxide emission from new hypothetical boilers
COE: Cost of electricity
D_i: *i*th boiler running with diesel
EIA: Energy Information Administration
E_{ij}: Actual electricity generation from *i*th fossil fuel using *j*th fuel for existing boilers (MWh)
E_{ij}^{max}: Maximum electricity generation from *i*th fossil fuel using *j*th fuel for existing boilers (MWh)
E_i^{NF}: Electricity generation for non-fossil fuel boilers (MWh)
E_i: Actual electricity generation from non-fossil fuel boilers (MWh)
E_i^{new}: Electricity generation for new power plant (MWh)
F: Fossil fueled power plants
$f_{ij}(f_i)$: Annual capacity factor for *i*th boiler/*i*th boiler running with *j*th fuel
GAMS: General Algebraic Modeling System
GHG: Greenhouse gases
GP: Goal Programming
H_i: Hydro
i: Boilers
IGCC: Integrated Gasification Combined Cycle
IG_i^{new}: New hypothetical IGCC power plant
IPP: Independent Power Producer
j: Different type of *j*th fuels, i.e. coal and natural gas
l_i: maximum annual capacity factor for non-fossil fuel boiler and hypothetical new boiler
l_{ij}: maximum annual capacity factor for *i*th fossil boiler running with *j*th fuel
M_i^{new}: Operating & Maintenance (O&M) cost for new power stations (RM/MWh)
MILP: Mixed Integer Linear Programming
MMt: Million metric tonne
MOLP: Multi-objective Linear Programming
new: New power plants
NF: Non-fossil fueled power plants
NGCC: Natural Gas Combined Cycle
NG_i: Natural Gas
NG_i^{new}: New hypothetical NGCC power plant
N_i^{new}: New hypothetical nuclear power plant
NO_x: Nitrous Oxide
O_i: Oil
PC: Pulverized Coal
PC_i^{new}: New hypothetical pulverized coal power plant
PV: Photovoltaic
r_i: maximum increase in the base load, $E_i^{current}$ due to operational constraints
R_{ij}: Retrofit cost (RM/MW) if boiler *i* is switch to *j*th fuel
S_i^{new}: Capital cost for new boiler (RM/MW)
SO_i^{new}: New hypothetical solar power plant
SO_x: Sulfur Oxide
TNB: Tenaga Nasional Berhad
UNFCC: United Nations Framework Convention on Climate Change
V_{ij}: Operating & maintenance (O&M) cost for existing power stations

$$x_{ij} = \begin{cases} 1, & \text{if coal-fired boiler } i \text{ is operational using fuel } j \\ 0, & \text{otherwise} \end{cases}$$

$$y_i = \begin{cases} 1, & \text{if power plant } i \text{ is operational} \\ 0, & \text{otherwise} \end{cases}$$

Greek letters

α_i: Total CO_2 emissions from all existing coal-fired boilers and new potential boilers