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Article

Cost Effective Options for Greenhouse Gas (GHG) Emission Reduction in the Power Sector for Developing Economies — A Case Study in Sabah, Malaysia

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Abstract: With their increasing shares of global emissions developing economies are increasingly being pressured to assume a greater role in global greenhouse gas (GHG) emission reduction. Developed countries have invested tremendously in and proclaimed renewable energy (RE) and associated smart power technologies as solutions to meet their energy demands and reduce their GHG emissions at the same time. However, in the developing economies, these technologies may not deliver the desired results because they have their unique characteristics and priorities, which are different from those of the developed world. Many GHG emission reduction technologies are still very expensive and not fully developed. For the developing economies, the adoption threshold may become very high. Therefore, the cost effectiveness and practicality of each technology in reducing GHG emission in the developing economies may be very different from that of the developed economies. In this paper, available RE and other GHG emission reduction technologies are individually considered in a case study on Sabah, one of the 13 states in Malaysia, in order to assess the effects of the individual technologies on GHG emission and electricity cost reductions.

Keywords: sustainable development; developing country; reduction in greenhouse gas emissions

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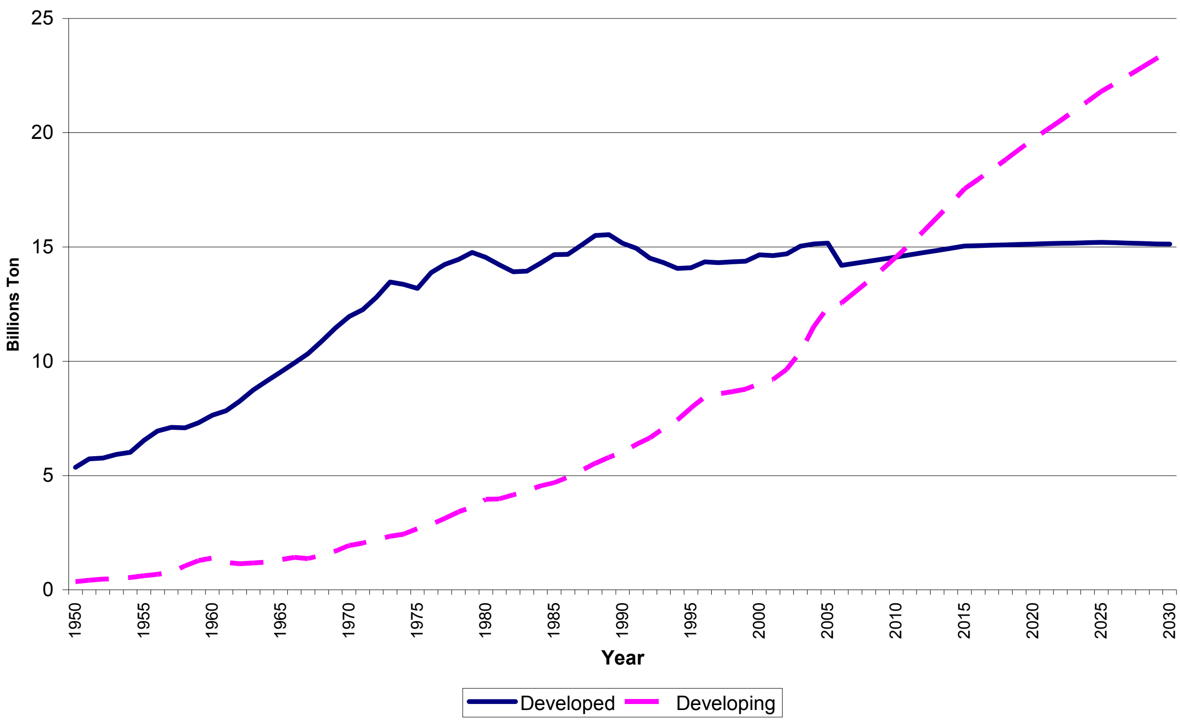
1. Introduction

The impacts of GHG emissions on the living environment are undoubtedly damaging if not contained. However, the world is still unable to reach a climate deal because of the complexity of the issues involved. One of the reasons for the failure is the difficulty for the developed and developing countries to achieve a mutually agreeable share of responsibility for solving the issue [1].

Historically, the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol have divided the nations into developed countries and developing countries, with common but differentiated responsibilities assigned to each group. The developed countries, commonly known as the Annex I countries, were mandated to implement control actions to reduce the GHG emission to a specific level in the Kyoto Protocol. The developing countries, or the non-Annex I countries were exempt from these control actions [2].

It was an effective short-term measure in 1997 when the Kyoto Protocol was first adopted. In 1997, the total CO_2 emission from the Annex I countries constituted 63% of the global CO_2 emission [3]. However, based on the projection by the International Energy Agency [4] as shown in Figure 1, the total CO_2 emission from the non-Annex I countries will overtake that of the Annex-I countries in 2011. By 2030, it will constitute 61% of the global emission. Therefore, it is important that the emission in the developing countries to be addressed seriously in the attempt to overcome the global warming issue.

Figure 1. Trend of CO_2 emission by developed and developing countries.



The developed countries have invested tremendously in the renewable energy (RE) because they believed that RE is an effective solution for meeting their energy demands while reducing their GHG emissions. As illustrated in the later sections of this paper, the generation cost using renewable energy technologies is very high. In addition, most of the RE technologies are still under development, and as a result, a high level of technical expertise is typically required for the implementation of RE technologies. Furthermore, RE resources are typically of low energy density and capital intensive for large scale implementation. These obstacles are hindering many developing countries from reducing their GHG emissions effectively. Furthermore, sufficient local renewable energy resource endowment for economical electricity generation is limited, hence restricting the widespread applications of RE technologies. Malaysia, for instance, has minimal potential for harnessing wind and ocean energies for electricity generation [5,6].

Malaysia, like many other developing countries, is facing the challenge of balance the economy growth and GHG emission reduction with limited financial resources. The common characteristics of developing economies that are relevant to the GHG emission reduction and electricity generation can be summarised below:

Limited Technical Expertise: In the global expenditure on research and development (R & D) on sustainable energy in 2009 [7], USD 18.9 billion or 77% are from the US and Europe. In terms of expertise and technological capabilities, the developing countries still lag far behind the developed countries. Therefore, during the attempts to adopt the state of the arts technologies touted by the developed world, the developing countries are having difficulties to recruit sufficient expertise to ensure the successful implementation and operations of these technologies.

Increasing Electricity Demand: Industrialisation is still a main transformation factor in the GDP growth of many developing nations. The electricity demand typically grows in tandem with the GDP. It is important to implement power generation technologies with low cost and high scalability to fuel the GDP growth. In Sabah, one of the 13 states in Malaysia, for example, the power plant capacity is to increase from about 1 GW in 2010, to above 5 GW by 2030.

Financial Constraint: *Per capita* income in the developing countries is lower than that of the developed countries. In Malaysia, for example, the current *per capita* income is 7,600 USD compared to that of developed countries of more than 15,000 USD. Therefore, consumers in the developing countries cannot afford a significant increase in electricity price to cover the costs of green technology. The established technologies such as photovoltaic panels, with a generation cost more than six times that of the conventional technology are simply not affordable,.

Fuel Mix: Malaysia, like other developing countries, is dependent heavily on fossil fuels, which account for more than 90% of its electricity generation [8]. Coal alone supply more than a quarter of the country's electricity meet and its share is projected to increase as part of the country's fuel diversification policy to avoid over dependent on natural gas.

Renewable Resources Availability: The adoption of renewable energy is also dependent upon sufficient local energy resource. The US has the average wind velocity of more than 5 m/s and Europe of more than 7 m/s. However, in Malaysia the wind speed in between 2 to 3 m/s. With a typical cut-in speed of 3 m/s [9], there is little energy to be exploited.

Need for Scalability of Technologies: The rapid increase in the power demands of the developing countries needs to be met using technologies with high scalability. In the developed countries, where the power demands are relatively constant, green energy sources can be added to merely reduce the usage of their existing power plants with high emission factors. In the developing countries, however, new power plants need to be installed to meet the increasing power demands. The outputs of renewable energy generators are usually intermittent. Their output profiles may not coincide with the demand profiles. As a result, reserved or standby power plants, such as gas power plants, need to be installed, hence causing a further increase in the already high cost of the technologies.

With these constraints in mind, the developing countries may be struggling to curb their GHG emissions effectively if those technologies with high adoption threshold are the only solutions for them. In Malaysia, for example, under the eighth Malaysia plan (2001 to 2005), a 5% target was set for renewable energy among the energy mix. However, the target cannot be achieved and subsequently in the ninth Malaysia plan (2006 to 2010), it was revised down to 1.8%. The target was again missed, with only 0.25% achieved in 2010 [10].

A technology with a low adoption threshold in terms of technological and financial requirements will be beneficial to the developing countries in reducing their GHG emission reductions. With a more cost effective technology, the developing countries should be able to achieve a much higher level of GHG emission reductions with constrained budgets. It is therefore necessary to explore various means that can be practically implemented in the developing countries for achieving their targets of GHG emission reductions while fulfilling their growing energy demands. In this paper, the effectiveness of the following emission reduction technologies is assessed:

1. Renewable energy;
2. Supply side energy efficiency;
3. Demand side energy efficiency; and
4. Transmission, distribution and ancillary technologies.

The objectives of the assessment are to quantify the economical and environmental benefits that these technologies can bring to the developing economies. The study is based on the power system in Sabah with projection for the next 20 years. The long range energy planning software, LEAP [11], was used in this study to create a number of scenarios and projections for the next 20 years. The findings of this case study are relevant to the developing countries because the situation in Sabah could be a typical scenario experienced by many developing countries. Furthermore, the power system network in Sabah is not interconnected with power system networks at other parts of Malaysia, hence presenting a unique opportunity to study it without involving other unnecessary complications.

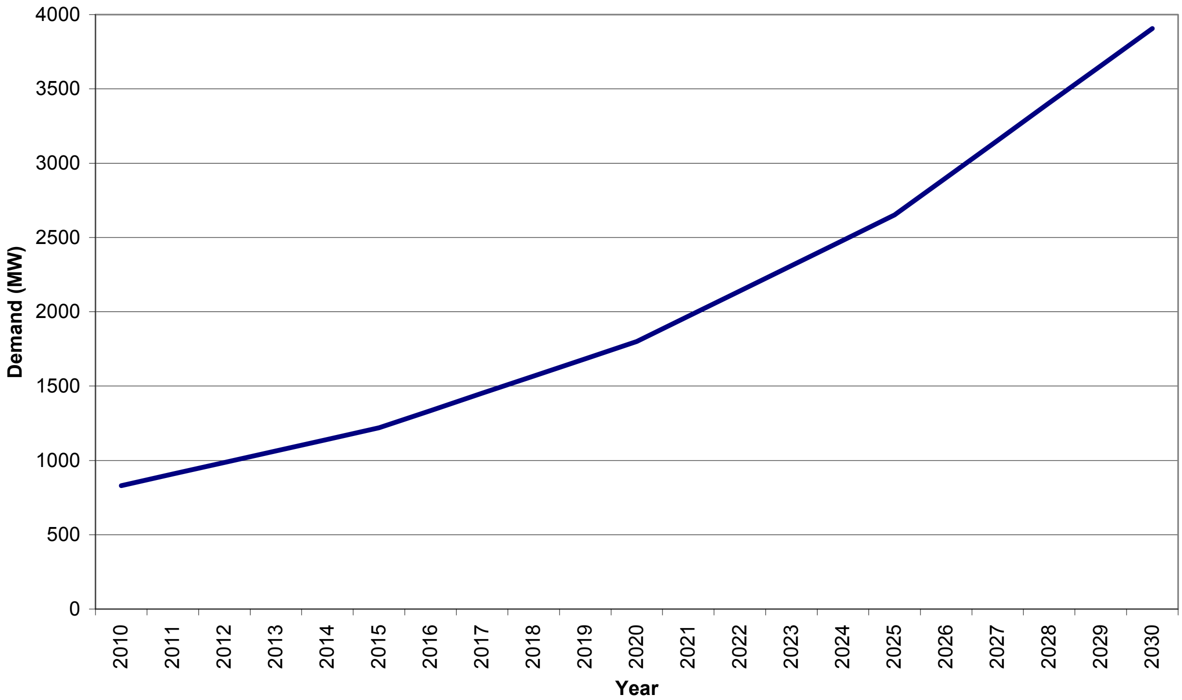
Most of the green technologies investigated in this study are equally effective in reducing the SO_2 and NO_X emission. SO_2 and NO_X emissions are among the key pollutants to our environment, with adverse impacts on our environment and health. The paper, however, will focus on the detailed analysis the GHG emissions. This is to be consistent with the main objective of the paper to investigate the cost effectiveness of technologies in GHG emission reduction.

This paper begins with the description of the power system in Sabah in Section 2. This is followed by an overview of the existing emission reduction technologies in Section 3. In Section 4, the methodology of this study is explained. Subsequently, the details of source data computation is presented in Section 5. In Section 6, the results are presented and discussed, followed by the conclusions in Section 7.

2. The Power System in Sabah

Sabah is one of the 13 states in Malaysia, with an independent power grid. Its electricity is supplied by all the power plants within the state. Based on the projection in Sabah Development Corridor (SDC) blueprint [12], as shown in Figure 2, the power demand in Sabah is expected to increase by almost 400%, from the current 830 MW to 3900 MW over the next 20 years. This is reflective of the tremendous growth expected in Sabah, as planned in the SDC blueprint.

Figure 2. Sabah power demand projection.



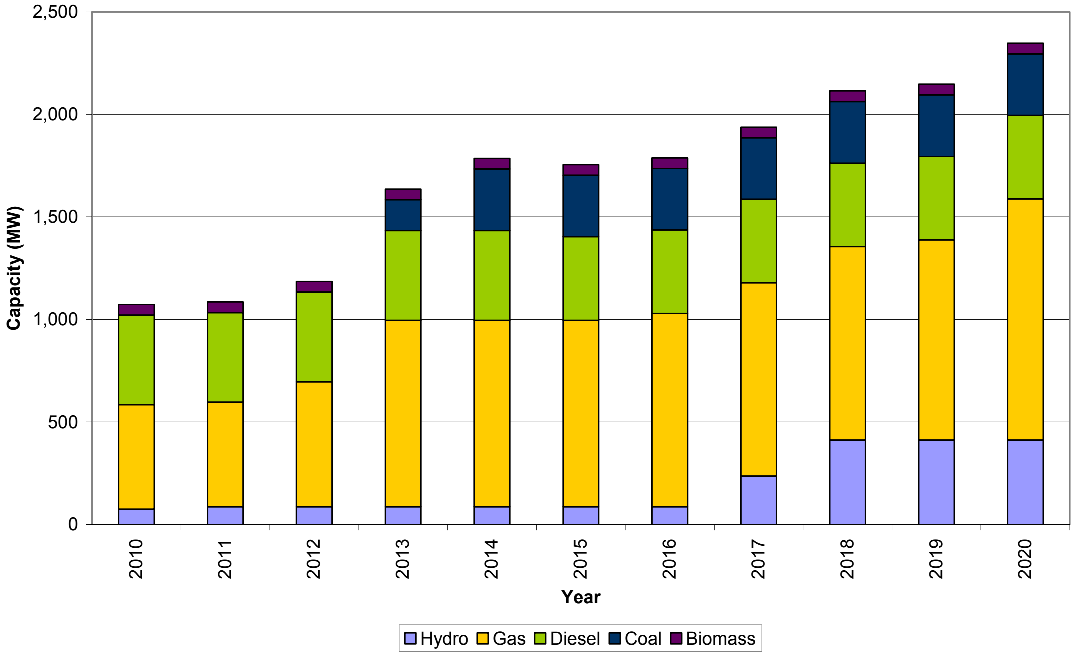
To meet the anticipated increase in the power demand, the power utility company, Sabah Electricity Sdn Bhd (SESB), has announced through press releases available at its website a plant-up plan [13]. Based on that information, the plant-up plan can be summarized as shown in Figure 3. Based on the planned capacity in 2020, the fuel mix for Sabah power sector will consist of gas (50%), hydro (18%), diesel (17%), coal (13%) and biomass (2%). The plan is to maintain a minimum reserve margin of 30%. It is expected that most of the diesel power plants will be de-commissioned over the period of the next 10 years. These diesel power plants are mostly old, inefficient and unreliable.

3. Emission Reduction Technologies

3.1. Renewable Energy

Renewable energy is defined as "energy flows which are replenished at the same rate as they are used" [14]. The RE sources that are commonly being explored include solar, wind, waves, tides, biomass, and geothermal energy. Most of these sources, except for tidal and geothermal energy, derive their energy directly or indirectly from solar energy [15].

Figure 3. SESB plant-up plan.



Solar radiation can be converted directly into useful energy using photovoltaic (PV) modules and solar-thermal electric power generation plants. Furthermore, the various natural phenomena including wind, ocean waves, rain and flowing rivers are driven by solar energy. All these natural phenomena can be tapped to generate useful energy. Photosynthesis in plants is also powered by the solar energy to convert water and carbon dioxide into carbohydrates or biomass, which can be used as fuel for power generation.

Tides, on the other hand, are generated by the rotation of the Earth and gravitational fields of the Moon and Sun. The flowing currents and the rising and subsiding of ocean water levels resulting from the tides can be tapped for power generation.

Geothermal energy refers to the heat from within the Earth. It is also a source of energy for power generation. It is originally generated from the gravitational contraction during the Earth's formation stage. The decay of radioactive materials within the Earth's core continuously enhances the geothermal energy.

The costs for wind power plant was found to be exceptionally high as computed in [6]. This is due to the low available wind speed and hence a low effective plant factor of only 8.76%. Therefore, it is not included in this study. Solar radiation, hydro and biomass from palm oil waste were found to be promising sources of RE in Sabah [5,6,9,16]. This paper presents a case study on these sources of energy in scenarios S1, S2 and S3, to be described in the following section. Other sources of RE are either too low in energy intensity for economical exploitation, or dependent on energy conversion technologies which are under development and not yet commercially available.

3.2. Supply Side Energy Efficiency

The efficiency of the combustion technologies adopted by power plants are having a significant impact on the GHG emissions, energy resources utilization, energy security and power generation costs. Fossil fuels are the main energy sources in the power generation industry. In 2005, coal contributed to 48% of the total power generation in the Asia Pacific Economic Corporation (APEC) countries, while natural gas contributed to another 18% [17]. Together, they contribute to more than 60% of the total power generation and will continue to play a major role in the foreseeable future. Research and development work on coal and natural gas combustion technologies has occurred continuously in the past 90 and 60 years, respectively. However, the most advanced and efficient technologies normally carry a premium price. Therefore, commercial power plant operators do not always adopt the most efficient option available due to their high capital costs. In this paper, the option of deploying high efficient plants in the combustion technologies for both the coal and gas power plants is studied in scenario S4 and S5 to be described in the following section.

3.3. Demand Side Energy Efficiency

According to a study by the US Energy Information Administration, energy efficiency can potentially account for more than half of the total saving in GHG emissions for the "450 Scenario", whereby the long range CO_2 concentration in the atmosphere is to be maintained at 450 ppm [18]. A successful energy efficiency measure shall be comprehensive; be customizable; deliver additional benefits such as cost savings and increased productivity to the users, and involve partnerships [19,20]. The measures are typically implemented through the following frameworks:

a. Policy and regulatory: These measures include energy price rationalization, reducing import duties, subsidization, appliance efficiency standards and labeling, and building energy efficiency codes.
b. Institutional: These measures include public information programs and training on energy efficiency.
c. Financial: These measures include affordable financing and financial incentives for the purchase of energy efficient appliances.

In Malaysia, the energy efficiency policy can be summarized in the following measures:

a. Enforcing the Efficient Management of Electricity Energy Regulation 2008 to ensure more efficient use of electricity among large users.
b. Incorporating the Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings (MS1525:2007) into the Uniform Building By-Laws (UBBL).
c. Promoting the use of highly energy-efficient appliances and equipment.
d. Developing local expertise in the manufacture of energy-efficient appliances and equipment.
e. Improving energy efficiency in government buildings.
f. Developing human capacity in the area of energy efficiency.

In this paper, only the first three measures (a, b and c) above will be investigated in scenarios S6, S7 and S8. For the other measures, there is insufficient data to establish the direct effect of these measures.

3.4. Transmission, Distribution and Ancillary Technologies

In the modern power system architecture, centrally located generation feeds the demands via transmission and distribution networks. Large generators supply electrical power to the transmission system via generator transformers. The transmission system transports the power over long distance in a single direction. Distribution networks are connected to the transmission system via distribution transformers for final distribution to the customers.

With the recent emphasis on renewable and alternative energy sources, there is an increasing necessity to connect a large number of small and dispersed generators to the weaker distribution networks. Furthermore, the dispatch of these generators is not controlled directly by the central network operator. This has created a number of technical issues for the existing networks, which are designed based on the central nature of generation and single direction electrical power flow in the network. To address these technical issues, network designs have to be updated with incorporation of new features. The enhanced network is generally referred to as the smart grid. It is designed mainly to: (a) assist in demand side management; (b) enable the integration of RE sources (distributed generation) with the distribution networks; (c) increase reliability of power supply and (d) reduce transmission and distribution losses [21]. To cater for the intermittent nature of some renewable energy sources, energy storage technologies are also being developed to enable wider adoption of these renewable energies.

As these technologies are merely complementary to other emission reduction technologies, they are not investigated as an independent scenario in this study. Among all the scenarios investigated, distributed generation is included only in S1 where PV panels are applied. However, the maximum penetration is only 3.63%. The penetration rate is low compared to the 20% penetration limit for the utility system as found in the literature review [22]. Therefore, it is assumed that it will not impose any issues associated with distributed generation and hence smart grid technologies are not implemented. To cater for the intermittent nature of PV sources, additional conventional power plant capacity is included so that the peak demand can be met even if there is no power output from the PV panels due to unavailability of sun light. In addition, in scenario S9, the transmission loss over the 500 km of transmission line linking to Bakun hydropower plant is taken into consideration.

4. Methodology

The Long-range Energy Alternatives Planning (LEAP) energy modeling and scenario planning tool was used in this study. It is used to track energy use, production and resource extraction in all sectors of an economy [23]. Using an annual time step, LEAP is suitable for modeling a national energy system, with the ability to project forward for an unlimited number of years. It can simulate all sectors, all technologies, all emissions and all costs within an energy system. With the built-in powerful scenario manager, it is able to generate multiple self-consistent storylines to describe different policy measures for comparison. It has a wide user base of more than 5,000 users in 169 countries, with more than 40 reports published based on its simulation results [24].

The following steps are carried out in this study:

1. Constructing the energy model for Sabah;
2. Creating GHG emission reduction scenarios;
3. Evaluating financial and GHG emission for every scenario; and
4. Assessing cost effectiveness in every scenario.

4.1. Sabah Energy Model in LEAP

The demand and supply model of the electrical system in Sabah was first modeled in LEAP. The model was constructed using the following data:

- Sabah electricity demand projection over the next 20 years from 2010 to 2030.
- The power plant-up plan over the next 20 years.
- Hourly load demand profile.
- Life-span, capital cost and other essential operating and maintaining expenditures for all electricity generation options.

The details of this data are presented in Section 5.

4.2. GHG Emission Reduction Scenarios

A reference scenario (S0) is first created in LEAP. This is the reference scenario in which no effort is carried out to reduce the CO_2 emissions. All new gas and coal power plants to be procured after 2010 are assumed to possess the national average efficiency of 33.15% and 45.2% respectively [25]. Combined cycle gas power plants are assumed in this scenario as all the recent gas power plants installed in the recent years belong to this type. Based on S0, other scenarios with GHG emission reduction options as discussed above are created to study the financial and environmental implications of applying the various carbon reduction technologies as summarised in Table 1.

Table 1. Key technologies applied in the scenarios.

Scenario	Technologies
S0	Business as usual
S1	Solar Photovoltaic cell
S2	Hydropower
S3	Biomass from palm oil waste
S4	Supply side energy efficiency–advanced combustion technology
S5	Carbon capture technology
S6	Demand side energy efficiency–Industrial Sector
S7	Demand side energy efficiency–Building
S8	Energy efficient device–Energy saving bulbs
S9	Energy import from Bakun

Scenario S1–PV: Based on S0, PV panel is added to the fuel mix in this scenario. The Renewable Energy Policy [10] has set a target to achieve 17% RE penetration in 2030, out of which 3.63% will be from PV panels. The PV panel capacity is ramped up from 0% to the targeted amount in 2030 in this scenario. The other power plant capacities are maintained as per S0 so that the peak demand can be met even if there is no power output from the PV panels due to unavailability of sun light.

Scenario S2–Hydropower: In this scenario, hydropower is prioritized in the plant up plan. It is utilized to the fullest to meet the power demand, based on available potential. In the previous studies carried out on hydropower in Sabah, 68 sites were identified to be suitable for hydropower projects, with a combined capacity of 1900 MW [26]. Hence, in this scenario the hydropower capacity is ramped up to the maximum 1900 MW. The other fuel types are increased based on the prevailing ratio among them to meet the projected power demand.

Scenario S3–Palm Oil Waste: In this scenario, the biomass from palm oil waste is exploited to the fullest to meet the projected power demand. There were 1.36 million hectares of oil palm plantations in Sabah in 2009 [27] and the area is growing at the annual rate of 2.1%. The growth rate is expected to decrease to reach zero in 2020. Due to the relatively low energy density of the biomass, it may not be economical to transport the biomass waste from the plantations for power generation. Instead, power plants should be built next to the existing palm oil processing plants so that the feedstock can be obtained directly from the existing processing plants, with minimum transportation. It was found that the processing plants with a minimum capacity of 60 ton per hour will be able to provide sufficient feedstock to the biomass power plants for effective operation [26]. It is computed that, in 2010, the total electricity that can be generated from these potential sites is 3300 GWh. This available capacity is incorporated into the fuel mix in this scenario, assuming the growth rate being consistent with that of the plantation areas. The other fuel types are increased based on the prevailing ratio among them to meet the projected power demand.

Scenario S4–Efficient Power Plant: In this scenario, all the new gas and coal power plants to be procured after 2010 are assumed to be of the most efficient types available. The coal power plants shall be of ultra-supercritical pulverised coal combustion (PCC) type with the thermal efficiency of 50% [17]. The gas power plants shall be based on the most advanced Class H turbine in the combined cycle configuration to achieve the plant thermal efficiency of 60%. In addition, all the gas power plants commissioned before 2010 are to be upgraded in 2016 and 2020 to increase their thermal efficiencies to 60%. The timing of their upgrades was chosen to coincide with the time for major refurbishments of all the power plants. Generally, a power plant requires a major refurbishment once every 10 years, starting from the time of its commission [17]. The refurbishment exercise does not include coal power plants as all the coal power plants are to be commissioned after 2010.

Scenario S5–Efficient Power Plant and Carbon Capture and Storage (CCS): In this scenario, the advanced combined cycle gas turbine power plants with the thermal efficiency of 60% as per S4 are assumed for the all new gas plants. For the new coal power plants, CCS technology is to be adopted. The integrated gasification combined cycle (IGCC) technology is adopted because the CCS technology is found to be more effective when used with the IGCC technology. The overall thermal efficiency of the resulted IGCC plants is 33.9% [28].

Scenario S6–Industrial Energy Efficiency: In this scenario, the findings from the Malaysian Industrial Energy Efficiency Improvement Project (MIEEIP) are implemented [29]. It was found that, on an average, the electricity use of the industrial sector can be reduced by 5.6% following the recommendations of MIEEIP [30]. Therefore, the energy demand from the industrial sector is reduced by 5.6% in this scenario.

Scenario S7–Energy Efficient Buildings: In this scenario, the benefits of energy efficient buildings are investigated. As part of the efforts in promoting energy efficiency, Malaysia will amend the Uniform Building By-Laws (UBBL) to incorporate energy efficiency of buildings [31]. The UBBL will likely to adopt Malaysian Standard MS 1525:2001 "Code of Practice on Energy Efficiency and use of Renewable Energy for Non-residential Buildings" which requires the yearly energy use of a commercial building shall be below 135 kWh/m^2. Based on the study of LEO building [32], the annual energy use of commercial buildings can be reduced from 275 kWh/m^2 to 114 kWh/m^2, with additional energy efficient features incorporated during the construction stage. Therefore, in this scenario, it is assumed that all new commercial buildings will have an annual energy use of 114 kWh/m^2.

Scenario S8–Energy Saving Light Bulbs: As part of the Malaysian government's efforts in Energy Efficiency, the country will stop the production, import and sale of incandescent light bulbs by 2014 [33]. It was found that the measures will reduce the electricity use by 1%. In this scenario, this energy saving measure is incorporated.

Scenario S9–Import Electricity from Bakun Hydropower Plant: The Bakun hydropower plant in Sarawak is scheduled to start generating electricity in 2011, with 2400 MW capacity to be added to the grid in stages. With the submarine cable project to transfer power to West Malaysia aborted, there will now be a surplus of generation capacity in Sarawak. Up to 400 MW of the excess capacity can be fed to meet the demand of Sabah via a 275 kV HVAC line [34], which will incur a 7.5% transmission loss. In this scenario, the 400 MW imported power is included.

4.3. Financial and GHG Emission Evaluation

From the energy model, the aggregated cost, GHG emissions and electricity output can be calculated using the following equations:

$$C0 = \sum_i \sum_j c0_j^i \tag{1}$$

$$G0 = \sum_i \sum_j g0_j^i \tag{2}$$

$$E0 = \sum_i \sum_j e0_j^i \tag{3}$$

where:

$C0$: Aggregated cost of all electricity generated over the projection period for S0. The cost includes annualised capital cost, variable operation and maintenance (O&M) cost, fixed O&M cost and fuel cost. (RM)

$c0_j^i$: Generation cost using technology i in year j for S0. The cost includes annualised capital cost, variable O&M cost, fixed O&M cost and fuel cost. (RM)

i: Index for type of power generation technology in the simulated scenario

j: Index for year in the simulation period

$G0$: Aggregated GHG emissions of all electricity generated over the projection period for S0. (ton CO_2 equivalent)

$g0_j^i$: GHG emissions using technology i in year j for S0. (ton CO_2 equivalent)

$E0$: Aggregated electricity output over the projection period for S0. (kWh)

$e0_j^i$: Electricity output using technology i in year j for S0. (kWh)

Using Equations (1)–(3), the following parameters can be calculated:

Unit electricity cost (RM per kWh): $$CE0 = \frac{C0}{E0} \quad (4)$$

GHG emission factor (ton per kWh): $$GF0 = \frac{G0}{E0} \quad (5)$$

Similarly, for each scenario SX (where X = 1 to 9), CEX (unit electricity cost for scenario X) and GHX (GHG emission factor for scenario X) can be calculated.

Unit electricity cost (RM per kWh): $$CEX = \frac{CX}{EX} \quad (6)$$

GHG emission factor (ton per kWh): $$GFX = \frac{GX}{EX} \quad (7)$$

4.4. Cost Effectiveness Assessment

Using the results in Equations (4)–(7), the cost per unit emission avoided (RM per ton CO_2 equivalent) and incremental electricity cost (RM per kWh) can be calculated for each scenario SX using the following equations:

Incremental electricity cost: $$CIX = CEX - CE0 \quad (8)$$

Cost per unit emission avoided: $$CGX = \frac{CIX}{GF0 - GFX} \quad (9)$$

Based on the computed CGX in Equation (9) above, the scenario with the lowest CGX is the most cost effective measure.

5. Source Data

5.1. Source Data for Energy Model

Sabah electricity demand projection for the next 20 years from 2010 to 2030 was obtained from the Sabah Development Corridor (SDC) Blueprint [12] as per Figure 2. The existing and new power plants from 2010 to 2020 were modeled based on SESB plant-up plan as shown in Figure 3. Within the 10-year period, new plants are to be built based on a capacity ratio of 2:1:1 for gas, coal and hydro power plants, respectively. From 2020 to 2030, new power plants were included in the model following the same ratio to maintain a minimum reserved margin of 30% [12].

The system load curve was computed based on the average daily load profile [26] and the latest daily maximum demand load obtained from SESB. The hourly demand load profile was computed and compiled from the source data as shown in Figure 4 and Figure 5. It is noted from Figure 5 that the peak load of 100% occurred on day 270, which is corresponding to the maximum demand of 704 MW. The computed system load profile is presented in Figure 6. The resulted load profile has an average load factor of 74.12%, which is consistent with the statistics published by the Energy Commission, Malaysia [25].

Figure 4. Hourly-load profile of Sabah electrical grid.

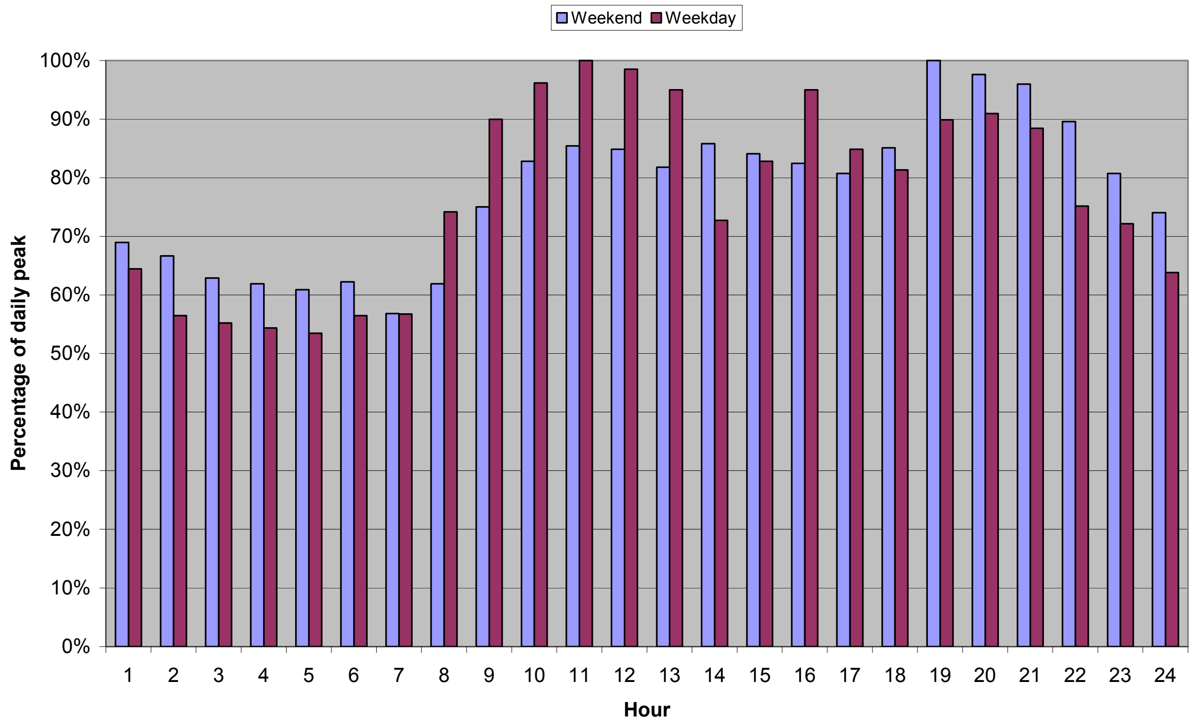


Figure 5. Daily maximum demand of Sabah electrical grid from 1 September 2008 to 31 August 2009 (Note: 100% load corresponding to 704 MW).

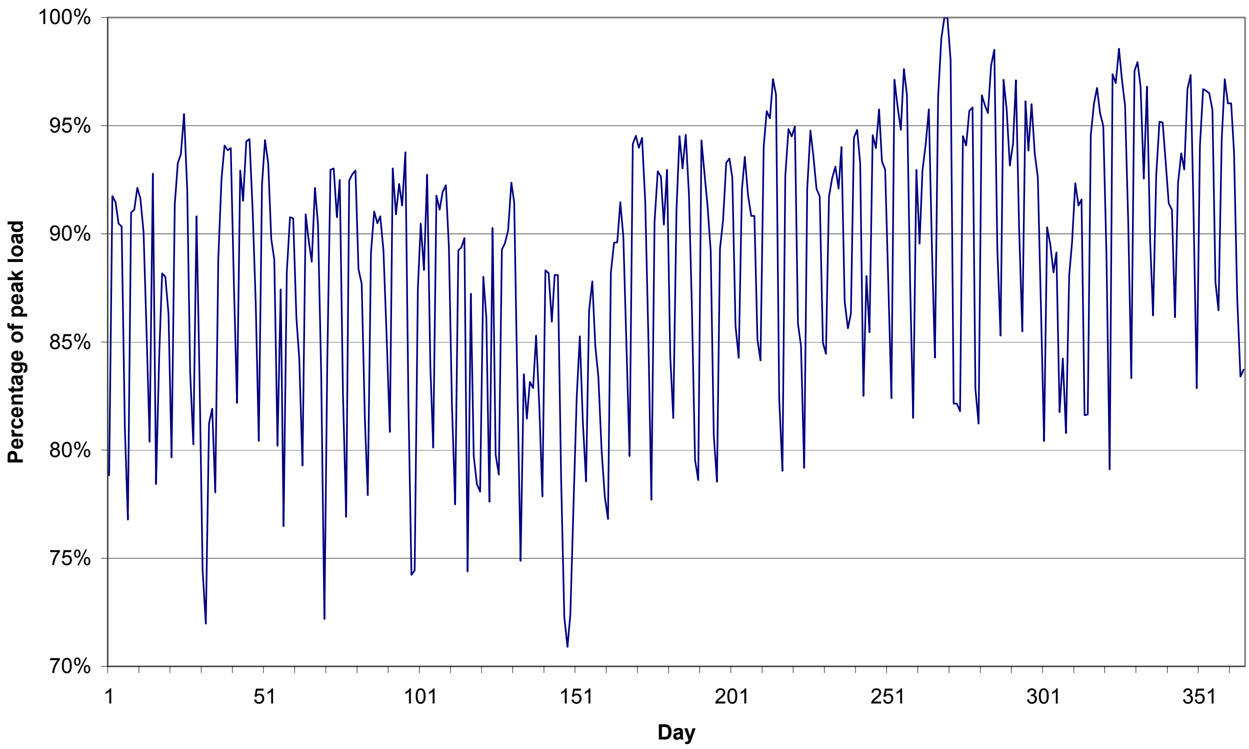
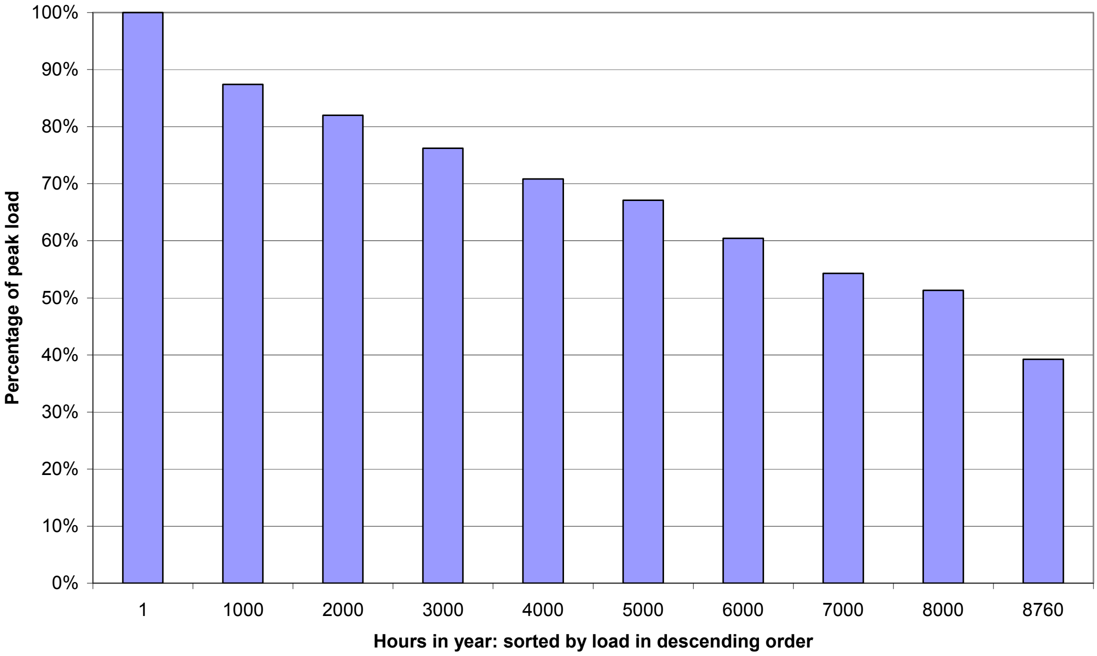


Figure 6. System load profile for Sabah electrical grid.



5.2. Source Data for Financial Assessment

The required input source data for financial computation are summarised in Table 2. Items 11, 12 and 13 of the table are the measures to reduce electricity use. They do not involve power generating technologies.

Table 2. Key parameters for cost analysis in LEAP.

No	Technology (Scenario)	Plant Life Time (Years)	Efficiency (%)	Capital Cost [RM (US$)/kW]	Fuel cost [RM (US$)/kWh output] [a]	Fixed O&M cost [RM (US$)/kW/Year]	Variable O&M cost [RM (US$)/GJ]
1	Hydro (S0, S2)	50 [b]	47 [b]	12270 [c] (3506)	0	173.25 [b] (49.50)	0.4200 [b] (0.1200)
2	Diesel (S0)	20	31 [b]	1200 [c] (343)	0.5100 [d] (0.1457)	0 [e]	6.0278 [f] (1.7222)
3	Biomass (S0,S3)	20 [b]	33 [b]	10762 [b] (3075)	0 [g]	27.30 [b] (7.80)	10.2200 [b] (2.9200)
4	Open Cycle Gas (S0)	20 [b]	28.7 [b]	3600 [c] (1029)	0.1272 [h] (0.0363)	177.21 [b] (50.63)	1.9600 [b] (0.5600)
5	Combined Cycle Gas (S0)	20 [b]	45.2 [b]	6000 [c] (1714)	0.0808 [h] (0.0231)	128.10 [b] (36.60)	2.2050 [b] (0.6300)
6	Conventional PCC Coal (S0)	30 [b]	33.15 [b]	5167 [c] (1476)	0.0664 [j] (0.0190)	241.50 [b] (69.00)	2.5200 [b] (0.7200)
7	PV (S1)	20 [b]	NA	28000 [k] (8000)	0	31.50 [b] (9.00)	4.3750 [b] (1.2500)

Table 2. *Cont.*

8	Advanced Combined Cycle Gas – Class H (S4,S5)	20 [b]	60	7820 [i] (2234)	0.0608 [h] (0.0174)	128.10 [b] (36.60)	2.2050 [b] (0.6300)
9	Advanced Ultra-supercritical PCC Coal (S4)	30 [b]	50	8877 [l] (2536)	0.0440 [j] (0.0126)	235.25 [b] (67.21)	2.6250 [b] (0.7500)
10	IGCC with CCS (S5)	20 [b]	33.9	9983 [m] (2852)	0.0649 [j] (0.0185)	315.00 [b] (90.00)	13.6500 [b] (3.900)
11	Industrial Energy Efficient Project (S6)	10 [n]	NA	1226 [o] (350)	0	0	0
12	Energy Efficient Buildings (S7)	10 [n]	NA	14009 [p] (4003)	0	0	0
13	Energy Saving Bulbs (S8)	Not Applicable	NA	0 [q]	0	0	3.0193 [q] (0.8627)
14	Import from Bakun (S9)	50	NA	2025 [r] (579)	0	0	33.0330 [s] (9.4380)

Note: [a] Fuel cost was computed separately and added to the LEAP analysis; [b] Data based on findings in [35]; [c] Cost computed based on SESB press release [13,36]; [d] Based on current subsidised diesel price of RM 1.70 per litre and average generator consumption of 0.3 litre per kWh output; [e] All O & M (operation and maintenance) costs for diesel plant are lumped in the variable O & M cost; [f] Cost obtained from [26]; [g] Zero fuel cost was assumed for the biomass plant as all the plants are to be built at the existing palm oil processing factories; [h] The fuel price is computed using subsidised gas price of RM 10.70 per mmbtu [37] in Malaysia and the corresponding plant efficiency for the respective technology; [i] Additional USD 520 per kW based on previous research [17] is added to the capital cost of a standard combined cycle gas plant of RM 6000 per kW; [j] The fuel cost is computed based on 2009 Indonesian coal price of USD 30.72 per ton for the coal grade of 4200 kCal/kg [38] and the corresponding plant efficiency of the technology; [k] Capital cost of PV includes installation of complete system [16] and assumed to reduce annually by 3.6% [39]; [l] Additional USD 1060 per kW based on previous research [17] is added to the capital cost of a conventional PCC coal plant of RM 6000 per kW; [m] Additional USD 316 per kW based on previous research [35] is added to the capital cost of a conventional PCC coal plant of RM 6000 per kW; [n] Conservative assumption of 10 years for mechanical and electrical equipments; [o] Additional capital cost invested to achieve the energy savings computed based on the MIEEIP findings [29,31,40], whereby an upgrade of RM 100.4 million resulting in annual energy saving of 2.583 million GJ; [p] Additional capital cost invested to achieve the energy savings computed based on: the LEO building results [32] whereby the additional energy efficient features increase the construction cost by 10.10% and result in the reduction of average annual energy use from 275 kWh/m^2 to 114 kWh/m^2; and the average commercial building construction cost of RM 2217.51 per m^2 in Sabah [41,42]; [q] The additional cost of purchasing compact fluorescent bulbs (14W, 8000 hours lifetime, 760 lumen, RM 20) [43] instead of incandescent lamp (60 W, 1000 hours lifetime, 630 lumen, RM 2) [44] is normalised to amount of energy saved over the lifetime (RM/kWh) and input as variable O&M cost for LEAP modeling purpose; [r] Capital cost of the 500 km 275 kV HVAC transmission line [6]; [s] The electricity purchased cost of RM 0.11 per kWh from Bakun hydropower plant [6] is input as the flexible O&M cost for LEAP modeling purpose, including 7.5% of transmission loss in the 500 km transmission line; [t] A foreign currency exchange rate of USD 1 = RM 3.50 applied for all above calculation; [u] All costs used in this paper are nominal current price

The LEAP program in this study has been configured to dispatch the available plant capacity dynamically according to the hourly load profile, based on the following parameters:

Maximum availability: A maximum allowable plant factor of 0.80 is assumed for all technologies, except that of PV. The PV plant factor of 18% is based on actual solar radiation resource profile measured in Malaysia [16].

Merit order: The merit order determines the order in which plants are to be dispatched when the load increases, in ascending order. The following merit order is used:

1. Hydro, biomass and PV
2. Advanced coal plants
3. Conventional coal plants
4. Advanced combined cycle gas plants
5. Conventional combined cycle gas plants
6. Open cycle gas plants
7. Diesel plants

The hydro plants in Sabah enjoy a very high plant factor of more than 80% and can be dispatched to meet the base load. The biomass plants and PV, on the other hand, being renewable energy plants, are the preferred choice of energy sources. All the three sources of energy are to be utilised to their fullest, hence making them to be the highest priority. If the total capacity of all the hydro and biomass plants is not sufficient to meet the base load, then the coal plants will be dispatched because of the lower generation cost. It is assigned a second highest priority after the hydro, PV and biomass. The gas plants are able to respond fast to load changes and are suitable for meeting the peak load. Among the gas plants, the most efficient advanced combined cycle gas plants are given a higher merit order, followed by the conventional combined cycle gas plants and then the open cycle gas plants. Diesel plants are being phased out because of the high cost and high emission factor. They are assigned the lowest priority and to be dispatched only when all other plants are exhausted. The annualized capital cost is computed using an interest of 6% according to the following Equation:

$$\text{Annualized Capital Cost} = \text{Total Capital Cost} \times \text{CRF} \tag{10}$$

where:

$$\text{CRF (Capital Recovery Factor)} = \frac{i \times k}{(k-1)}$$

$k = (1+i)^n$

$i =$ annual interest rate

$k =$ plant lifetime (years)

5.3. Source Data for GHG Emission Assessment

The IPCC (Intergovernmental Panel on Climate Change) tier 1 emission factors within the LEAP database were applied for all the power generation processes except the CCS technology and hydropower. For the IGCC with CCS option, the CO_2 emission factor of 0.089 ton/MWh is adopted as described in [28]. For the hydropower, an emission factor of 0.090 ton/MWh is used, adopting the

Clean Development Mechanism (CDM) criteria for hydropower power dam with energy density of 4 to 10 W/m^2. For the option in S9 whereby electricity is imported from Bakun, an additional 7.5% is added to account for the losses over the 500 km transmission line.

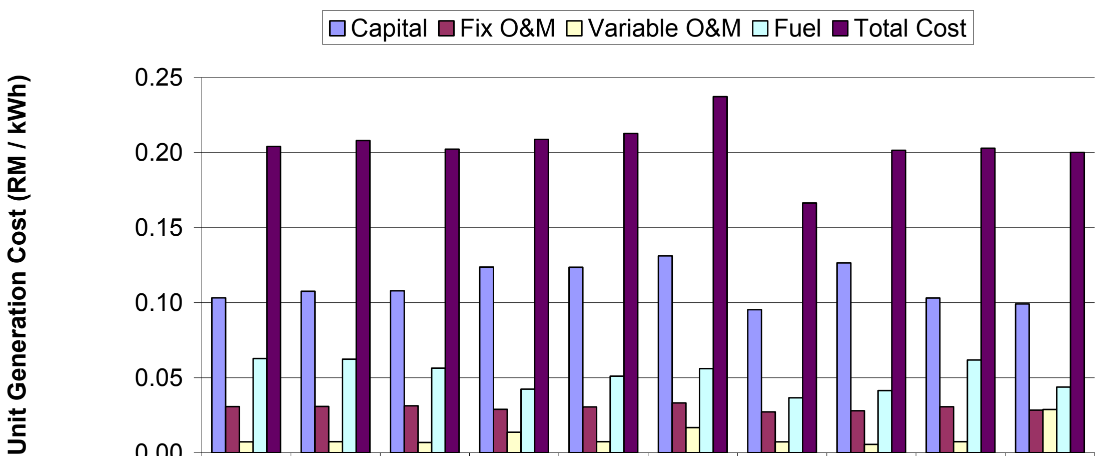
6. Results and Discussion

Using the output data obtained from the LEAP model, the results are computed and analyzed in terms of electricity cost, GHG emissions and sensitivity to fuel price increase.

6.1. Cost

The output data from LEAP for all the scenarios are exported for further computations using Equations (1), (3), (4) and (6) to obtain the unit electricity costs plotted in Figure 7. The annualized capital costs, fixed O & M costs, variable O & M costs and fuel costs are considered and shown in this figure. The LEAP program considers only the annualized capital costs for capacity added during the simulation period. The capital cost of the existing power plant at the start of the simulation is not included in the program output. In order to maintain the consistency with the analysis of the unit generation cost for the various technologies, the annualized capital costs were computed and included in the graph for all existing power plants.

Figure 7. Unit electricity cost for all the scenarios invested.

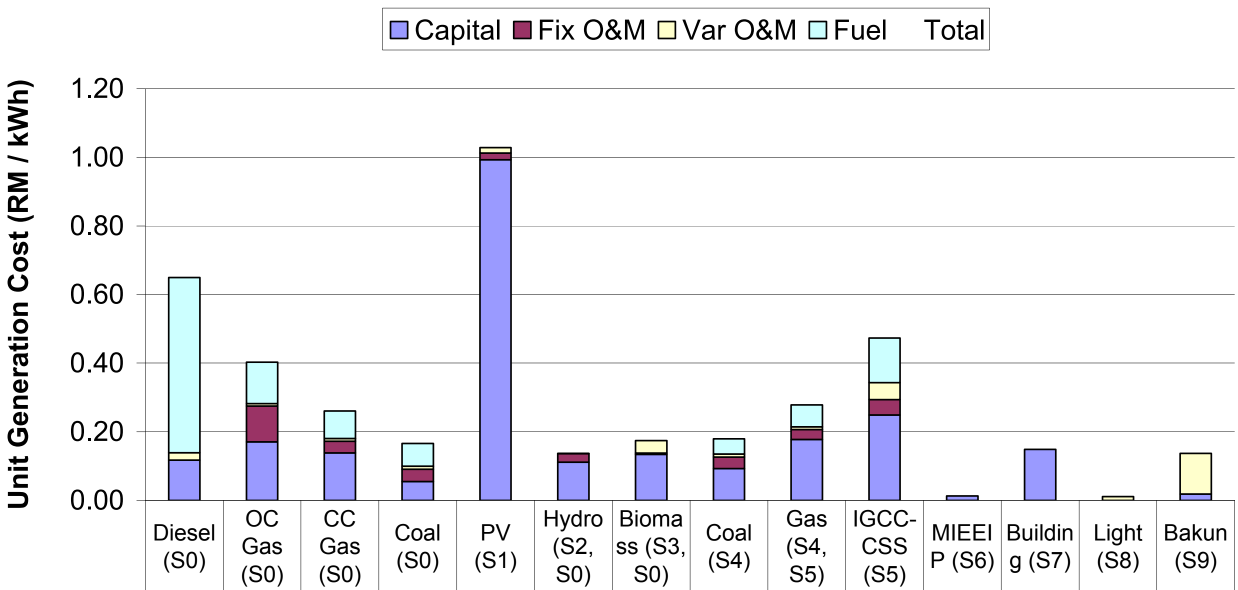


	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
Capital	0.10	0.11	0.11	0.12	0.12	0.13	0.10	0.13	0.10	0.10
Fix O&M	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Variable O&M	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.03
Fuel	0.06	0.06	0.06	0.04	0.05	0.06	0.04	0.04	0.06	0.04
Total Cost	0.20	0.21	0.20	0.21	0.21	0.24	0.17	0.20	0.20	0.20

It can be seen from Figure 7 that the electricity cost of RM 0.17 per kWh in S6 is lower than that of S0, which is RM 0.20 per kWh. It shows that the energy efficiency measures recommended in MIEEIP are very cost effective in achieving a significant saving in electricity usages with low capital investment. The electricity cost in S2, S7, S8 and S9 are similar to that of S0, at RM 0.20 per kWh. The costs in S1, S3 and S4 are marginally higher, at RM 0.21 per kWh or 5% higher than S0 cost. The cost of RM 0.24 per kWh in S5 is the highest. It is 20% higher than that of S0.This is mainly due to the higher capital cost and variable O&M cost of the CCS technology used. Figure 8 shows the computed average unit cost of electricity generation for all the technologies considered in this paper. The costs are obtained by computing the average generation cost for each technology in all the scenarios. In this figure, among the technologies currently used in S0, the electricity cost from diesel power plants is highest at RM 0.65 per kWh. This is followed by that of the open cycle gas turbine power plants of RM 0.40 per kWh. These plants are used only to meet the peak demands. The electricity costs of the other technologies in S0 are in between RM 0.14 and RM 0.26 per kWh.

The PV panel in S1 results in the highest electricity cost of RM 1.03 per kWh. It is 415% above the average cost of RM 0.20 per kWh in the reference scenario. This is followed by that from IGCC-CCS plants at RM 0.47 per kWh, or 135% higher than the S0 average cost. The electricity costs from the other technologies in the alternative scenarios (S2, S3, S4, S5 and S9) are in between RM 0.14 and RM 0.28 per kWh.

Figure 8. Average unit cost of power generation for all technologies.



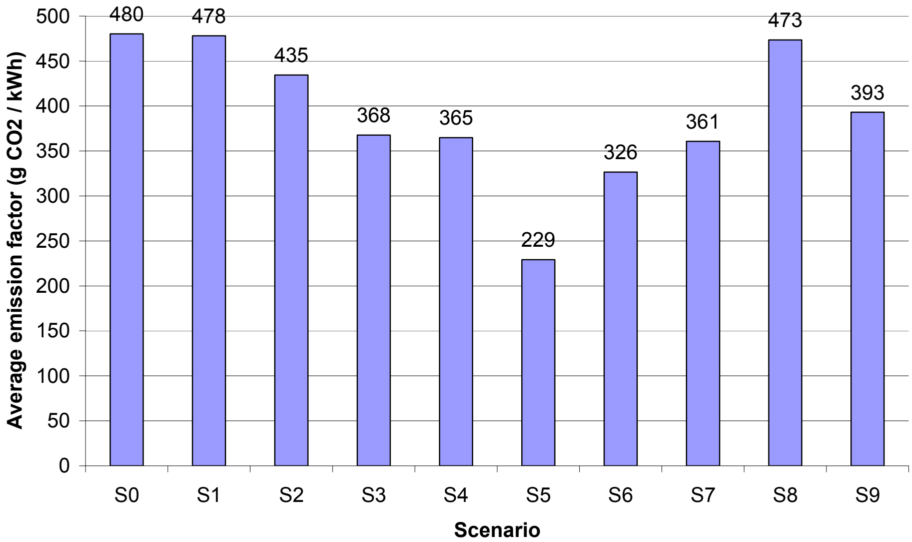
	Diesel (S0)	OC Gas (S0)	CC Gas (S0)	Coal (S0)	PV (S1)	Hydro (S2, S0)	Biomass (S3, S0)	Coal (S4)	Gas (S4, S5)	IGCC-CSS (S5)	MIEEIP (S6)	Building (S7)	Light (S8)	Bakun (S9)
Total	0.65	0.40	0.26	0.17	1.03	0.14	0.17	0.18	0.28	0.47	0.01	0.15	0.01	0.14
Fuel	0.51	0.12	0.08	0.07	0.00	0.00	0.00	0.04	0.06	0.13	0.00	0.00	0.00	0.00
Var O&M	0.02	0.01	0.01	0.01	0.02	0.00	0.04	0.01	0.01	0.05	0.00	0.00	0.01	0.12
Fix O&M	0.00	0.10	0.03	0.04	0.02	0.02	0.00	0.03	0.03	0.05	0.00	0.00	0.00	0.00
Capital	0.12	0.17	0.14	0.05	0.99	0.11	0.13	0.09	0.18	0.25	0.01	0.15	0.00	0.02

The energy efficiency measures in S6, S7 and S8 are found to be very cost effective. The cost to achieve the energy saving in S6 and S8 is merely RM 0.01 per kWh of electricity saved. The cost in S7 is RM 0.15 per kWh.

6.2. GHG Emission Reduction

The output data from LEAP for all the scenarios are exported for further computations using Equations (2), (3), (5) and (7) to obtain the unit GHG emission factor for all the scenarios as plotted in Figure 9.

Figure 9. Average GHG emission factor for all scenarios.



It can be seen from Figure 9 that the emission factor for S0 is 480 g CO_2 equivalent per kWh. The emission factors of all the alternative scenarios are lower, ranging from 229 to 478 g CO_2/kWh. The highest reduction is achieved in S5, using IGCC-CCS technology to reduce the emission factor by 52% to 229 g CO_2/kWh. Only marginal reduction of the emission factor is achieved in S1 and S8, by 0.4% and 1.5% respectively.

6.3. Cost Effectiveness

The cost of GHG emission avoided is computed using Equation (9) and summarised in Table 3. From the table, it can be seen that the cost in S1 is the highest, at RM 1798.83 per ton CO_2 avoided. In comparison, the CO_2 is traded at around RM 50.80 (12.70 Euro) per ton at European Climate Exchange [45], based on the current spot price retrieved on 7 July 2010 for CER (Certified Emission Restrictions) for the CDM scheme from the European Climate Exchange. Therefore, the cost of using PV panels for emission reduction is much higher than the prevailing market price.

Table 3. Cost of GHG emission avoided.

Scenario	[A] Emission Factor (g CO_2/kWh)	[B] Unit Cost (RM/kWh)	[C] = ([B] − [B0])/([A0] − A) Cost of Emission Avoided (RM/ton CO_2)
S0	A0 = 480.2602	B0 = 0.2042	-
S1	478.0643	0.2081	1798.83
S2	434.5562	0.2023	−40.54
S3	367.6682	0.2088	41.25
S4	364.8380	0.2127	74.16
S5	229.1243	0.2373	131.78
S6	326.4213	0.1665	−245.20
S7	360.8535	0.2016	−22.07
S8	473.4192	0.2029	−188.47
S9	393.1160	0.2001	−46.71

The negative values for S2, S6, S7, S8 and S9 indicate that the costs of electricity for these scenarios are lower than that of S0. Therefore, by implementing these measures, GHG emission can be cut down while reducing the cost of electricity. For S3, S4 and S5, the costs are in between RM 41.25 and RM 131.78 per ton CO_2 avoided. This compares well with the price of CER at RM 50.80 per ton. Therefore, most, if not all, of the cost can be paid back through the CDM by implementing these measures.

6.4. Sensitivity to Fuel Prices

In Malaysia, natural gas is heavily subsidized in the power generation sector. The price of natural gas for power sector is fixed at RM 10.70 per MMBTU, compared to the market price of RM 41.16 per MMBTU in December 2009 [37]. By removing the subsidy on natural gas, the impact on the electricity costs for all the scenario is investigated as shown in Table 4.

Table 4. The impact on electricity generation cost by removing subsidy on natural gas.

Scenario	Unit Electricity Cost with Subsidised Natural Gas (RM/kWh) [A]	Unit Electricity Cost with Unsubsidised Natural Gas (RM/kWh) [B]	[C] = ([B] − [A])/[A]*100% Percentage Price Increase
S0	0.20	0.31	51%
S1	0.21	0.31	50%
S2	0.20	0.29	45%
S3	0.21	0.28	34%
S4	0.21	0.30	40%
S5	0.24	0.32	36%
S6	0.17	0.23	37%
S7	0.20	0.27	35%
S8	0.20	0.31	51%
S9	0.20	0.27	37%

Table 4 shows that the cost increase 51% in S0 is the highest. S1 and S8 present a similar impact, with cost increases of 50% and 51%, respectively. Lesser impacts are shown in S3, S5, S6 and S9 as the cost increases are in the 34 % to 37% range. It is expected that increases in other fossil fuel prices will have a similar impact on the electricity price.

7. Conclusions

The energy efficient measures in S6, S7 and S8 are found to be effective in GHG emission reduction, which is consistent with other studies in the developed countries. The investment cost for energy efficiency is as low as RM 0.01 per kWh of electricity saved. This results in the average cost of electricity for these scenarios to be in between RM 0.17 and RM 0.20 per kWh. The emission factor is reduced significantly in S6 and S7, by 32% and 25% respectively. The PV panel, which has gained a wide adoption in the developed countries, is found to be very expensive to implement. The average electricity cost is RM 1.03 per kWh, which is significantly higher than the prevailing price. With such a high cost, only a very small penetration rate of PV is targeted in the Renewable Energy Policy of

Malaysia. With the modest penetration rate as modeled in S1, the emission reduction is negligible. It results in merely 0.4% of reduction in the emission factor. The rest of the scenarios (S2, S3, S4, S5 and S9) are more effective, with an emission factor reduction of between 9% and 52%. The advanced power plant technologies investigated also reduce the emission factor significantly in S4 and S5, by 24% and 52% respectively.

It is found that all the alternative scenarios are less sensitive to the fossil fuel price increase, compared to the reference scenario. Apart from S1, the costs of all the alternative scenarios are below RM 131.78 per ton CO_2 avoided. At the CER price of RM 50.80 per ton, a substantial portion of the cost for implementing these measures can be financed through CDM or other carbon trading schemes.

With the above findings, it can be concluded that, while the energy efficient measures are effective in both developed and developing countries, the other technologies such as renewable energy may not be effective. The high cost of the PV panels, for example, is not affordable for a wide implementation in the developing countries for any substantial emission reductions. Non-renewable energy technologies, such as the advanced power plant technologies investigated in S4 and S5 are found to be more effective and affordable in the environment of the developing countries. It is hoped that these findings will provide a better insight for the national and international policy makers in the developing countries. While drawing up green energy policies, all other less conventional green technologies should be taken into consideration to achieve the most significant impact in emission reduction with the available resources.

As Sabah is a developing economy with high projected growth, it is believed that the positive results obtained from this research are also applicable to other developing economies. However, there will be some differences in other economies such as the electricity demand growth rate, fuel mix and resources endowment, which may result in different levels of emission reductions and expenditures. A detailed study should be carried out for each target economy to obtain accurate results. Also, the possible implementation of a worldwide CO_2 tax will create impacts on the cost effectiveness of these measures. If such taxation is in place, any technology with high CO_2 emission factor will attract a high CO_2 tax and result in higher operation cost.

The scenarios described in this research show the influences of individual technologies on the electricity costs and GHG emissions. If multiple technologies are implemented together in one scenario, then the overall effect should be unique and studied separately as the influences of these technologies are mutually coupled.. Therefore, future research should be carried out to study the financial and environmental effects when multiple technologies are implemented together.

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